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OAO STATE OF CHARGE UNIT

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GSFC
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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Information Processing Division

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by

W. Miller, W. Stewart, and J. Yagelowich

ABSTRACT

The State of Charge Unit (SOCU) is designed for use as an auxiliary controller of the Orbiting Astronomical Observatory (OAO) battery charge control system. State of Charge of the batteries is monitored in ampere-hours by integrating the charge and discharge currents flowing through each of three batteries. The current is monitored by measuring the voltage drops across shunts in the negative lead to each battery. State of charge is also monitored by measurement of the adhydrode potential of one adhydrode (third electrode) cell in each of the three batteries.

This report describes the design and instrumentation of this unit.

OAO STATE OF CHARGE UNIT

GENERAL

The State of Charge Unit (SOCU) is designed for use as an auxiliary controller of the Orbiting Astronomical Observatory (OAO) battery charge control system. State of charge of the batteries is monitored in ampere-hours by integrating the charge and discharge currents flowing through each of the three batteries. The current is monitored by measuring the voltage drops across shunts in the negative lead to each battery. State of charge is also monitored by measurement of the adhydrode potential of one adhydrode (third electrode) cell in each of the three batteries.

A block diagram of the SOCU is shown in Figure 1. With the SOCU in control, the first indication of full charge on a battery enables a circuit which causes a transfer to a lower or trickle charge state. Selection of operation of the control circuit by either the ampere-hour or the third electrode circuit is by command. A "Nite" signal resets the control circuit to a high-current charging state. Upon entering daylight the spacecraft's power control system will not go to a low charging rate until full charge is reached. Full charge in the ampere-hour mode is when the charge-discharge, ampere-hour, counting register is filled; third electrode full charge occurs when the adhydrode voltage reaches a specified threshold.

SHUNT

A three element shunt is used with the three batteries of the OAO Power Control Unit (PCU) to provide an input voltage, dependent upon shunt current, to the integrators. About 40 amperes sustained current is possible through the shunt under the most favorable solar aspect angle and low battery charge conditions. A current of 60 amperes was selected as a peak which the shunt need safely handle. In order to minimize the power lost in the system the shunt resistance was kept to a value of the order of the lead resistance. A shunt resistance of 0.0025 ohms was therefore selected. This provides a signal to the integrator of 50 mv., when a 20

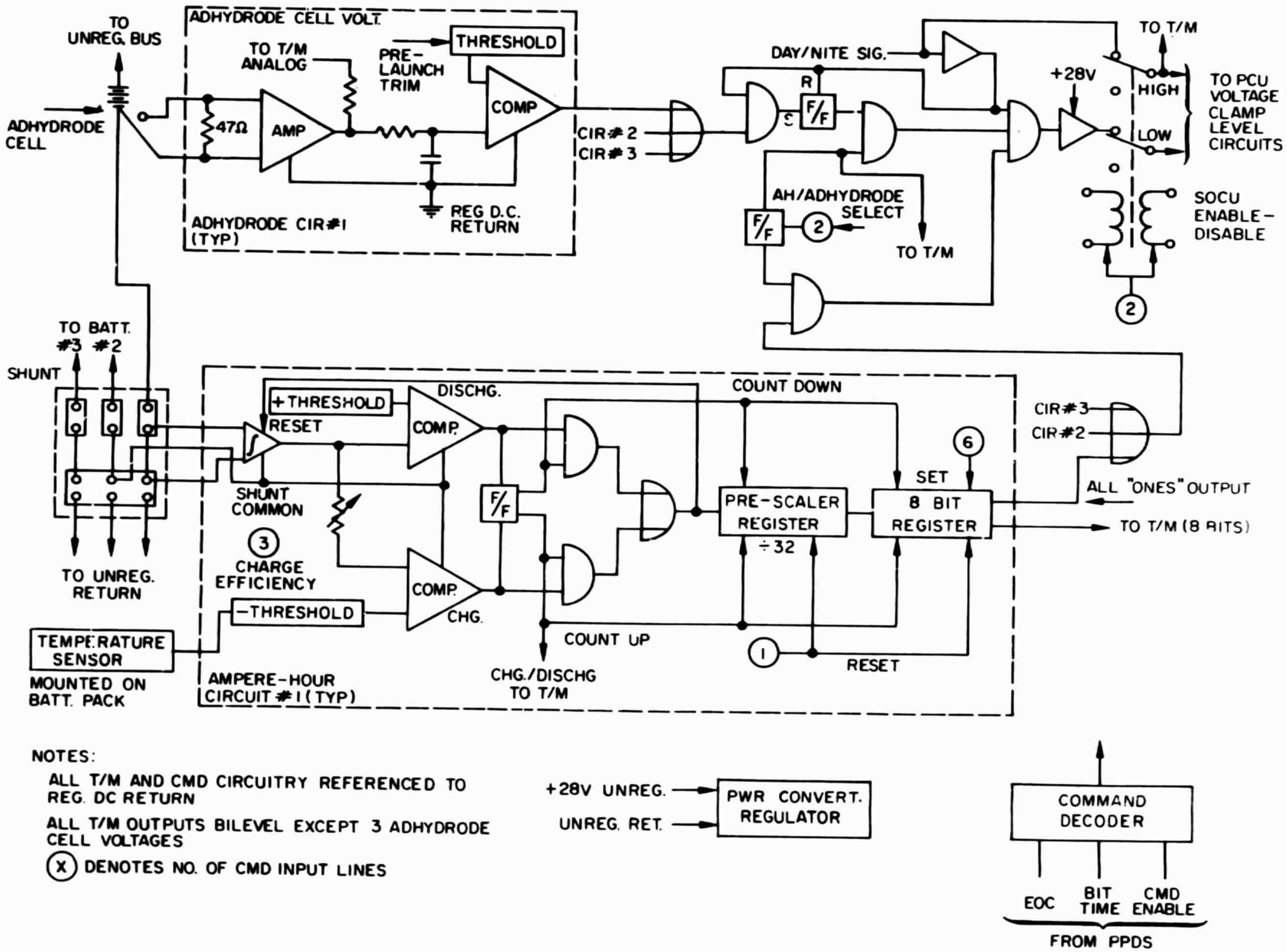


Figure 1-State of Charge Unit Block Diagram

ampere current is flowing. During the night-time portion of an orbit the average discharge current is about 8 to 10 amperes; while in daylight the current averages about 12 to 14 amperes, but it initially has a peak of as high as about 40 amperes. Trickle charge current into the battery is about one ampere. Thus the above listed currents cause the shunt voltage to vary from a low of 2.5 mv to as high as 150 mv.

SHUNT CONSTRUCTION

The shunt element is made of manganin, a low temperature coefficient material ($\pm 2 \times 10^{-5}$ relative change in resistivity /°C) especially made for use in shunts. The ribbon elements are silver-soldered to brass blocks. Current terminals and voltage pick-off terminals are tapped and silver soldered into the brass blocks. A common block is used at one end of the shunt elements and is designated shunt common. Figure 2 is a photograph of the shunt.

MEASURED SHUNT RESISTANCE

The following table shows the uniformity of shunt resistance versus current:

5.1 amperes	2.498 milliohms
9.9	2.500
19.4	2.500
28.9	2.501
43.9	2.501

Considerable overheating occurred with the first shunts fabricated, see Figure 3. The shunt temperature, for normal currents, rose to nearly 300°F. Notice that the leads connected to the shunt also get very hot due to the resistance of the wire. The wiring used for this test duplicated the wiring in the OAO Spacecraft. Tests were conducted in a vacuum. The test results show how hot spacecraft wiring can become without the convective air cooling we take for granted in the lab. With a current of 60 amperes the shunt ribbon temperature rises from 78°F to 235°F in 30 seconds. Since the shunt is mounted over a cable tray in

