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# TWO LEVEL VOLTAGE LIMITER

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by

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January 1966

Goddard Space Flight Center
Greenbelt, Maryland

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ILLUSTRATIONS

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## INTRODUCTION

Although sealed silver cadmium cells have attributes such as low self-discharge and nonmagnetic properties that make them a good source of power for spacecraft, in the past, difficulties have been experienced because of excessive pressure rise within the cells. The pressure rise occurs after a 100 percent state of charge has been reached and the cells are on overcharge as shown in Figure 1.

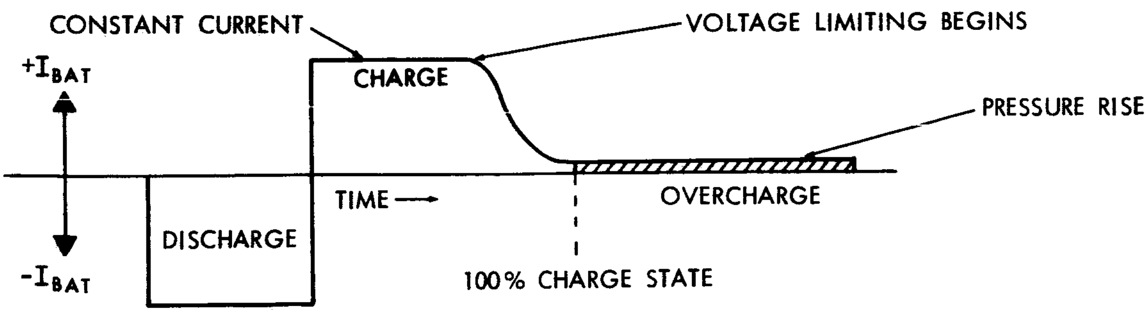


Figure 1–Typical Discharge-Charge Curve for a Sealed AgCd Battery

Fortunately, silver cadmium cells give an indication when they reach the fully charged state. If the battery is charged at a constant current with a voltage limit, there will be a sharp reduction of charge current as the fully charged state is approached (Figure 1). Note in Figure 1 that a current still flows after the fully charged state has been attained. It is the current flowing after the attainment of full charge that is responsible for the pressure problem.

If the charge current were to be interrupted at the 100 percent state of charge, the pressure problem would be alleviated. This report describes the circuitry used to accomplish this.

## FUNCTIONAL APPROACH

The following facts are known about sealed silver cadmium cells:

- The safe voltage limit during charge is 1.5 volts/cell (19.6 volts for a 13-cell battery). However, if 1.5 volts/cell appears across the battery for an extended time, excessive pressure will be built up inside some of the cells.
- The open circuit voltage of a fully charged cell is 1.40+ volts (18.3 volts for a 13-cell battery).
- The self-discharge of a silver cadmium cell is negligible.

Figure 2 shows a simplified charge control system for a 13-cell 5-ampere-hour battery.

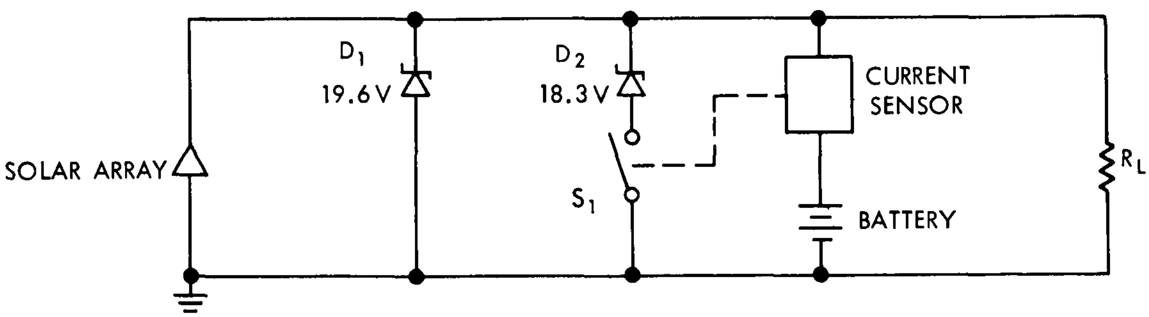


Figure 2–Charge Control System (Simplified)

At the beginning of the sunlight period, current flows from the solar array, through the current sensor, and into the battery. The battery current at this time will be maximum, $S_1$ will be open, and $D_1$ will not allow the battery voltage to exceed 19.6 volts.

As the battery charges, the battery voltage will approach 19.6 volts, which results in a decrease of battery current. When the battery current diminishes to approximately 50 ma, the current sensor develops a signal that closes $S_1$, which allows $D_2$ to limit the battery voltage to 18.3 volts (the battery open circuit voltage). Battery current at this time is essentially zero.

