FINAL REPORT

PROJECT A-629

RESEARCH AND DEVELOPMENT OF A PERIODIC ANGULAR ROTATOR

WINSTON C. BOTELER
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LEE H. KNIGHT
JOYCE J. FOUST

Contract No. N600(204)-58449

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Prepared for
Commanding Officer
U.S. Navy School of Aviation Medicine
Pensacola, Florida

1964

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

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FOREWORD

This report contains a summary of the development and design of a rotating device for use in studying the behavior of the human vestibular system to an oscillating stimulus. The project was sponsored under the provisions of U. S. Navy Purchasing Office Contract No. N600(204)-58449. Mr. W. C. Hixson of the U. S. Navy School of Aviation Medicine, Pensacola, Florida acted as technical administrator for the work carried out under this contract.

ABSTRACT

A device capable of rotating or oscillating a human subject under closely controlled velocity and acceleration conditions is described. A direct drive D.C. torque motor driven by a rotating amplifier provides the motive power. The servo system operates in both position and velocity modes.

The device permits the oscillation of seated subjects about a vertical axis through the head at frequencies up to 1/2 cycle/sec. at an amplitude of ± 10 degrees. The minimum oscillating frequency is less than 0.002 cycles/sec. The device can be programmed for constant angular accelerations from 0.5 to 100 degrees/sec.^{2} and velocities from 0.05 to 600 degrees/sec. The device includes precision slip rings for transmission of D.C. power, instrumentation, and communications to and from the rotating chair. A fiberglas and plastic foam enclosure permits complete control of the ambient lighting around the subject. A relay and interlock system is provided to stop the chair in case of reference power supply failure, open hatches, excessive speed, excessive error signal, and other indications of system malfunction.

ACKNOWLEDGEMENTS

The function generator command system relay logic, and servo circuits were designed by Mr. Frank Williamson of the Special Problems Branch.

Joyce J. Foust wired the complete system, and debugged the unit during the operational tests. William Tucker constructed the enclosure and provided valuable assistance in all mechanical phases of the work. Mr. Lee H. Knight coordinated the final assembly and operational tests. The significant contributions of these people to the project is greatly appreciated.

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I. INTRODUCTION

The imminence of manned space laboratories has created a demand for more detailed information about the human vestibular system. Frequency response phenomena of the vestibular canals must be studied in a controlled laboratory environment if accurate quantitative data are to be obtained. Whole body response data obtained from astronauts are useful; however, because all the canals are stimulated simultaneously in the space environment, these data add little to the study of the basic canal behavior.

A detailed study of the frequency response phenomena requires that the subject be oscillated sinusoidally about one of the principal axes. Ideally, the stimulator would oscillate the subject without noise or vibration cues. The development of high torque D.C. servo motors has made it possible to design a direct drive stimulator. Noiseless, vibration free motion for subject stimulation can be produced by mounting the subject's chair directly on the motor shaft. The use of position control with rate feedback for the oscillating motion permits reversing the direction of rotation with no perceptible deadband. The specifications require a maximum angular acceleration of 100 degrees/sec^2 at 0.5 cycles/sec. This implies an amplitude of $\pm$ 10 degrees. These requirements were met by fabricating the enclosure of 3/4 inch thick plastic foam sheets sandwiched between thin coatings of fiberglas reinforced epoxy plastic.

II. GENERAL DESCRIPTION OF THE APPARATUS

The periodic angulator rotator consists of three major components; chair and pedestal, the D.C. servo controlled drive system, and the command functional generator. The rotating chair is mounted on the flange of a vertical shaft which is mounted in bearings in a fabricated steel pedestal. The shaft is driven by a D.C. torque motor, the armature of which is mounted on the shaft. Velocity and position feedback information are provided by a tachometer and potentiometer mounted on the same shaft. Power for the torque motor is provided by a rotating amplifier. The rotating-amplifier is controlled by an analog servo system. A low frequency function-generator provides the command input signal.

Power and communications signals are transmitted to and from the chair during rotation by a set of 36 slip rings mounted on the motor shaft.

The command input and servo control systems are controlled from an operating console which contains all the electrical and electronic circuits. All circuits are routed through patch panels on the console and the chair.

A removable enclosure permits complete isolation of the subject from ambient light.

III. ROTATING CHAIR AND PEDESTAL

A. Canopy and chair

Figure 1 shows the assembled rotator. The air intake baffle is barely visible at the top center of the enclosure. Figure 2 shows the rotator with the front access hatch open. The canopy consists of an aluminum tubing frame which is covered with foam sandwich panels. The canopy is attached to an aluminum plate which is bolted to the spindle nose beneath the spindle nose extension. This connection can be seen in Figure 2 beneath the chair seat. A skirt which extends downward from the coupling ring, encloses the upper part of the pedestal and serves as a mounting for the two D.C. brushless motor driven fans in light baffles. The two 28 volt D.C. lamps

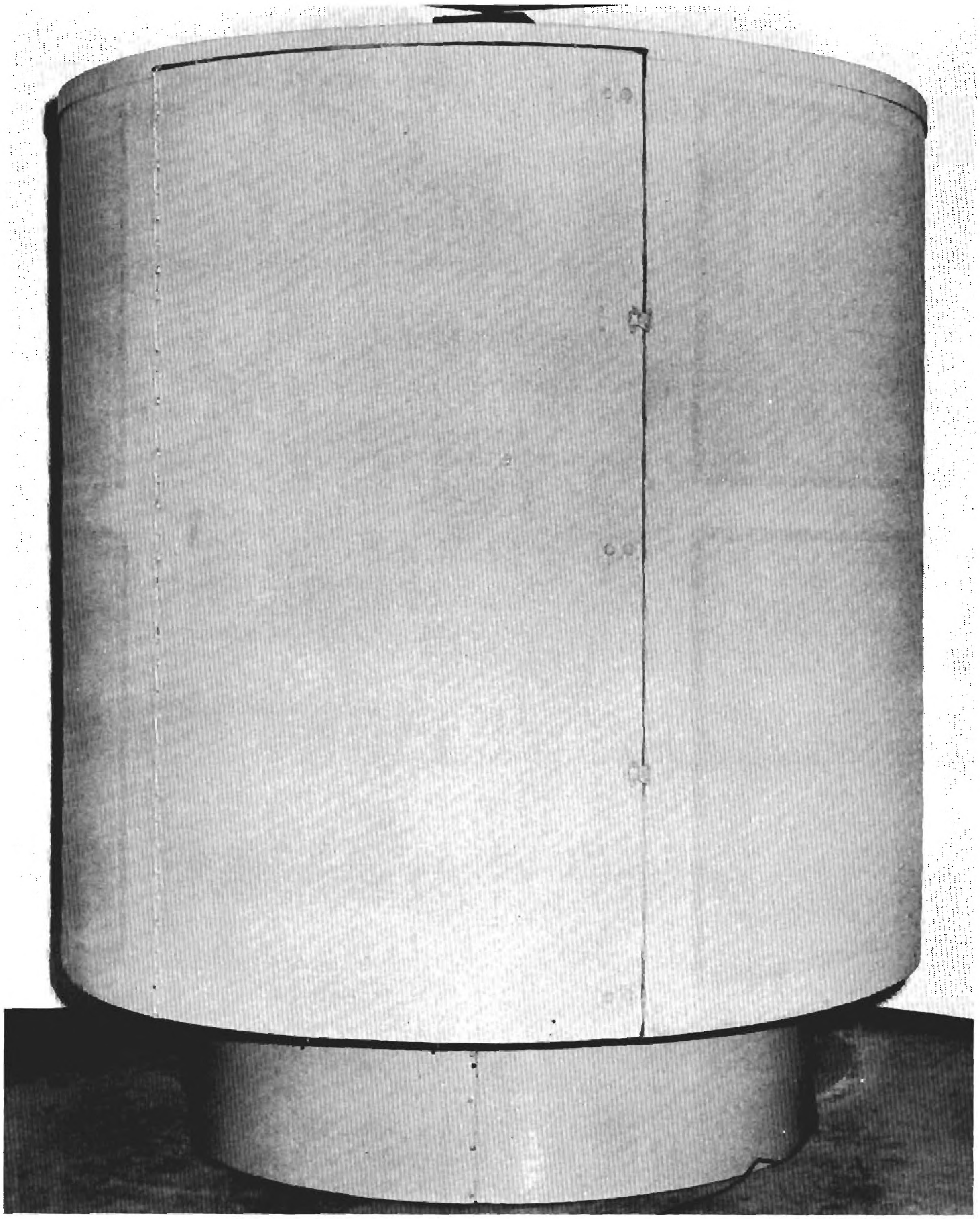

Figure 1. Peraodic angular rotator assembly.

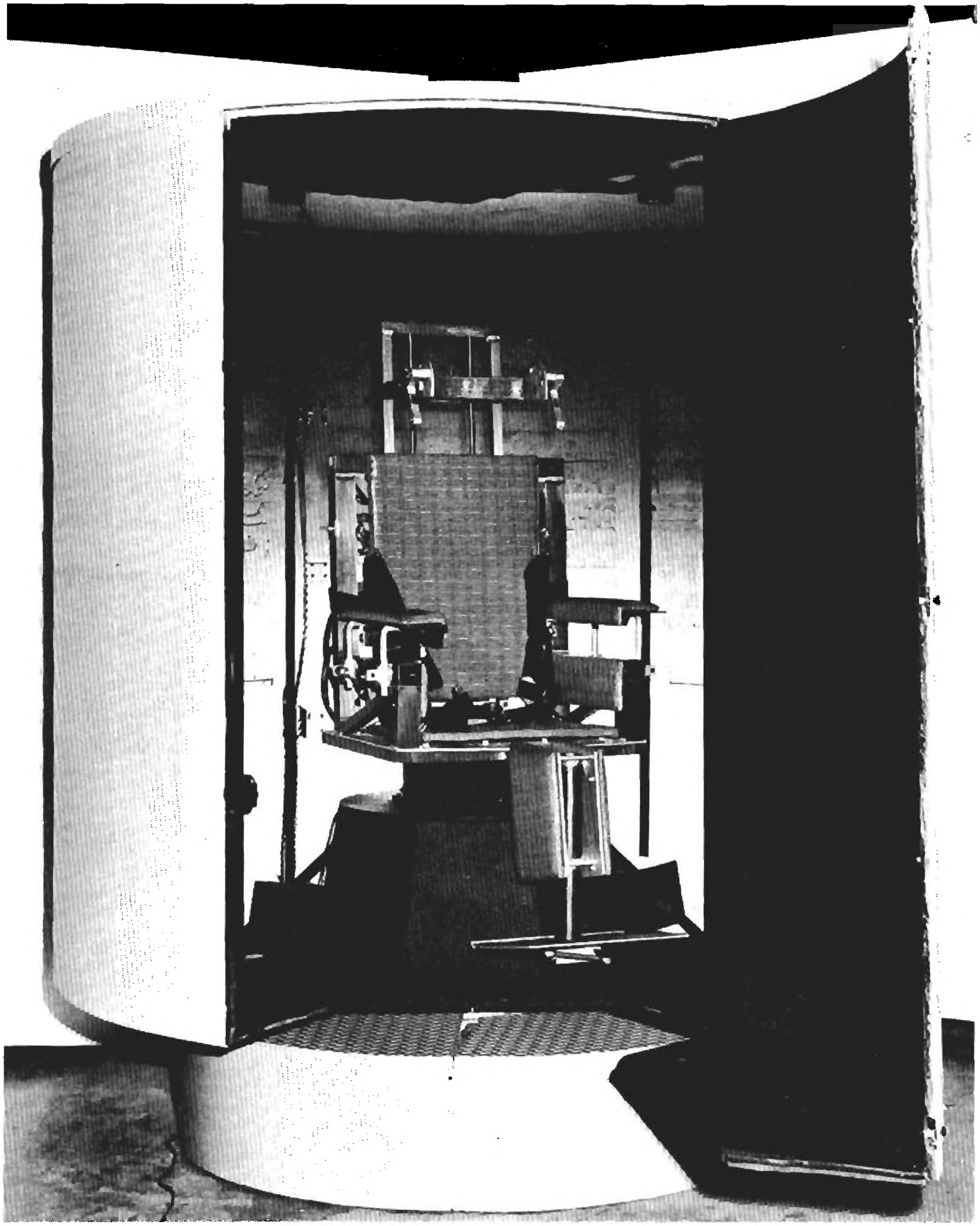

Figure 2. View of front interior of periodic angular rotator.

are visible inside the canopy top. These provide illumination when the doors are closed. Two interlock switches are mounted on each door. These are visible in Figure 2 to the left of the chair.

Figure 3 shows the rotator interior with the rear access hatch open. The on-board patch panel and A.C. power junction box mounting arrangements are shown. These boxes are pin mounted and may be removed quickly. The cylindrical housing below the enclosure is a false floor or step which enables the subject to enter the chair more easily.

Front and side views of the chair are shown on Figures 4 and 5, respectively. The chair is fabricated from hollow square aluminum extrusions. The chair was stressed to take the loads encountered when the motor shaft is tilted to a horizontal position. A much lighter chair could be used for acceleration about a vertical axis only. Adjustable arm, head, and foot rests are provided. An adjustable support is provided for adjustment of a bite bar. The cushions consist of 1/2 inch thick Goodyear Tulok fabric covered with woven Saron fabric. As shown on Figure 5, the chair is attached to the spindle nose extension. The chair may be removed quickly by removing the seat cushion and releasing nine bolts.

General arrangement of the restraining devices is shown on Figure 6. Three inch wide latch-type quick release straps are used for the chest and lap belts. Two inch wide belts with metal-to-metal quick release buckles are used for the arm, thigh, and toe straps. The pull through thigh strap shown on Figure 6 was a temporary belt. The two inch over-arm belt was added because subjects found it extremely tiring to hold their arms in at speeds from 50 to 100 revolutions per minute. The forearms are free for manipulating switches or controls.

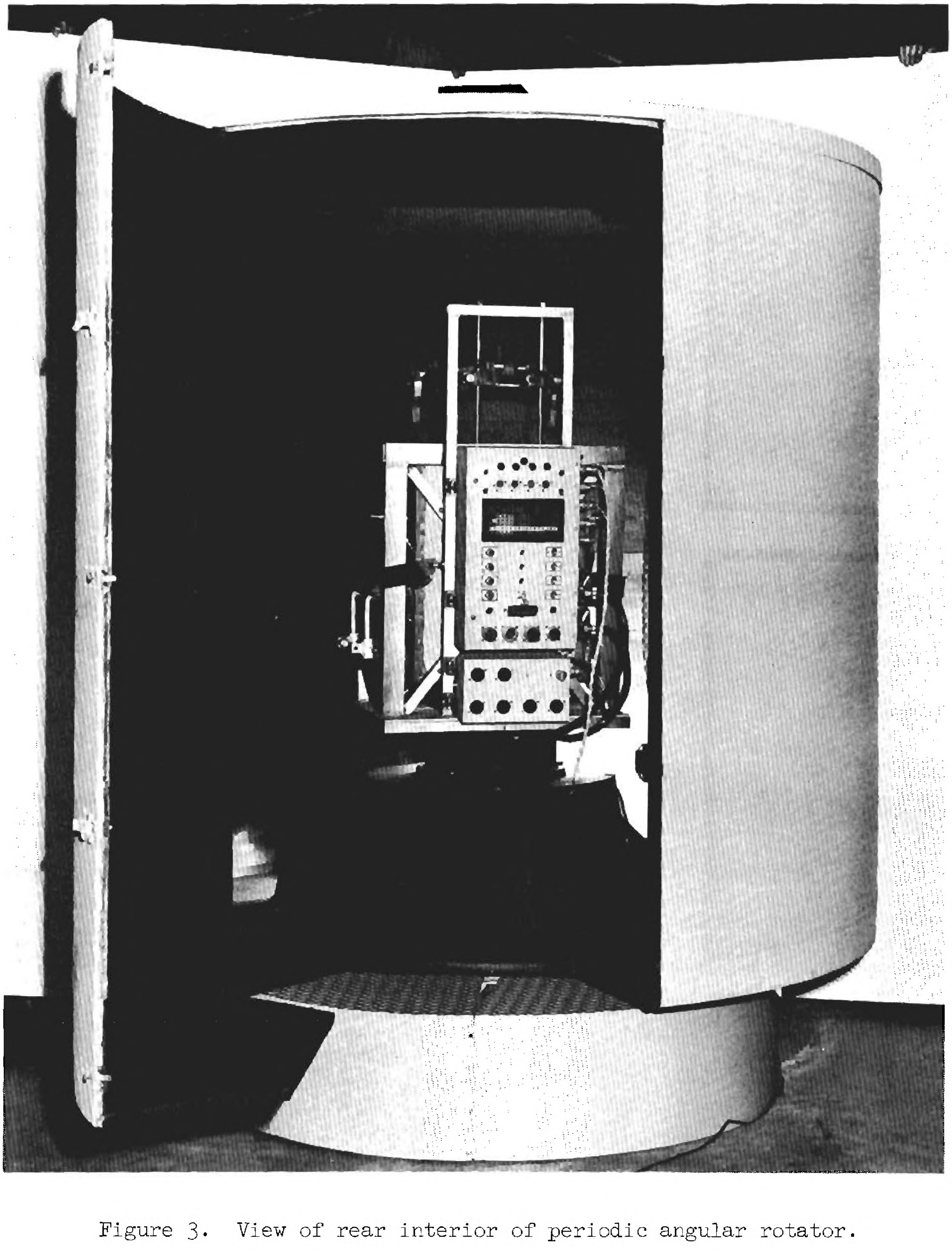

Figure 3. View of rear interior of periodic angular rotator.

