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Shunt Voltage Regulator Circuit for Nickel-Cadmium Cells with Auxiliary Electrodes

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MEL R&D Report 93/66
April 1966

By
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ABSTRACT

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A circuit to control charge current entering nickel-cadmium cells with auxiliary electrodes ("three-terminal" cells) using a shunt method of control has been developed by MEL for use in satellite power systems requiring minimum weight and space with optimum control and temperature compensation. Reduction in charge current is caused when the set limits of either the total battery terminal voltage, or the potential of an auxiliary electrode of any individual cell, is exceeded.

Author

ADMINISTRATIVE INFORMATION

The work described in this report was sponsored by the Goddard Space Flight Center and accomplished under NASA Contract S 12730-G as amended, (4), 2 October 1964.

REFERENCES

(a) Interplanetary Monitoring Platform S-74 Technical Data Book, March 1963, Goddard Space Flight Center
(b) Potter, N. and R. Morrison, "Two Level Voltage Limiter," Goddard Space Flight Center Report X-716-66-7

TABLE OF CONTENTS

SHUNT VOLTAGE REGULATOR CIRCUIT FOR NICKEL-CADMIUM CELLS WITH AUXILIARY ELECTRODES

1.0 INTRODUCTION

The National Aeronautics and Space Administration, Goddard Space Flight Center, (GSFC), having requirements for miniaturized electronic equipment, contracted with MEL to develop charge control circuits for satellite battery power systems. A shunt voltage regulator circuit is described in references (a) and (b). This circuit was used as a base to develop a shunt voltage regulator for use with nickel-cadmium cells containing an auxiliary electrode.

1.1 Background. Charging a nickel-cadmium cell to a nominal 100 percent of its rated capacity and than holding it in this condition without overcharging is a critical problem. The easily measured terminal voltage of the cell cannot be used as an indicating signal for control purposes, since it is relatively flat in the region of 100 percent recharge. The voltage characteristic does not change materially when the cell goes into overcharge and will remain at approximately 1.45 volts for a moderate charge rate at 25 C,* even though gassing may be taking place within the cell proper. Without a method for determining the stage of gas generation the cells could easily be undercharged, with resultant reduced capacity, or overcharged, with resultant excessive gas generation and therefore possible destruction of the battery. The inconsistency in recharging a battery of nickel-cadmium cells is obviously a critical disadvantage in satellite applications.

1.2 Problem. Nickel-cadmium cells have been developed with an auxiliary electrode whose potential, with respect to the cadmium electrode, is controlled by the gas condition within the cell. When a nickel-cadmium cell is charged, no gas is generated until approximately 80 percent recharge has been obtained. The potential of the auxiliary electrode is low during this period. As the cell approaches 100 percent recharge, the gas generation within the cell increases rapidly, and this causes a corresponding increasing potential on the auxiliary electrode.

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*Abbreviations used in this text are from the GPO Style Manual, 1959, unless otherwise noted.

2.0 SOLUTION.

The shunt voltage regulator for nickel-cadmium cells described here utilizes the auxiliary electrode potential from each cell in a battery to determine automatically when a cell has obtained 100 percent recharge. It is designed to monitor continually the auxiliary electrode potential of each cell in a battery being charged and allows optimum recharging of the battery under given conditions. As the auxiliary electrode potential of any one cell rises above a preselected value, the control circuit will reduce the charge current to the battery to a predetermined trickle charge level by "clamping" the system terminal voltage at its lower level. In addition, should the battery terminal voltage reach a maximum set level before an auxiliary electrode voltage increases, the control circuit will "clamp" the system terminal voltage to an upper voltage level. All excess available charging current will be shunted around the battery.

A block diagram of this control circuit appears in Figure 1, with a complete component diagram, Figure 1-A of Appendix A. Appendix B gives a detailed explaination of the voltage detector used in this device. A laboratory model, which combines this shunt voltage regulator circuit and an improved version of a series charge current control circuit (MEL Report 25/65 of April 65), is described in Appendix C and shown in block diagram form in Figure 1-C and schematically in Figure 2-C.

3.0 FUNCTIONAL CIRCUIT DESCRIPTION

3.1 <u>Circuit Operation</u>. The shunt voltage regulator circuit for nickel-cadmium cells with auxiliary electrodes is shown in block diagram form in Figure 1. The unmodified shunt voltage regulator used as a basis for this circuit is described in the Data Book, reference (a), and its use as a two-level voltage limiter as used in this circuit is explained in reference (b). The main difference between this shunt regulator and the one in reference (b) is that the lower battery terminal "clamp" voltage is controlled by the output from the auxiliary electrode detectors rather than by a current detector.

3.1.1 The shunt regulator for cells with auxiliary electrodes consists of four subcircuits: a detector section (one for each cell), a square-wave generator, a control circuit, and a current-dump section.