## TWO LEVEL VOLTAGE LIMITER CIRCUITRY

It was decided in the design of the two level voltage limiter to use as many circuits as possible that have already proven reliable in spacecraft work. However, since the device will be used initially in a battery test program, some of the components in the original circuits were replaced with inexpensive ones. For example, $Q_{11}$ through $Q_{14}$, which were originally 2N1724's, are now 2N3232's.

The two level voltage limiter can be divided into two parts:

- The voltage limiter performs the same function as $D_1$ and $D_2$ of Figure 2, but will produce much sharper limiting than is possible with zener diodes.

- The current sensor detects the battery current and, when the battery current diminishes to 50 ma, will produce a signal to command the voltage limiter to limit at 18.3 volts. The basic current sensor was conceived by John Paulkovich, Spacecraft Technology Division, Goddard Space Flight Center, and was adapted by the authors for use in the two level voltage limiter.

### Voltage Limiter

The voltage limiter consists of a differential amplifier ($Q_6$, $Q_7$), amplifier stages ($Q_9$, $Q_{10}$) and dumping circuit ($Q_{11}$) as shown in Figure 3.

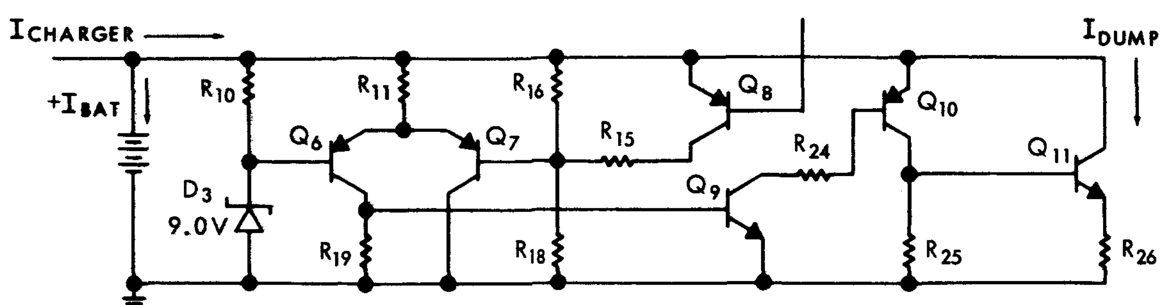


Figure 3–Voltage Limiter

The base of $Q_6$ is held at +9.0 volts with respect to ground by zener diode $D_3$. The voltage appearing at the base of $Q_7$ will depend on the battery voltage since the voltage divider resistors $R_{16}$ and $R_{18}$ are directly across the battery. When the battery voltage is less than 19.6 volts, the voltage appearing at the base of $Q_7$ will be less than +9.0 volts, causing $Q_7$ to conduct. Since $Q_7$ is an emitter follower, the voltage appearing at the emitter will also be less than +9.0 volts. The resultant reverse bias at the base-emitter junction of $Q_6$ cuts $Q_6$ off. Because the base of $Q_9$ is now at ground potential, $Q_9$ through $Q_{11}$ are cut off. Essentially all of the current from the charger will now flow into the battery and the battery voltage will be rising. When the battery voltage rises to 19.6 volts, the voltage appearing at the base of $Q_7$ will have risen above +9.0 volts, which turns off $Q_7$ and allows $Q_6$ to conduct (the base-emitter junction of $Q_6$ is now forward biased). Because of the conduction of $Q_6$, the base of $Q_9$ is forward biased and $Q_9$ through $Q_{11}$ will conduct. Some of the current from the charger will now be diverted from the battery and will flow through the dumping transistor $Q_{11}$. This reduction of battery current prevents the battery voltage from rising above 19.6 volts.

If $Q_8$ is turned on, the battery voltage will no longer be limited to 19.6 volts, but to some lower value. $R_{15}$ at this time will shunt $R_{16}$, which changes the effective resistance of the upper part of the voltage divider. $R_{15}$ was so chosen that, at any time $Q_8$ is fully on, the base voltage of $Q_7$ will be above +9.0 volts anytime the battery voltage is above 18.3 volts; i.e., current dumping will be of such a magnitude to maintain the battery voltage at 18.3 volts.

Note that if $Q_8$ is not fully on, the voltage limit will be somewhere between 19.6 volts and 18.3 volts.

The current sensor consists of a square wave generator, switching stage ($Q_3$ and $Q_4$), and output stage ($Q_5$).

The square wave generator (not shown in Figure 4) develops an output of 180 cps that is used to alternately switch $Q_3$ and $Q_4$ into conduction.