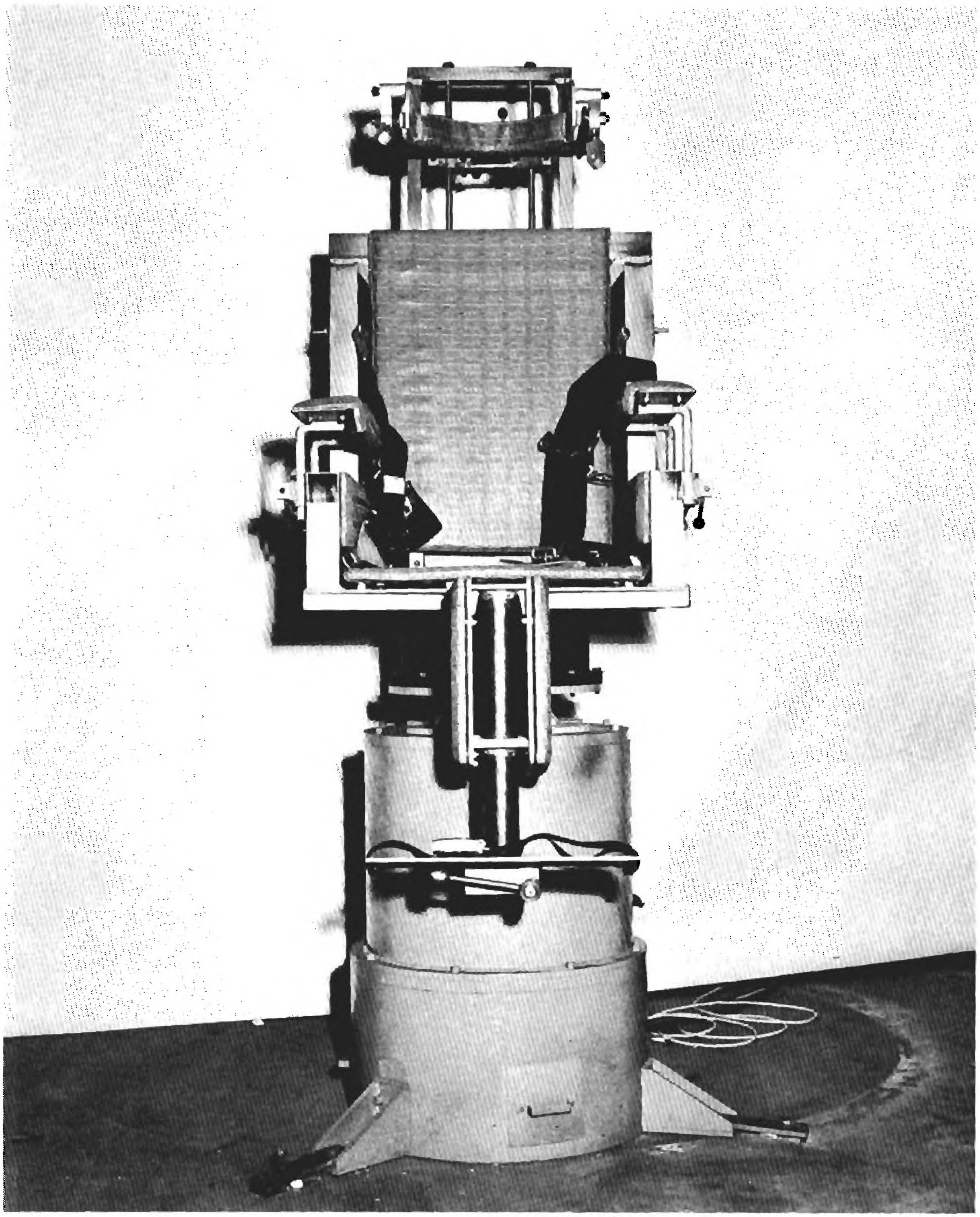

Figure 4. Front view of rotator chair assembly.

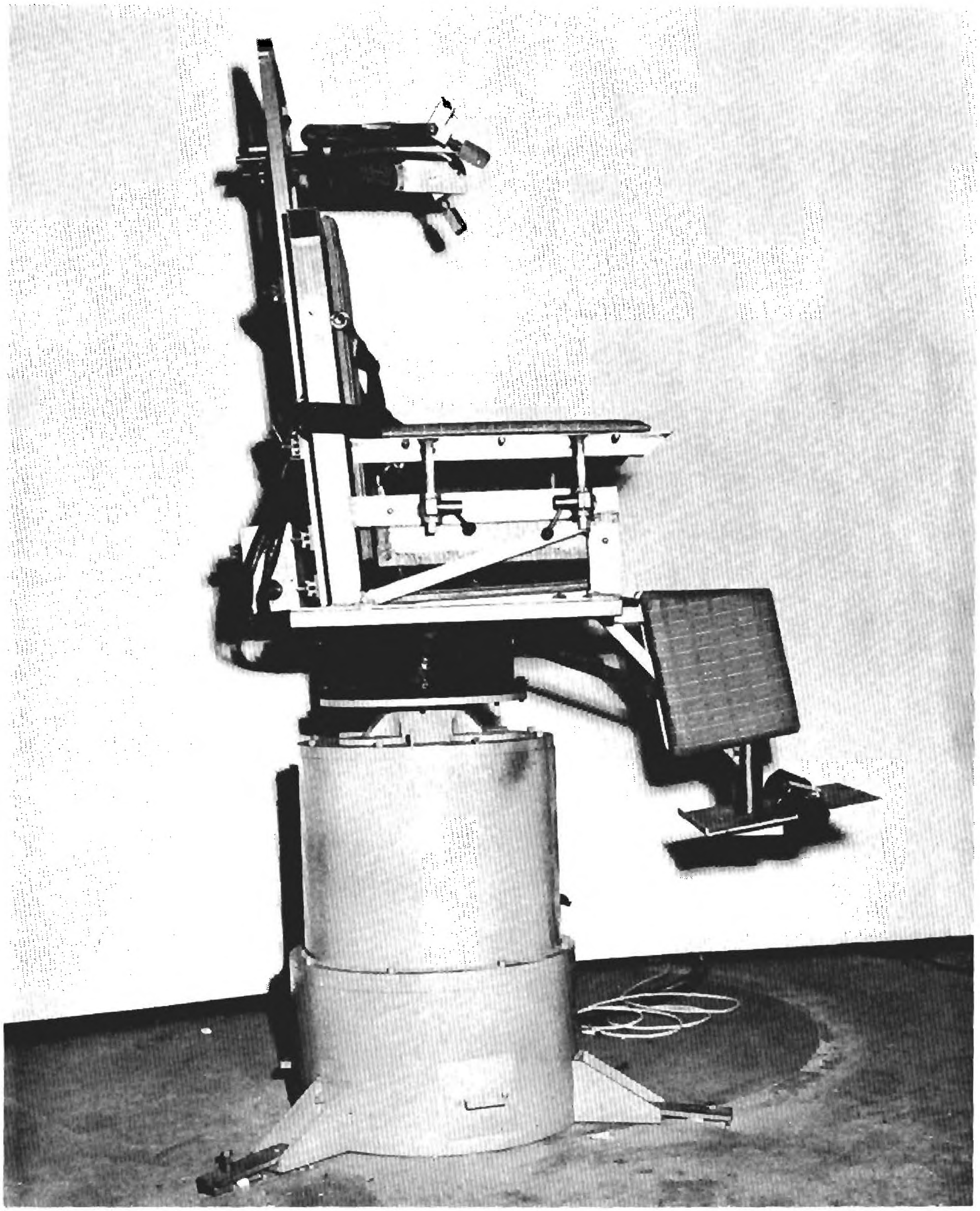

Figure 5. Side view of rotator chair assembly.

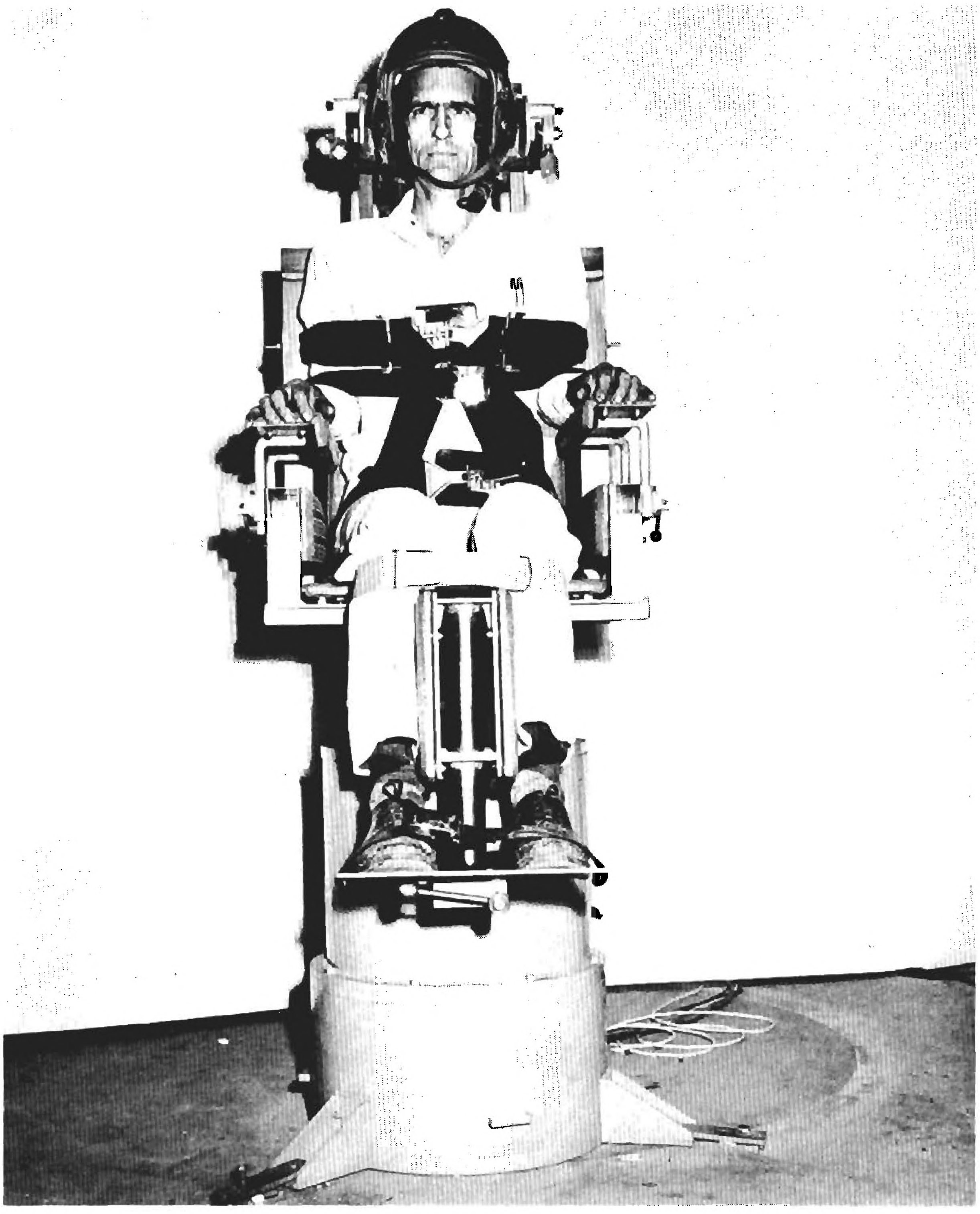

Figure 6. Arrangement of subject restraining devices.

B. Pedestal

Details of the pedestal are shown also on Figures 5 and 6. The upper cylinder contains the D.C. torque motor and D.C. tachometer mounted on a 3-3/4 inch diameter steel shaft. The shaft is supported by two tapered roller bearings. The lower cylinder, to which the leveling feet are attached, provides space for the two sets of instrument slip rings and the position feedback potentiometer mounted on the projecting shaft end. Four hand access holes are provided on top of the pedestal. Three square openings are located around the lower cylinder to provide access to the slip rings and feedback potentiometer. The cylinders are machined from heavy wall steel tubing, and the bearing housing are machined from steel plates.

IV. SERVO SYSTEM

A. General description

The function of the servo system is to control the rotation of the chair with a velocity or position corresponding to an input command signal. The servo system consists of five major components; namely, the drive motor and rotary amplifier, the servo control unit, the alarm circuitry, the readout buffer amplifiers, and the relay logic. The last four units are contained in three chassis which are controlled from the Control Panel.

The primary servo loop used for controlling the chair motion is constructed around an Inland 100 lb-ft torque motor (Model T-10035A) which is powered by a 1000 watt rotary amplifier (Model 3315A). A transister power amplifier buffers the error signal for the input to the rotary amplifier. Signal conditioning by means of compensating networks and summing of input signals is performed at low power levels using operational amplifiers as computing elements.

Changes between a position servo and a velocity servo are effected through relay contacts which modify the feedback sources, the compensation network, and various gain and bias settings throughout the control network. Two limiter circuits are included in the control network when the system is operating as a position servo. These limiter circuits form secondary control loops to prevent over-travel of the chair at the ends of the feedback potentiometer. Limiting is accomplished by rendering the primary control loop incapable of supplying power to the torque motor in the direction protected by the limiter. The operation of one of these position limiters leaves the servo in an unsaturated state for driving out of the position limit condition. The servo loop returns automatically to the normal operating state after the chair leaves the limited region.

Three alarm detectors are provided in both modes of operation to monitor the performance of the servo loop. These detectors serve to notify the operator of some existing undesired condition and to generate a signal which may be used as a stop command for the control circuits.

The control of the servo system is effected from switches on the control panel. A relay logic circuit is connected to these control switches and to the rest of the servo control circuits. The purpose of the relay logic is to require that certain conditions have been met for safety reasons before the chair can be operated.

B. System components

1. D.C. torque motor

The chair is powered by a Model T-10035A direct current torque motor manufactured by the Inland Motor Corp. This permanent magnet field motor has a peak torque of 100 lb-ft at an armature current of 21 amperes. The maximum motor speed is 114 revolutions per minute. The motor is 12-3/4 inches in diameter, 5-3/4 inches thick, and weighs 110 lbs. The rotor has a 3-1/2 inch diameter hole, thus permitting the use of a large stiff shaft. The friction torque for this unit is 1 lb-ft.

2. D.C. tachometer

Velocity feedback signals are provided by an Inland Motor Corp. Model TG-10017B tachometer generator. This tachometer has 297 commutator bars, and has a voltage sensitivity of 20.5 volts per radian per second. The measured linearity of this unit is 0.7 per cent from 10 to 100 revolutions per minute. The measured ripple is 0.089 per cent at a frequency of 297 times the rotor speed. The tachometer feedback signal is used successfully for rate feedback to the position servo.

3. Rotary amplifier

The torque motor is powered by an Inland Motor Corp. Model MG-3315A rotary amplifier. This unit has an output of 1000 watts with 30 watts applied to the split field control. The split field is controlled by a transistor power amplifier.

4. Servo control unit

a. General description. The servo control circuitry occupies one chassis which includes six chopper-stabilized operational amplifiers to supply the error voltage to the cascaded power amplifier driving the torque motor. This unit is shown on Figures 7, 8 and 9. These operational

Figure 7. Front view of servo control analog amplifier chassis.