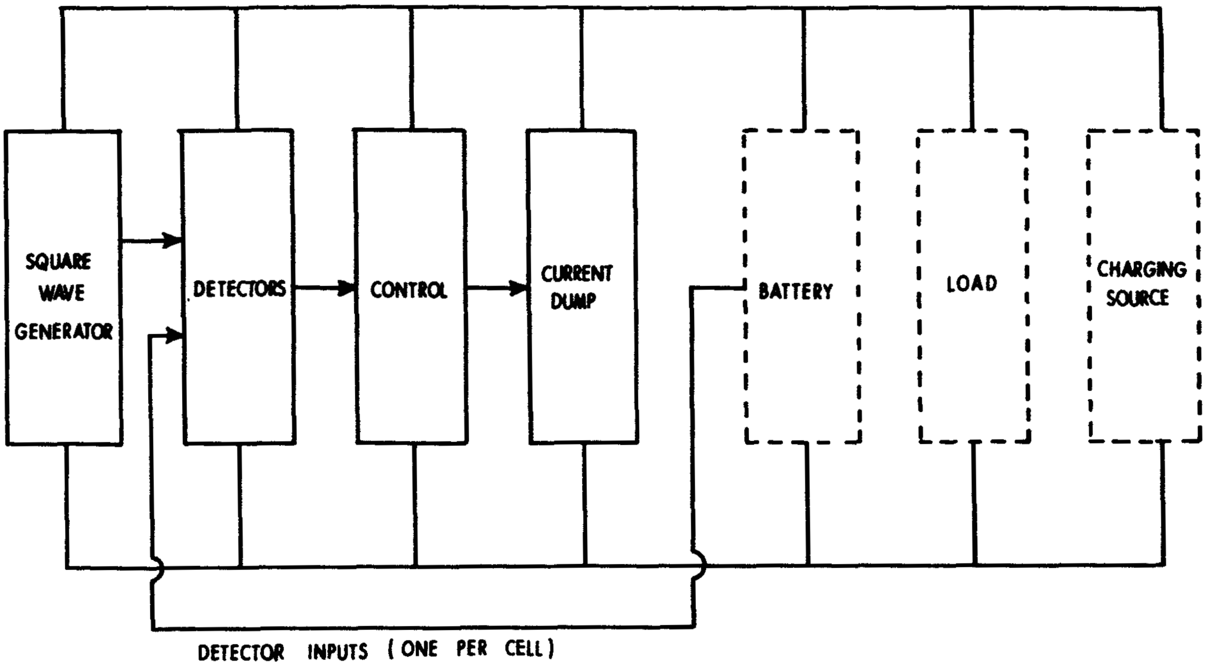

Figure 1

Shunt Regulator for Cells
with Auxiliary Electrodes

- Each detector monitors the auxiliary electrode potential of its cell and translates this to a direct-current voltage level.

- The square-wave generator provides the drive signal necessary for detection operation.

- The control circuit amplifies the output of the detector section to control the current-dump circuit.

- The current-dump circuit acts as a voltage-controlled impedance to "clamp" the voltage of the battery at a level determined by the control circuit.

3.1.2 The purpose of this shunt regulator for cells with auxiliary electrodes is to allow a battery to receive maximum current until gas generation within a cell of the battery produces a voltage level on the auxiliary electrode that causes the shunt regulator to voltage-limit the battery. As the cells in the battery approach 100 percent recharge, gas is generated, producing a rising auxiliary electrode potential. The first cell's auxiliary electrode to reach the preset "control initiation" value will cause the current-dump circuit to begin to shunt current around the battery. As the cells' auxiliary electrode potential continues to increase, the current-dump circuit shunts an increasing amount of current to ground thus decreasing the charging current into the battery (assuming the charging source is current limited). That is to say, the effective impedance of the shunt regulator has been decreased thus allowing an increased current flow through it. This action continues until any cell's auxiliary electrode reach the "final" value, at which point the current-dump circuit is shunting virtually all available current from the charging supply to ground. That is, the effective impedance has been lowered to a point such that the terminal voltage of the shunt regulator has been lowered to a point such that the terminal voltage of the shunt regulator has been clamped at the proper value, this voltage being determined by the number of cells in the battery and the ambient temperature. The battery will then float on the regulator and receive just enough current to maintain its terminal voltage at this lower clamped value.

Should the battery terminal voltage reach a predetermined maximum value before auxiliary electrode potential reaches the control value, the shunt regulator will clamp at this upper maximum value. Afterward, if a third-terminal potential rises beyond the control value, the system terminal voltage will be reduced and clamped in the lower clamped terminal voltage condition.

The upper clamped terminal voltage is adjusted for the number of cells in the battery and is automatically compensated for variations in battery voltage with temperature changes.

A graph of the upper and lower terminal voltage clamped states with respect to temperature, for a battery of 11 cells, appears as Figure 2.

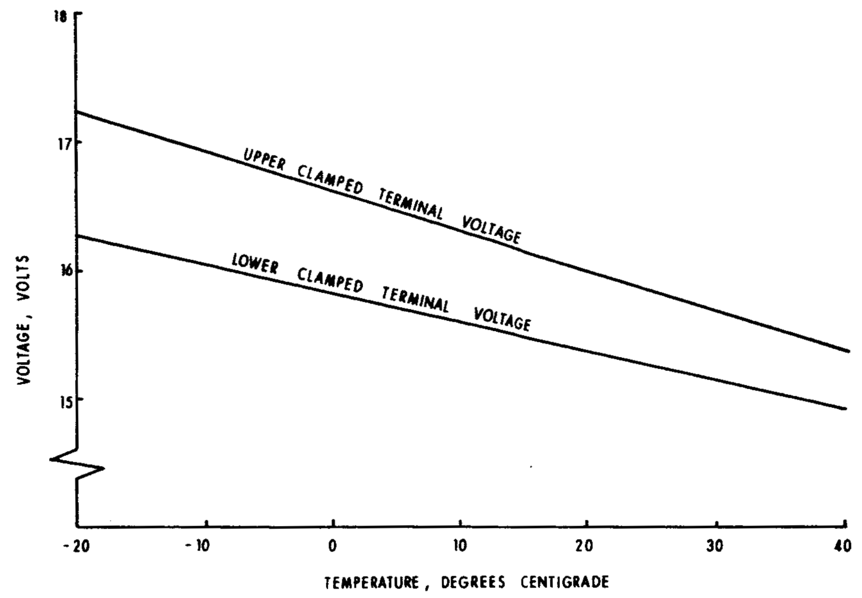

Figure 2

Temperature Characteristics of
Shunt Voltage Regulator

4.0 SUMMARY AND CONCLUSIONS

A shunt voltage regulator for nickel-cadmium cells has been developed that fully meets the original design objectives. The circuit has been temperature compensated to yield the desired terminal voltage characteristic over the range of -20 to +40 C. Because of this compensation, the circuit's terminal voltage will conform to the terminal voltage characteristics of nickel-cadmium cells over this temperature range, as shown in Figure 2. Compensation for temperature-caused changes in auxiliary electrode potential can be added to the detector circuit if it is found to be necessary.