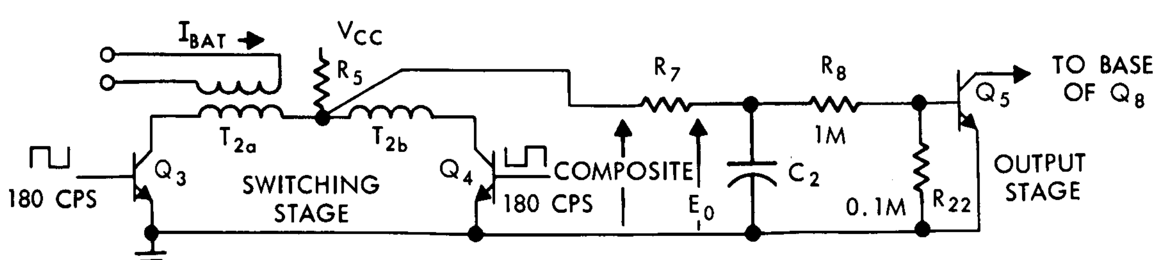


Figure 4–Current Sensor

The switching stage develops a dc voltage signal ($E_0$) that is inversely proportional to the magnitude of the battery current. This is accomplished by the magnitude of the battery current controlling the amplitude of the composite square wave appearing at the bottom of $R_5$. The average level of the composite wave, after filtering, appears across $C_2$ as the output voltage ($E_0$). Note in Figure 5, which shows the composite square waves for three different values of $I_{bat}$, that the average amplitude of the composite square wave increases as the battery current decreases.

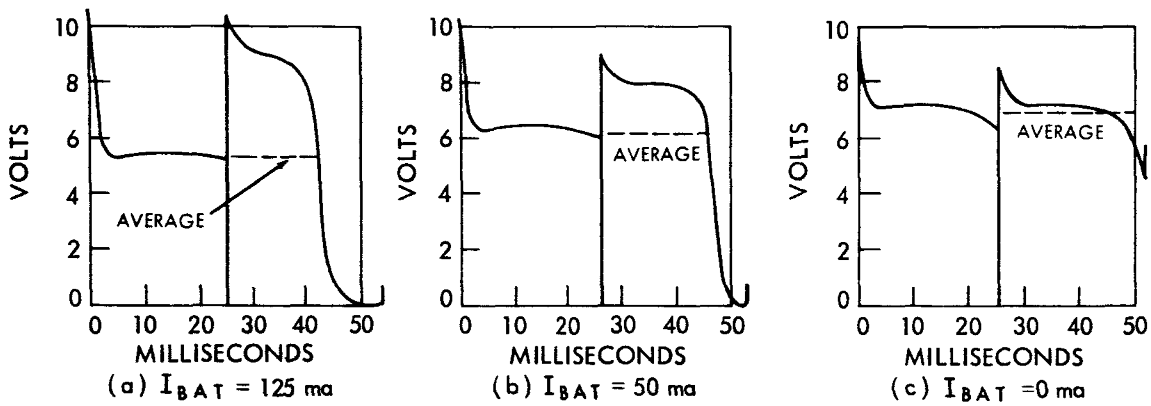


Figure 5–Composite Square Waves for Three Values of $I_{bat}$

The output stage is driven by $E_0$. Whenever $E_0$ is less than 5.8 volts, $Q_5$ will not conduct. As $E_0$ rises above 5.8 volts, $Q_5$ will begin to conduct. Since $E_0$ is a function of $I_{bat}$, the conduction $Q_5$ is also a function of $I_{bat}$. Figure 6 shows that $Q_5$ will conduct anytime the magnitude of $I_{bat}$ is less than 50 ma.

The conduction of $Q_8$ of the voltage limiter depends directly upon the conduction of $Q_5$. Therefore, anytime $Q_5$ conducts, the voltage limit will be less than 19.6 volts.

From the foregoing, the following generalizations can be made:

- Whenever the absolute value of $I_{bat}$ is greater than 50 ma, the voltage limit level is 19.6 volts.
- Whenever $I_{bat}$ is zero, the voltage limit level is 18.3 volts.
- Whenever the absolute value of $I_{bat}$ is between 50 ma and 0 ma, the voltage limit level is somewhere between 19.6 volts and 18.3 volts.

