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STATE-OF-CHARGE INDICATOR FOR ZINC-MERCURIC OXIDE BATTERIES

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RADIAN CORPORATION

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Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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13. ABSTRACT

The feasibility of using a short duration, high current, constant voltage pulse charging technique to predict the state-of-charge of zinc-mercuric oxide cells and batteries was examined in this investigation. RM828 and RM1NCMC single cells and ten cell batteries composed of RM1NCMC cells were tested at both 70°F and 32°F. The approach used in this study was (1) determine the test parameters which provided the greatest variation of the test variable (Δi) as a function of state-of-charge, (2) construct a standard curve for each battery and temperature of interest by testing new batteries in various states-of-charge, and plotting the response of the test variable as a function of state-of-charge, (3) test unknown batteries and match their test response to the standard curve to yield a predicted state-of-charge, and (4) discharge the unknown batteries to determine their true state-of-charge at the time of the test, and compare this value to the predicted state-of-charge. The results of this study were extremely encouraging. Even though this was only a feasibility study, this technique was able to predict the state-of-charge of RM828 cells at 70°F and 32°F with a standard deviation of only 6.7%. For the ten cell RM1NCMC batteries at 32°, the standard deviation was only 3.4%. In addition, whenever the test predicted that a cell or battery was less than eighteen percent discharged, in no case for any cell or battery did the actual percent discharge exceed that value by more than five percent. This is extremely important in terms of a practical state-of-charge indicator.

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STATE-OF-CHARGE INDICATOR FOR ZINC-MERCURIC OXIDE BATTERIES

David C. Jones

FOREWORD

This is the final technical report prepared by Radian Corporation, Austin, Texas, under Air Force contract F33615-71-C-1773 concerned with determining the feasibility of using a pulse charging technique to predict the state-of-charge of zinc-mercuric oxide cells and batteries. Program funding and technical assistance in carrying out of this effort was provided by Maj C. Brown of the Aeronautical Systems Division (ASD/SML). The program was technically directed by Mr. R. A. Marsh, Project Scientist, Air Force Aero Propulsion Laboratory (AFAPL/POE-1). This report was submitted by the author in March 1972. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

JAMES D. REAMS
Chief Energy Conversion Branch
Aero Propulsion Laboratory

ABSTRACT

The feasibility of using a short duration, high current, constant voltage pulse charging technique to predict the state-of-charge of zinc-mercuric oxide cells and batteries was examined in this investigation. RM828 and RM1NCMC single cells and ten cell batteries composed of RM1NCMC cells were tested at both 70°F and 32°F. The approach used in this study was (1) determine the test parameters which provided the greatest variation of the test variable (Δi) as a function of state-of-charge, (2) construct a standard curve for each battery and temperature of interest by testing new batteries in various states-of-charge, and plotting the response of the test variable as a function of state-of-charge, (3) test unknown batteries and match their test response to the standard curve to yield a predicted state-of-charge, and (4) discharge the unknown batteries to determine their true state-of-charge at the time of the test, and compare this value to the predicted state-of-charge. The results of this study were extremely encouraging. Even though this was only a feasibility study, this technique was able to predict the state-of-charge of RM828 cells at 70°F and 32°F with a standard deviation of only 6.7%. For the ten cell RM1NCMC batteries at 32°, the standard deviation was only 3.4%. In addition, whenever the test predicted that a cell or battery was less than eighteen percent discharged, in no case for any cell or battery did the actual percent discharge exceed that value by more than five percent. This is extremely important in terms of a practical state-of-charge indicator.

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LIST OF SYMBOLS

Δi - initial (peak) current minus final current of a current-time curve (amps)

E_d - discharge voltage as measured at the end of a discharge period (volts)

$i_1 - i_2$ - magnitude of current at t=10 msec during first charging pulse minus value of current at t=10 msec during second charging pulse (amps)

i_i - initial peak current of a current-time curve (amps)

i_f - final current of a current-time curve (amps)

R_L - load resistor through which cell is discharged (ohms)

t_{dis} - discharge time (seconds)

t_{del} - delay time between end of discharge and initiation of charging pulse (milliseconds)

E_p - charging pulse voltage (volts)

t_p - length of time of charging pulse (milliseconds)

Δt - delay time between end of first charging pulse and beginning of second charging pulse (milliseconds)

I. INTRODUCTION

This report describes an investigation to determine the feasibility of measuring the state-of-charge of zinc-mercuric oxide batteries with a new pulse charging technique.