At the request of NASA, instead of a prototype of this circuit alone, one of this circuit integrated with an improved form of the series charge current control circuit (MEL 25/65 of April 1965) was built and delivered. This device is described in Appendix C.

Appendix A

Circuit Description of the Shunt Voltage Regulator for Nickel-Cadmium Cells with Auxiliary Electrodes

References in this appendix are to Figure 1-A which illustrates the stage-by-stage operation. The appendix is a narrative description of the circuit proper and adjustments in the main portions of the shunt voltage regulator for nickel-cadmium cells with auxiliary electrodes. Finally, a parts list is provided.

The square-wave generator is a standard astable multivibrator followed by an emitter-follower stage. It consists of Resistors R_1 through R_4, Capacitors C_3 and C_4, and Transistors Q_1, Q_2, and Q_{22}. It provides approximately a 500-cycle, 5.5-volt positive square wave to the detectors as a sampling signal. The combination of R_5 and Diodes D_3 and D_7 provide a nearly constant bias voltage for the square wave generator.

Each detector consists of Q_4, D_4 through D_6, R_6 through R_8, R_{41}, C_2, and Transformer T_1. If a cell is in a discharged condition, its auxiliary electrode potential is virtually zero; thus, virtually no direct current flows through D_6, R_8 and the direct-current side of T_1. For the square-wave sampling signal in the alternating-current side of T_1, this path appears as a high reflected impedance. Therefore, the energy of the square wave is stored in C_2, since the path through D_5, C_2 is a lower impedance. This allows C_2 to maintain a direct-current voltage level sufficient to bias Q_4 in a near saturation state. As the nickel-cadmium approaches 100 percent recharge, its auxiliary electrode potential increases, thus allowing a low direct-current to flow through D_6, R_8, and the direct-current side of T_1. As this current increases (with an increasing auxiliary electrode potential), the dynamic impedance of Diode D_6 decreases, thus lowering its reflected impedance as seen by the square wave. As this impedance decreases, more energy is dissipated through T_1, and less is stored in C_2. This will lower the direct-current voltage maintained by C_2 and will cause Q_4 to travel through its active region toward cutoff. When Q_4 is near saturation, its collector voltage is held at less than 1 volt; but as it moves through the active region toward cutoff, its collector voltage increases from less than a volt toward a maximum voltage nearly equal to the bias voltage. With Diodes D_4 of all detectors connected at this cathodes, they act as an "OR" circuit, meaning that the highest anode voltage is that which appears at the cathode connection of the diodes. Therefore, the detector with the highest output voltage will be the controlling signal.

The control section consists of Q_3, Q_5 through Q_9, C_1, C_5, R_9 through R_{22}, R_{42}, D_{11}, D_2, and TC_1 through TC_4. This section of the circuit performs two functions.

The first function is to act as the sensing and amplifying portion (i.e., the feedback loop) of a shunt voltage regulator. To perform this function, voltage divider R_{15}, R_{16}, TC_4 monitors the system terminal voltage and applies a portion of it to the base of Q_6. The differential amplifier, Q_6, Q_7, compares this voltage to a standard, maintained by D_1, D_2, and R_{20}. If the system terminal voltage tends to increase beyond its design limit, the output voltage of the differential amplifier will increase (an error signal) causing increased conduction in Q_8. This, in turn, causes increased conduction in Q_9 by direct application and thus increases the output voltage of the control section. The second function of this section is to amplify the detector output signal, modify it, if necessary, according to the desired temperature characteristic, and apply this signal to the current-dump section. This is accomplished by applying the detector output signal to the gate of Q_3 through R_9 and R_{42}. The field effect transistor (FET) Q3 is used as a variable impedance across the bottom half of Voltage Divider R_{12}, R_{13}, R_{11}, TC_1, TC_2, TC_3. As the detector output increases, the effective impedance of Q_3 increases, thus allowing a higher voltage at the base of Q_5 causing the conduction of Q_5 to increase. The effect of increased conduction of Q_5 on Q_6 is similar to the effect of an increase of system terminal voltage. Therefore, the subsequent action will be as described above until the output voltage of the control section is increased due to the increase in detector output.

The current-dump section performs as its name implies. A rising control-section output applied directly to the bases of Q_{10}, Q_{11}, Q_{12}, Q_{13} causes these transistors to conduct enough current from the charging supply so that its terminal voltage cannot increase above the desired value. This system was designed with four parallel dumping transistors so that, for space applications, the heat dissipated can be distributed. Resistors R_{23}, R_{24}, R_{25}, R_{26}, are for feedback purposes to cause the dumping transistors to self-balance.

Temperature compensation of the terminal voltage of this circuit is accomplished by the sensistors* TC_1 through TC_4. From the

---

*A trade name for a silicon resistor with a temperature coefficient of +0.7%/°C above explanation it is easily seen how the system terminal voltage clamp (upper voltage clamp), initiated by a rising battery terminal voltage, is temperature compensated by TC_4. For example if the ambient temperature increases, the resistance value of TC_4 increases, raising the base bias voltage of Q_6 which results in a lowered system terminal voltage as desired. It is also realizable that this will aid the compensation of the system terminal-voltage clamp (lower voltage clamp) initiated by the third-terminal inputs. However, the principal compensating elements for this voltage clamped state are TC_1, TC_2, TC_3. If the system were in this lower clamped state, a rising ambient temperature would increase the resistance values of these sensistors, thus increasing the base bias voltage of Q_5 which will in turn decrease the system terminal voltage. By using various temperature-sensitive elements elsewhere in the two-voltage dividers containing TC_1 through TC_4, a wide range of system terminal voltage temperature characteristics can be obtained.