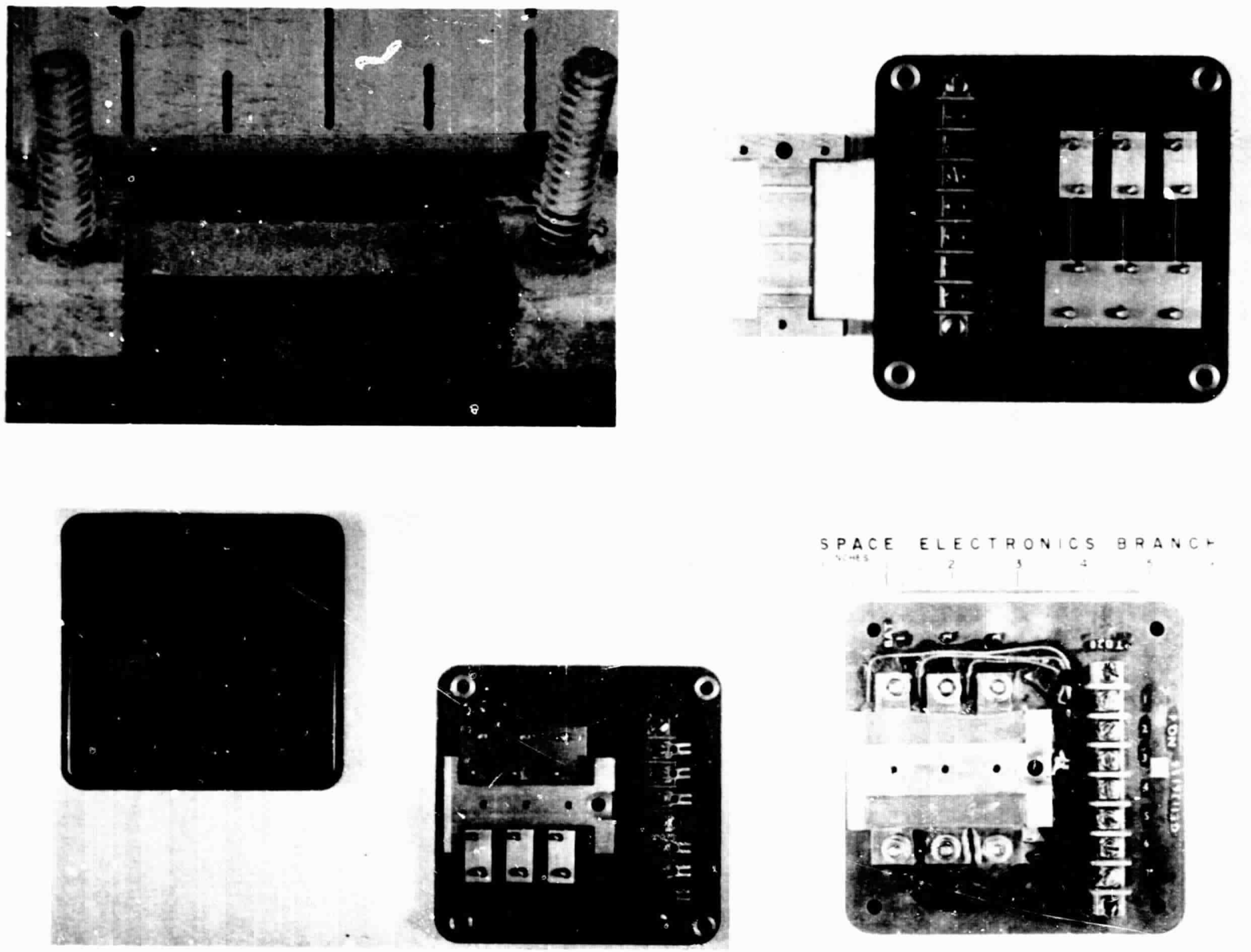


Figure 2-Shunt Assembly

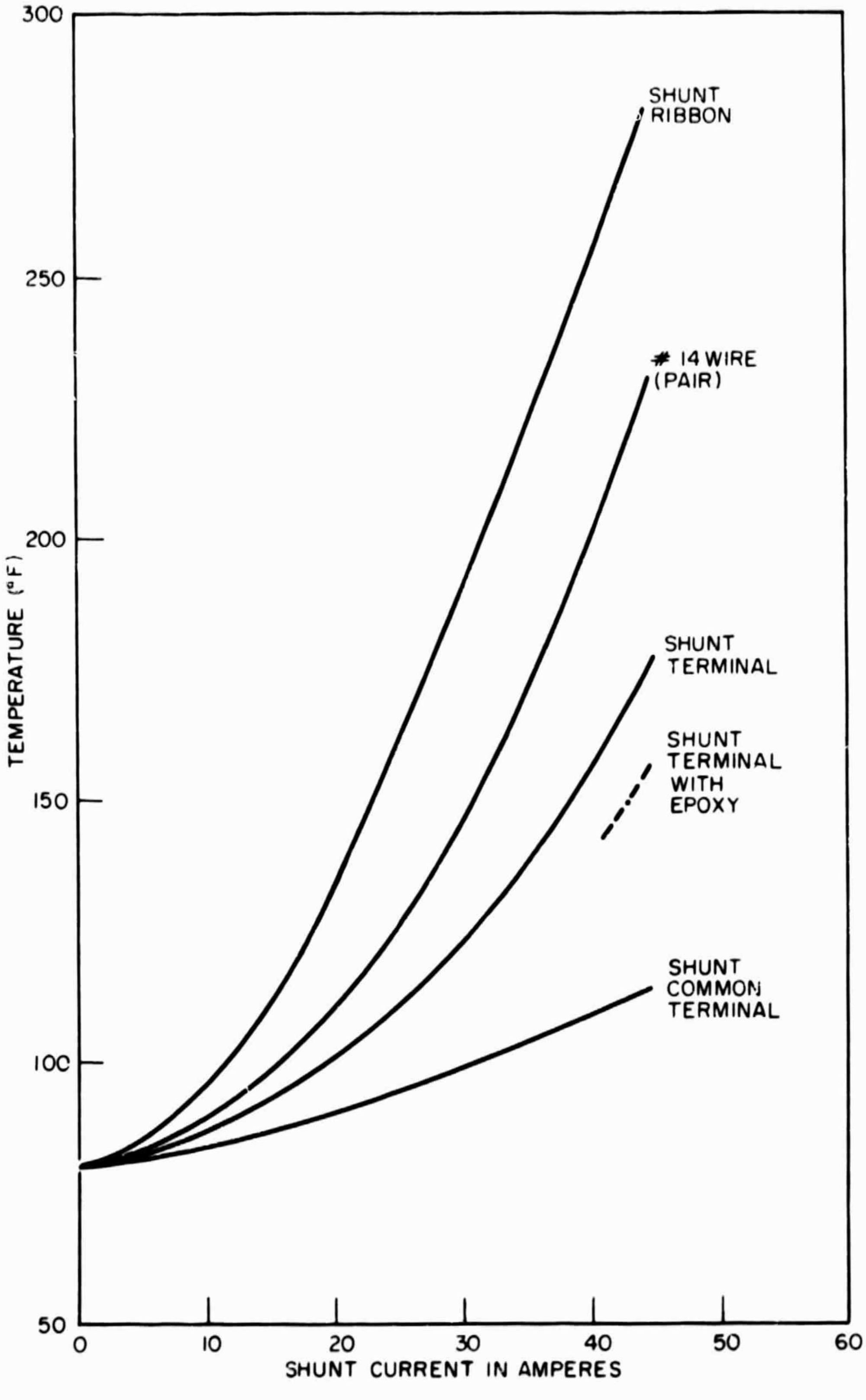


Figure 3-Shunt Temperature vs Current in Vacuum

the OAO spacecraft some way was required to lower these temperatures and to radiate heat away from the cabling in the tray. An electrically isolating but thermally conductive epoxy (Hysol 6c) was used to transfer heat from the shunt components to the shunt lid. The lid was painted flat black to help radiate the heat.

The shunt was tested to 60 amperes per element for 6 minutes. No noticeable degradation or change in shunt resistance was noticed, with the element's resistance returning to its lower current resistance value.

AMPERE-HOUR (AH) CIRCUIT

Each ampere-hour circuit consists of an automatically reset integrator which monitors the current flowing through the 0.0025 ohm shunt installed in the negative lead of each battery circuit. Depending upon direction of current flow, either a charge or discharge comparator is triggered when a prescribed d.c. level of the integrator output is reached. This signal is used to reset the integrator to zero and one count is added to the ampere-hour register for charge current or one count is subtracted for discharge current. The reset time of the integrator is kept very small compared to integration time to minimize errors. Temperature sensitive resistors installed on the battery packs, one for each ampere-hour circuit, automatically adjust the charge comparator trip level for changes in charge efficiency due to battery temperature variations. Adjustable compensation by command of charge efficiency (eight levels) is also provided in parallel with the automatic compensation for power subsystem matching and to adjust for effects due to battery age and cyclic history. Compensation is approximately as indicated in Figure 4.

A flip-flop, controlled by the outputs of the charge and discharge comparators, is used to control the direction of the up-down counter, consisting of a five stage prescaler up-down counter followed by an eight stage up-down counter. The output of this flip-flop is telemetered as a binary digit to indicate current direction.

The eight stage register for each AH circuit presents a running total of the net state of battery charge. Each pulse into the register represents one tenth of an ampere-hour of charge or discharge. When the battery is fully charged,

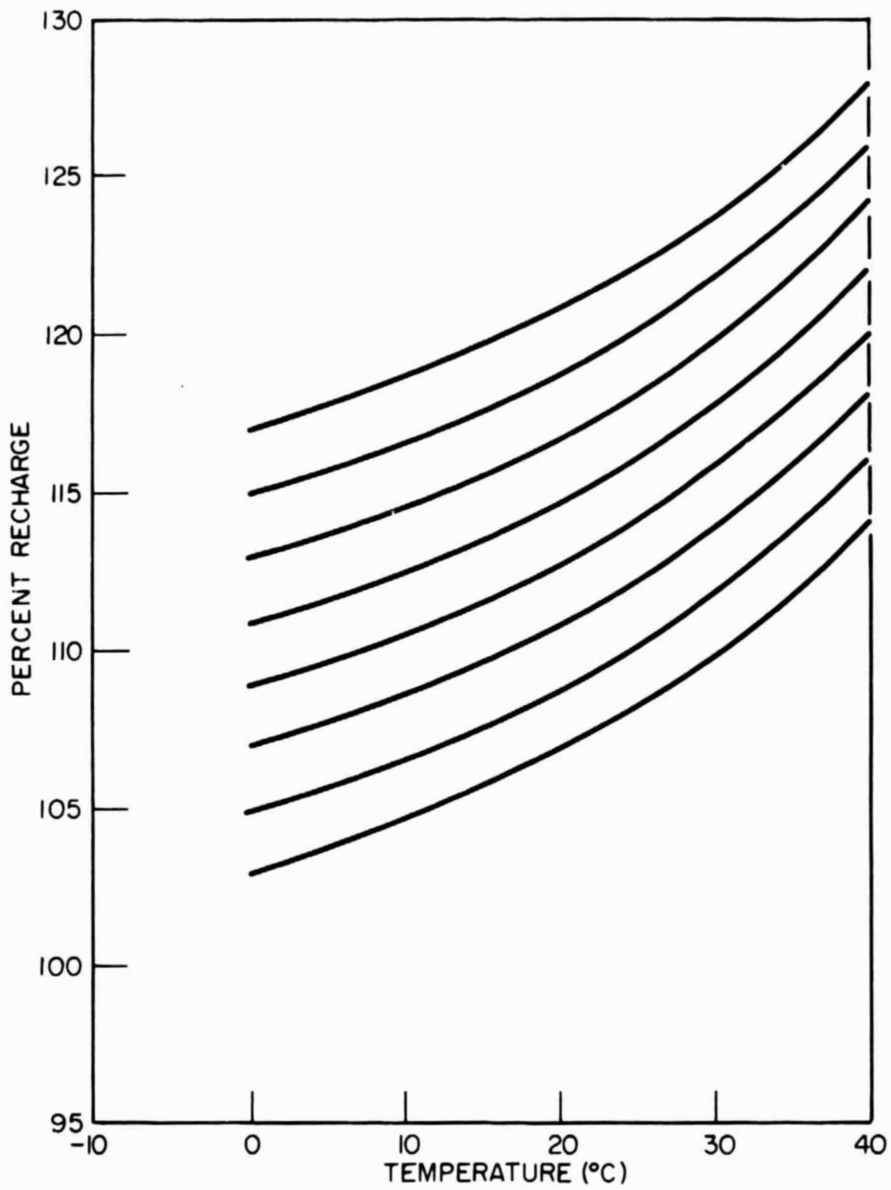


Figure 4–Charge Compensation vs Temperature

the register indicates all ones, which corresponds to a charge of 25.5 ampere-hours, slightly more than the actual capacity of the battery which may vary from pack to pack and with age. The register remains in the all ones condition as long as the battery is fully charged. If the register should go to all zeros, due to fully discharging the battery, the register remains all zeros until battery charging current is applied. The presence of all ones in any one of the three ampere-hour registers enables an output current to power a relay so as to reduce the charging current through the batteries, if the SOCU is in the ampere-hour mode of control. The binary states of all eight stages of the three registers (24 bits) are telemetered.