Zinc-mercuric oxide batteries (hereafter referred to by their more common name mercury batteries) have good voltage stability and high energy density, and are thus attractive power sources for portable communications equipment. They have the big disadvantage that there is presently no means to reliably predict the amount of "life" a particular battery has left. As a result, many good batteries are discarded as a preventive maintenance step, thereby increasing battery costs, or what is far worse, a pilot may be left in an emergency situation with inoperative communications equipment.

Three types of mercury cells were specified for testing in this feasibility study, the RM828 cell which is used in the PRC-90 battery for the AN/PRC-90 Survival Radio, the RM-1NCMC cell which is used in the RT-10 battery for the AN/ACR RT-10 Survival Radio, and the RM3WA cell which is used in the URC-64 battery for the AN/URC-64 Survival Radio. In addition to single cell tests, ten cell batteries each composed of ten RM-1NCMC cells were tested to determine the response of multi-cell batteries to this test. All tests were conducted at both 70°F and 32°F.

The basis of this test method is a constant voltage, high current, very short duration charging pulse which is applied to the cell or battery being tested. The current-time trace during this charging pulse is the parameter of interest.

To measure state-of-charge, some parameter must be found which varies in a regular, predictable manner with state-of-charge. Radian found in an in-house study on a state-of-charge test for mercury cells that the current-time trace during a constant voltage, short duration pulse is strongly dependent on the state-of-charge of the cell being tested.[1]

The following sections describe the test methods, experimental results, and conclusions obtained from this feasibility study.

II. EXPERIMENTAL METHODS

A. Test Procedure

To aid in understanding the test equipment and test parameters described in the following section, the test sequence which evolved from this study will be described.

(1) The cell is placed in the cell holder and a start button depressed.

(2) The circuit automatically discharges the cell for 16 seconds across a 1Ω (10Ω for a ten cell battery) resistor. The operator records the discharge voltage (displayed on a digital voltmeter) at the end of the discharge period.

(3) After the end of the discharge, the circuit delays 200 milliseconds, then pulse charges the cell to 1.50 volts (15.0 volts for a ten cell battery) for 55 milliseconds, delays 105 milliseconds, and again pulse charges the cell to 1.50 volts for 55 milliseconds. The operator opens the shutter on an oscilloscope camera during the last few seconds of the test to record the two current-time traces and the cell voltage during the charging pulses.

(4) The cell is removed from the holder, and the pertinent data extracted from the current-time curves which are recorded on the Polaroid film.

A plot of cell voltage as a function of time during the test is helpful in describing the test environment as seen by the test cell. Such a diagram is shown in Figure 1. Note that the time scale is not linear.

B. Test Circuit

It was found in previous work on a state-of-charge test for RM-42R mercury batteries that it was advantageous to subject a battery to a brief, high current discharge as a conditioning procedure immediately prior to application of the charging pulse.[1] A test instrument to apply the charging pulse to the battery had been devised and constructed during the earlier work. To facilitate the optimization of the test parameters for the cells of interest in this study, an automatic timing and discharge circuit was added to that test instrument. This system permitted selection of the desired discharge load, discharge time, delay time between end of discharge and beginning of charging pulse, cell voltage during the charging pulse, and time duration of the charging pulse.

A block diagram of this test circuitry is shown in Figure 2. The start button triggers a timing circuit which controls the discharge time and the delay time between discharge and charging pulse, and then sends two triggering pulses to the Tektronix 453A oscilloscope. This results in two charging pulses being applied to the battery. The oscilloscope