A number of adjustments have been provided in this circuit design so that a wide range of operating characteristics can be selected. The shunt voltage regulator as described here was designed to operate with nominally 11 cells. If it is desired to operate with greater than 13 cells, or less than 9 cells, then some minor changes in component values may be necessary besides the addition or subtraction of detectors.

It is obvious from the previous compensation discussion that adjusting Potentiometer R_{15} can alter the level of upper clamped voltage since it controls the base bias voltage of Q_6. Increasing R_{15} raises the level of the upper clamped voltage. Again, this control will have some effect on the lower clamped voltage. However, the primary level control for the lower clamped voltage is R_{13} which controls the base bias voltage of Q_5.

Obviously then, when this circuit is calibrated, the upper clamped voltage should be set first before the lower clamped voltage. This can be accomplished by setting R_7 in each detector to approximately 8000 ohms, ascertaining that all detector inputs are below 50 millivolts (or by disconnecting them), setting the charging supply terminal voltage higher than the desired upper clamped voltage, then adjusting R_{15} until the dump circuit conducts enough current to lower the charging supply terminal voltage to the desired upper clamped voltage. (If a laboratory power supply is used as the charging source, its output current should be limited to the maximum value allowable for the cells to be used. i.e., 3 amperes for the design described here). Now raise any detector input to or above 300 millivolts and adjust R_{13} until the system terminal voltage is reduced to the lower clamped value. This completes the terminal voltage calibration.

Now with one detector input set at the desired "initiation" value, and all others below 50 millivolts, and with R_9 and R_{42} adjusted to zero, adjust R_7 in the detector with the desired input until the system terminal voltage just begins to decrease. Next, raise this detector input to the desired "final" value (this will put the system terminal voltage in the lower clamped state) and increase the value of R_9 and/or R_{42} until the system terminal voltage just begins to increase. This sets the active region of third-electrode input control. Repeat this readjustment of R_7 for each detector using the desired input "initiation" value and the calibration procedure will be complete.

The losses of this voltage regulator circuit itself are nominal. The maximum possible loss which occurs just prior to current-dumping action, is 750 milliwatts.

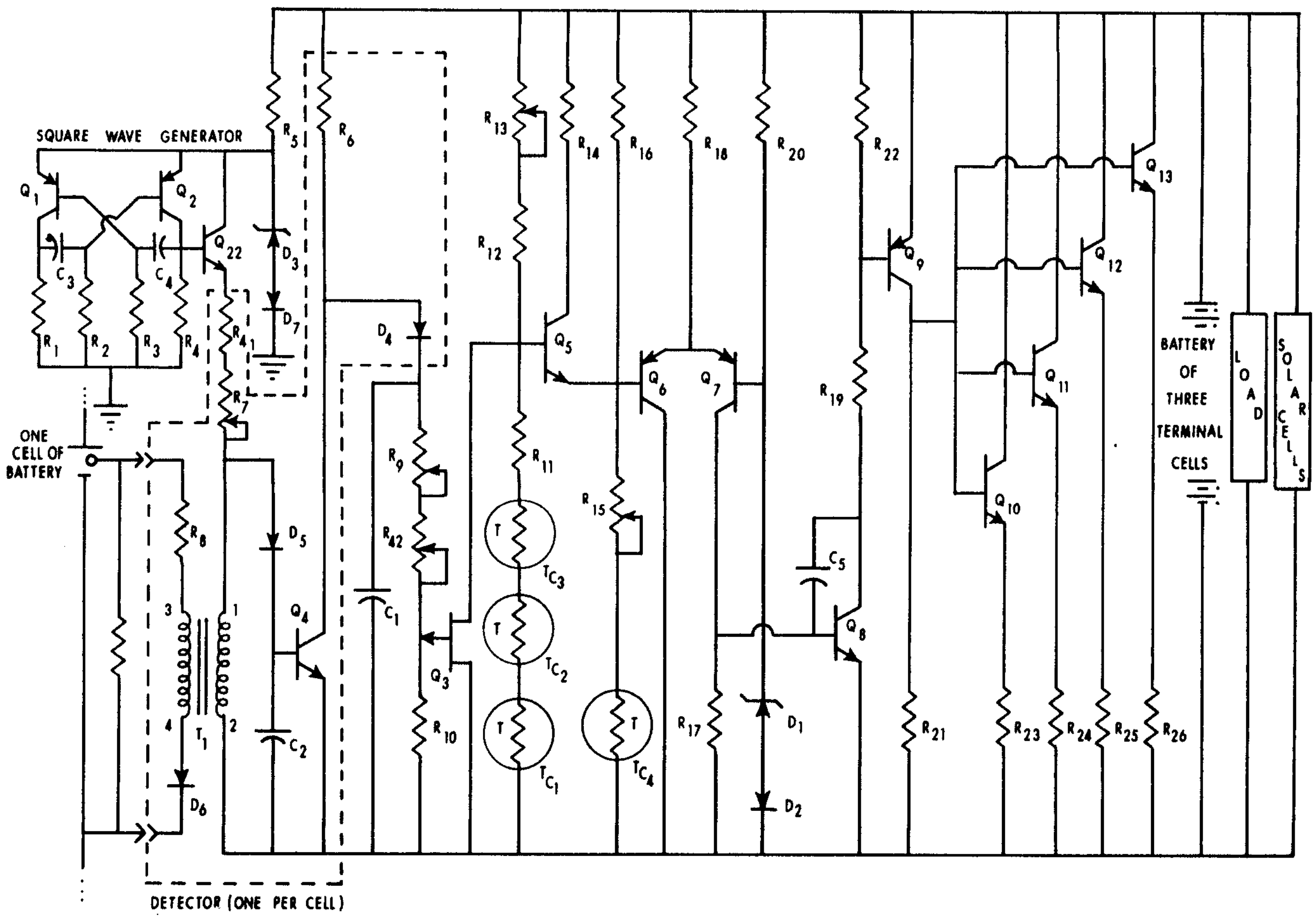

Figure 1-A, Shunt Voltage Regulator Control for Nickel-Cadmium Cells with Control Electrodes