It is possible to preset the eight stage register to all ones or to any desired combination of ones and zeros for the six most significant bits of the registers. The two least significant bits are always set to ones and the five stage pre-scaler register bits are always reset to zeroes during a register command.

INTEGRATOR DESIGN

Using the criterion of one false count into the eight stage up-down count register per orbit, the drift rate period of the integrator must be greater than 169 seconds. This calculation comes about from a series of compromises reached between integrator capacitor size (capacity in mfd, and physical dimensions), the voltage to which the integrator output is permitted to reach, and the number of pre-scaler stages. From a reliability viewpoint it is desirable to increase the capacitance so as to reduce the number of pre-scale flip-flops, and also to reduce the rate at which the reset circuit operates. However, the physical size of large capacitance, low leakage capacitors is prohibitive. The capacitance-leakage product for a given type of capacitor is a constant so there is no reason to select a capacitor on this basis. An operational amplifier (op amp) integrator is used to provide linear charge-discharge characteristics. Its output voltage can be as large as ±10 volts before saturation occurs. Reset must occur before saturation to avoid non-linearity and also to avoid "latching" and possible overheating of op amp components. Two factors favor the use of a much lower integrator voltage. The first is to avoid operating the comparators near their common mode limit of 10 volts, while the second reason is to restrict the maximum current flow through the reset circuit when the integrator capacitor charge is dumped. For the capacitor value chosen (1 mfd) the capacitor must be discharged in less than 3 msec to maintain a 1% accurate system. For the above reasons the integrator output is not permitted to go beyond ±2 volts. Since the dumping rate is low and also to provide complete isolation from the op amp a reed relay is used to reset the capacitor. A small resistor is used to limit dump current to prevent contact pitting and sticking. With the moderate type cycling of the above circuit the reed relay is predicted to have a lifetime of 50 x 10^6 operations. The orbital OAO type of operations is estimated to have the requirement for 5 x 10^6 resets per year.

Integrater drift is minimized by selecting a high quality capacitor, by selection of a balanced operational amplifier, and then by further careful balancing of the op amp's current drift. A chopper-stabilized op amp has much lower drift but was not used because of its higher power drain, and because these lower power chopper stabilized op amps use FET choppers which would be damaged at OAO's orbital altitude due to Van Allen Belt radiation. A polycarbonate capacitor having a leakage resistance greater than 40,000MΩ at 25°C was chosen. (A polystyrene capacitor has higher resistance but was rejected because it is larger physically.) The effect of leakage is further reduced by using a low value resistor feeding the op amp; more of the leakage current is then shunted away from the input to the op amp. Integration drift is also balanced somewhat by placing a series resistor in the plus input of the op amp which matches the resistance in the minus input. Balance versus temperature is achieved by the use of dissimilar resistors in a network from both (±) supply voltages into the plus input, see Figure 5. Metal film resistors have a positive temperature coefficient, while carbon resistors have a negative coefficient. Integrator drift is measured versus temperature and resistance is inserted in the op amp input circuit to balance the integrator. This step allows the measurement of the effective resistance needed to maintain balance. A combination thin metal film and carbon resistance network must then be found which matches the measured effective resistance. What complicates matters is that carbon resistors initially change with temperature cycling and therefore must be temperature cycled several times so they will age and their subsequent change with temperature will be repeatable.

An op amp integrator has no common mode rejection capability. As it is used in OAO there is a common mode voltage at the input to SOCU since there is finite resistance in the leads between the shunt and regulated d.c. ground. With as much as 40 amps flowing through these leads and also due to noise pulses and switching transients there may be as much as ±2 volts between these two points. An operational amplifier could be used ahead of the integrator to provide common mode rejection. However its use will cause an increase in false counts due to offsets and drifts due to temperature by a factor of about twice what has been obtained with the direct connection of the shunt to an integrator. Common mode protection is provided by referencing the two comparators, as well as the integrator, to shunt common. The voltage swing of the output of the comparator is so much larger than the ±2 volts common mode voltage that the effect of the ±2 volts on the input is overcome. In essence, the integrator and comparators ride up and down with the common mode voltage with no effect on the rest of the circuit; the integrator operates on the differential voltages from the shunt element; when the reset voltage is reached the comparator fires and only then is the reset circuitry enabled. A separate regulated voltage supply must be used to power the integrators, with the supply referenced to shunt common.

Figure 6 shows the pre-scaler, main register circuit.