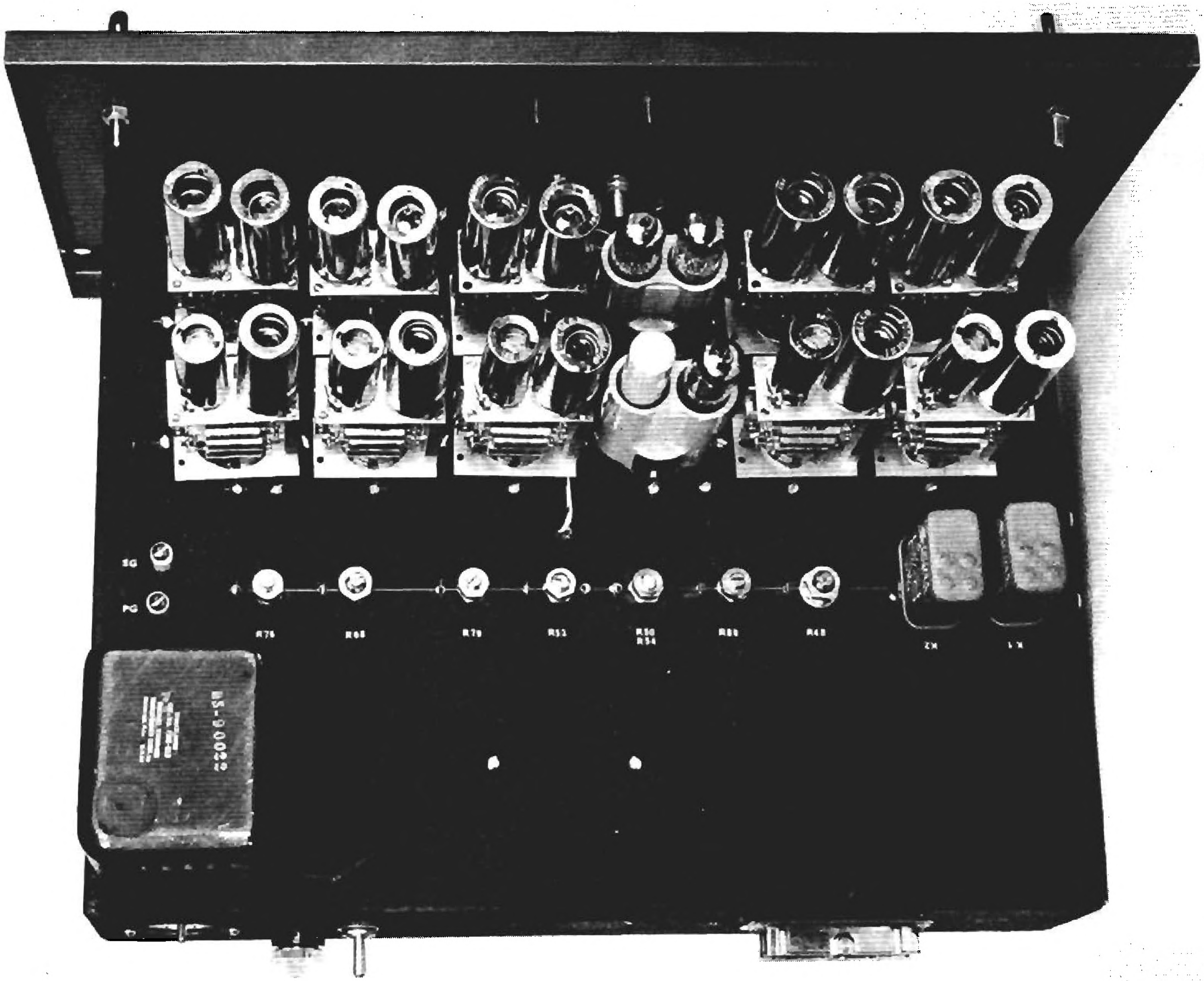

Figure 8. Rear view of servo control analog amplifier chassis.

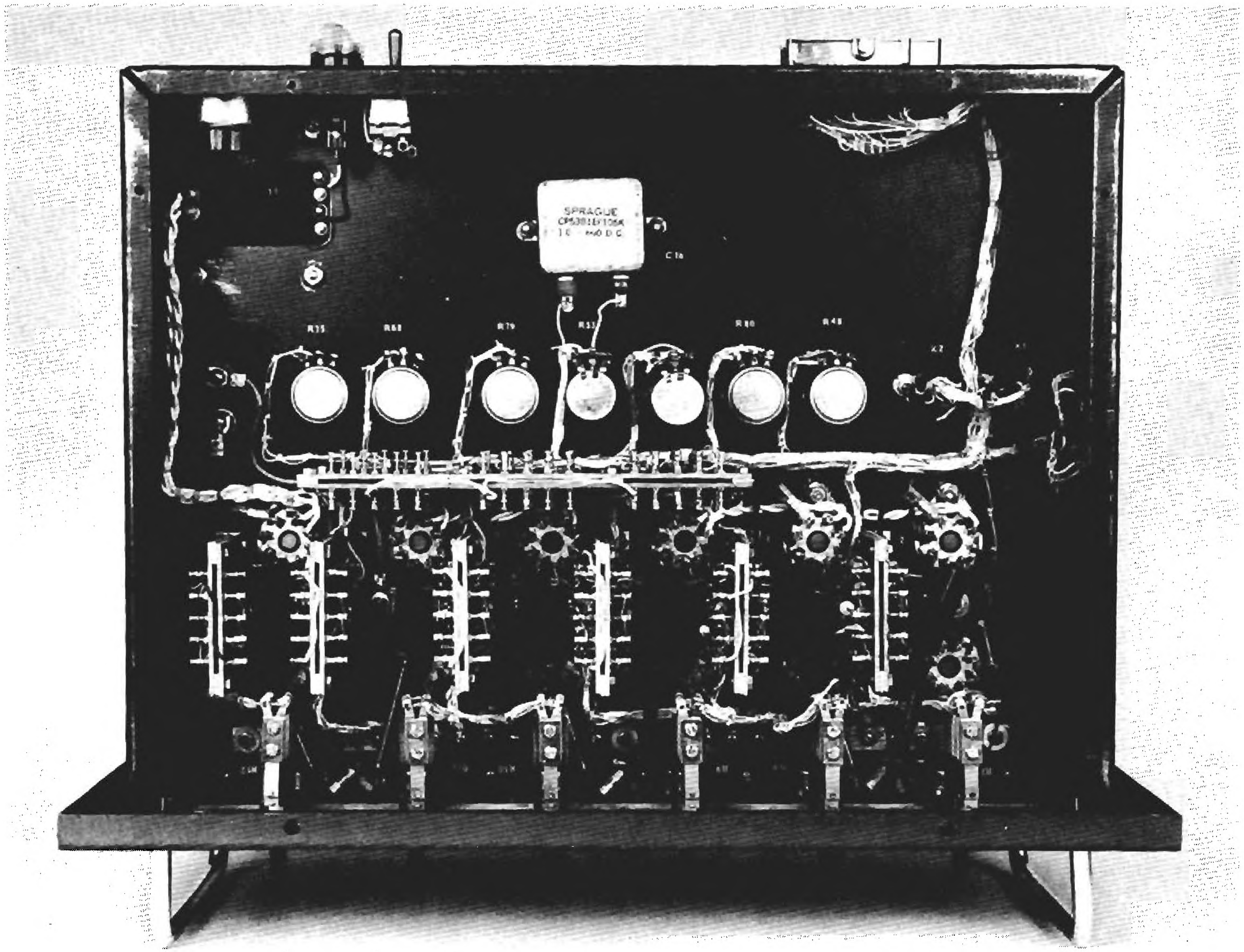

Figure 9. Bottom view of servo control analog amplifier chassis.

amplifiers have been assigned the numbers 1 through 6 for identification. The primary servo loop uses amplifiers 2, 3 and 6. The secondary loops formed by the position limiters use amplifiers 4 and 5. Amplifier 1 is used for summing the input command voltages.

b. Error amplifier. The error signal is produced at the grid of amplifier 3 which shall be referred to as the error amplifier. The error quantity is produced by summing the net input command signals with the voltage from the feedback transducers. For the velocity servo, only the tachometer output is used as the feedback voltage. For the position servo, positional information is obtained from the follower potentiometer and combined with the tachometer output to give a position plus rate feedback voltage. A diode limiter is in parallel with the feedback element of the error amplifier in order to limit the magnitude of the error voltage. The amplifier operates essentially linearly between the positive and negative limits but has a sharp saturation characteristic as either limiting level is reached. This limiting is necessary to prevent overdriving the following two amplifiers, and the level is set so that full power may still be applied to the torque motor. Overdriving of the chopper-stabilized operational amplifiers results in a short recovery period during which the error voltage may be erroneous; this condition is avoided by the limiters on amplifier 3.

c. Drive amplifiers. The output from the error amplifier is further amplified and inverted by amplifiers 2 and 7 so as to provide a suitable push-pull driving signal for the Inland Model 625 transistor power amplifier. Diodes are in series with the outputs of the latter two operational amplifiers to protect the transistors from negative input voltages which can damage them. A bias signal is introduced at the summing junction of both amplifiers, producing equal reference levels of the push-pull error signal at the amplifier outputs. The single-ended input to amplifier 2 contains a diode clamp with clamping inputs obtained from the position limiters (amplifiers 4 and 5).

d. Position limiters. Amplifiers 4 and 5 form the clockwise and counter-clockwise position limiter circuits. These two circuits are identical in design (except for bias voltage polarities). In the position servo mode, an input is applied to the grid of each from the wiper of the follower potentiometer. The diode limiter networks serving as the feedback impedance allow the output voltage to have only stable status. The values of these states are set by the resistive voltage dividers connecting each diode to the amplifier outputs. The condition for switching between the two output states occurs when the net input voltage to the amplifier passes through zero. A biasing current is added to the signal from the follower potentiometer to allow easy adjustment of the position limits which are made by potentiometers R68 and R75.

The operation of the primary loop is unaffected when the output voltages of the position limiters are at the higher values, having a polarity that keeps the clamped diodes at a reversed bias. The position limiting condition applies a voltage that forward biases the clamping diode and brings the voltage at the junction of R43A and R43b to essentially that of the active limiter. This voltage may be adjusted to be zero or to cause a reverse torque to produce a braking action. It is also recommended that the position limits be set to restrict the travel in the position mode to abort plus or minus 150 degrees. Settings too close to the ends of the follower potentiometer will increase the chances of large signals overdriving the chair into the no-feedback condition.

e. Input summing amplifier. Amplifier 1 combines the input command voltages from four possible sources and feeds their sum to the input resistor of the error amplifier while also driving a meter on the control panel. Relay contacts are included in two of the inputs to allow selection by the control panel switches. The two external inputs are accessible through patchboard connections and have no switching provisions.

f. Compensating network. The compensation networks for the position mode and the velocity mode consist of parallel RC networks that are used as the feedback element of the error amplifier. The value of the capacitor for either network should be kept as small as possible. Its purpose is to reduce the gain at frequencies above those normally contained in the error voltage.

g. Gain adjustments. The loop gain of the velocity servo should be set at a value greater than that necessary for the maximum allowable error. Loop gain in the velocity mode is controlled by the variable resistor (R53) used as the feedback resistor on amplifier 3. The minimum loop gain requires that R53 be approximately 0.5 megohm or greater. In practice, it is desirable to adjust this control to give as large a value of gain as can be tolerated without causing instability or excessive noise.

For the position mode, loop gain is controlled by potentiometer R80. Damping of the position servo is controlled by the gain of the tachometer feedback potentiometer R48.

The following procedure is recommended for adjusting the gains of the position servo.

(1) Set the damping control at maximum value to create an overdamped condition. (2) Increase the gain on the position feedback until the error limit is satisfactory. This may be checked by displacing the chair by hand until a restoring torque is felt, and the gain should be set so that the displacement dead zone is small. (3) After the desired setting is reached, the damping control may be adjusted by watching the system response to a small step function. (In the actual checkout procedure, steps of both 5 and 10 degrees were used.) The fastest response will be obtained when the system is slightly underdamped and gives a slight overshoot to the step input. For best performance this adjustment should be made using a step size that is comparable with the expected operating range.

h. Scale factors. The servo system is designed around a stable reference voltage of plus and minus 50 volts. This reference is used to supply the follower potentiometer, the manual command potentiometer, and biasing controls used in the servo circuits. The gains of the amplifiers are intended to be adjusted so that a 50 volt input signal from the manual command potentiometer or the external inputs will produce maximum rotation of the chair (approximately ± 117 degrees) in the position mode at maximum speed (100 rpm) in the velocity mode. Inputs from the function generator are scaled so that its maximum output signal of 75 volts corresponds to 50 volts on the other inputs. Only the velocity servo has an adjustable scale factor, controlled by potentiometer R79. The system should not be set to operate at more than 100 revolutions per minute, the maximum rating of the tachometer. Since the inputs are compared to the reference voltage, the scale factors may be affected if this reference voltage is not at the proper level.

i. Bias controls. A separate bias control is included for each servo circuit to compensate for any drift or offset accumulated in the servo loop. These controls are R51 and R57 and should be adjusted after a reasonable warm-up time. The servo adjustments of the operational amplifiers (see below) should preceed this overall servo offset adjustment.

The bias adjustment for the reference levels of the push-pull output signals of amplifiers 2 and 6 is made while the servo loop is closed (i.e., with the system in Start-Rotation condition) and with all input commands at zero. The setting of R50 should be increased from zero output until the supply current to the transistor power amplifier is approximately 100 to 200 milliamperes. The equal reference levels presented at the push-pull inputs of the transistor amplifier are required in order to set the operating point of this amplifier slightly above cutoff to eliminate the introduction of a dead band in the servo loop. This level should not be at a value higher than absolutely necessary or the performance of the unit may be degraded by saturation of the rotary amplifier. The minimum value can be determined more closely by the basic criterion that no bands of zero acceleration can be observable in the accelerometer response to a sinewave input to the unit in the velocity mode.

j. Amplifier zero adjustments. The zero balance of the six operational amplifiers in the servo control unit should be checked periodically and reset if found to be off appreciably. This offset is checked by the central meter and individual amplifier switches located on the front panel of the chasis. Operating a switch will place the corresponding amplifier in a high-gain zeroing circuit and connect its output to the meter. The amplifiers in this chasis are all chopper stabilized and should be adjusted as close to zero as possible by the potentiometer located adjacent to the zeroing switch. Do not attempt to check more than one amplifier at a time since their outputs will be added at the meter and may give an erroneous reading. Since it is characteristic for these chopper-stabilized amplifiers to go through a transient when put in the zeroing mode, any reading should be delayed until the amplifier has recovered. The zero check should be made only when the servo system is in the stop or reset state in order to avoid removing the amplifier from the servo loop. As a further precaution, a contact on the zero switch of each critical amplifier has been connected to the relay logic to put the servo system automatically in the stop state when zeroing is attempted while running.

5. Alarm detector circuits

There are three alarm detector circuits designed to monitor the operation of the servo system and provide a means of shutting off the power to the drive motor when the performance is not as desired. The quantities that are monitored are the velocity and error voltage. The alarm amplifier chassis is shown on Figures 10, 11, and 12.

a. Circuit description. The basic circuit of the three alarms is an absolute-value network commonly encountered in analog computer programming. The computer version has been modified by the addition of a biasing circuit and the replacement of the output amplifier feedback impedance by a diode limiter network. The resulting circuit is used as a

Figure 10. Front view of alarm amplifier chassis.