PARTS LIST FOR SHUNT VOLTAGE CIRCUIT

	Transistors	Regulator Less expensive Equivalents for Laboratory Instruments	Wakefield Heat Sink No.
Q_1	2N1303		
Q_2	2N1303		
Q_3	2N2841		
Q_4	2N930	(2N3643)	
Q_5	2N1613	(2N3564)	
Q_6	2N2907	(2N3638)	
Q_7	2N2907	(2N3638)	
Q_8	2N1482	(2N3568)	
Q_9	2N2905	(2N3638)	NF-209
Q_{10}	154-04 Westinghouse or	2N3232	NC-403
Q_{11}	154-04 Westinghouse or	2N3232	NC-403
Q_{12}	154-04 Westinghouse or	2N3232	NC-403
Q_{13}	154-04 Westinghouse or	2N3232	NC-403
Q_{22}	2N1302		

NOTE: Semiconductors noted in parenthesis are Fairchild Semiconductor Epoxy Packages

	Sensistors
Tc_1	10K
Tc_2	10K
Tc_3	10K
Tc_4	3.9K

Tc = Sensistors 1/4 watt (Silicon resistors by Texas Instruments)

Resistors			Wakefield Heat Sink No.
R_1	10K		
R_2	47K		
R_3	47K		
R_4	10K		
R_5	255 ohm		
R_6	10K		
R_7	25K Pot.		
R_8	475 ohm		
R_9	1 Meg Pot.		
R_{10}	22 Meg		
R_{11}	39K		
R_{12}	31.6K		
R_{13}	10K Pot.		
R_{14}	5.1K		
R_{15}	5K Pot.		
R_{16}	3.92K		
R_{17}	5.1K		
R_{18}	5.1K		
R_{19}	5.1K		
R_{20}	10K		
R_{21}	10K		
R_{22}	560 ohm		
R_{23}	10 ohm, 10W	(Dale)	NC 623
R_{24}	10 ohm, 10W	(Dale)	
R_{25}	10 ohm, 10W	(Dale)	NC 623
R_{26}	10 ohm, 10W	(Dale)	
R_{41}	4.7K		
R_{42}	1 Meg Pot.		

NOTE: All Resistors 1/2 watt unless noted otherwise. 5% for Laboratory instrument. 1% for space model

All Potentiometers 25 turns wire wound except R_9 and R_{42}.

Capacitors

C_1	10 uf
C_2	10 uf
C_3	.033 uf
C_4	.033 uf
C_5	10 uf

All Capacitors solid tantalum 20%, 35 WVDC unless noted otherwise.

Diodes

D_1	1N757 (Zener)
D_2	1N191
D_3	1N751 (Zener)
D_4	1N457
D_5	1N457
D_6	1N191
D_7	1N457

Transformer

T_1 - Sprague Electric Company R1111

Appendix B

Theory of Diode Detector Operation

The circuit diagram of a detector from the charge-current control circuit for nickel-cadmium cells with control electrodes (three-terminal cells) is shown in Figure 1-B. The basic concept which governs the operation of this detector is shown in the equivalent circuit of the input portion of this detector in Figure 2-B. The variable impedance, R_R, in Figure 2-B is the effective impedance of Diode D_6 and Resistor R_8 reflected to the alternating-current side of the 1 to 1 transformer, T_1. D_6 and R_8 are connected to the direct-current side of T_1. The characteristic curve is equal to the inverse of the impedance of this D_6, R_8 combination. It can be seen from Figure 3-B that, as the voltage across D_6, R_8 increases, the current through them increases and their effective impedance decreases. Therefore, as the potential on the control electrode (third terminal) increases, the effective impedance of D D_6, R_8 decreases. The impedance of the direct-current side of T_1 remains constant and is small compared to the impedance of D_6, R_8, and is therefore ignored. Now it can be seen from Figures 1-B and 2-B that a rising third-terminal potential, causing a reduction in the reflected impedance, R_R, will decrease the power from the square wave generator available to the amplifying portion of the detector, through D_5 and C_2, by dissipating it in R_R. The square-wave generator and resistor R_7 supply a relatively constant current to the parallel combination of R_R and R_A (the effective impedance of the input to the amplifying portion of the detector) and L, the alternating-current winding of transformer T_1. Therefore, as R_R decreases, it will decrease the impedance of this parallel combination, and a smaller voltage drop will appear on the base of Q_4.