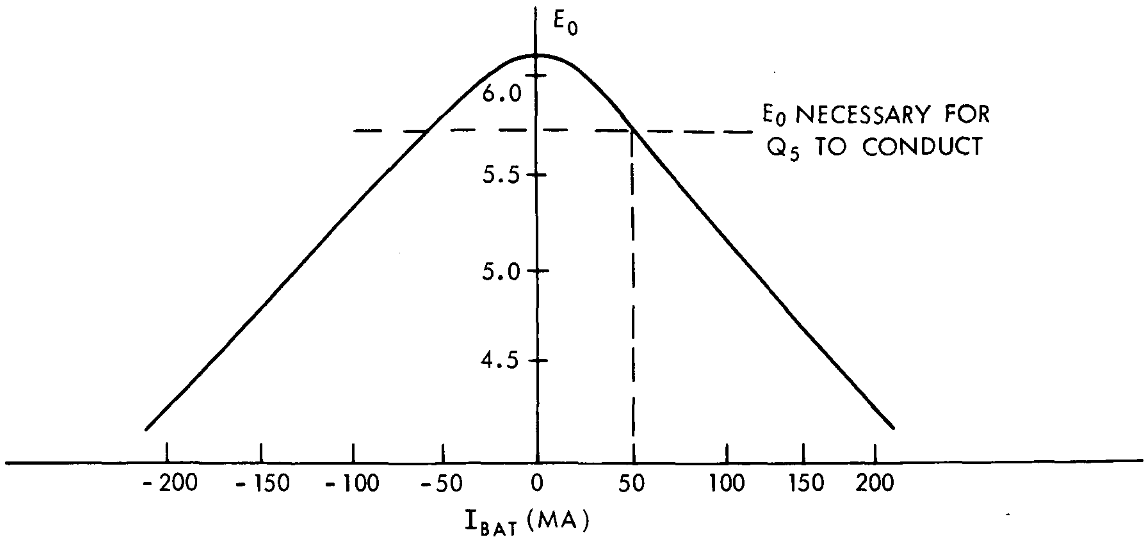


Figure 6–$E_0$ vs $I_{bat}$

## TYPICAL CHARGE OF A SILVER CADMIUM BATTERY USING THE DEVICE DESCRIBED

Assume that the battery is at approximately 14 volts because it is in a partially discharged state. The charge period begins as the solar array enters the sunlight. At this time, $I_{bat}$ will be high (a typical value would be 500 ma) and there will be no signal developed by the current sensor. The voltage limiter will limit the voltage to 19.6 volts should the battery voltage reach that level.

As the battery charges and the battery voltage approaches 19.6-volt limit, there will be a reduction of $I_{bat}$ because part of the current from the solar array now flows through the dumping circuit of the limiter. When $I_{bat}$ decreases to +50 ma, the current sensor produces a small signal that causes the limiter to

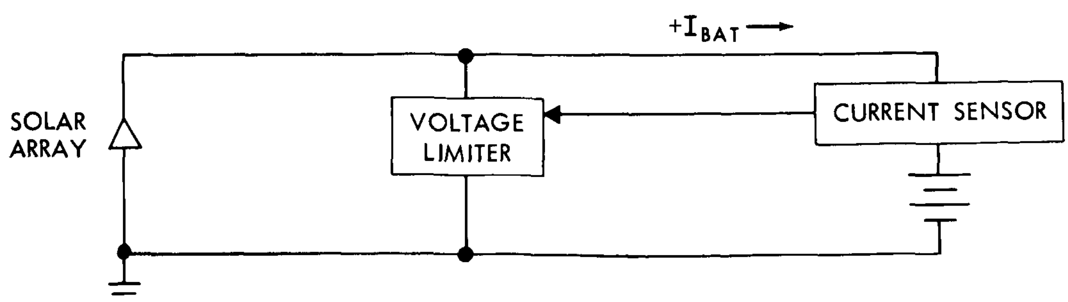


Figure 7–Two Level Voltage Limit System

start limiting at a new level slightly lower than the 19.6-volt level which causes $I_{bat}$ to decrease further. This further reduction of $I_{bat}$ causes the current sensor to develop a slightly larger signal which will lower the voltage limit even more. The result is a regenerative action that continues until the voltage limit level is 18.3 volts and $I_{bat}$ is 0 ma.

This regeneration occurs only between +50 ma and 0 ma. Between 0 ma and -50 ma, the output of the current sensor is such that an increase in magnitude of $I_{bat}$ in the negative direction will cause the voltage limit to be raised. The resultant change in $I_{bat}$ will then be in the positive direction; i.e., $I_{bat}$ becomes less negative. $I_{bat}$ must finally "position" itself at 0 ma.

## TWO LEVEL VOLTAGE LIMITER SPECIFICATIONS

Figure 8 shows the two level voltage limiter as it is being used in a battery test program. Since the device is being used with batteries other than the one described at the beginning of this report, it was necessary to make the voltage limit level and the battery current trip point adjustable. $R_{12}$, $R_{13}$ and $R_6$ provide this capability.