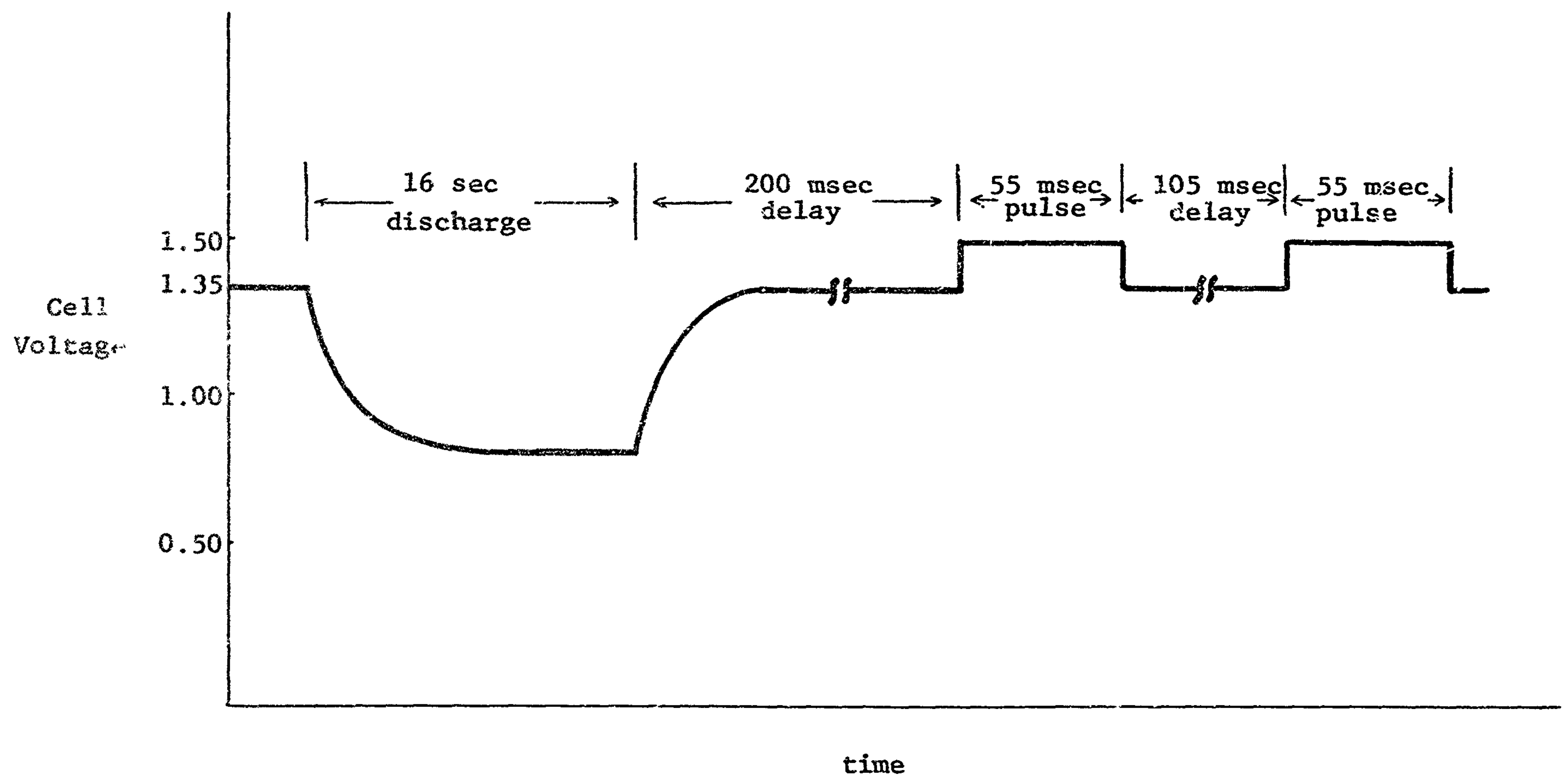


FIGURE 1

Cell Voltage During Test