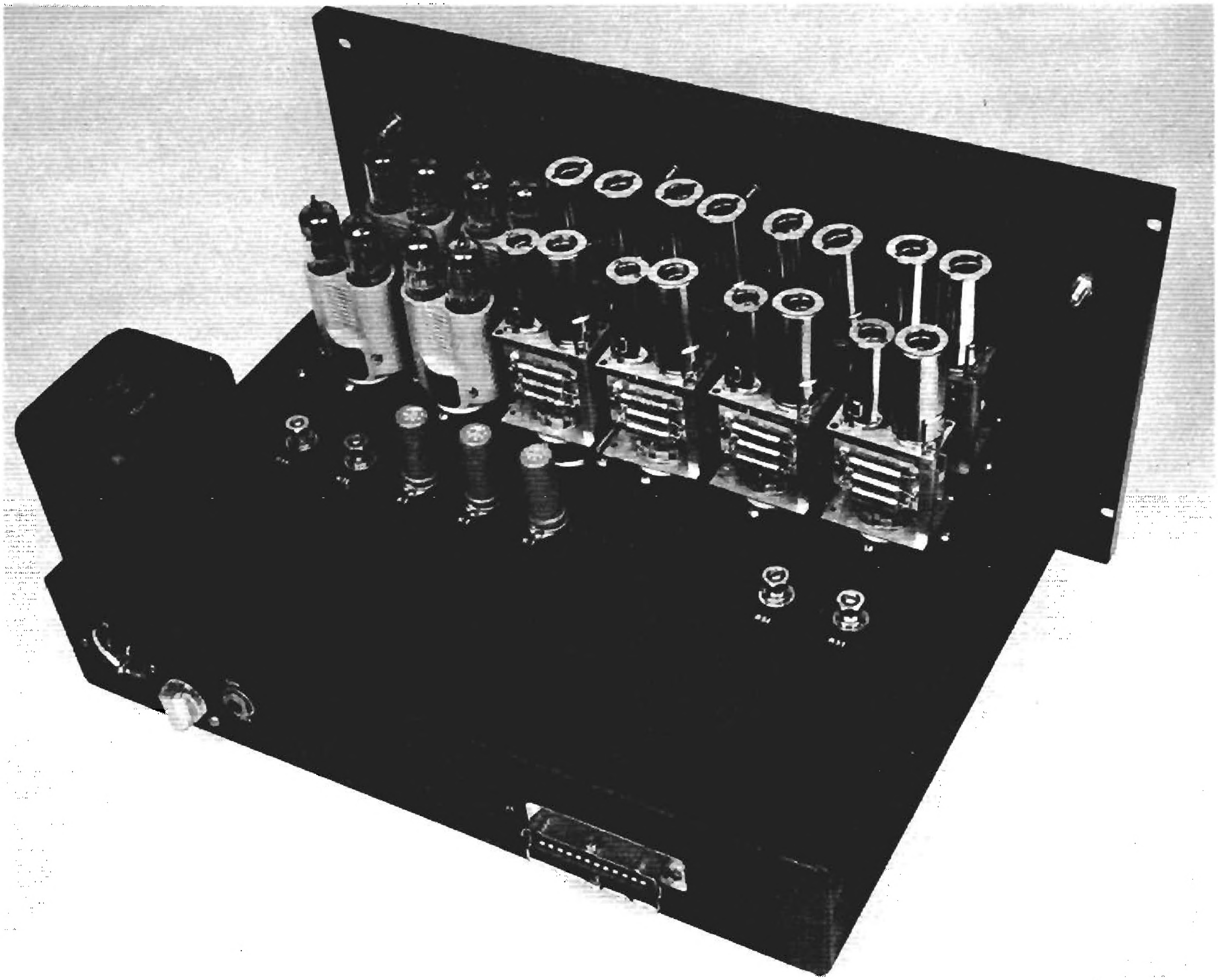

Figure 11. Rear view of alarm amplifier chassis.

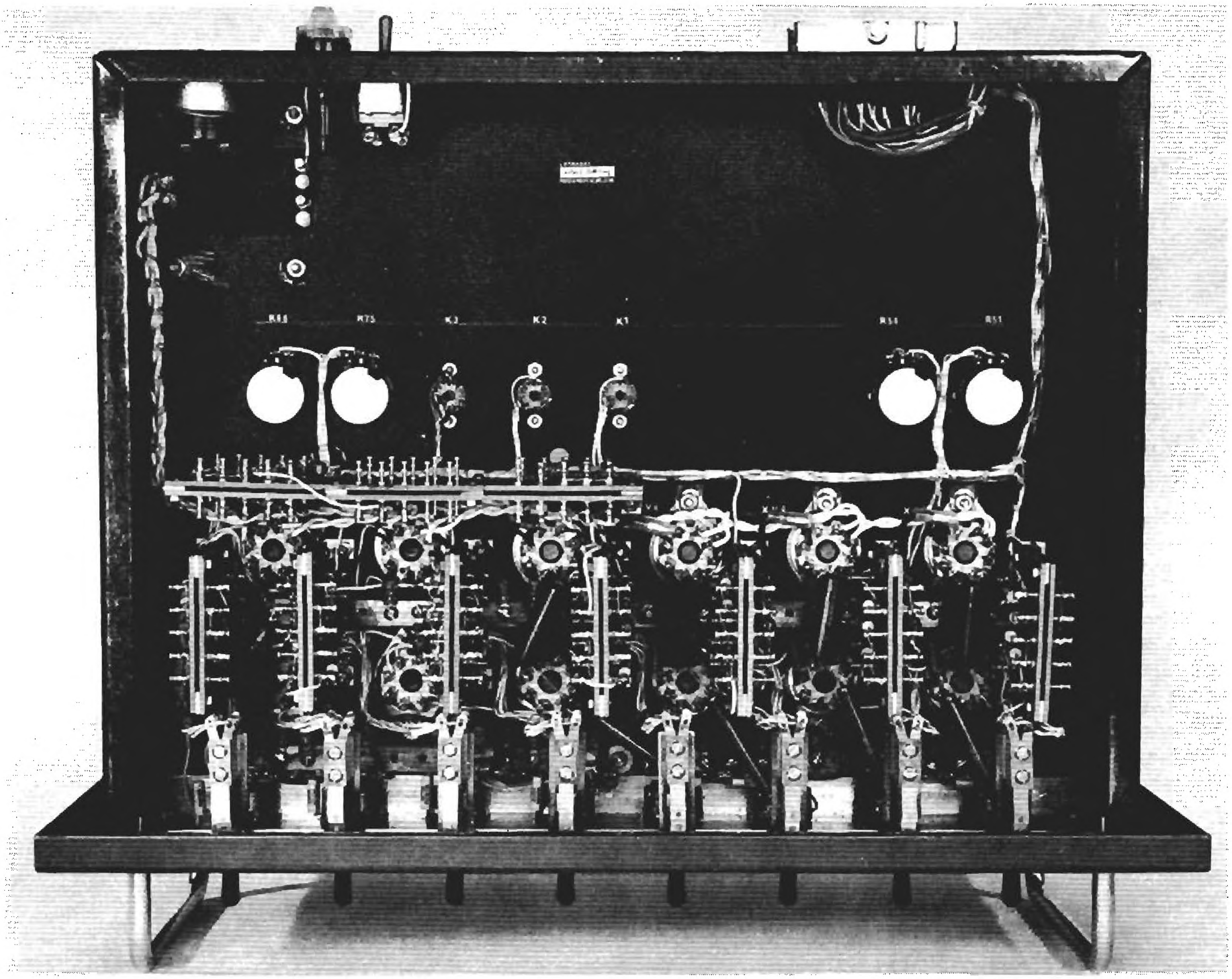

Figure 12. Bottom view of alarm amplifier chassis.

relay driver that switches when the absolute value of the input voltage exceeds the value set on the biasing potentiometers.

b. 100 revolutions per minute exceeded alarm. The threshold level of the 100 rpm exceeded alarm is adjusted by potentiometer R66. It is recommended that this alarm be set slightly above the intended limit in order to allow reliable operation at 100 rpm. Exceeding the threshold of this alarm places the servo system in the stop state and lights an indicator on the control panel. The circuit is reset after removal of the overload condition by means of a push-button switch associated with the alarm indicator.

c. Programmed velocity exceeded alarm. The threshold level of the programmed velocity exceeded alarm is adjustable by a ten-turn potentiometer located on the control panel. When the chair velocity exceeds the setting of this control, the servo system is placed in the stop state.

d. Error exceeded alarm. The threshold of the error exceeded alarm is set by potentiometer R75. This alarm is used to monitor the magnitude of the error voltage (as seen at the output of amplifier 6) and lights an indicator on the control panel when the error exceeds the preset threshold. As presently connected, the alarm does not interrupt the operation of the servo system and will reset automatically after removal of the overload condition.

e. Amplifier zeroing. Chopper-stabilized operational amplifiers are used only in the programmed velocity exceeded alarm. The other two alarm circuits use unstabilized amplifiers. Amplifier zero offset adjustments are identical to those in the servo control unit with the exception that the unstabilized amplifiers may be considered to be adequately zeroed if within plus or minus ten units of zero on the panel meter.

f. Readout buffer amplifiers. Amplifiers 7 and 8 are used to buffer the position feedback and the tachometer output for the meters located on the control panel and the recorder output connections on the patch board. Potentiometers are included at the inputs of these amplifiers to permit easy adjustments of the scale factors. These two circuits are located on the alarm amplifier chassis. Both of the amplifiers are unstabilized and should be zeroed as described in the section on the alarm detector circuits.

6. Relay logic chassis and system operation

Circuitry involving relay logic is used to control the application of power to the servo drive motor according to a fixed set of input requirements. These requirements were developed primarily for reasons of safety in the operation of the system. The relay logic chassis is shown on Figures 13 and 14. The following description is included to explain the relationship of the relay logic to the operation and control of the servo system.

a. Operating mode. The choice between a velocity servo and a position servo is determined by a single switch in the control panel. This selector is connected so that it comes on in the velocity mode when power first applied to the unit. A change between the two types of servos may be made in any operating state except that start rotation state. The control switching layout is shown on Figure 15.

Figure 13. Rear view of relay logic chassis, also showing the dc servo amplifier.

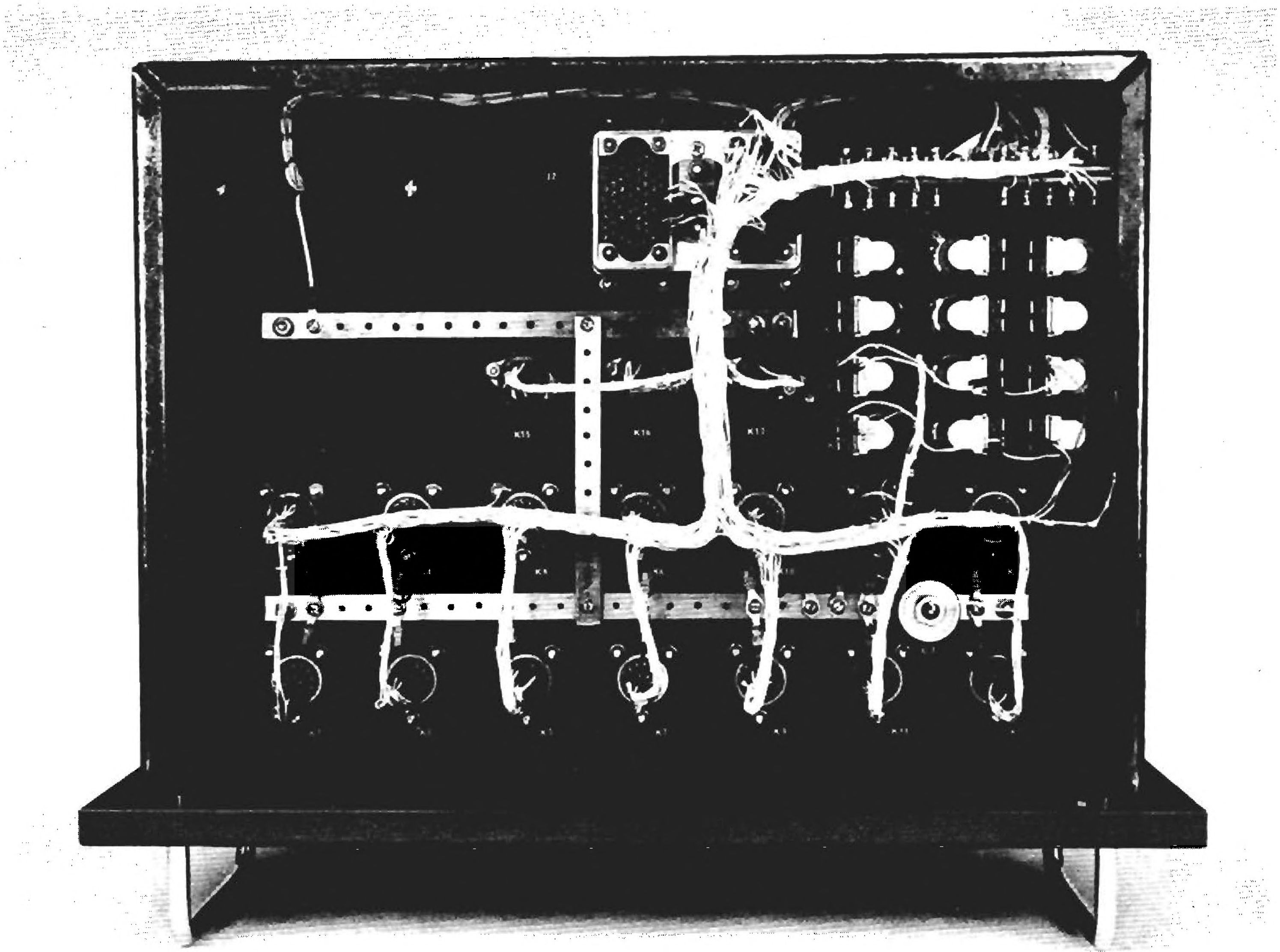

Figure 14. Bottom view of relay logic chassis.

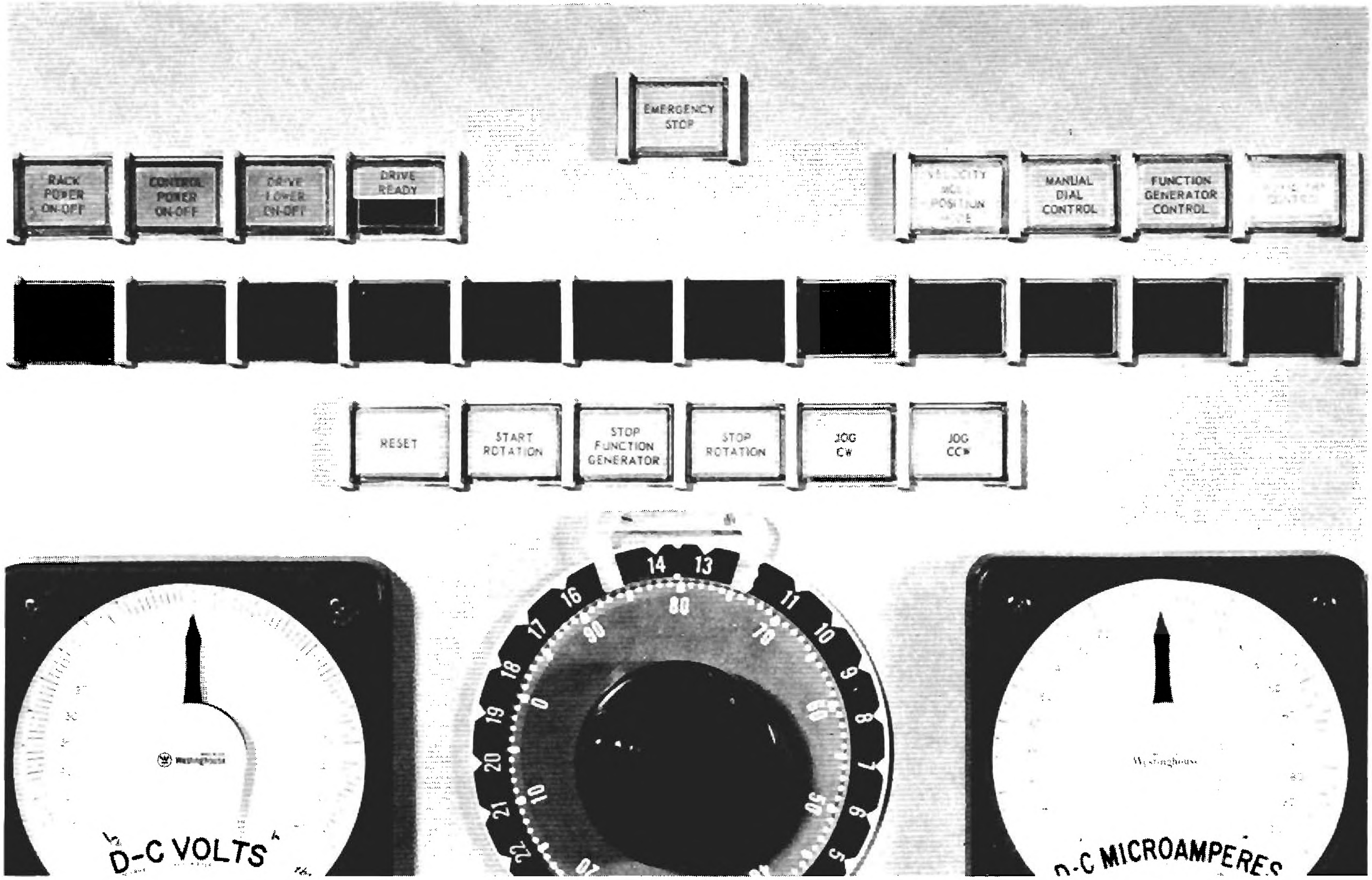

Figure 15. Operator's control switching panel.

b. Input selections. Two switches are included in the control panel for selecting the input from the function generator and the manual command potentiometer. A third switch, marked auxiliary input, disconnects both of the above sources and leaves the two external inputs connected to the patch panel. These two auxiliary inputs are connected to the servo input at all times and the auxiliary input switch serves to eliminate the other two inputs.