The specifications are:

<u>Range 1</u>

| | |
|---|---|
| Upper voltage limit ....... | 19.6 volts, adjustable from 19 to 20 volts |
| Lower voltage limit ....... | 18.3 volts, adjustable from 18 to 19 volts |
| Current trip point ........ | 50 ma, adjustable from 35 ma to 200 ma |
| Current handling capability of the limiter .......... | 4 amperes |

<u>Range 2</u>

| | |
|---|---|
| Upper voltage limit ....... | 15.3 volts, adjustable from 15 to 16 volts |
| Lower voltage limit ....... | 14.2 volts, adjustable from 14 to 14.5 volts |
| Current trip point ........ | 50 ma, adjustable from 35 ma to 200 ma |
| Current handling capability of the limiter .......... | 4 amperes |

Figures 9 and 10 are photographs of the front and rear of the two level voltage limiter.

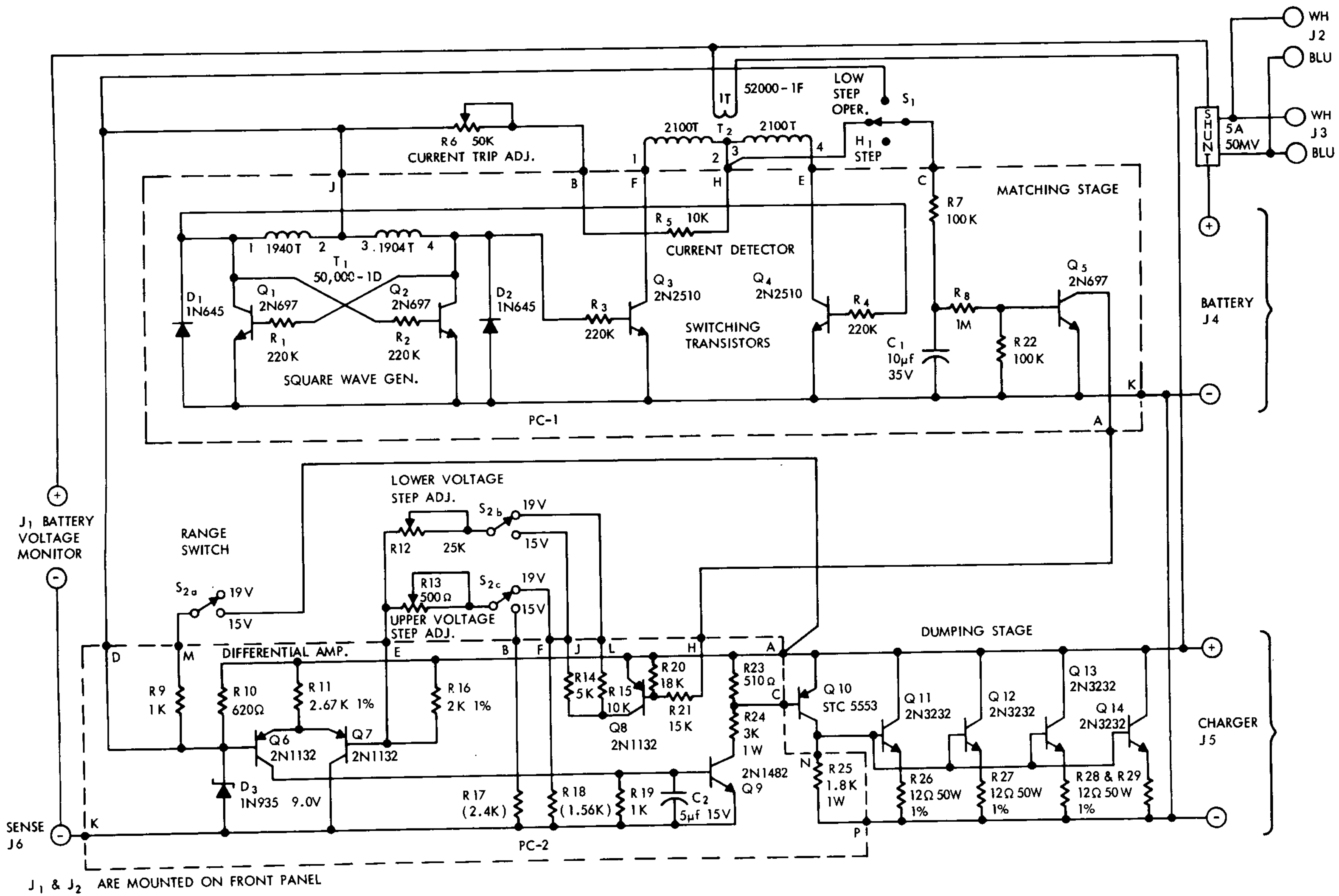


Figure 8–Two Level Voltage Limiter Circuit Diagram

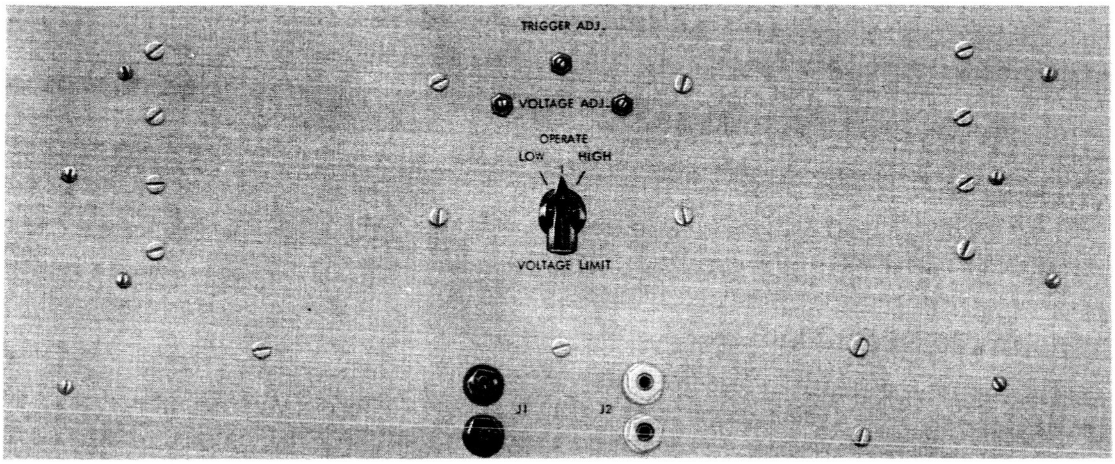


Figure 9—Two Level Voltage Limiter, Front View

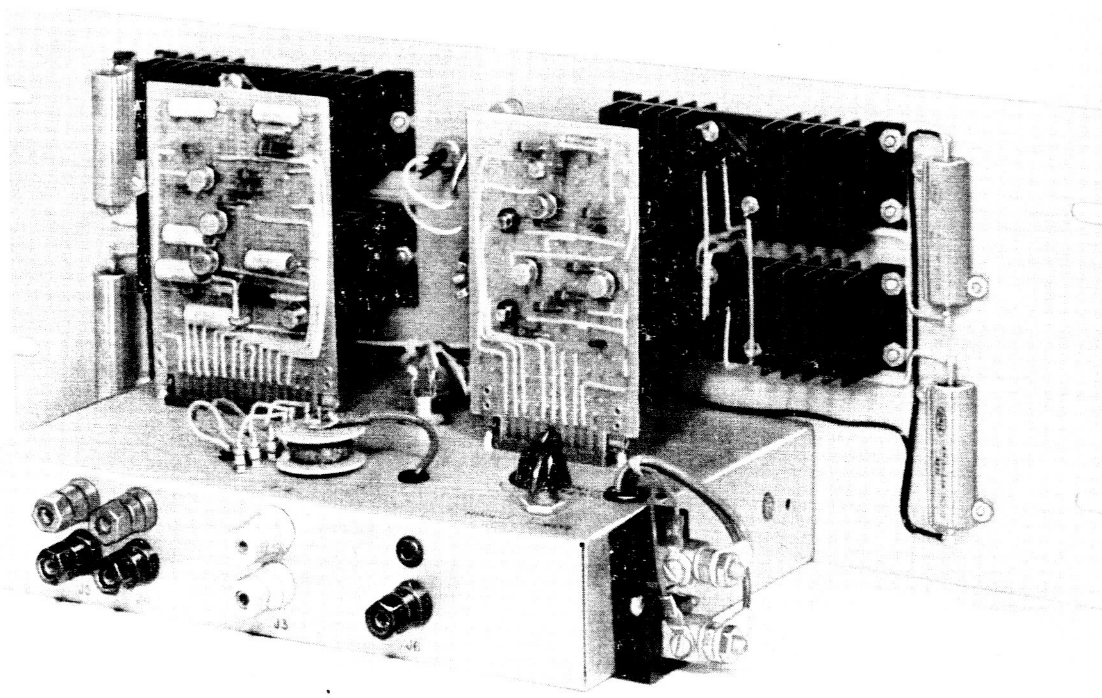

Figure 10—Two Level Voltage Limiter, Rear View

PARTS LIST

| Circuit Symbol | Description | | |
|---|---|---|---|
| $R_1$, $R_2$, $R_3$, $R_4$ | 220K | 1/2 W | 5% |
| $R_5$, $R_{15}$ | 10K | 1/2 W | 5% |
| $R_6$ | 50K potentiometer | Type RV6LAYSA503A | |
| $R_7$, $R_{22}$ | 100K | 1/2 W | 5% |
| $R_8$ | 1.0M | 1/2 W | 5% |
| $R_9$ | 1.0K precision | 1/2 W | 1% |
| $R_{10}$ | 620 ohms precision | 1/2 W | 1% |
| $R_{11}$ | 2.67K precision | 1/2 W | 1% |
| $R_{12}$ | 25K potentiometer | Type RV6LAYSA253A | |
| $R_{13}$ | 500 ohm potentiometer | Type RV6LAYSA501A | |
| $R_{14}$ | 5K | 1/2 W | 5% |
| $R_{16}$ | 2K precision | 1/2 W | 1% |
| $R_{17}$ | (2.4K) TBD precision | 1/2 W | 1% |
| $R_{18}$ | (1.56K) TBD precision | 1/2 W | 1% |
| $R_{19}$ | 1.0K | 1/2 W | 5% |
| $R_{20}$ | 18K | 1/2 W | 5% |
| $R_{21}$ | 15K | 1/2 W | 5% |
| $R_{23}$ | 510 ohms | 1/2 W | 5% |
| $R_{24}$ | 3K | 1 W | 5% |