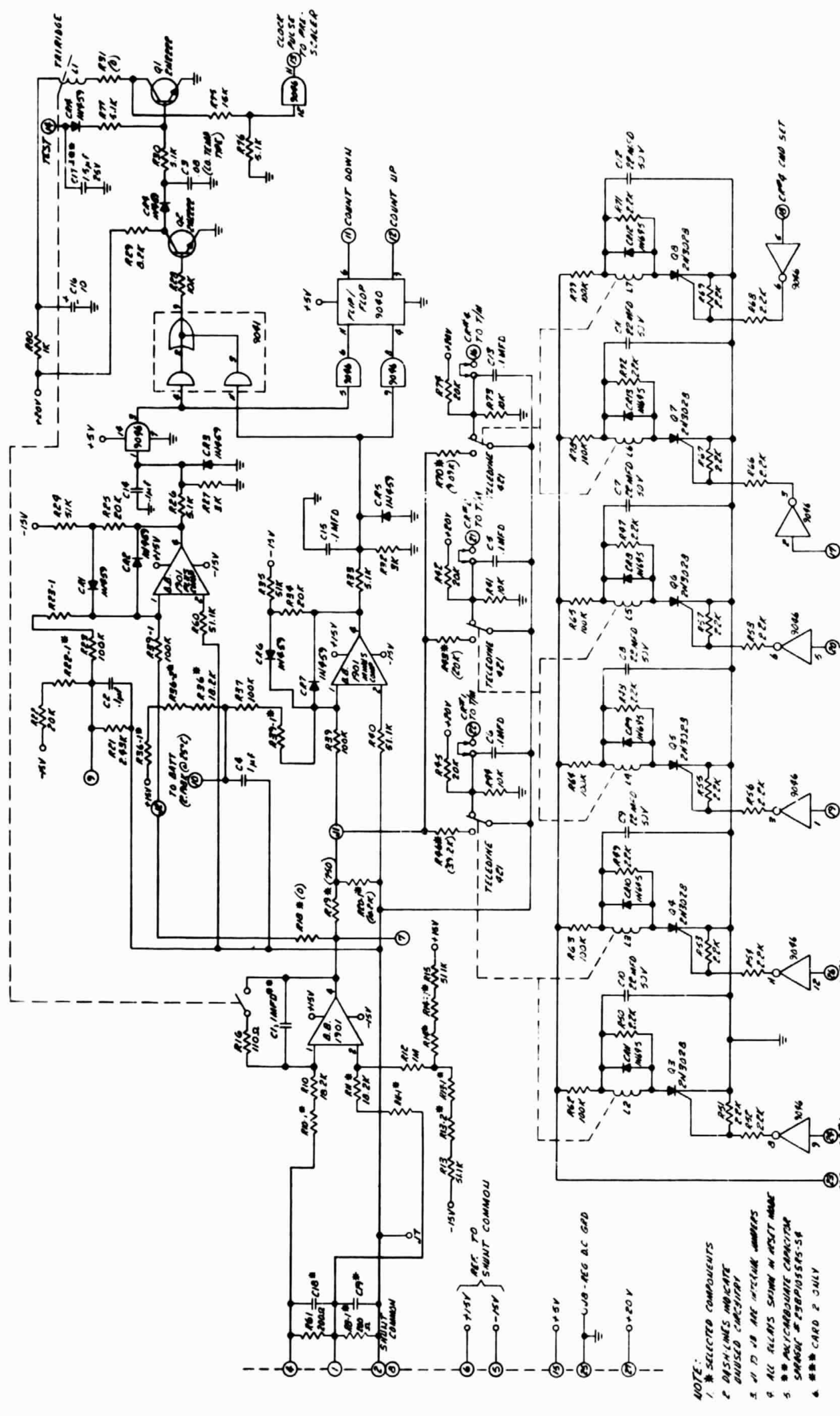


Figure 5-Integrator Circuit

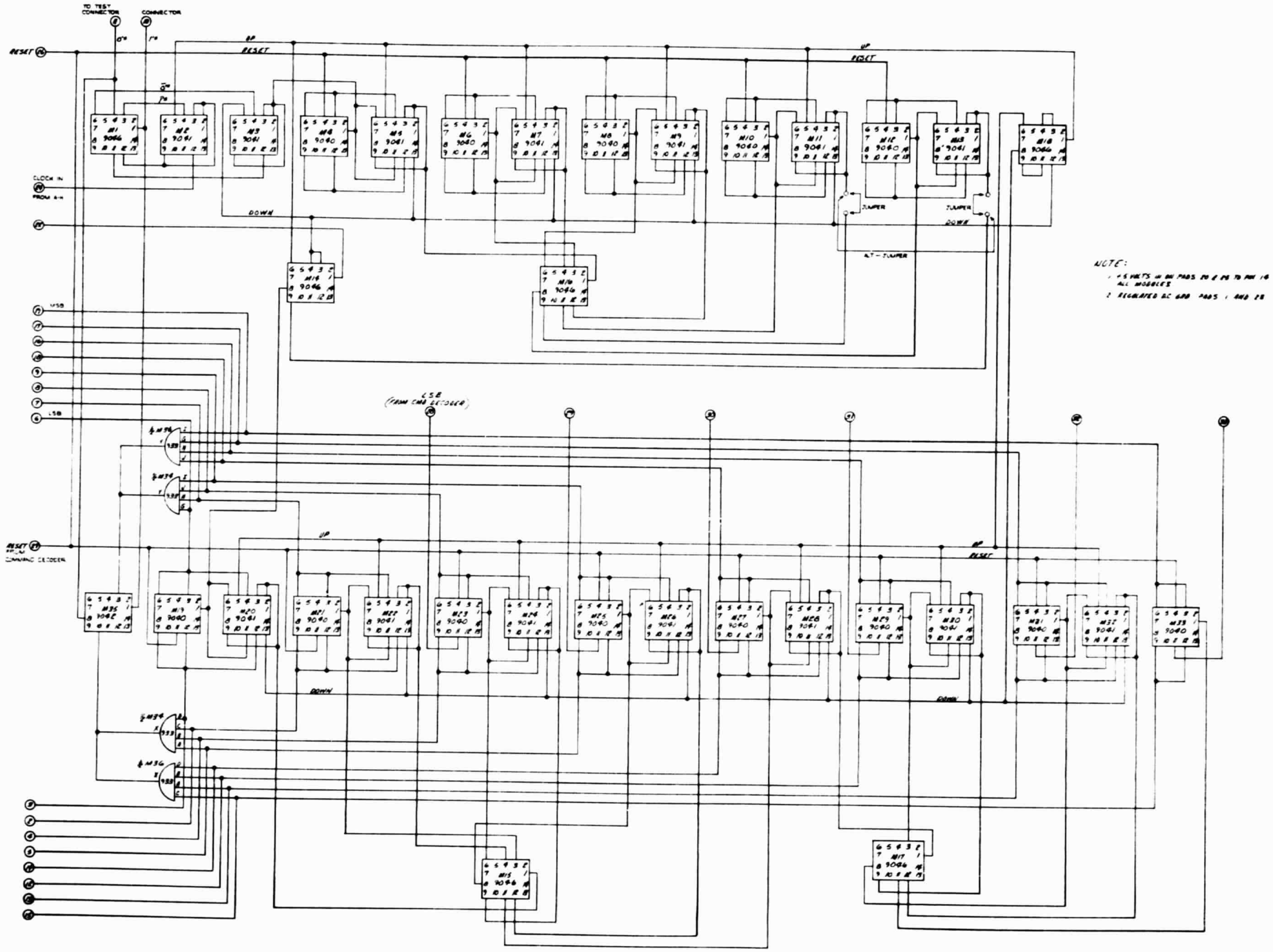


Figure 6–Pre-Scaler, Main Register Circuit

MEASURED INTEGRATOR PERFORMANCE:

False count period (>169 sec. desired)		232 sec. (124 min/count into main register)
Accuracy	Discharge	1% worst case @ 20A
	Charge	0.9% worst case @ 20A
Battery temperature compensation		2% worst case
Common mode capability (±2V desired)		+2.7V worst case
		-3.5V worst case

THIRD ELECTRODE CIRCUITRY

The third electrode cell, sometimes referred to as an adhyhdrode cell or auxiliary cell, is an electrochemical device which senses the amount of oxygen within the battery, and thereby provides a signal voltage. The signal voltage from the cell provides a method of detecting when the battery is fully charged, and can be used as an overcharge control of the spacecraft battery pack.

The ability to control overcharge of 20 ampere-hour rated, nickel-cadmium batteries (of the type used on the OAO spacecraft) with the third electrode cell voltage has been demonstrated in Reference 1. In this report, the affect on the signal voltage by the cell's load resistance (R1 in Figure 7) was considered and also, the optimum signal voltage range for control purposes was determined. It was determined that the signal voltage versus temperature slope is negative for a constant R_1, and also that the slope of percentage increase of overcharge current needed with increasing temperature was positive. By proper selection of R_1 the slope magnitudes can be made equal; hence the above characteristics compensate each other over the spacecraft's temperature range, thus causing the third electrode signal voltage to be independent of temperature. This results in an R_1 of 47 ohms. Also determined experimentally was the optimum signal voltage range that represents the end of charge-signal voltage (hereafter called third electrode threshold voltage). This voltage range is centered at 300 mv with a ±50 mv variation.

A typical controlled charge-discharge cycle for a 20 ampere-hour, nickel-cadmium battery is shown in Figure 8. For this test the third electrode threshold was set at 290 mv. The third electrode voltage exceeded threshold at point A, whereupon the battery was placed on a trickle charge. Note the change in third electrode voltage and charging rate. The signal voltage step when going from night to day results from the cell's internal resistance and the change in battery current.