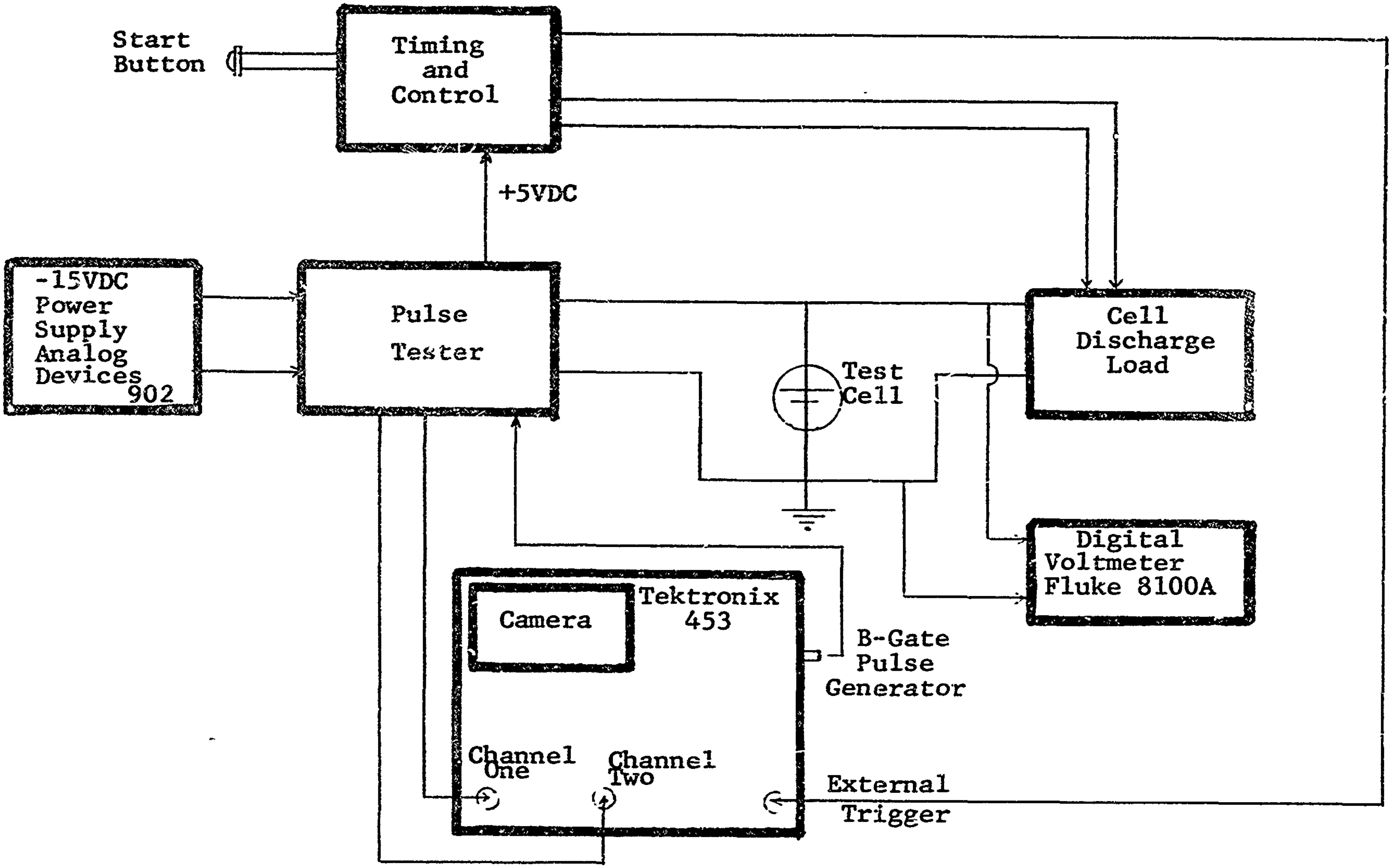
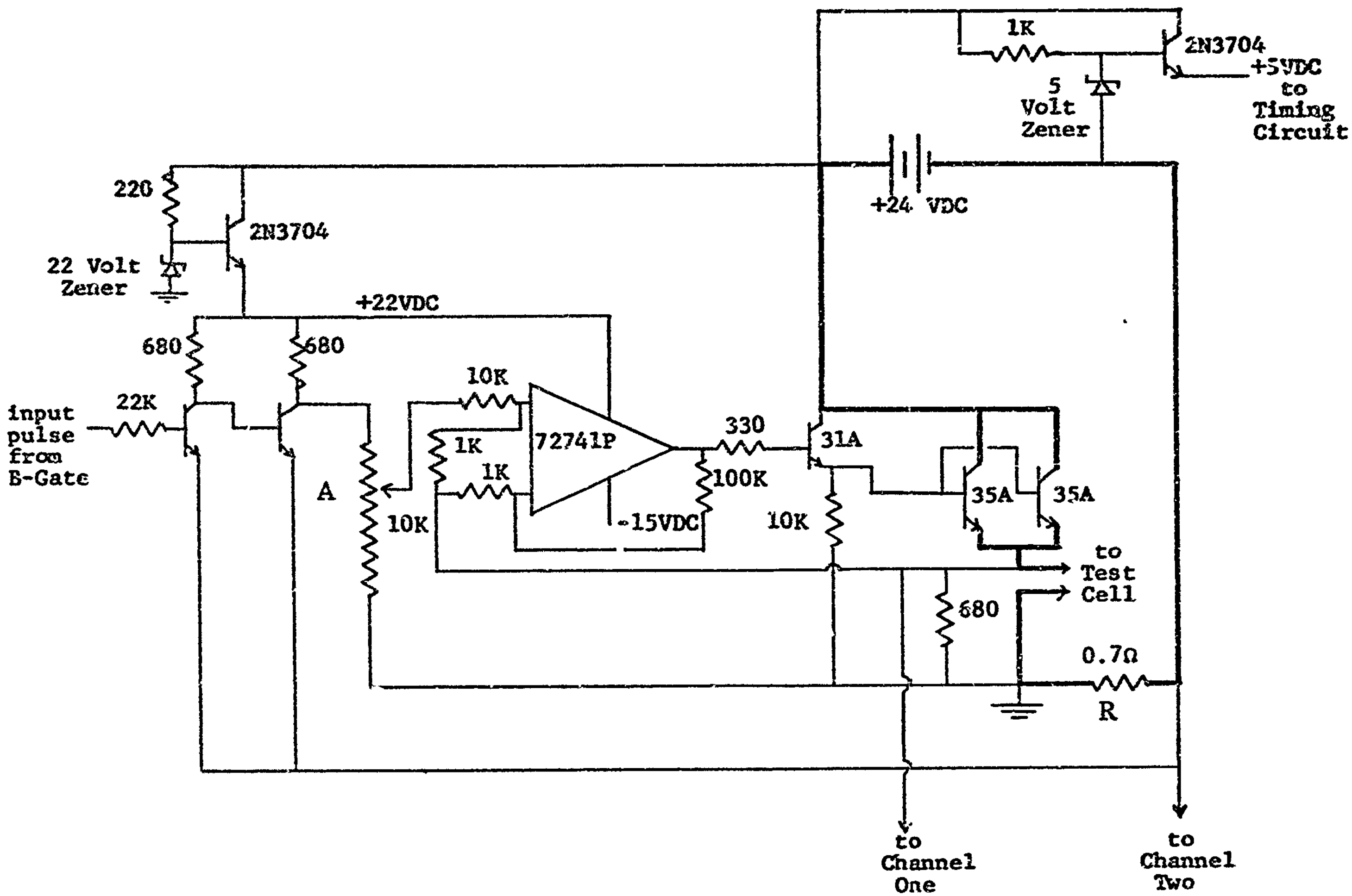