| $R_{25}$ | 1.8K | 1 W | 5% |

PARTS LIST (Cont'd.)

| Circuit Symbol | Description | | |
|---|---|---|---|
| $R_{26}$, $R_{27}$, $R_{28}$, $R_{29}$ | 12 ohms | 50 W | 1% |
| $C_1$ | 1 $\mu$F | 35V | |
| $C_2$ | 10 $\mu$F | 35V | |
| $C_3$ | 5 $\mu$F | 15V | |
| $D_1$, $D_2$ | 1N645 | | |
| $D_3$ | 1N935 9.0V | | |
| $Q_1$, $Q_2$, $Q_5$ | 2N697 | | |
| $Q_3$, $Q_4$ | 2N2510 | | |
| $Q_6$, $Q_7$, $Q_8$ | 2N1132 | | |
| $Q_9$ | 2N1482 | | |
| $Q_{10}$ | STC5553 or 2N3175 | | |
| $Q_{11}$, $Q_{12}$, $Q_{13}$, $Q_{14}$ | 2N3232 | | |
| $S_1$ | Rotary switch | 1 pole, 3 position | |
| $S_2$ | Rotary switch | 3 pole, 2 position | |
| $T_1$ | Core, 50000-1D | 1-2 1940 turns #40<br>3-4 1940 turns #40 | |
| $T_2$ | Core, 52000-1F | 1-2 2100 turns #40<br>3-4 2100 turns #40<br>6-7 1 turn (bolt) | |

## ADJUSTMENT PROCEDURE

A. Voltage Level Adjustments

1. Connect a power supply to the charger terminals (J5) and connect a jumper wire between the minus battery sense terminal (J6) and the minus charger terminal (J5).
2. Connect a voltmeter to the battery voltage terminals (J1).
3. Adjust the power supply so that the current limit is no greater than 4 amperes and the open circuit voltage is at least two volts above the upper voltage limit. The exact value of power supply open circuit voltage depends on what is desired for a given test.
4. Set the VOLTAGE RANGE switch to the desired position, HIGH or LOW.
5. Set the VOLTAGE LIMIT switch (on front panel) to HIGH and adjust the corresponding VOLTAGE ADJ. screw to the desired upper voltage limit.
6. Set the VOLTAGE LIMIT switch to LOW and adjust the corresponding VOLTAGE ADJ. screw to the desired lower voltage limit.

   Note: Steps 5 and 6 should be carried out in the order given, since the HIGH adjustment changes the lower voltage limit level.

7. Tighten the lock nuts on the adjustment screws and recheck voltage limit levels.

B. Current Trip Point Adjustment