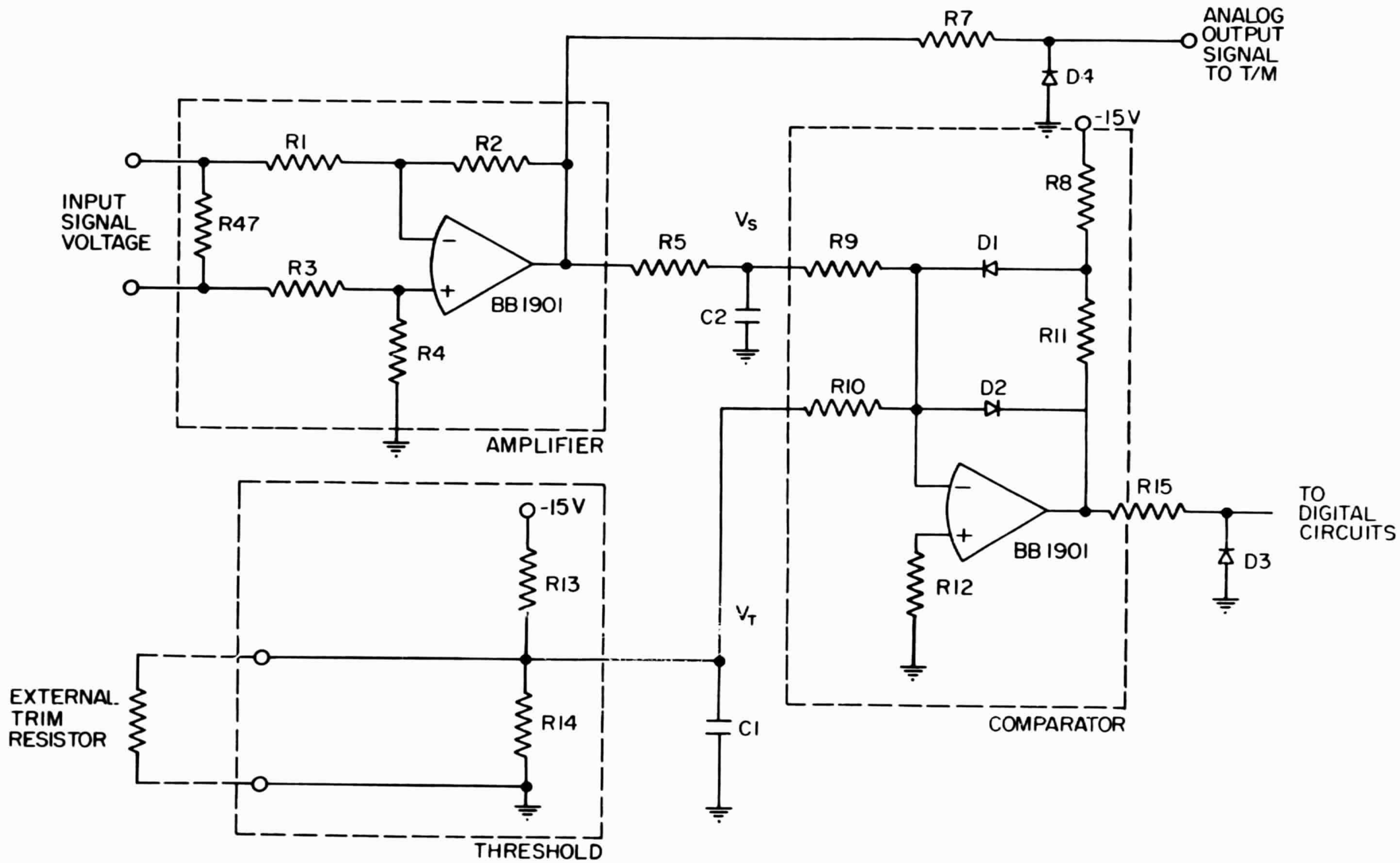


Figure 7–Third Electrode Functional Diagram

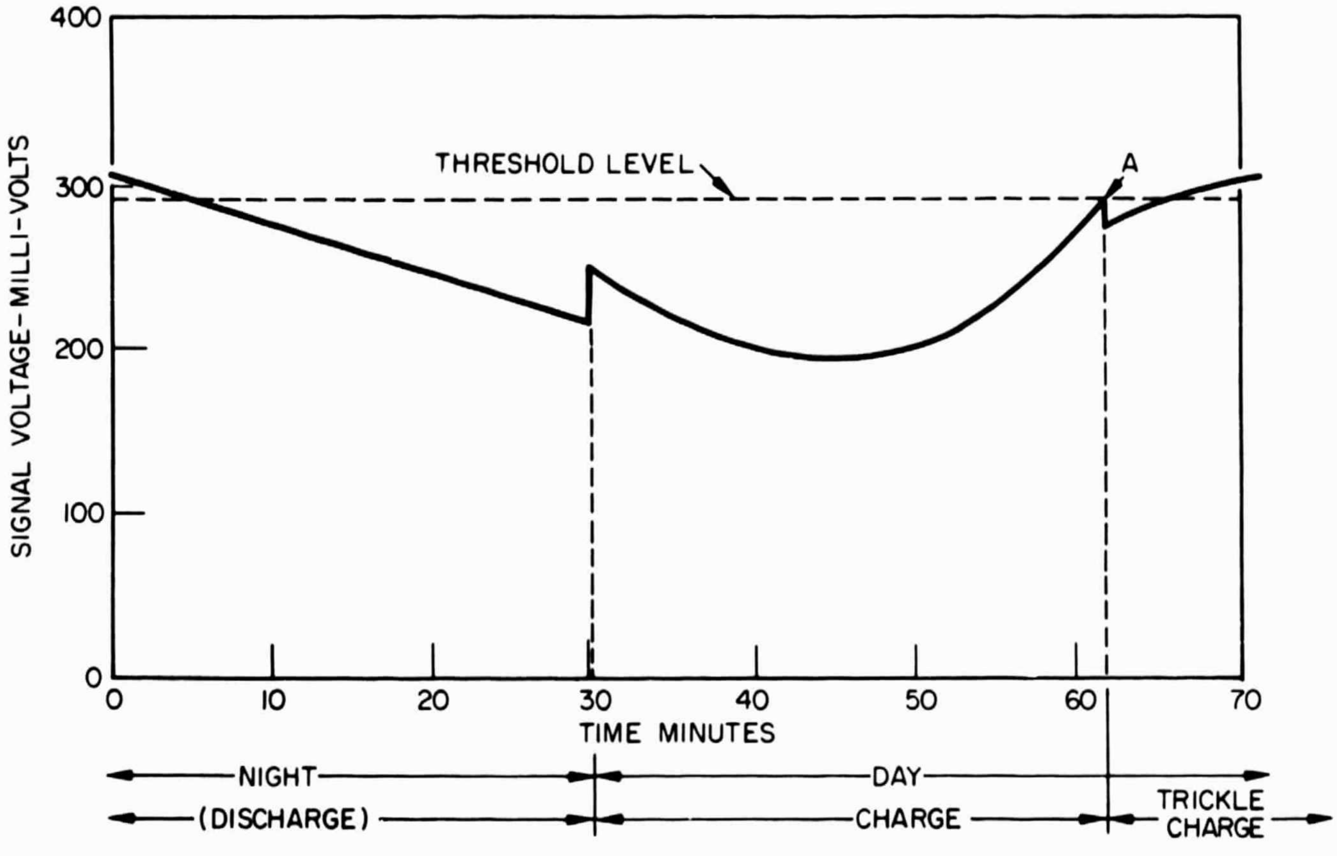


Figure 8–Third Electrode Cell Charge/Discharge Voltage

The third electrode circuitry contained within the SOCU unit has two functions; it amplifies the cell voltage to be compatible with the spacecraft's telemetry system and senses when this signal voltage reaches the third electrode threshold. When at this threshold, the unit provides a control signal to the power control unit (PCU). Control of the PCU is determined by the command system which will be discussed later.

CIRCUIT DESCRIPTION

Detailed circuit description of the third electrode circuitry follows, with the circuit diagram shown in Figure 7. Only one of three channels is shown since the other two channels are identical.

Amplification of the differential signal from the cell is accomplished by an operational amplifier. This amplifier is a commercially available unit, Burr-Brown Model BB1901, and was selected on the basis of its common mode rejection ratio (80 db), and its low power consumption (300 m watt maximum). This high common mode rejection is needed to suppress unwanted noise that may be injected into the input signal lines. The amplifier gain was set to 15 so that the cell's maximum signal level of 350 millivolts would be compatible with the maximum telemetry signal level of 5 volts. Resistors R_1, R_2, R_3, and R_4 determine the operational amplifier's gain. The analog output signal was buffered with resistor R7 (1K) which protects the amplifier against an accidentally short-circuited output terminal. This resistor does not appreciably affect the systems accuracy since the telemetry channel input impedance is 500K ohms. Diode D4 protects the telemetry channel from negative signals.

The comparator circuit used in both the third-electrode and ampere-hour circuits are similar in design. A schematic diagram of the circuit is shown in Figure 7. This type of comparator was selected instead of an integrated circuit comparator since it consumes less operating power. The integrated circuit comparator considered and rejected was the Fairchild 710. This circuit used an additional 122 milliwatts per circuit under similar working conditions as the BB1901 operational amplifier. Since the SOCU unit uses a total of nine comparator circuits this resulted in a power saving of two watts, when considering the power supply regulator efficiency of 50 percent.

Functionally, the comparator circuit operates in the following manner. The algebraic sum of the signal voltages (Vs) and the threshold voltage (Vt) is made with resistors R9 and R10. When Vs is greater than Vt the amplifier output tries to go negative. This forward biases diode D2 which clamps the amplifier output to ground. When Vs is less than Vt the summed voltage is negative and the amplifier output goes positive until the bias on diode D1 is exceeded. This bias level is set to seven volts by resistors R8 and R11. Note that the clamped output signal depends on the algebraic sum of Vs and Vt and could be either zero or seven volts. Clamping to these levels instead of letting the amplifier output saturate at plus or minus 10 volts was done for three reasons: to conserve operating power, to protect the amplifier from latching, and to condition the output signal to the digital circuit logic levels.

The measured comparator trip level varies 15 mv over a temperature range of -20°C to +58°C. Input to the comparator, at trip level, is 4.35 volts.

The comparator output signal from the three cells are then combined digitally with an "or" gate module M2 in Figure 9. Hence, if either of the three cell's signal voltage exceeds the threshold level a control pulse is generated. This control pulse sets a flip-flop (M1) to a "one"state, and it is this signal which is used for control purposes. Resetting this flip-flop can only be done with the "nite" signal.

The threshold voltage (Vt) is determined by resistors R13, R14, and an external trim resistor. This trim resistor was mounted into an external plug J908. It was mounted in this manner so that the threshold level could be easily changed up to launch day without having to go into the potted SOCU unit.

Resistor R5 and capacitor C2 are used as a filter to protect the comparator circuit from premature firing if a noise spike should enter via the telemetry output line.

Resistor R15 and diode D3 are used to buffer the digital circuit from negative going signals at turn-on and turn-off times.

THIRD ELECTRODE AMPLIFIER
AND COMPARATOR EXPERIMENTAL RESULTS

	TEMPERATURE		
PARAMETER	-18°C	+25°C	+55°C
Common mode rejection ratio in db	58	54	52
Gain stability in percent (Referenced to gain at +25°C)	0.10	0	0.09
Comparator sense level stability in percent (Referenced to sense level at +25°C)	0.18	0	0.21

SOCU COMMAND DECODER

The decoder utilizes digital techniques in the form of a matrix system to cause the SOCU to respond to proper commands from the OAO spacecraft command system.

The following command functions are provided by the SOCU:

1. SOCU control ON/OFF to the spacecraft power system.
2. Ampere-Hour/Third Electrode SOCU Mode
3. AH Circuit #1, #2, #3 together or separately – Set the six most significant bits to any desired combination of ones and zeros while setting the prescaler to zeros, and the two least significant bits to ones.

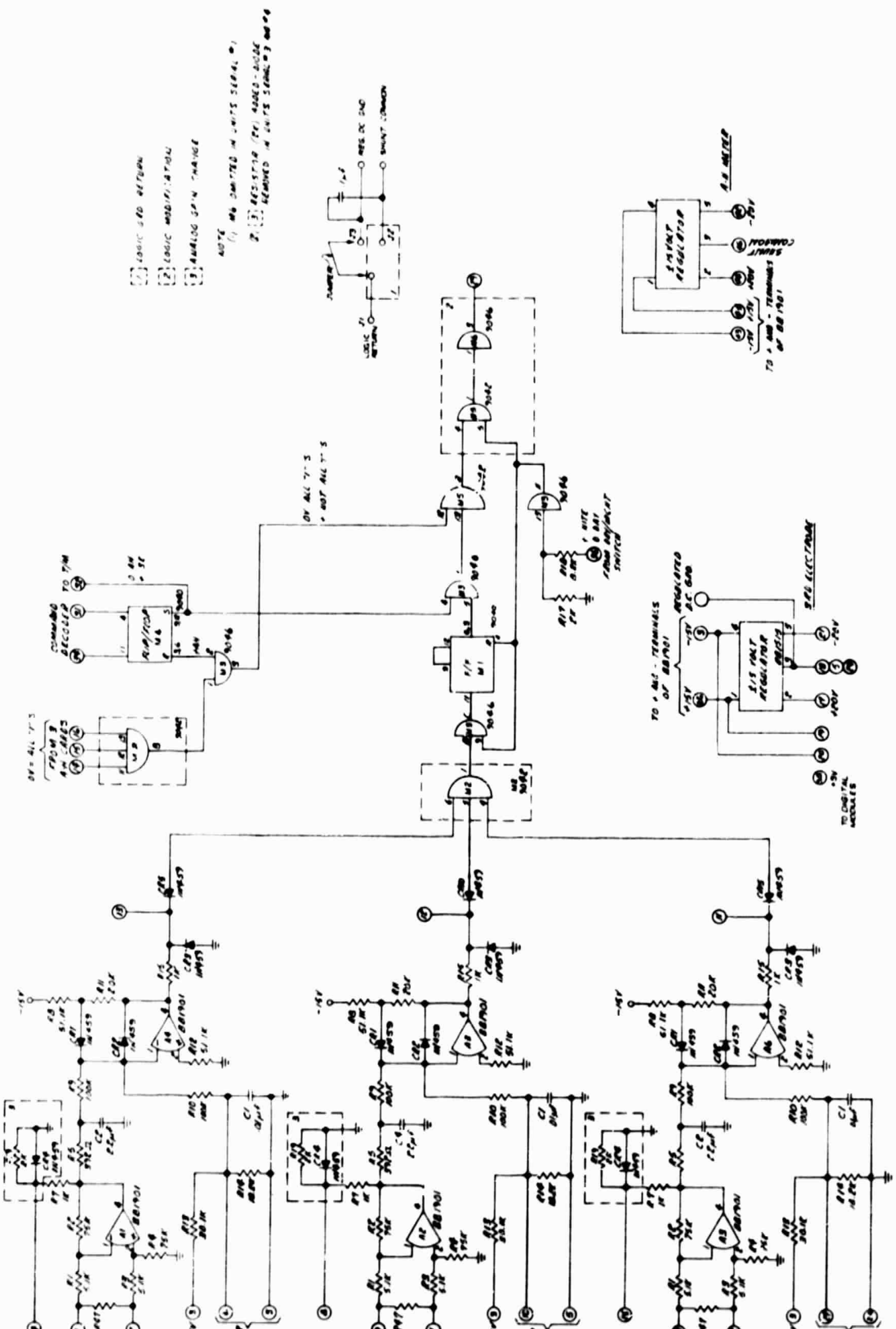


Figure 9–Third Electrode Circuit

4. AH Integrator Circuits 1, 2, 3 together or separately may be commanded to set charge efficiency to any of eight different levels on each circuit.