FIGURE 2

Tester Circuitry

is used not only to record the test data (via a C-30A Tektronix camera), but also to control the duration of the charging pulse. This is accomplished via the output signal available at the B-gate of this oscilloscope. This output signal is essentially a square wave pulse whose duration can be set by control knobs on the oscilloscope.

A diagram of the pulse tester is shown in Figure 3. The heart of this system is a 72741P operational amplifier. The positive input to this amplifier is a 1.5 volt signal (15 volt for ten cell batteries) whose duration is controlled by the signal from the oscilloscope B-gate. The negative input is the voltage of the battery being tested. When no signal comes from the B-gate, the amplifier is turned off, which keeps the transistors 31A and the two parallel 35A's turned off. When a signal is sent from the B-gate, a 1.50 volt signal (adjustable at potentiometer A) enters the positive input, which turns on the amplifier, which in turn turns on the transistors. As the transistors turn on, charging current is forced into the test battery by the 24 volt power supply, and this charging current polarizes the test cell. (The path of the charging current is shown by heavy lines.) The test cell voltage is fed into the negative input of the amplifier. The amplifier compares the test cell voltage to the 1.50 volt input, and continues to turn on the transistors until the charging current is of such magnitude that the test cell is polarized to the voltage which is fed to the positive input of the amplifier, namely, 1.50 volts. As long as a signal is received from the B-gate, the amplifier controls the charging current at such a level as to keep the cell voltage at 1.5 volts. The current required to accomplish this polarization decreases with time, and this current is monitored by measuring the iR drop across resistor R and feeding this to channel 2 of the oscilloscope



PULSE TESTER CIRCUIT

FIGURE 3

where the current-time trace is recorded on film. The cell voltage during the charging pulses is recorded on channel 1 of the oscilloscope.