The operation of these three switches allows only one to be on at a time, and changes can be made in any operating state except the start rotation state. The logic is set so that the first selection on applying power to the circuit will be the manual potentiometer command input.

c. Servo control switches. There are four switches used for controlling the operation of the system in both operating modes. These are the reset switch, start rotation switch, stop function generator switch, and the stop rotation switch.

The manual operating sequence is reset, start rotation, stop function generator (for function generator inputs only), and stop rotation. The logic is connected so that the absence of any control state constitutes the stop rotation condition. This is the condition when power is first applied to the circuit. The logic is set so that the system will return to the stop state from any other state if any of the following conditions occur:

a. The programmed velocity is exceeded

b. Chair velocity exceeds 100 rpm

c. Capsule interlock switch is open

d. The emergency stop switch is operated

e. A power supply failure occurs

f. The stop rotation button is depressed

The first step in placing the servo into operation is to press the reset switch. The operating state will change to this condition provided that no other operating state switch is depressed and that the above conditions are met. This includes the requirement of resetting the two alarm circuits listed above (items a and b) if they have been tripped. This reset command is used to reset the logic of the programmer when the servo system is operating with inputs from the function generator.

The servo system may now be placed in the operating state by pressing the start rotation switch if the following additional conditions are satisfied.

a. Pilot not ready lamp is off

b. Check list incomplete lamp is off

c. No other operating state switch is depressed.

When operating with inputs from the function generator, the next action in the sequence may be to press the stop function generator switch. This switch generates a command signal for the programmer that overrides the automatic timer and disconnects the Servomex output function at the next zero crossing. An interim operating state exists from the instant of normal command until the next zero crossing, at which time the system goes into the stop rotation state. If the programmer is allowed to terminate the run automatically, the system passes directly to the stop rotation state at the end of the run. When the function generator is not in use, the stop function generator switch is inoperative.

Pressing the stop rotation switch returns the system to its original condition (not reset) and leaves the power removed from the drive motor. To reactivate the unit the foregoing procedure must be repeated.

d. Emergency stop switch. The emergency stop switch provides a means for removing power from the drive motor in emergency conditions. It differs from the normal stop rotation by applying a fast dynamic braking to the drive motor. The emergency stop switch must be depressed a second time (after the chair has stopped) in order to return the system to the normal stop state. The system is then ready to be moved to the reset state as described above.

e. Jog controls. Two jog controls are provided for changing the position of the chair when the servo loop is open. These two switches provide a choice of direction of the slow rotation commanded by them. To operate the jog controls, the following conditions must be met:

a. The system must be in either the stop rotation or reset state

b. The drive power switch must be on

c. The system must not be in an emergency stop condition

d. There must be no power supply failure

The chair may then be rotated in the jog mode by depressing simultaneously the reset switch and the clockwise or counter-clockwise jog switch.

The system leaves the jog mode when either of the depressed switches is released.

f. Program sequence interlocks. Two circuits are provided for safety interlocks that must be manually set before each run. The first is the pilot not ready indicator which may be operated only in the reset state.

The second is the check list incomplete indicator that may be set in any state except stop rotation. Both circuits return to the original condition when the system goes from the start rotation state to the stop rotation state.

g. Power supply failure. The initial power supplies that can affect the operation of the servo when the loop is closed are monitored by relays. The contacts of the relays are series connected to provide a single signal source to the relay logic, indicating that the all critical power supplies are operative.

h. Capsule interlock switch. The capsule is fitted with interlock switches to guarantee that its doors are secured during the operation. The contacts of these switches are connected in series to give a single signal to the relay logic.

C. Logic equations

The logic equations provide a compact and complete description of the requirements placed on the servo system through the relay logic chassis. Several of the conditions have been indicated above to give an understanding of the operation of the switches on the control panel. The transmission logic equations, which are presented following the list of symbols below, may be of value in trouble-shooting and servicing the system.

1. Notation

Symbols in the form tabulated below always refer to a normally-open (N/O) contact in the closed condition. Note that there are usually both a switch (capital letter) and a relay (lower case letter) associated with a given operating function. A bar placed over any of the listed symbols designates a corresponding normally-closed (N/C) contact in the closed condition. A bar placed under one of the lower case letters denotes the associated relay coil in its energized conditon.

SWITCH	RELAY	OPERATING FUNCTION
--	a_2	Programmed velocity exceeded alarm
--	a_3	100 rpm exceeded alarm
--	b_1	Normal brake
--	b_2	Emergency brake
C_1	--	Capsule interlock open
C_2	c_2	Check list incomplete
D	d	Drive power on
E	--	Emergency stop
--	f	Program completed (function generator)
I_1	i_1	Manual input
I_2	i_2	Function generator input
I_3	i_3	Auxiliary input
J_1	j_1	Jog right
J_2	j_2	Jog left
M_1	m_1	Velocity mode
M_2	m_2	Position mode
O	o	Start rotation
--	p_1	Power supply failure
P_2	p_2	Pilot not ready
R	r	Reset

SWITCH	RELAY	OPERATING FUNCTION
S	s	Stop rotation
T	t	Stop function-generator

2. Transmission logic equations

a. Input controls.

$$\underline{i}_1 = \bar{i}_2 \, \bar{i}_3$$

$$\underline{i}_2 = \bar{o} \, \bar{I}_1 \, (I_2 + i_2) \, I_3 \, o \, i_2$$

$$i_3 = \bar{o} \, \bar{I}_1 \, (I_3 + i_3) \, \bar{I}_2 + o \, i_3$$

b. Drive condition controls.

$$\underline{s} = \bar{t} \, \bar{r} \, \bar{o}$$

$$\underline{r} = \bar{a}_2 \, \bar{a}_3 \, C_1 \, \bar{E} \, \bar{p}_1 \, \bar{S} \, (R \, s \, \bar{T} \, \bar{O} + r \, \bar{o})$$

$$\underline{o} = \bar{a}_2 \, \bar{a}_3 \, C_1 \, D \, \bar{E} \, \bar{p}_1 \, \bar{S} \, \left[\bar{p}_2 \, \bar{c}_2 \, O \, r \, \bar{T} \, \bar{R} + o \, (f + \bar{i}_2)\right]$$

$$\underline{d} = o \, \bar{j}_1 \, \bar{j}_2 + j_1 \, \bar{j}_2 + \bar{j}_1 \, j_2$$

$$\underline{t} = \bar{a}_2 \, \bar{a}_3 \, C_1 \, \bar{E} \, f \, \bar{p}_1 \, \bar{S} \, (O \, i_2 \, T \, \bar{R} \, \bar{O} + t)$$

c. Breaking relay contact.

$$\underline{b}_1 = \bar{d}$$

$$\underline{b}_2 = E$$

d. Jog relay controls.

$$\underline{j}_1 = D\ \bar{E}\ \bar{p}_1\ R\ (s + r)\ J_1\ \bar{J}_2$$

$$\underline{j}_2 = D\ \bar{E}\ \bar{p}_1\ R\ (s + r)\ \bar{J}_1\ J_2$$

e. Mode relay controls.

$$\underline{m}_1 = \bar{m}_2$$

$$\underline{m}_2 = \bar{o}\ (M_2 + m_2)\ \bar{M}_1 + o\ m_2$$

f. Interlock relay controls.

$$\underline{p}_2 = p_2\ \bar{s} + P_2\ r$$

$$\underline{c}_2 = c_2\ \bar{s} + C_2\ r$$

V. COMMAND FUNCTION GENERATOR*

A. General description

The function generator consists of the Servomex low-frequency waveform generator (Servomex Controls, Ltd., Type LF-51) and a programmer chassis. The purpose of the function generator is to provide two basic waveforms as input commands for the servo control circuit. The parameters of these waveforms are selected by the existing front panel controls of the Servomex unit. Connections are made between the control panel and the programmer chassis to allow a degree of automatic operation with the servo system. The

*Design considerations are presented although actual unit was not completed.

following description indicates some of the special considerations involved in the programmer design to make it compatible with the Servomex unit.

B. Output functions

The function generator is required to produce two types of output signals from the Servomex unit which will be suitable as input signals for the servo control system. These two signals are defined as follows:

(1) A trapezoidal waveform providing a linearly increasing voltage ramp starting at zero and ending at some preset value, where it remains for a period determined by an adjustable timer as a signal from the operator. At that instant, the output signal decreases linearly to zero, and the programmer signals the servo control circuit that the run is complete.

(2) A constant-amplitude sine wave starting at a zero crossing and ending at a zero crossing, with an integral number at half cycles determined by the frequency of the wave and the time of occurrence of the end-of-run signal from the adjustable timer or the operator. The programmer signals the servo control circuit at the end of a run after the last zero crossing. (The design allows for a means of changing the starting and end positions of the sine wave to a point that will produce a signal that is offset from zero about some bias value. This offset is produced by adding an appropriate constant voltage to the generator output, and starting and ending the combined signal at the instant of its near zero value.)

C. Servomex low frequency waveform generator

The Servomex function generator is a specialized instrument capable of producing a variety of electrical test signals. A choice of operating modes provides for half-cycle, single cycle, or continuous generation of a chosen waveform. The half-cycle function is obtained by placing a front-panel mode selector switch on the Servomex unit in either the "single" or the "external" position, while for the complete cycle function this switch is placed in the "double" position.

Generation of output signals in either of these modes requires an input command to the generator in the form of the manual operation of a front panel switch or as a pulse applied to the external sync connection. When generating half-cycle functions, the front panel switch for manual starts works with the unit in the "single" position. The external sync input in disconnected internally in this switch position, but electrical control of the half-cycle function can be accomplished by placing the switch in the "external" position. Either method of starting a cycle may be used in the "positive double" position or the "negative double" position.

The output signal from the Servomex unit before attenuation varies between plus and minus 75 volts. These two voltage limits are the steady state levels of the output signal between cycles when generating functions in the half-cycle or single-cycle modes discussed above. Synchronizing pulses are available from the sync output terminal of the Servomex unit at the end of a half-cycle in the "double" setting.

Generating of continuous functions in the "external" or "double" settings is accomplished by feeding the sync output pulses to the sync input of the Servomex unit. Gating the sync pulses allows the generator output to be controlled electronically. Diodes are included in the Servomex input circuit in the "double" setting and allows a wide range of trigger pulses to be passed to the bistable circuit of the generator for the purpose of starting a cycle of the output function. The "external" setting of the control removes the diodes from the sync input which leaves the bistable circuit of the generator connected to this input terminal through a simple high-pass filter. Generating half-cycle output signals in this mode (which is necessary for the trapezoidal function) provided difficulties since the sync input signals are derived from pulses in the logic of the programmer. Special considerations were necessary in redesigning the sync driver to operate in the trapezoidal function mode and still be compatible with the logic circuits common to the sine wave function. A more detailed description of this circuit will follow, but it is important to the development of the programmer logic that separate inputs for positive and negative triggers are necessary with this sync generator. Monopolarity sync input pulses suffice for the generation of the sine wave function.

D. Programmer design

The design of the programmer is based on the ability to control the output signal of the Servomex unit in either the "external" setting for half-cycle generation, or in the "double" setting for complete cycle generation. This design was based on logic that would include both direct-coupled and ac-coupled techniques. The instrumentation of the initial design used transister circuits as the logic elements and the revised design covered here was built around the already assembled circuits. Under these conditions, the following statements apply to the design in its present state.

The operation of the programmer logic is dependent upon the following input commands from the control panel:

1. Reset command
2. Start rotation command
3. Stop function generator command

4. Emergency stop command

5. Bias input voltage to the programmer and the servo unit for generating sine wave functions about a bias level. (Provisions for biasing the sine wave at the input to the servo unit and at the input to the zero crossing detector are used for the sine wave function only.)

The following connections to the Servomex unit are necessary for operation of the programmer described herein:

1. Sync input
2. Sync output
3. Square wave output
4. Unattenuated analog output (wiper of segment 4e of waveform selector switch)
5. Function generator attenuated analog output (output 1 or 2)

Automatic operation of the control panel requires a run-completed signal from the programmer logic in the form of a contact opening.

Inasmuch as the Servomex unit generates its waveforms between $\pm$ 75 volts steady-state limits, the problem of obtaining the desired servo control functions requires a means of connecting and disconnecting the generator at the instant when the output signal is of zero level. Failure to do so will apply a step function to the input of the servo at the start and end of the run when the velocity or position commands are generated in the Servomex. (The special case of the biased sine wave will be covered in detail later; it requires also that the output be connected to the servo unit at zero value.) This requirement of producing a switching capability at the instant of the zero crossing calls for a signal to indicate the occurrence of a zero crossing. Since no signals of this nature exist at the outputs of the Servomex unit or in the circuit, it is necessary to include suitable circuits in the programmer design. This is accomplished by using the output signal of the Servomex before attenuation as the input to the Schmitt-trigger circuit. The output of this bistable circuit switches when the net input voltage passes through a narrow threshold region near zero. The polarity of the function generator output is indicated by the state of the Schmitt-trigger circuit, while the instant of the zero crossing is given by differentiation.

The background material above and the requirements of compatible and automatic operation of the function generator from the control panel set the basic design philosophy for the system. The programmer is placed in a reset state by the reset switch on the control panel. The generation of the output function chosen is initiated by the start switch which causes power to be applied to the drive motor. A delay is produced between the instant that the Servomex unit receives its first sync pulse and the instant that the output signal reaches its first zero crossing. This gives a stand-by condition imposed by the design of the Servomex unit and the required output functions. Relay contacts are included between the output of the Servomex unit and the input of the servo control unit to connect and disconnect it to the generator output at the first and last zero crossings of the output signal. Manual termination of the program is accomplished by depressing the stop function generator switch that over rides the automatic timer and disconnects the generator output at the next zero crossing. Program termination by either the timer or manual control places the programmer in a stop condition, and it must be reset before starting another run. The emergency stop command terminates the program immediately and the programmer may be reset after the output of the function generator reaches the next steady-state level for the particular mode of operation. The operation of the control panel with a choice of inputs not including the function generator is identical, except that the stop function generator control is not required.

A block diagram of the function generator is shown on Figure 16, and shows the signal flow paths between the logic elements for the two separate circuits used in generating the different output signals. The change between these two circuits is accomplished by relay contacts placed at critical positions. An attempt has been made to reduce duplication of circuits utilizing the logic elements common to both functions.

A functional division of the above block diagram is possible for purposes of discussing elements common to both signals being generated. One important function is detecting the zero crossing time of the output signal, as mentioned earlier. The outputs of the zero crossing detector are used as input signals for the three bistable circuits (FF3, FF4, and FF5 on the block diagram) that serve as a memory for the operating state of the programmer. These three circuits are in a reset state at the beginning of a run and provide an output (from FF5) that changes state at the occurrence of the first zero crossing, and resets at the last zero crossing. The relay contacts used for switching the output signal to the servo input are controlled by this signal. The end-of-run signal is also derived from these three bistable circuits.