To stimulate the decoder the following inputs from the spacecraft command system are needed; the experiment command enable line, the experiment operations code line, and fifteen Primary Processor and Data Storage Unit (PPDS) bit time lines.

A "one" state of 18 volts on the experiment command line indicates that the experimenter's operations code is being transmitted to the SOCU. The "one" state is initiated by clock time two of bit one and reset by clock time three of the following bit one when a stored experimenter's command is distributed, see Figure 10. The "one" state is initiated by either clock time two of bit one or clock time one of bit two and reset by either clock time three or clock time four of the following bit one when a real-time experimenter's command is distributed.

One Experiment Operations Code (EOC) line is allocated for command control of the SOCU. The line is energized during the time that the experimenter's command enable line is in the "one" state. A 32 bit operation code is transmitted to SOCU on the line designated as the SOCU EOC line. The first two bits are disregarded by SOCU. The operation code is in the form of a train of "one" state pulses as determined by the second command word of the experimenter's command. The waveform characteristics are as outlined in Table 1 and Figure 10.

The PPDS Bit Times – Fifteen odd bit time signals, beginning with bit time three, are used. The bit times are coincident with the command bit assignments. Each bit gate pulse has a width of 20 ± 2 microseconds and occur once every 640 microsecond word time. The waveform characteristics are as outlined in Figure 13. The functions of the individual bits are indicated in Figure 11.

The decoder, shown in Figure 12, is a matrix addressed by seven matrix flip-flops and seven matrix gating circuits. Each flip-flop and gating circuit is set or enabled by the coincidence of a PPDS bit time and an operations code "one" state. The setting of a particular flip-flop enables a column of secondary gates which may be turned on by the matrix gates depending upon the command received. At the end of each command, bit time 31 is used to reset all matrix flip-flops, which prepares the decoder for the next command. The decoder produces 43 separate switching pulses that are utilized throughout the SOCU to set or reset flip-flops, relays and counter circuits.

TABLE 1

PULSE CHARACTERISTICS, PPDS COMMAND ENABLE, EOC AND BIT TIMES

Signal Definition	No. of Lines	Description	Frequency	Rise and Fall Times	Voltage Levels		Current Levels		Timing Diagram
					"One"	"Zero"	"One"	"Zero"	
Exp. Command Enable	1	Pulse, One		3.0μ sec R 3.0μ sec F	16 to 18v	0 to 1.0v	+50ma	+0.08ma	Figure 3
Exp. Operation Code	1	Pulse, One	50 KC	6.0μ sec R 1.0μ sec F	8 to 18v	0 to 1.0v	+1.0ma	-7.5ma	Figure 3
PPDS Bit Times	15(ODD) 3 - 31	Pulse, One	1.562 KC	3.0μ sec R 3.0μ sec F	10 to 18v	0 to 1.8v	+3.0ma	±0.75ma	Figure 4

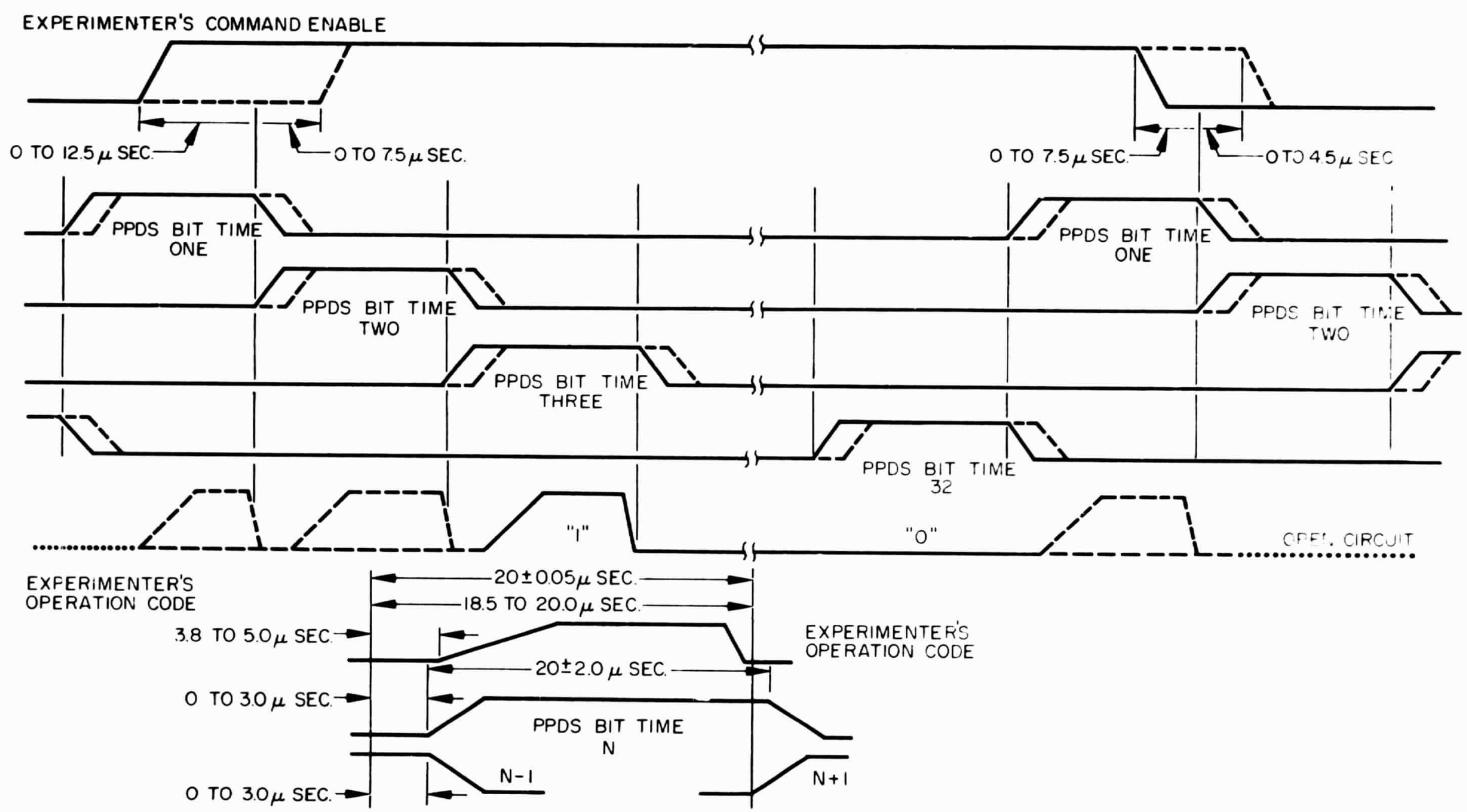


Figure 10—Pulse Characteristics, Command Enable and Operations Code

BIT ASSIGNMENTS, SOCU COMMANDS

BIT TIMES	FUNCTIONS	ALTERNATE FUNCTIONS	
		NOTE: Do not set and reset an individual Eff. at same time.	NOTE: Do not select SOCU control on and off at same time. Do not select AH and TE at same time.
#3	Command Ampere Hour (AH) #1		
#5	CMD AH #2		
#7	CMD AH #3		
#9	CMD Register		
#11	CMD Efficiency (Eff)		
#13	CMD (AH&TE) or SOCU Control		
#15	Selects AH or TE (Third Electrode)		
#17	Reset Register		
#19	Register 3rd LSB	Set Eff. #1	SOCU Control On
#21	Register 4th LSB	Reset Eff. #1	SOCU Control Off
#23	Register 5th LSB	Set Eff. #2	
#25	Register 6th LSB	Reset Eff. #2	
#27	Register 7th LSB	Set Eff. #4	AH Control
#29	Register MSB	Reset Eff. #4	TE Control
#31	Reset all Command Flip/Flops		

NOTE – AH - Ampere Hour Meter

TE - Adhydrode (Third Electrode)