   Note: Steps 1 through 4 of Voltage Level Adjustments must be completed before proceeding.

1. Set the VOLTAGE LIMIT switch to OPERATE and connect a rheostat to the battery terminals (J4). A 1,000 ohm rheostat connected in series with a 100 ohm rheostat will usually suffice.
2. Connect a millivoltmeter to the shunt output (J2 or J3) so that current can be read (shunt output is 10 mv/amp of battery current).
3. Adjust the rheostat connected to J4 to give a current flow equal to that of the desired trip point. Start with the TRIGGER ADJ. completely counter-clockwise and turn it clockwise until the voltage just begins to reduce from its upper limit.
4. Tighten the lock nut on the adjustment screw and recheck the trip point.

## CALIBRATION PROCEDURE

### A. Voltage Level Calibration

1. Connect a power supply to the charger terminals (J5) and connect a jumper wire between the minus battery sense terminal (J6) and the minus charger terminal (J5).
2. Connect a voltmeter to the battery terminals (J1).
3. Turn on and adjust the power supply so that the current limit is 2 amperes and the open circuit voltage is 23 volts.
4. Set the VOLTAGE RANGE switch to HIGH.
5. Set the VOLTAGE LIMIT switch to HIGH. Rotate the corresponding VOLTAGE ADJ. screw between its two extreme positions and observe whether the voltage limit specifications are met (19 to 20 volts). If they are not, a decade resistance box must be substituted for R18 on PC-2 (wide board) and a new value for R18 must be determined.
6. Adjust HIGH VOLTAGE ADJ. screw to obtain a voltage limit of 19.6 volts.
7. Set the VOLTAGE LIMIT switch to LOW. Rotate the corresponding VOLTAGE ADJ. screw between its two extreme positions and observe whether the voltage limit specifications are met (18 to 19 volts). If they are not, a decade resistance box must be substituted for R15 on PC-2 (wide board) and a new value for R15 must be determined.