A second important set of elements in the block diagram comprises the loop for generating the sync input signals to the Servomex unit. The

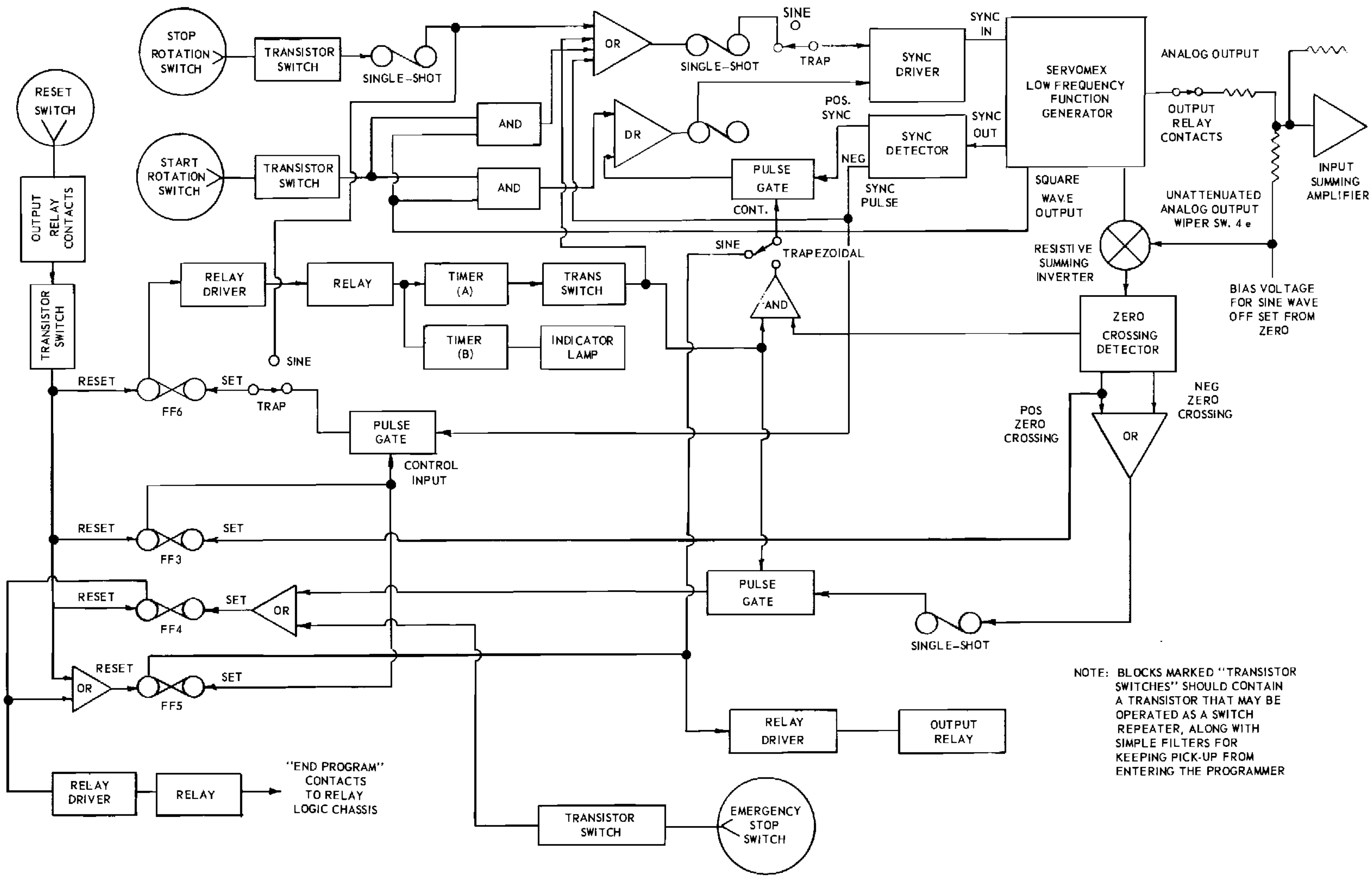

Figure 16. Revised block diagram for function generator programmer.

contacts of the start command switch generate the first sync pulse to start the output function. Sine wave generation requires a single pulse to be passed from the sync output to the sync input for each complete cycle of the generated signal. Trapezoid generation uses the sync output pulse to start a mechanical timer that sets the period at maximum voltage. The signal from this timer or an alternate command from the stop function generator switch will apply the proper polarity sync pulse to the unit, causing the downward half cycle in the output signal. An extra consideration is necessary in the trapezoidal mode since there is no way to guarantee that the generator output signal will be at the negative steady state level when the unit is first placed in the "external" setting. Because of this problem, a logic restriction was placed on the first zero crossing of both waveforms so that it must be increasing in a positive direction to cause the output relay to connect the generator to the servo unit.

E. Circuit details

Figures 17 through 23 are schematic diagrams of the circuits used in the construction of the programmer. The revised logic diagram presented in Figure 16 covers the system intended to be built using the logic elements already constructed. Major revisions were required in the sync detector and sync driver circuits. These two circuits required changes in the separation of the positive and negative reset pulses for generating the trapezoidal signal. The difficulties in triggering the Servomex unit in the "external" setting were solved by a sync driver circuit which has separate positive and negative step generating capabilities obtained through the use of complementary transistor switches. A command pulse on either input saturates the corresponding transistor and causes the Servomex sync input to receive

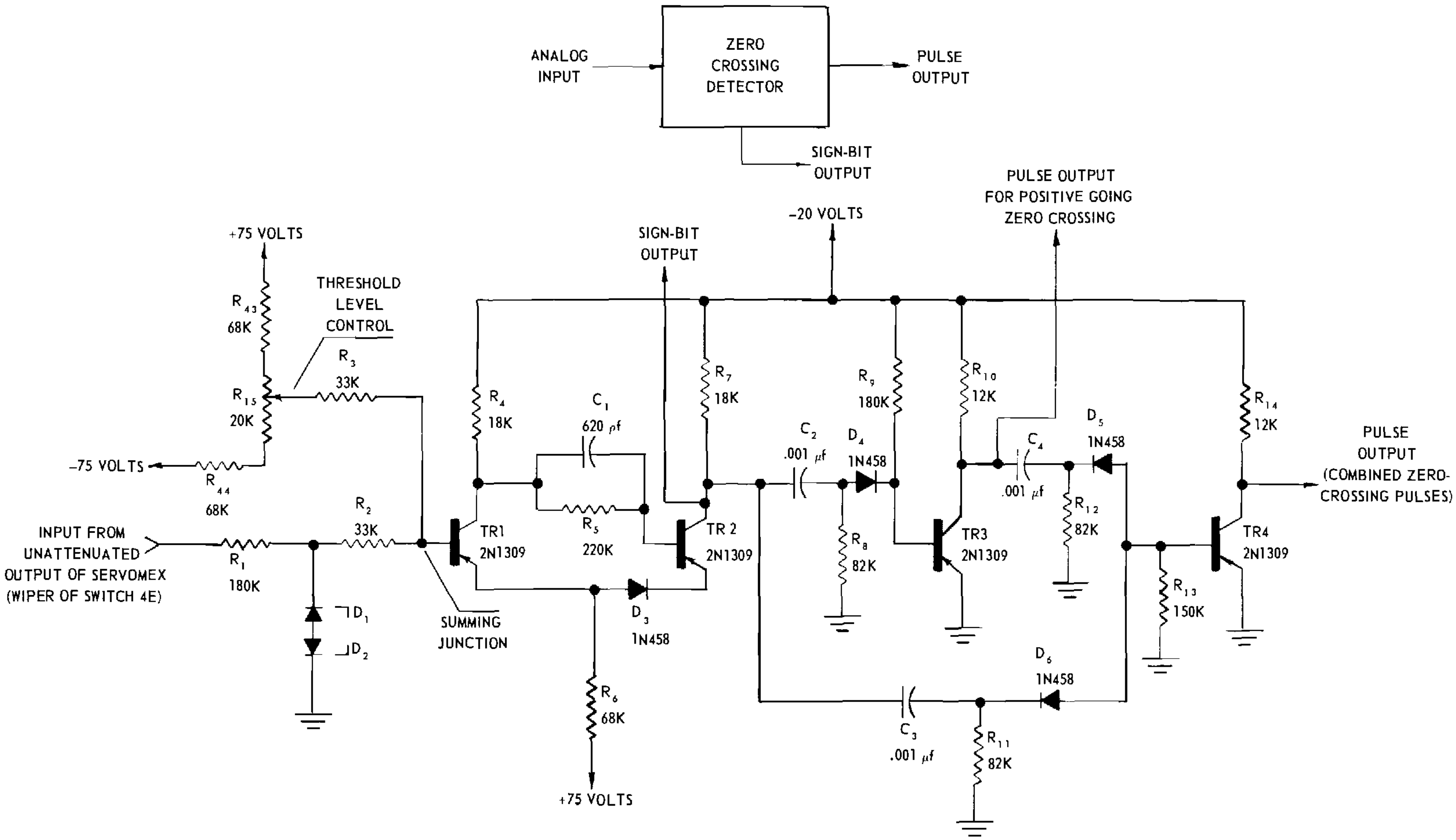

Figure 17. Zero crossing detector.

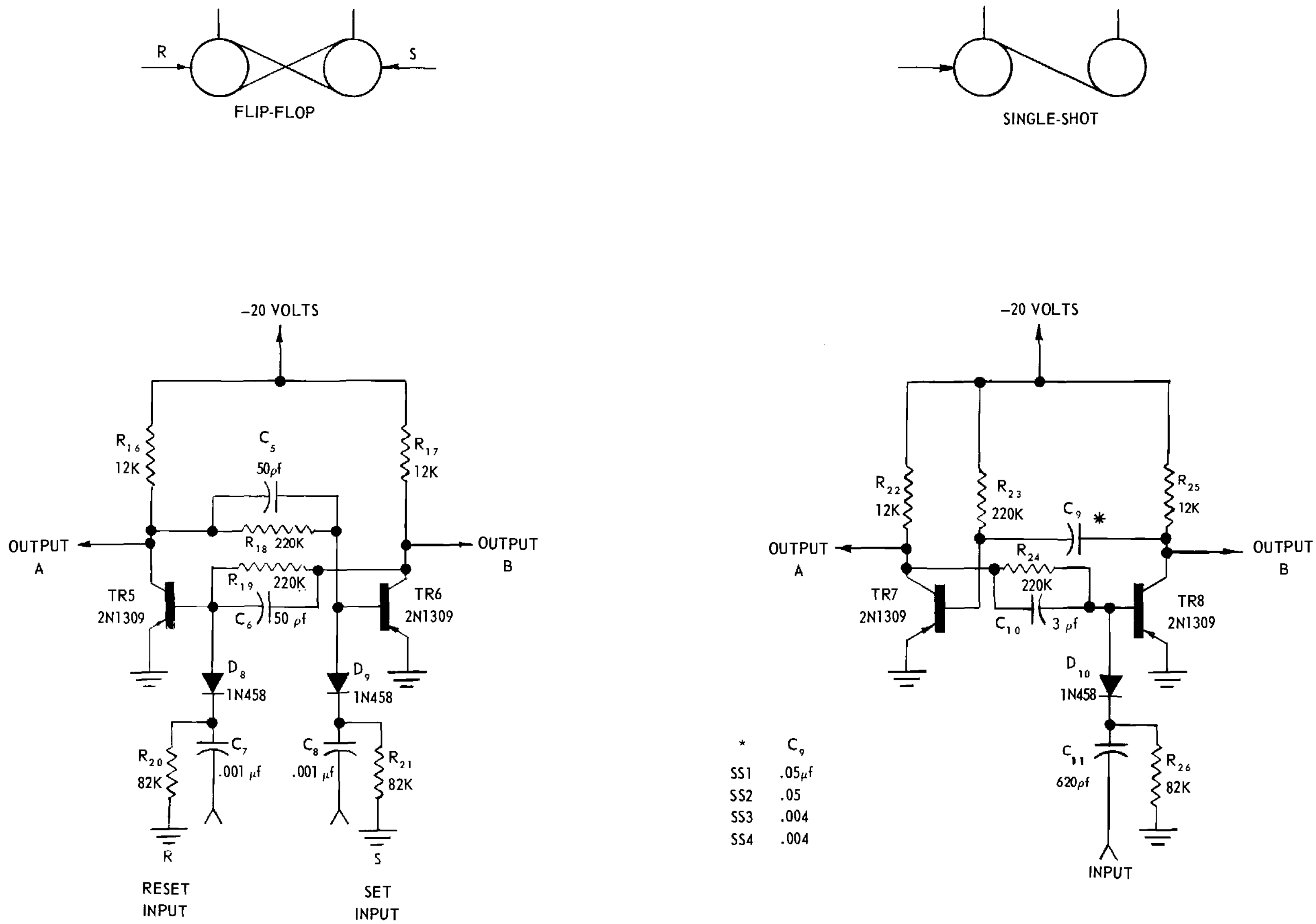

Figure 18. Flip-flop and single-shot.

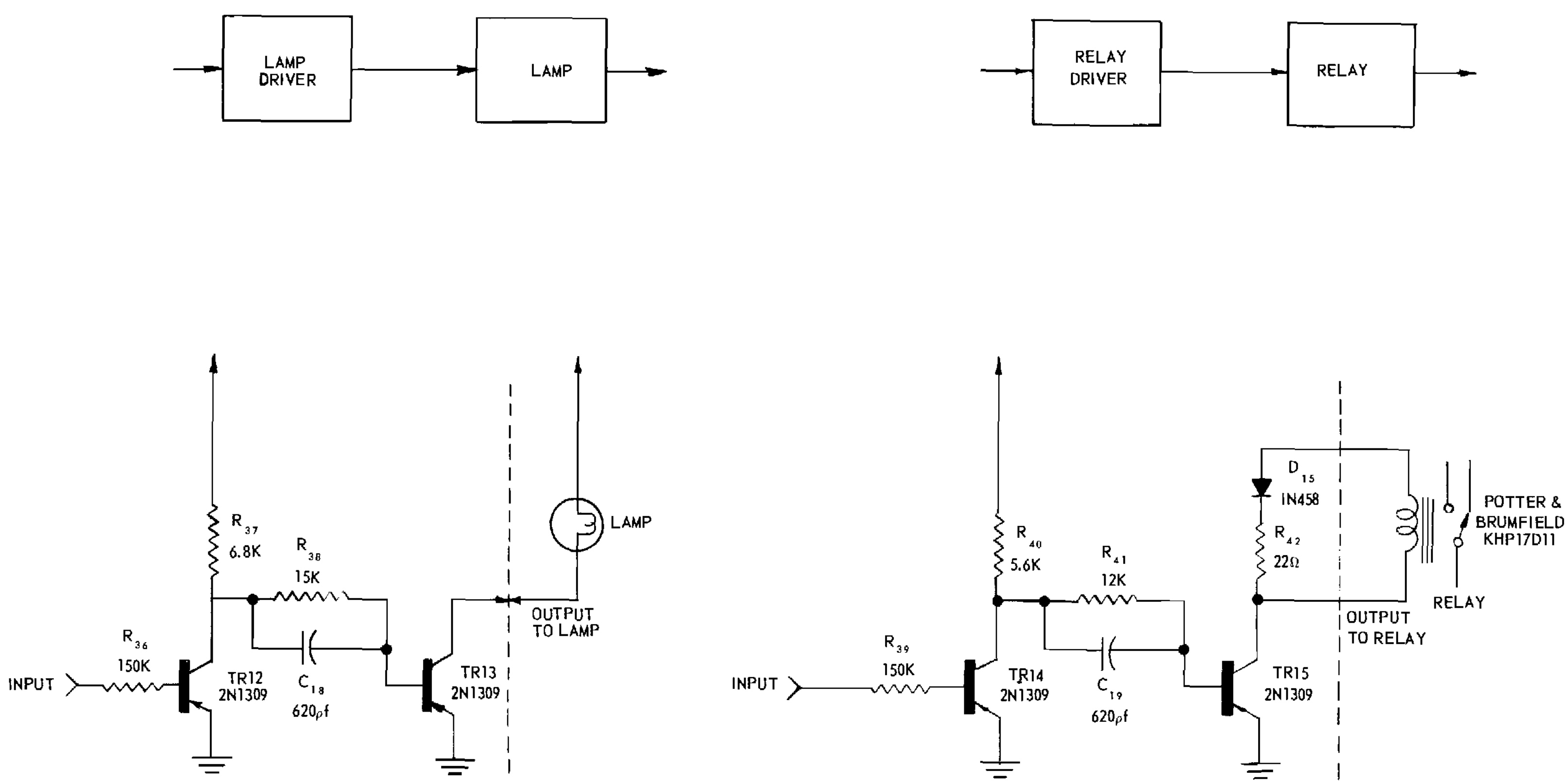

Figure 19. Lamp driver and relay driver.