Figure 11–Bit Assignments, SOCU Commands

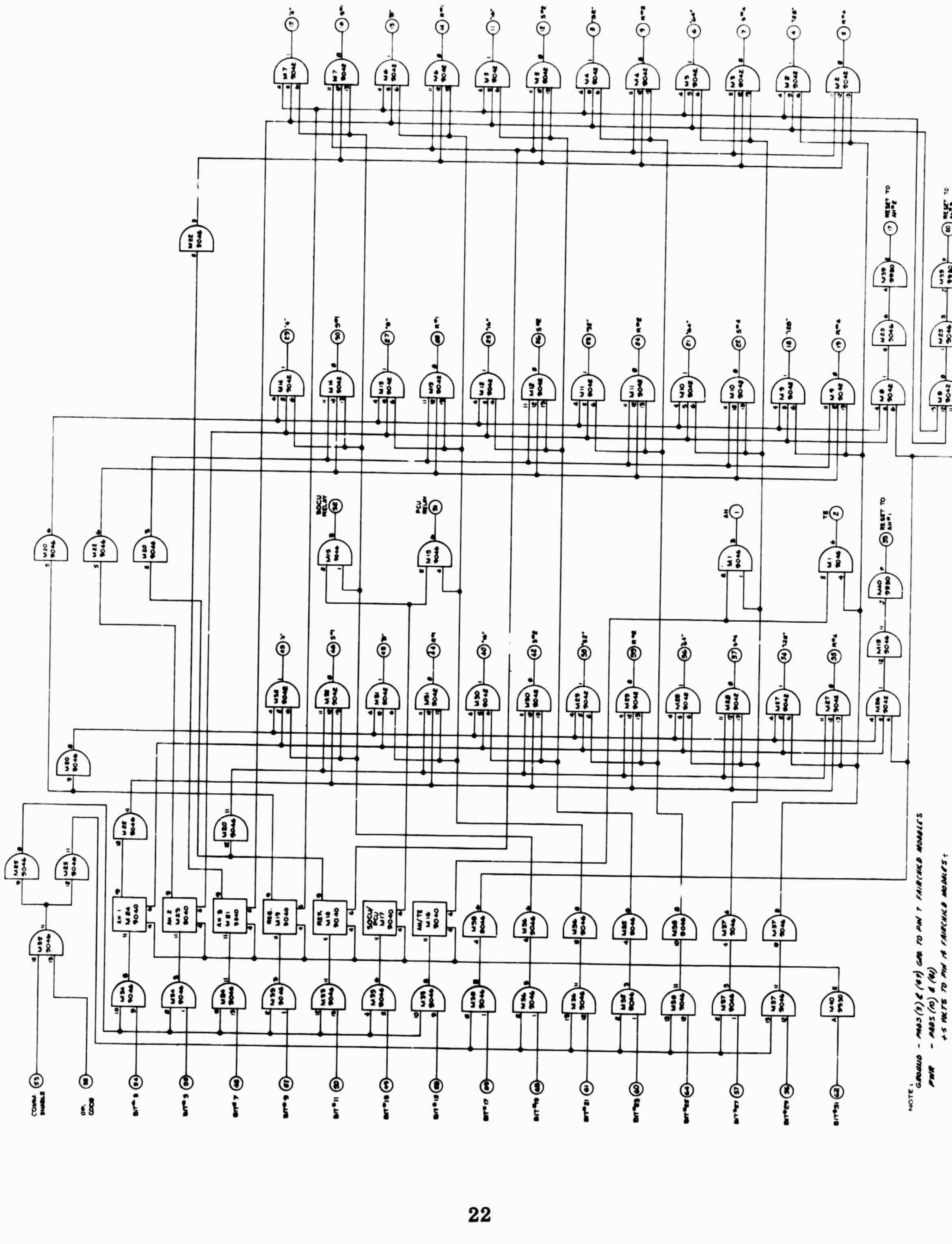


Figure 12—Command Decoder Circuit

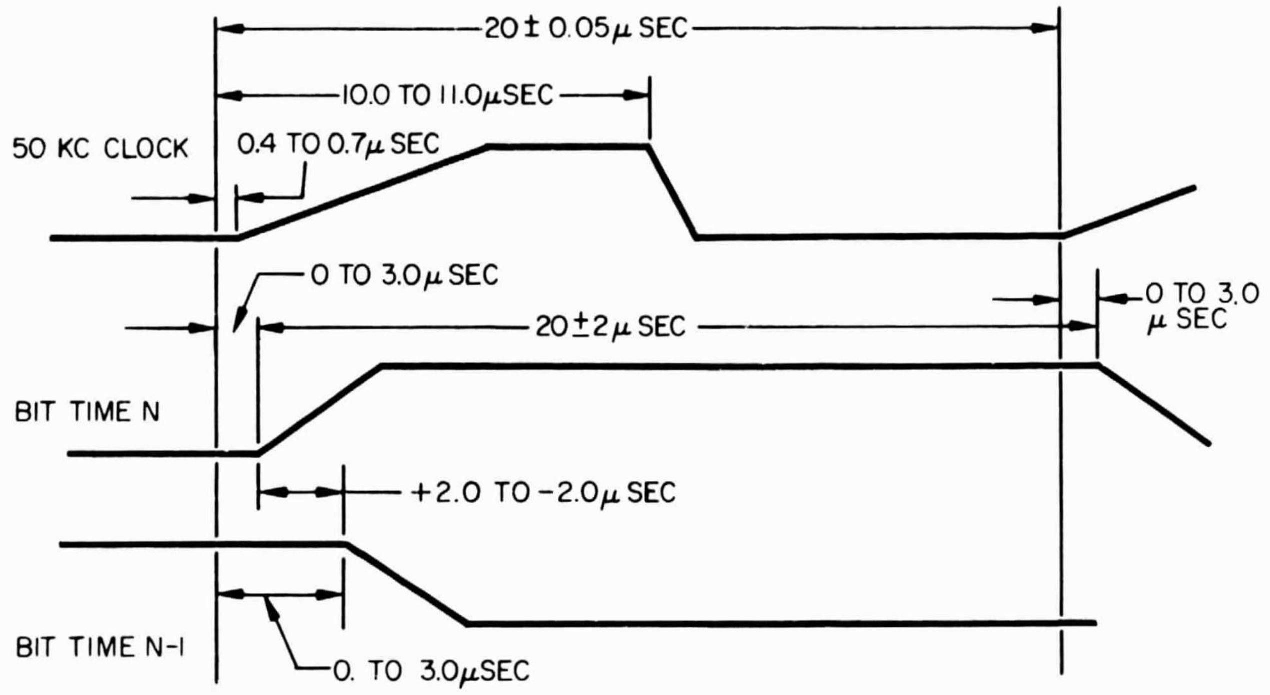


Figure 13—Pulse Characteristics, PPDS Bit Times

SOCU POWER CONVERTER

The dc to dc converter used in the SOCU (Figures 14 and 15) is a pulse type converter utilizing pulse width control to obtain both line and load regulation of about 2% over a temperature range of -35°C to +71°C. The basic operating frequency is obtained from a nominal 9.9 KHz astable multivibrator whose output is used to maintain a constant duty cycle input to the pulse width generator. The pulse width generator provides pulse drive to the final power driver and is varied in width according to line and load demands relayed from the comparator. Comparison is made against input variations and against load variations via sampled data from the input and feedback from the secondary-load windings of the transformer.

The dc outputs are derived from separate windings isolated from each other and isolated from the input unregulated buss. Each dc output uses half wave rectification and pi section filtering. All input lines are filtered with electromagnetic interference suppression filters. In addition, a double "L" section choke input filter is used on the unregulated dc input to provide turn-on surge current limiting.