Mathematically, this concept is expressed by:

$$R_R = R_8 + R_D$$

$$R_D = \frac{V_D}{I_D}$$

$$I_D = I_R \left(e^{\frac{qV_D}{kT}} - 1\right) \quad \text{the diode equation}$$

$$R_R = R_8 + \frac{V_D}{I_R\left(e^{\frac{qV_D}{kT}} - 1\right)}$$

$$V_D + V_{R8} = V$$

where

R_D = effective impedance of Diode D_6

V_D = voltage across D_6

I_D = current through D_6

I_R = saturated value of reverse current through D_6

q = electron charge

k = Boltzmann's constant

T = absolute temperature, K

V_{R8} = voltage across R_p

V = third-terminal potential

It is easily seen that R_R will decrease as V increases, since $e^{qV_D/kT}$ increases at a faster rate than V_D alone as V increases. It is understood that R_R and the combined impedance of D_6 and R_8 are identical, since an impedance can be "reflected" from one side of a transformer to the other with a multiplying factor equal to the transformer turns ratio (in this case, 1 : 1). This proves the inverse dependence of the reflected impedance, R_R, on the control electrode (third-terminal) potential of the cell to which this detector is connected.

Also (from Figure 2-B):

$$I_{R_A} = \frac{V_{R_A}}{R_A}$$

$$V_{R_A} = \left(\frac{X_L \parallel R_R \parallel R_A}{X_L \parallel R_R \parallel R_A + R_7} \right) V_G$$

$$V_G = A \left[u(t) - u(t-a) + u(t-2a) - \ldots \right]$$

$$X_L \parallel R_R \parallel R_A = \frac{\left(\frac{R_R\ R_A}{R_R + R_A}\right) X_L}{\frac{R_R\ R_A}{R_R + R_A} + X_L}$$

$$\therefore\ V_{R_A} = \frac{\left(\frac{\frac{R_R\ X_L}{R_R + R_A}}{\frac{R_R\ R_A}{R_R + R_A} + X_L}\right) A \left[u\ (t) - u\ (t-a) + u\ (t-2a) - \ldots\right]}{\left(\frac{\frac{R_R\ R_A\ X_L}{R_R + R_A}}{\frac{R_R\ R_A}{R_R + R_A} + X_L}\right) + R_7}$$

where

I_{R_A} = current into R_A

V_{R_A} = voltage across R_A

R_A = effective impedance of the input to the amplifying portion of the detector

X_L = impedance of the alternating-current winding of the transformer, T_1

V_G = output voltage of square wave generator

A = amplitude of V_G

u(t), u(t-a) ... = time displaced unit step functions

It is evident that as R_R decreases, V_{R_A} and I_{R_A} decrease, thus reducing the voltage (and hence the base current of Q_4) available to the amplifying portion of the detector.

The initial point of the active region (sensitivity) of these detectors can be varied from zero up to several hundred volts by a proper choice of the detector diode, D_6, and Resistor R_8. Conventional diodes or stabistors are used for the low voltage range and Zeners can be used for high voltages.

The width of the active region is also affected slightly by the choice of D_6 and R_8, but in the main is set by the choice of circuitry immediately following the detector outputs. The input impedance and current required from the third terminal will vary accordingly.

Transformer T_1 in each detector provides complete isolation between cells and between each cell and the circuitry which follows it. Also the mode to which all detector outputs are connected constitutes an "OR" circuit which gives both control logic and electrical isolation between individual detector outputs.

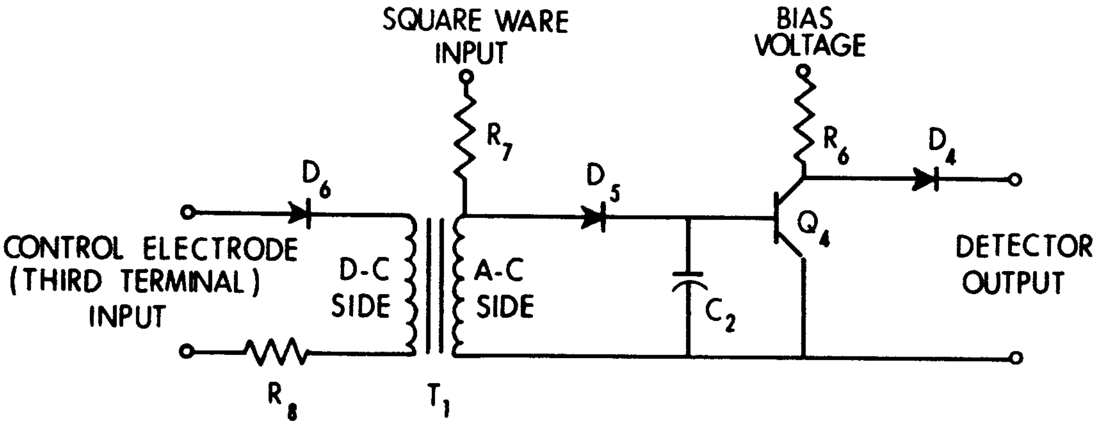

Figure 1-B, Detector

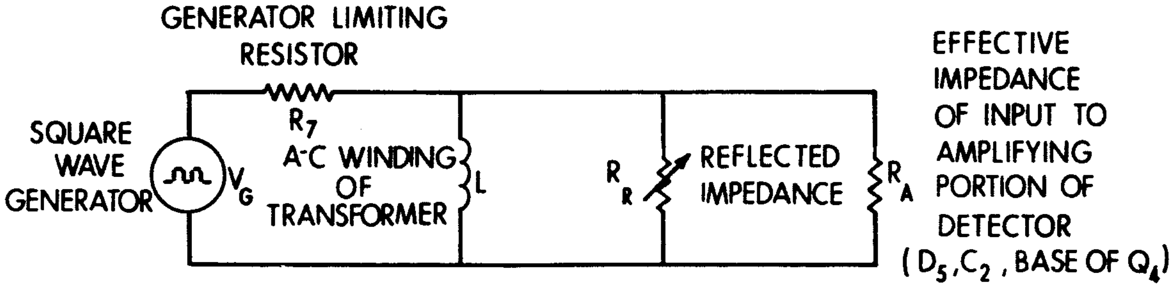

Figure 2-B, Equivalent Circuit of Diode Detector

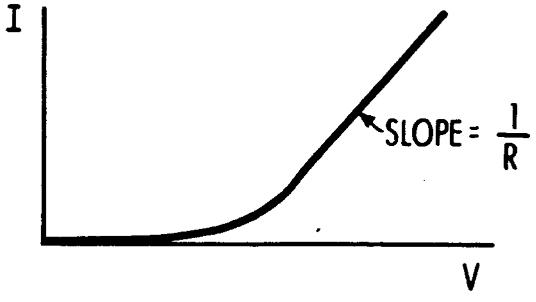

Figure 3-B, Characteristic Curve of D_6, R_8 Combination

Appendix C

The Combined Shunt Voltage Regulator and Series Charge Current Control Circuit for Three Nickel-Cadmium Cells with Control Electrodes