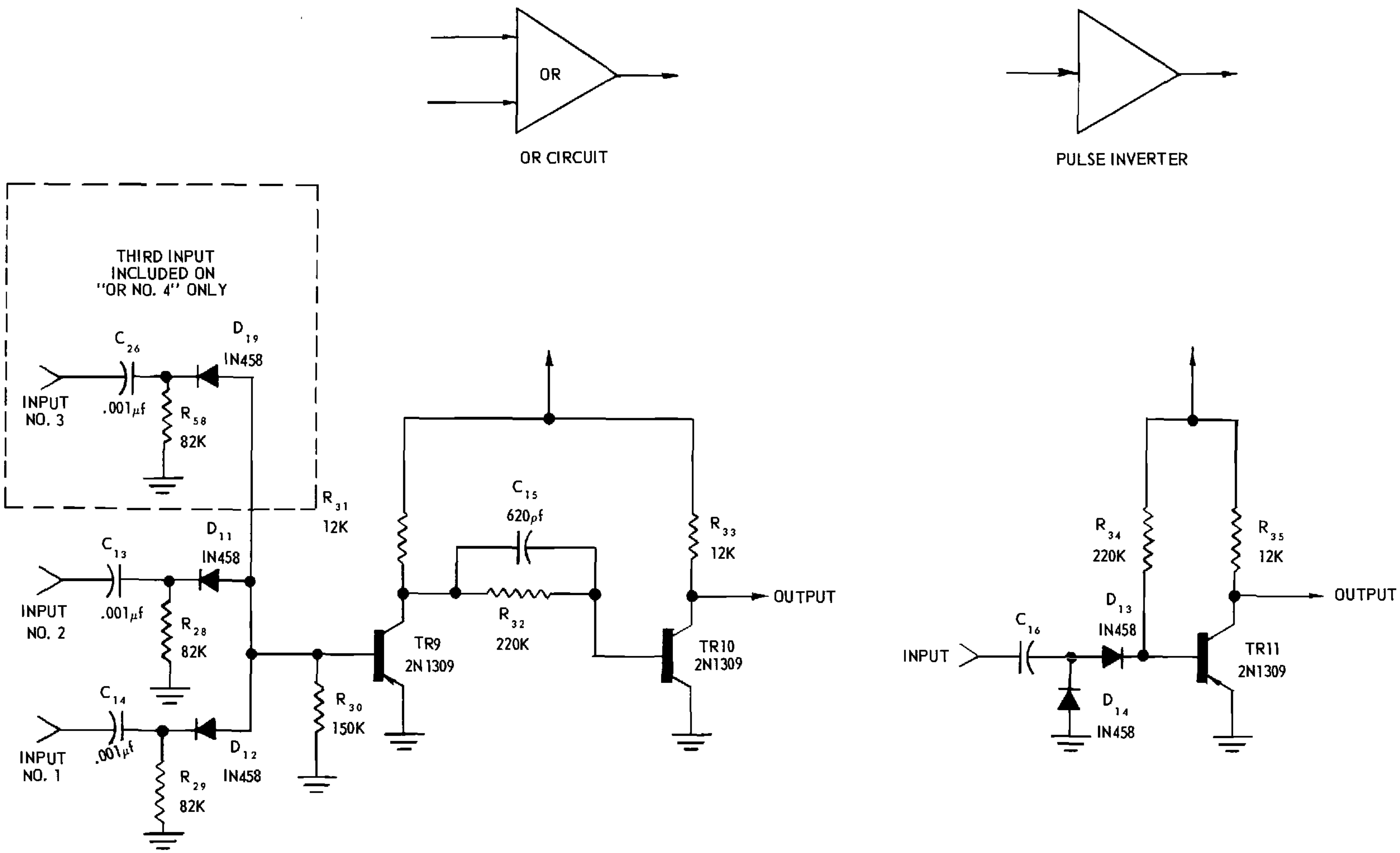

Figure 20. OR circuit and pulse inverter.

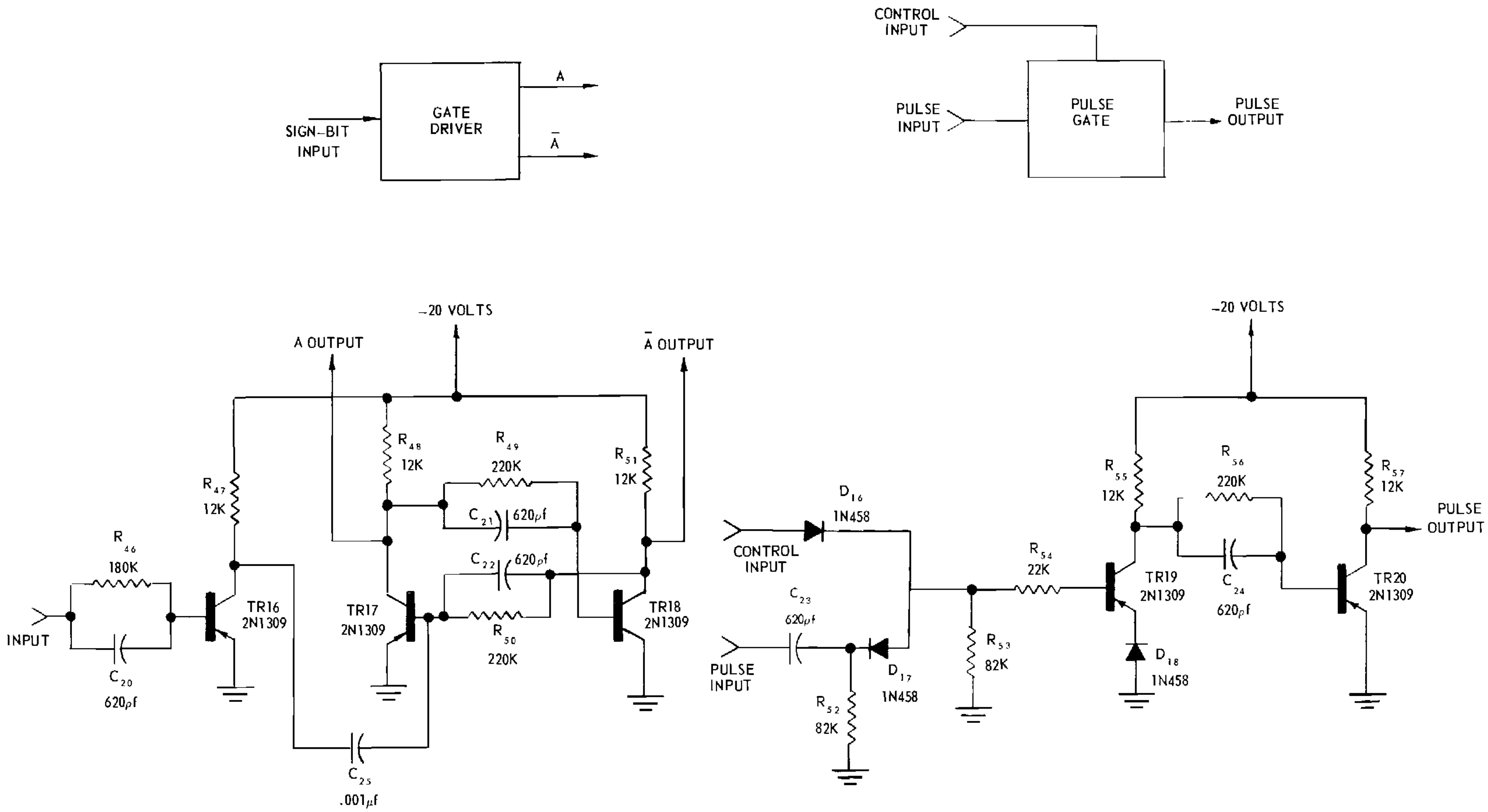

Figure 21. Pulse gate and gate driver.

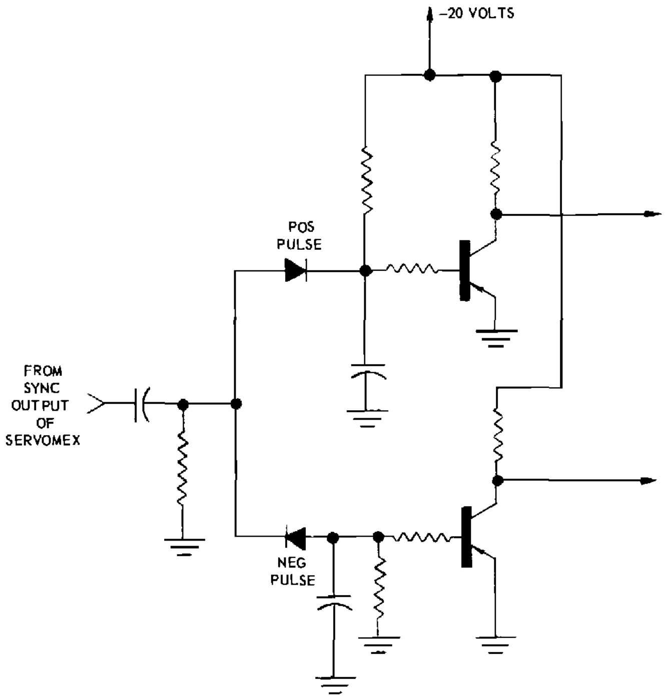

Figure 22. Sync detector.

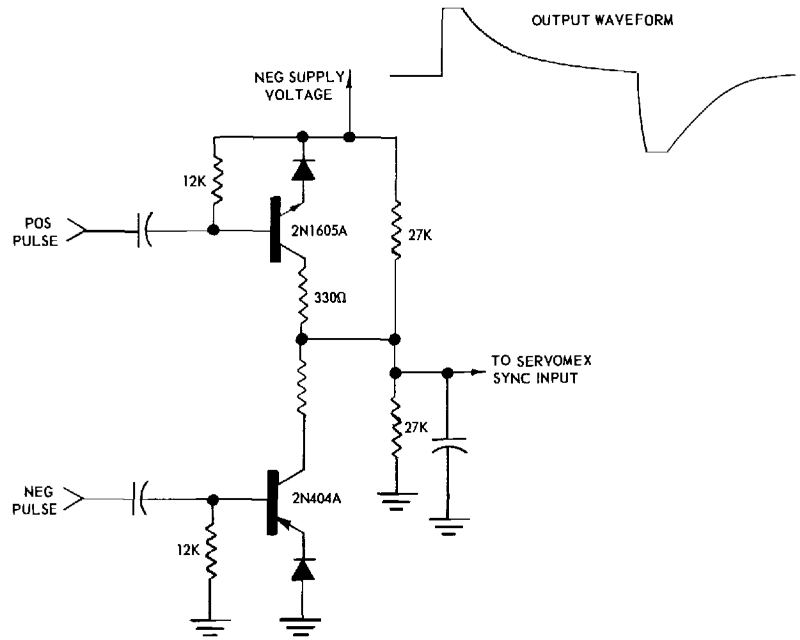

Figure 23. Sync driver.

a step with a fast rise time that will trigger the output function. Removal of the input pulse from the sync driver takes the active transistor out of conduction. The sync input voltage to the Servomex unit is limited in its fall time by the output filter capacitor of the sync driver. This large difference in the rise and fall time of the sync pulse is necessary in the "external" condition to prevent retriggering the Servomex unit on the trailing edge of the pulse. This retriggering on the trailing edge of the pulse presented a major problem in the initial design.

The special case mentioned previously for generating a sine wave biased above zero requires that voltage be added to the Servomex output signal at the input to the Schmitt-trigger circuit of the zero crossing detector and at the grid of the summing amplifier in the servo control unit. Operation of the function generator will be identical otherwise to that described for the unbiased sine wave. The vaules of the biasing voltages and the scale factors used in combining them with the Servomex output must be chosen so that zero crossings occur simultaneously both at the input of the summing amplifier and at the summing junction of the zero crossing detector. The bias voltage to the input of the summing amplifier must be applied only during the period in which the output of the Servomex unit is connected also to this input. A spare set of contacts on the output relay of the function generator can be used for that purpose.

VI. ELECTRICAL FEATURES

A. Control console

The operator's control panel is shown on Figure 24. Rack No. 1, on the left, contains all the switches and timers required for system operation. The servo analog amplifiers, alarm amplifiers, and relay logic chassis are

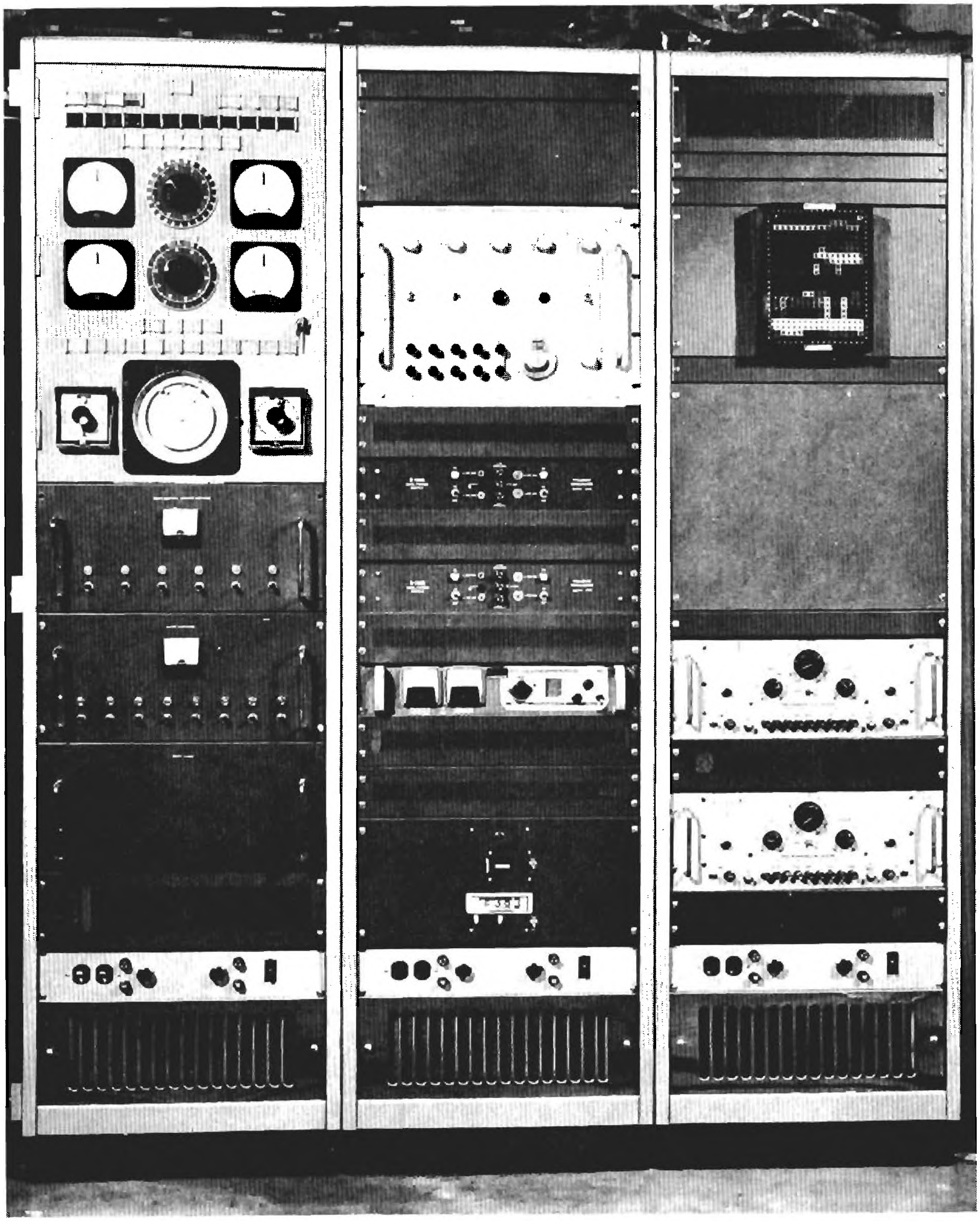

Figure 24. Operator's control panel.

mounted in this rack. Racks No. 2 and 3 contain the command function equipment and the power supplies necessary for system operation. The patch panel shown in Rack No. 3 of the figure allows great flexibility in system trouble shooting, as well as facilitating the use of various data recording equipment.

VII. PERFORMANCE

A. System response

Figures 25 and 26 present graphical representations of the performance of the Periodic Angulator Rotator during early check-out runs. In each figure traces 1 through 5 represent the command signal, tachometer output signal, accelerometer output signal, error signal, and position potentiometer feedback signal, respectively. Figure 25 shows the response of the position mode of the system to a sine function generated by the Servomex unit. Frequencies of 0.1 cps and 0.5 cps are shown at a maximum input signal amplitude of 4 volts. The trace of the position potentiometer output signal indicates that the unit faithfully reproduces the input waveform at 0.5 cps; however, the amplitude of the oscillation is reduced by approximately 1-1/2°, a decrease in response of 1.4 db.