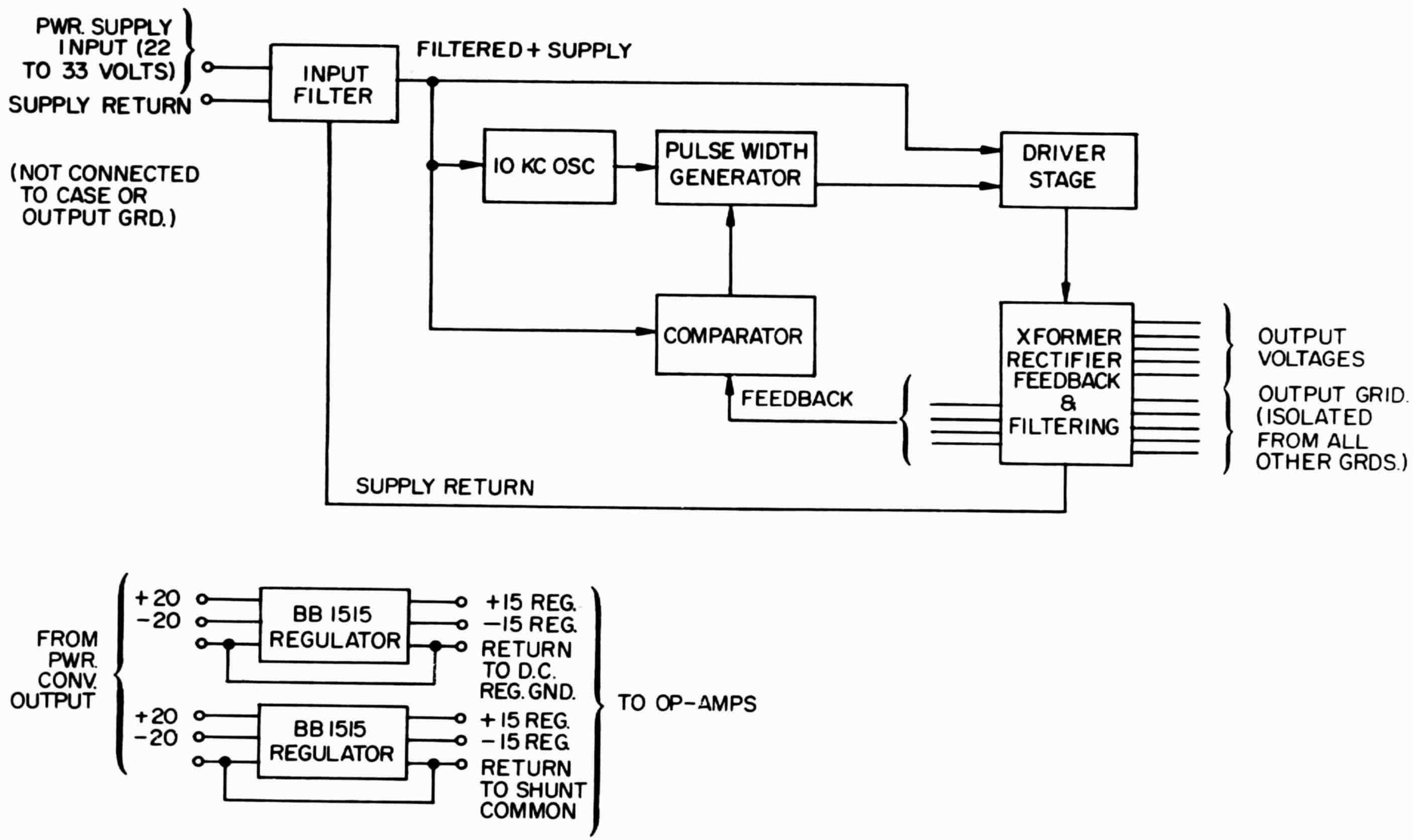


Figure 14—SOCU Power Converter, Block Diagram

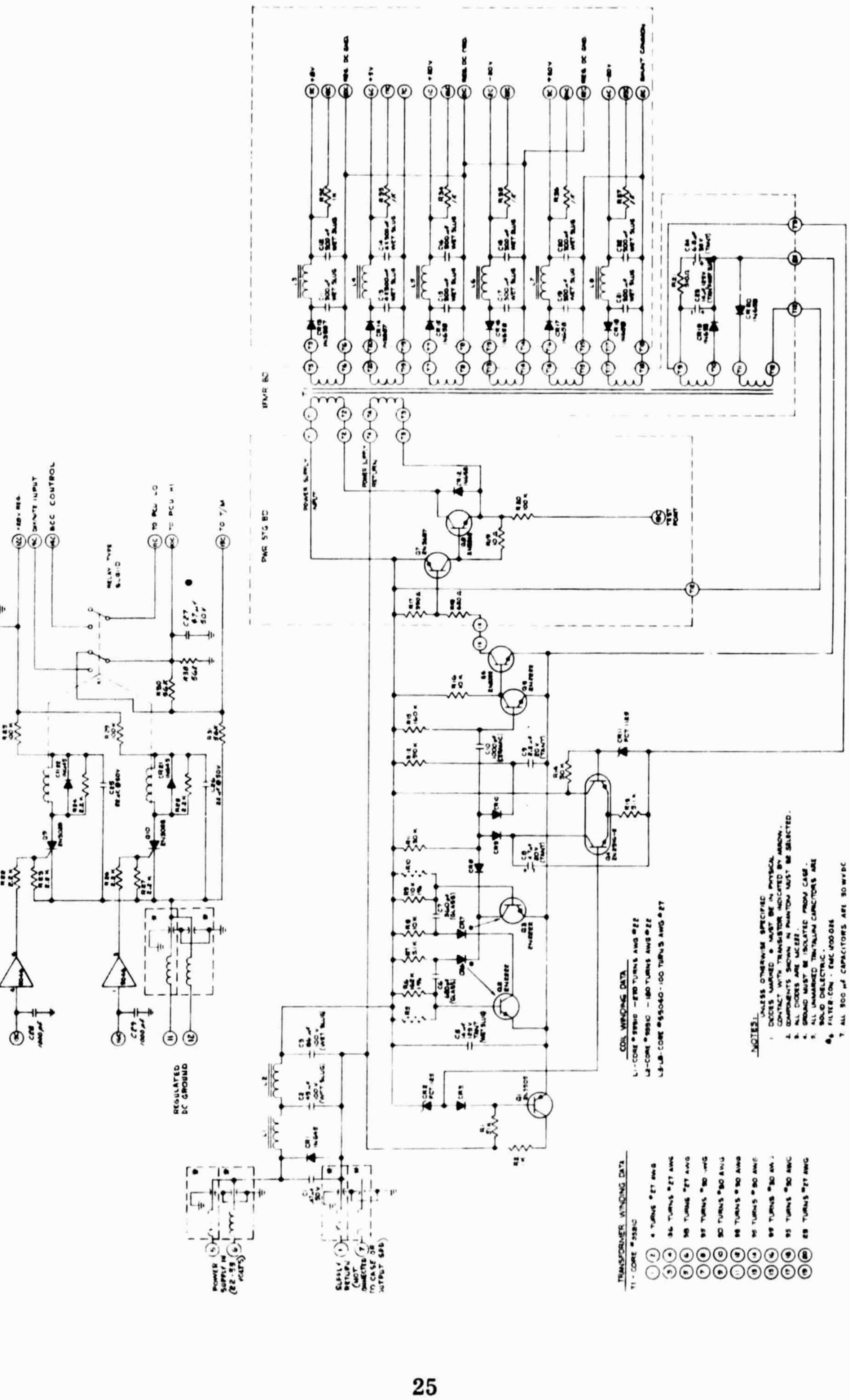


Figure 15—SOCU Power Converter, Schematic

The converter operates within the following specifications:

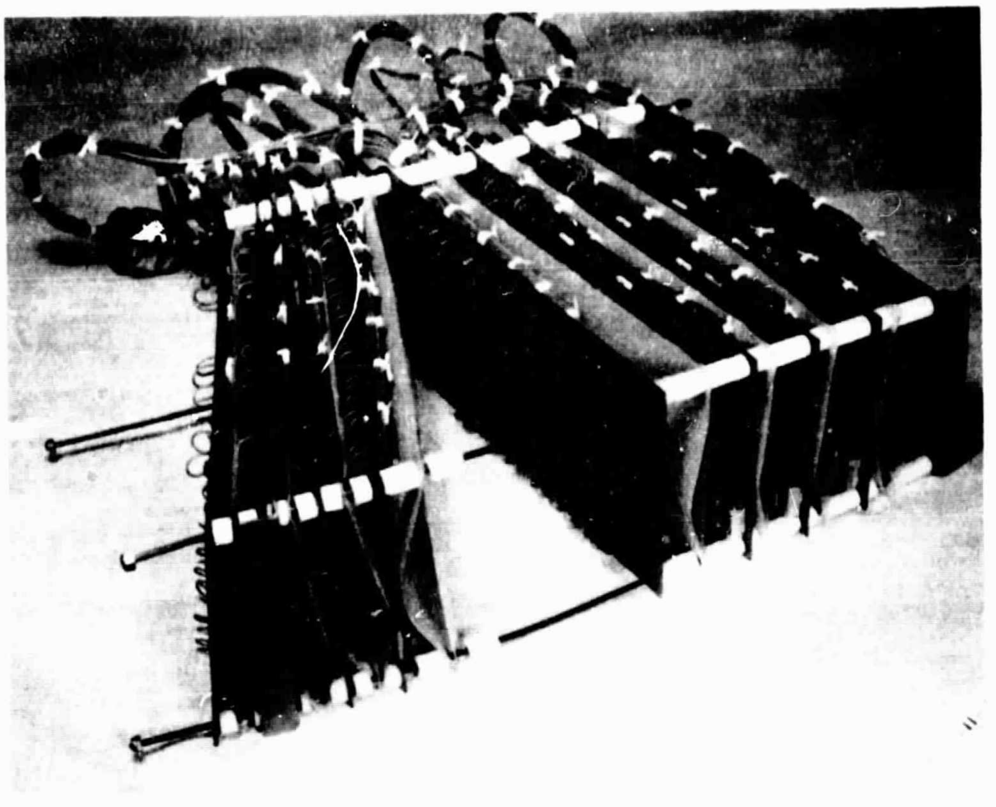
Input:	+22 to +32 volts dc unregulated normally, with capability of operating up to +50 volts dc input.
Outputs:	+8 volts Regulation line and load of 2% +5 volts
	-20 volts Regulation line and load of 1% +20 volts
Operating Frequency:	Nominal 9.9 KHz
Temperature Range:	-35°C to +71°C
Efficiency:	83%
Power Input:	4.65 watts at 25°C

PACKAGING

As can be seen in Figure 16 the SOCU unit is made up of 9 cards and a power converter module. There are 3 integrator cards, 3 pre-scaler main register cards, one third electrode card, one command decoder card, and one input-output card. There are 62 circuits (and 125 leads) on the input-output card to connect SOCU to the power control system, command circuit, and to telemetry. The input-output card is necessary to adapt the normal OAO signals of 8 (to 18) volt logic to the integrated circuit (Fairchild low power 9040 series) logic of 5 volts. One hundred sixty nine integrated circuits are used in SOCU and are welded onto the printed circuit cards.

Because there are so many heavy components mounted on the cards (e.g. the Burr-Brown modules) the unit was potted. The voids in the unit were filled with small, hollow spheres (Eccosphere EP-250, approximately 1/8 inch in diameter) and with silicone rubber (RTV 602). The potting was vacuum drawn into the SOCU unit and then cured at 55°C for 4 hours.

SOCU dimensions are 5-1/2" × 9" × 11-5/8". Unit weight is 23-1/2 lbs., potted.



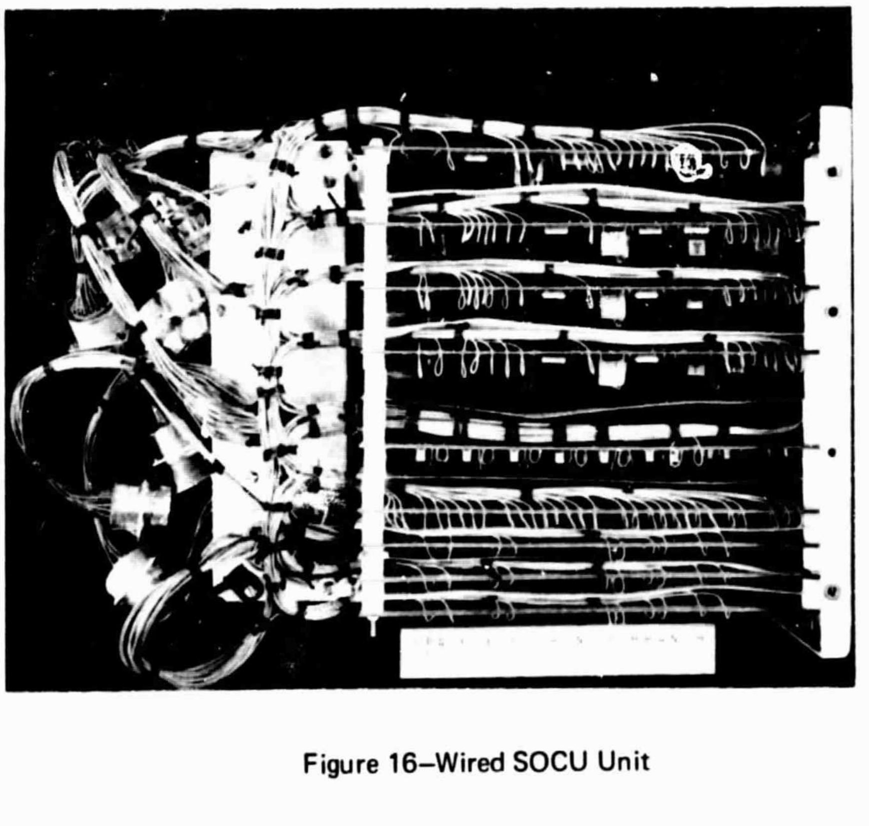


Figure 16–Wired SOCU Unit

REFERENCE

1. F. Ford, "Overcharge Control of Nickel-Cadmium Spacecraft Batteries Using the Auxiliary Electrode Signal," GSFC X-716-68-121, March 1968.