The shunt voltage regulator and the series charge current control circuit for auxiliary electrode nickel-cadmium cells integrated into one laboratory instrument are shown in block diagram form in Figure 1-C and schematically in Figure 2-C. This device provides the user with the choice of using either a shunt or series form of current control in a three-terminal cell testing program.

As seen in Figure 1-C, the same square-wave generator and detector sections are used in the two control systems. (The shunt control system used in this instrument is exactly as described above in this report). However, since the entire instrument will not be temperature cycled with the cells under test, the temperature compensating elements are connected at the end of a cable, as noted in Figure 2-C, instead of internally in the circuit. Placing the compensating elements in the temperature chamber along with the cells will insure maintenance of the desired system terminal voltage temperature characteristics. The shunt control system, as shown in Figure 2-C, is selected by throwing switch S, to its "shunt" position and plugging the charging power source into its "shunt" receptacle. As shown, this system is designed to handle a 9-, 10-, or 11-cell battery. Any unused detector inputs are to be left open-circuited.

The series control system shown in Figure 2-C is an improved version of that described in MEL Report 25/65 of May 1965. The most obvious change is that it is now self-powered, no external power supply is needed. The inverter power supply is a two-transformer inverter, filter, and direct-current voltage regulator which transforms power from the charge current supply to a stable bias voltage for the control circuite. The Switches S_3 and S_5 are included to alter the biasing conditions so that the series control system can be used with batteries of 5 cells or batteries of 10 or 11 cells. The input to the control section has been improved to allow a higher fan-in from the detector section. The input impedance of the field effect transistor, Q_{17}, which is in excess of 100 megohms, is used for this purpose. The FET, Q_{17}, operates as a noninverting amplifier which raises the input to Q_{16} when the detector output increases. An increasing input to Q_{16} lowers its output, thus lowering the input to Q_{15} and tending to turn it off. As Q_{15} is turned off the base drive of the series control element, Q_{14} is decreased which action, in turn, decreases the charge current.

All other operations of the series control system are as reported in MEL Report 25/65 of May 1965. Operation of the series system is selected by throwing Switch S_1, to its "series" position, plugging the charging power source into its series receptance, and selecting operation for either a 5-cell battery or a 10- or 11-cell battery by means of Switches S_3 and S_5.