An indication of maximum acceleration is shown in Figure 26, which shows the ability of the device to follow linear acceleration ramp inputs in the velocity mode. As shown by the accelerometer output trace, the angular acceleration of the unit remained essentially linear up to a value of 75 degrees/sec^2. The maximum acceleration of the device has since been increased to the specification value of 100 degrees/sec^2 by modifying the Inland Model 625 power amplifier to supply greater field current to the rotary amplifier. The increased acceleration of the unit provides a sine

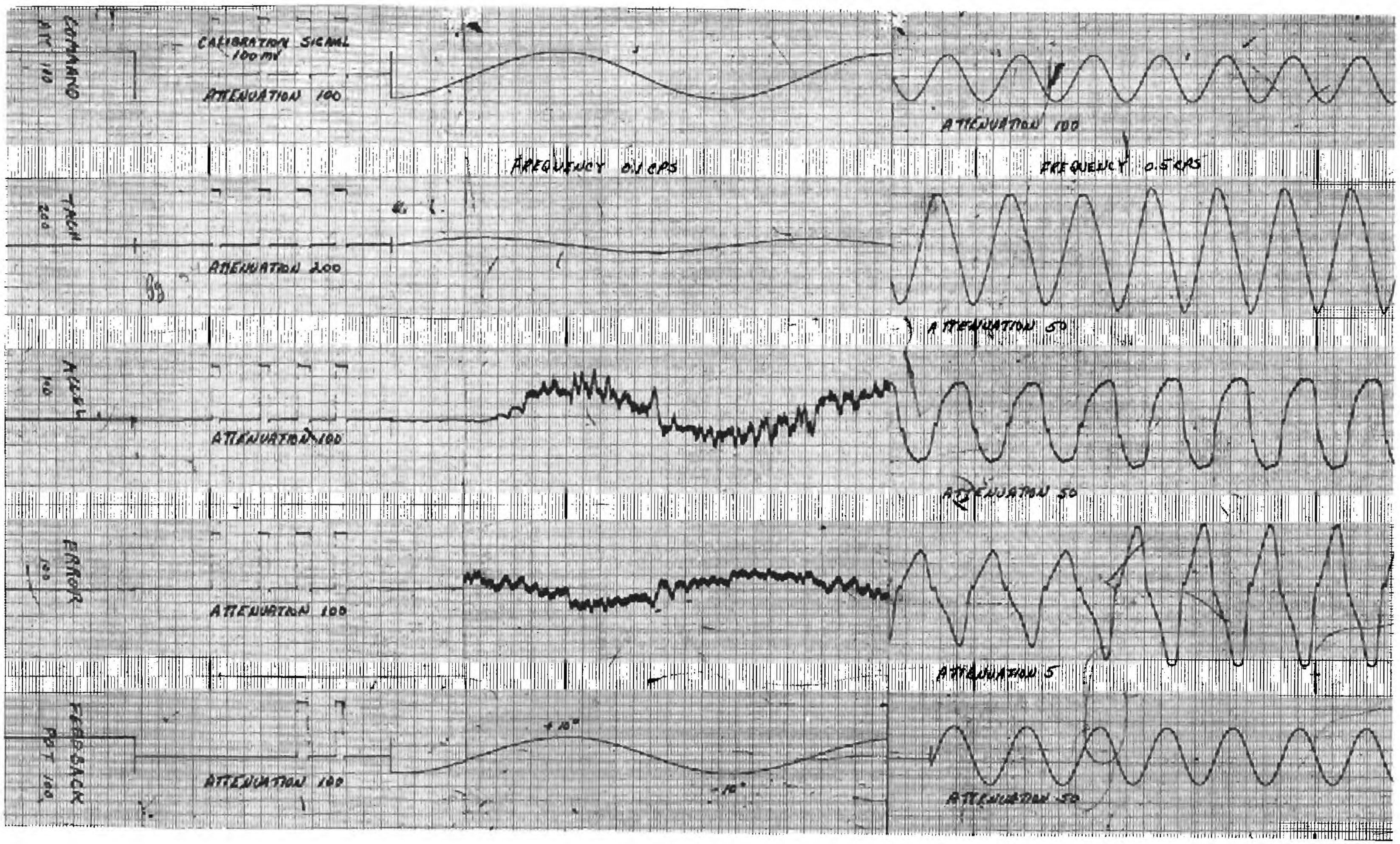

Figure 25. System response to sine wave oscillation.

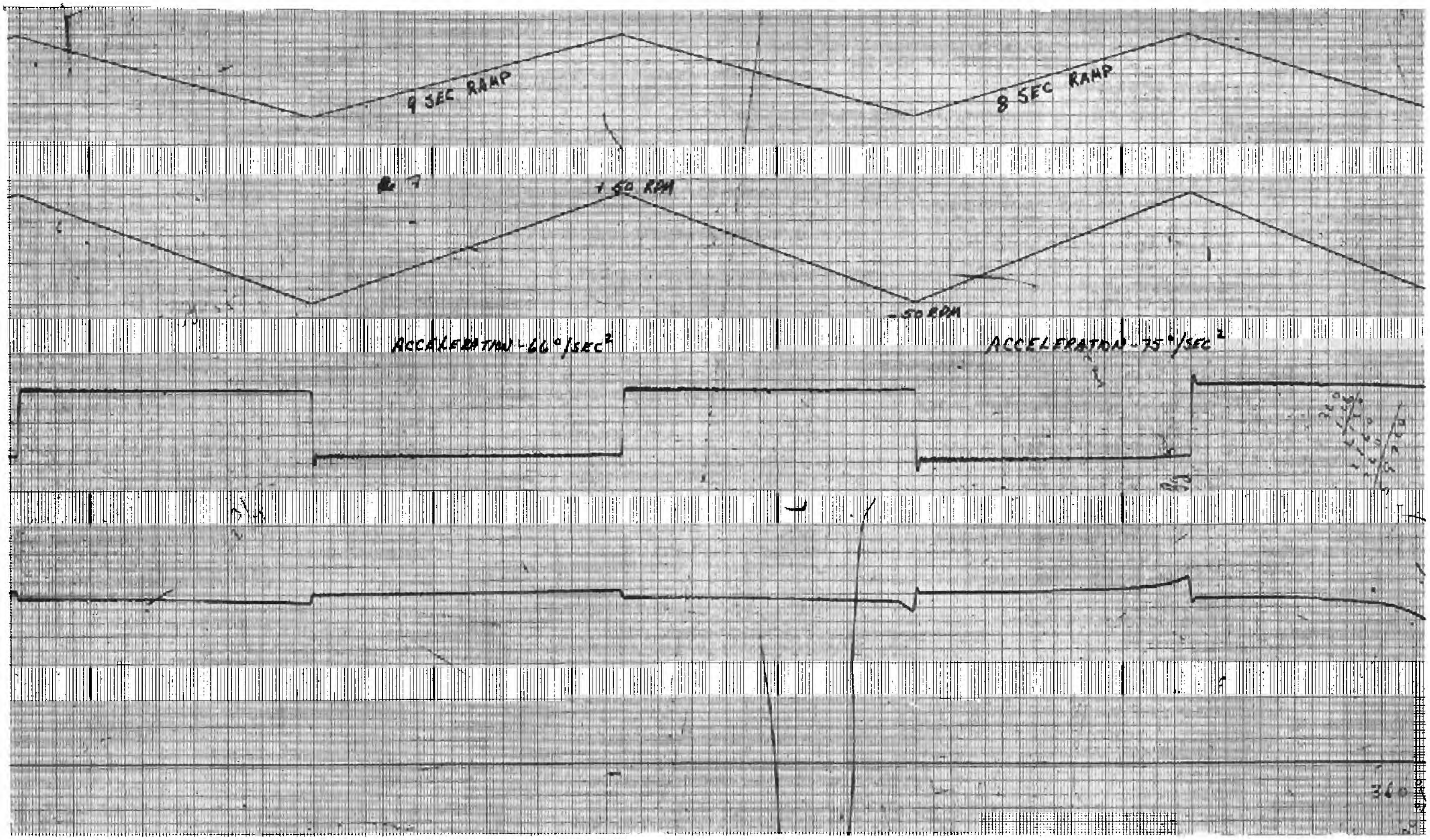

Figure 26. System response to constant acceleration ramp function.

wave frequency response which is flat up to 0.5 cps. The method of modification of the Inland amplifier is shown as Insert A on Drawing No. A629-501.

B. System threshold and linearity

The system threshold has been determined to be 250 mv input to the error amplifier. Thereafter, the speed of the capsule is a linear function of the input voltage from -100 rpm to +100 rpm.

VIII. APPENDIX

APPENDIX A. OPERATION AND MAINTENANCE

A. Operation

The procedure which must be followed for operation of the Periodic Angular Rotator, is outlined below.

1. System turn on

a. Power is supplied to the entire servo system by depressing the switch marked Rack Power on the operator's control panel.

b. Drive power is turned on by depressing switch marked Drive Power located on the control panel.

c. Control power is turned on by depressing switch marked Control Power located on the control panel.

d. After all power is turned on, allow the system to warm up for approximately one hour.

e. Zero all amplifiers in the servo control amplifier chassis and in the alarm amplifier chassis. Zeroing is accomplished by lifting the switch levers and adjusting the potentiometers until the meter reads zero.

2. Program Selection

A. Select servo command input source by depressing one of the three switches located at the upper right of the control console. The switches are labeled Manual Dial Control, Function Generator Control, and Auxilliary Control. (Note: Logic is set so that the system is in Manual Dial

Control condition when power is first applied. For a complete description of the input select system, see Section IV, 6b, page 30, of this report.)

b. Select operating mode (velocity or position) by depressing the Velocity Mode - Position Mode switch on the operator's console until the desired mode lamp is on.

3. Reset alarm circuits

a. If the warning lamp on the 100 RPM Exceeded Alarm switch is on, depress the switch to reset the alarm circuit. For details of this circuit see Section IV, 5b, page 25 of this report.

b. If the warning lamp on the Program Velocity Exceeded switch is on, depress the switch to reset the alarm circuit. Adjust the threshold level of this alarm to the desired value by means of the 10 turn potentiometer located on the operator's control console.

c. If the Capsule Door Interlock Warning Lamp is on, the capsule doors are improperly closed and must be corrected before operation is possible.

d. If the red indicator lamp on the Emergency Stop Switch is on, the switch must be depressed until the red lamp disappears, indicating that the system is in an operational state.

4. Starting run

a. Press reset switch on operator's control panel to place the unit in the reset state.

b. Determine if pilot is ready to commence run, then depress Pilot Not Ready switch until lamp is off.

c. Depress Check List Incomplete switch. If the lamp does not go off, steps a and b above have not completed in proper sequence.

d. Press start rotation switch to place the servo unit in operation.

5. Stop run

a. For operation with input from the function generator, the Stop Function Generator switch may be depressed to command the programmer to stop the input function at the next zero crossing.

b. For any input, depression of the Stop Rotation switch will terminate the run by placing the system in the stop condition. (This condition is obtained automatically in step a above.)

6. Additional Runs

a. The steps listed above, starting with Section 3, must be repeated in order to begin additional runs.

7. Manual capsule position control

a. Manual positioning of the capsule is accomplished by use of the two Jog Controls located on the operator's control panel. These controls function when the servo loop is open and/or interlocked with the reset switch. To rotate the chair in a desired direction, depress simultaneously the reset switch and the CW Jog or CCW Jog switch. A detailed description of these controls is given in Section IV, 6e, page 32 of this report.

B. Maintenance

1. Electrical

a. The $\pm$ 50 volt reference power supplies should be thoroughly checked after each 10 hours of operation to determine that no drift occurs. These voltage levels are very critical in insuring good system operation.

b. Should it become necessary to inspect or replace the position feedback potentiometer, slip ring, or magnetic velocity sensor, these units may be reached by removing the plate at the base of the pedestal.

2. Mechanical

a. No mechanical maintenance is anticipated other than insuring tightness of bolts and screws. However, should it become necessary for any reason to remove the motor or tachometer, the procedures outlined below must be rigidly followed.

(1) Torque motor.

(a) Remove chair and spindle nose extension.

(b) Align the arrow on the spindle with the arrow on the torque motor and install the eight 1/4-20 Allen head cap screws in the shipping clamp. The bolt holes are reached through the four large holes in the upper bearing housing. The shipping clamp bolts should screw in easily by hand. If difficulty in starting the bolts is encountered, rotate the shaft slightly to insure proper alignment of the rotor and stator. Tighten the 8 bolts with an Allen wrench. Under no circumstance should further disassembly be carried out unless shipping clamp bolts are installed and tightened.

(c) Remove the upper bearing housing bolts and lift off housing.

(d) Remove bearing, spacers and seal. Note order of removal for replacement purposes.

(e) Remove bolts which secure the motor rotor to the spindle.

(f) Remove four bolts which secure the motor stator to the housing.

(g) Lift the torque motor rotor-stator assembly out of the housing.

(2) Tachometer.

(a) Follow steps a through g as listed above.

(b) Install keepers on tachometer stator (keepers furnished with unit).

(c) Remove sheet metal cover from bottom of base.

(d) Disconnect and remove the position feedback potentiometer. Disconnect the magnetic pick-up and tachometer leads. (The tachometer is disconnected by following the wire through a hand-hole and unscrewing an Amphenol connector.)

(e) Remove slip ring and slip ring wiring from spindle shaft.

(f) Remove pedestal base from motor housing.

(g) Remove spindle shaft with tachometer rotor attached from the motor housing.

(h) Remove tachometer rotor from spindle shaft and tachometer stator from motor housing.

IMPORTANT -- Shipping clamp bolts must always be in place in the torque motor stator-rotor unit when unit is not assembled for use. Keepers must always be fixed on the tachometer stator when the tachometer rotor is not in place in the stator.

APPENDIX B. PARTS LIST

The following parts list includes major components of the Periodic Angular Rotator system. Component parts lists for sub-assemblies are given on pertinent drawings.

Quantity	Part No.	Description	Source
1	A629-7-10035A	Torque Motor, Model 7-10035A	Inland Motor Corp. of Virginia Radford, Virginia
1	A629-MG3315A	Rotary Amplifier Model MG3315A	Inland Motor Corp. of Virginia Radford, Virginia
1	A629-TG10017B	Tachometer Generator Model TG10017B	Inland Motor Corp. of Virginia Radford, Virginia
1	A629-625	Power Amplifier, Model 625	Inland Motor Corp. of Virginia Radford, Virginia
2	A629-R-100B	Dual Power Supply Model R-100B	Philbrick Researches Boston, Mass.
1	A629-LF51	Servomex Waveform Generator Model LF51	Servomex Controls, Ltd. Crowborough, Sussex, England
1	A629-DR36-4	Power Supply, Model DR 36-4	NJE Corporation Kenilworth, N. J.

APPENDIX C. LIST OF DRAWINGS

Drawing No.	
A629-200	Base Assembly
A629-201	Base Bottom
A629-202	Motor Support Housing
A629-203	Shaft
A629-204	Lower Bearing Housing
A629-205	Spindle Nose
A629-206	Spindle Nose Extension
A629-207	Leveling Foot
A629-208	Seal (Bearing 47680)
A629-209	Seal (Bearing 52400)
A629-210	Bearing Housing (Bearing 47680)
A629-211	Brush Support Bracket (2 Required)
A629-212	Slip Ring Wiring Holes
A629-214	Magnetic Pickup and Potentiometer Support Bracket
A629-215	Shaft Extension for Magnetic Pickup Gear and Potentiometer
A629-216	Accelerometer Brackets
A629-217	Flinger (Top)
A629-300	Chair Assembly
A629-301	Chair Details
A629-302	Chair Details
A629-303	Chair Assembly Details
A629-304	Adjustable Chair Arm
A629-305	Head Rest Details
A629-306	Head Rest

Drawing No.	
A629-400	Stop Weldment
A629-500	Wiring Diagram, Rack #1 and Relay Logic
A629-501	Block Diagram, Servo System
A629-502	Schematic Diagram, Servo Control, Analog Amplifier, Reference Designation A3
A629-503	Power Connections, Servo Control, Analog Amplifier, Reference Designation A3
A629-504	Component Layout, Servo Control, Analog Amplifier, Reference Designation A3
A629-505	Schematic Diagram, Alarm Amplifier, Reference Designation A4
A629-506	Power Connections, Alarm Amplifier, Reference Designation A4
A629-507	Component Layout, Alarm Amplifier, Reference Designation A4
A629-508	Instrument Panel
A629-509	Amplifier Chassis #1 Layout, Reference Designation A3
A629-510	Front Panel Layout, Amplifier Chassis #1, Reference Designation A3
A629-511	Amplifier Chassis #2 Layout, Reference Designation A4
A629-512	Front Panel Layout, Amplifier Chassis #2, Reference Designation A4
A629-513	Schematic Diagram - Relay Logic
A629-514	Control Room Patch Panel Wiring Diagram
A629-515	Control Room Patch Panel Wiring Diagram
A629-516	Control Room Patch Panel Wiring Diagram
A629-517	Interconnecting Instrumentation and Control Wiring Diagram
A629-518	Electric Layout
A629-519	Electric Layout