   Note: Steps 5 through 7 should be carried out in the order given, since the HIGH adjustment changes the lower voltage limit.

8. Set the VOLTAGE RANGE switch to LOW.
9. Set the VOLTAGE LIMIT switch to HIGH. Rotate the corresponding VOLTAGE ADJ. screw between its two extreme positions and observe whether the voltage limit specifications are met (15 to 16 volts). If they are not, a decade resistance box must be substituted for R17 on PC-2 (wide board) and a new value for R17 must be determined.
10. Adjust the HIGH VOLTAGE ADJ. screw to obtain a voltage limit of 15.3 volts.
11. Set the VOLTAGE LIMIT switch to LOW. Rotate the corresponding VOLTAGE ADJ. screw between its two extreme positions and observe whether the voltage limit specifications are met (14 to 14.5 volts). If they are not, a decade resistance box must be substituted for R14 on PC-2 (wide board) and a new value for R14 must be determined.

B. Current Trip Point Calibration

Note: The purpose of this calibration procedure is to establish the two extremes to which the TRIGGER ADJ. can be set to cause the voltage limiter to go from the upper limit to the lower limit. The upper voltage limit must be set to 19.6 volts and the lower voltage limit must be set to 18.3 volts before proceeding.

1. Electrical Connections

   a. Connect a power supply to the charger terminals (J5) and connect a jumper wire between the minus battery sense terminal (J6) and the minus charger terminal (J5).

   b. Connect a voltmeter to the battery terminals (J1).

   c. Turn on and adjust the power supply so that the current limit is 2 amperes and the open circuit voltage is 23 volts.

   d. Set the VOLTAGE LIMIT switch to OPERATE and connect a rheostat to the battery terminals (J4). A 1,000 ohm rheostat connected in series with a 100-ohm rheostat can be used.

   e. Connect a millivoltmeter to the shunt output (J2 or J3) so that current can be read (the shunt output is 10 mv/amp of battery current).

2. Preliminary check

   a. With TRIGGER ADJ. screw completely counterclockwise, the voltage at J1 at least 18.5 volts, and $I_{bat} = 0$, rotate TRIGGER ADJ. screw clockwise until 18.3 volts is just reached.

   b. Increase $I_{bat}$ until 19.6 volts is just reached. The current at this time should be 40 ± 10 ma.

   c. With TRIGGER ADJ. screw completely clockwise, increase $I_{bat}$ until 19.6 volts is just reached. $I_{bat}$ at this time should be greater than 200 ma.

3. If the results listed in the preliminary check cannot be obtained, proceed as follows:

   a. Substitute decade resistance boxes for R5 (initial setting 10K), R7 (initial setting 100K), and R8 (initial setting 910K).

   b. Rotate TRIGGER ADJ. screw to extreme counterclockwise position (maximum resistance).

   c. With $I_{bat} = 30$ ma and R5 adjusted to produce 18.5 volts, rotate TRIGGER ADJ. screw clockwise until the voltage reading just reaches 18.3 volts.

d. Increase $I_{bat}$ until the voltage just reaches 19.6 volts. Call this new value of battery current $I_2$.

The current band spread can now be calculated:

$$I_{bs} = (I_2 - 30) \text{ ma}$$

If $I_{bs} > 40$ ma, decrease R7
If $I_{bs} < 40$ ma, increase R7

(R7 must be greater than 50K. If necessary, R8 can be reduced to keep R7 above 50K)

e. Repeat steps b., c., and d. until $I_{bs} = 40$ ma.

f. Rotate TRIGGER ADJ. screw completely clockwise and increase $I_{bat}$ until the voltage just reaches 19.6 volts. $I_{bat}$ at this time should be at least 200 ma.

g. If $I_{bat}$ in step f. is not at least 200 ma:

1. Decrease the value of R5 until it is possible to just reach 19.6 volts at 200 ma.

2. Rotate TRIGGER ADJ. screw completely counterclockwise and with $I_{bat} = 0$, increase R7 until the voltmeter reads 18.5 volts.

h. Solder resistors R5, R7, and R8 in place using the values to which the decade boxes are set.

i. Repeat the Preliminary Check. The conditions listed should now be satisfied.