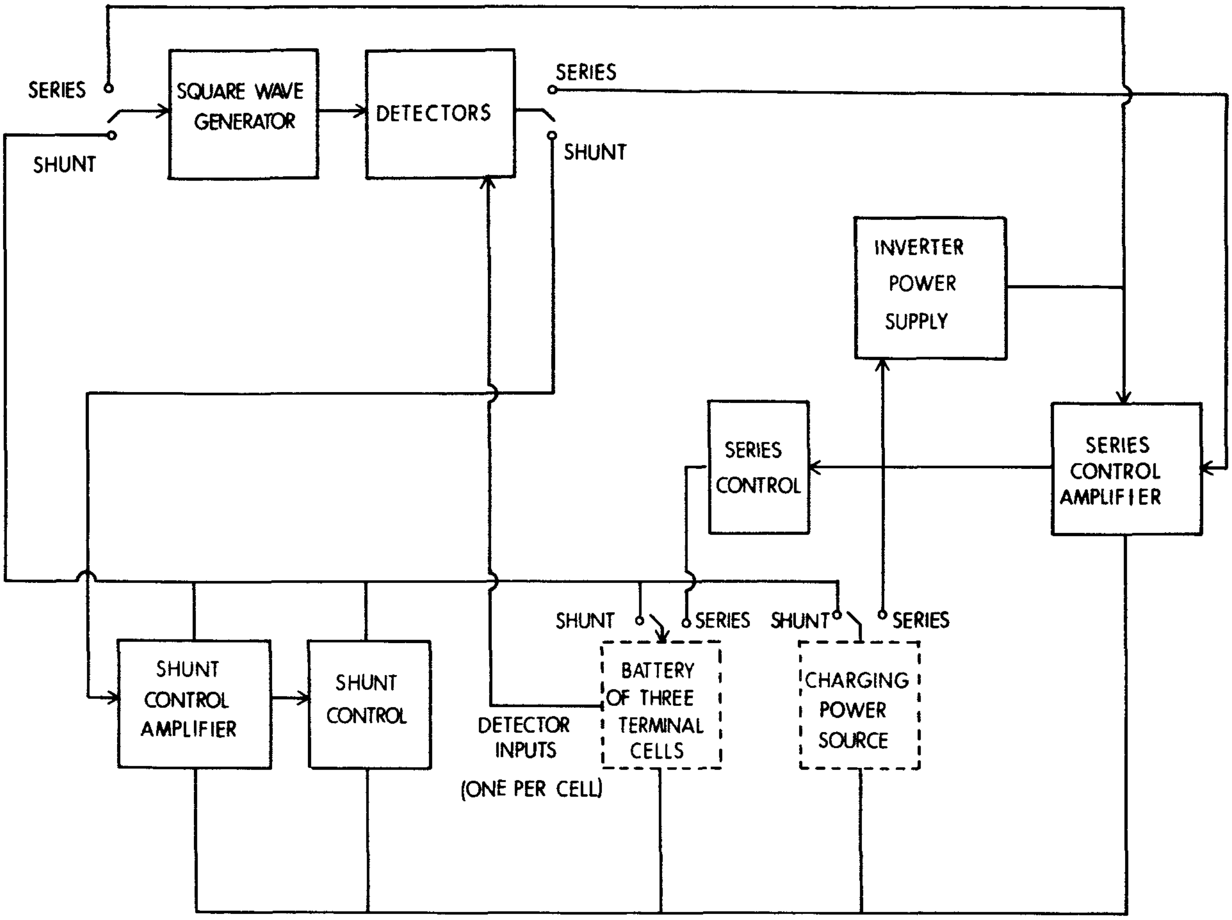

Figure 1-C

Integrated Series Charge Current Control Circuit and Shunt Voltage Regulator for Nickel-Cadmium Cells with Control Electrodes

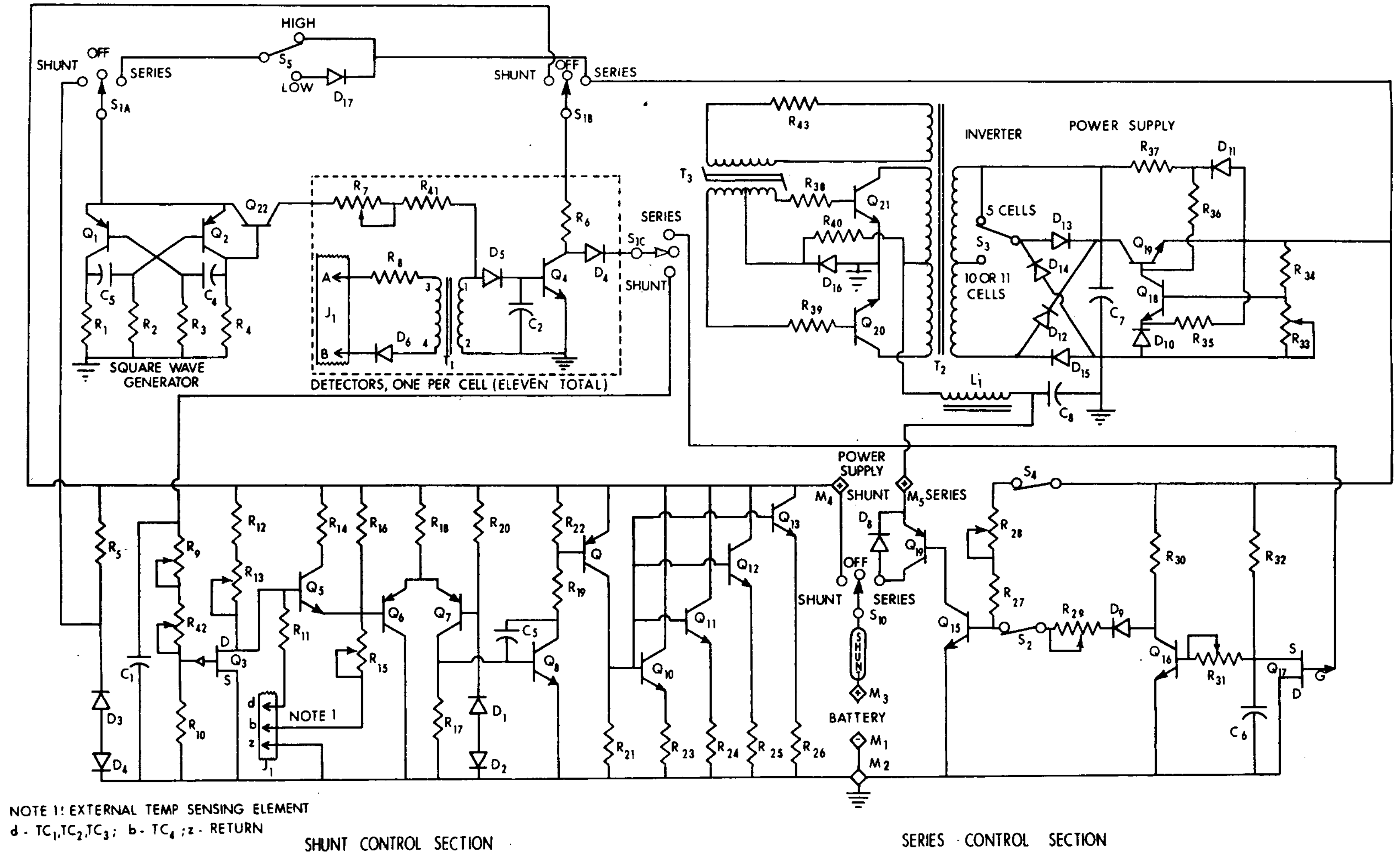

Figure 2-C, Integrated Charge Current Control Circuits

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A circuit to control charge current entering nickel-cadmium cells with auxiliary electrodes ("three-terminal" cells) using a shunt method of control has been developed by MEL for use in satellite power systems requiring minimum weight and space with optimum control and temperature compensation. Reduction in charge current is caused when the set limits of either the total battery terminal voltage, or the potential of any individual cell at this auxiliary electrode, is exceeded.

(author)

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	ROLE	WT	ROLE	WT	ROLE	WT
Change current control						
Circuit						
Current control						
Shunt control						
Shunt voltage control						
Three terminal cells						
Nickel-cadmium cells						
Nickel-cadmium cells with auxiliary electrodes						
Satellite electric power systems						
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II. Ford, Floyd E
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