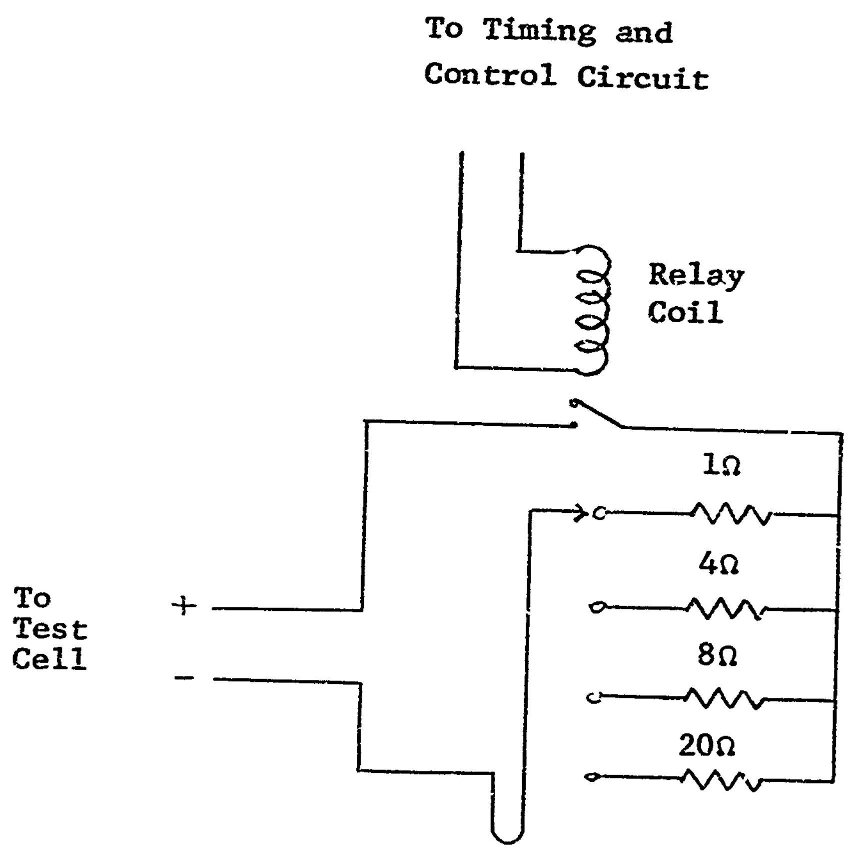
A diagram of the cell discharge load circuit is shown in Figure 4, and is self explanatory.

The timing and control circuit is a digital circuit whose diagram is shown in Figure 5. This circuit can be adjusted to provide discharge times from 0.2 to 25.6 seconds and delay times from 0.2 to 25.6 seconds.

Figure 6 shows a diagram of the single-cell holder used in this study. This is essentially a small C-clamp with an insulated plate on the bottom which acts as a contact for the positive pole of the cell. As the clamp is tightened, the cell is rotated with the fingers to assure a wiping contact at both positive and negative poles. Very little actual pressure is applied with the clamp because of the possibility of damage to the cell. This special holder was constructed because earlier work had shown that it is important to minimize contact resistance. When ten cell batteries were tested, soldered connections to the battery leads were used.

C. <u>Test Parameters</u>

As noted earlier in the description of the test procedure, one of the recorded test parameters is the cell voltage immediately before the end of the discharged period. This voltage is displayed on a digital voltmeter, and is recorded by the operator. By itself, this discharge voltage (E_d) is a poor indicator of state-of-charge, but when used in



CELL DISCHARGE LOAD CIRCUIT

FIGURE 4

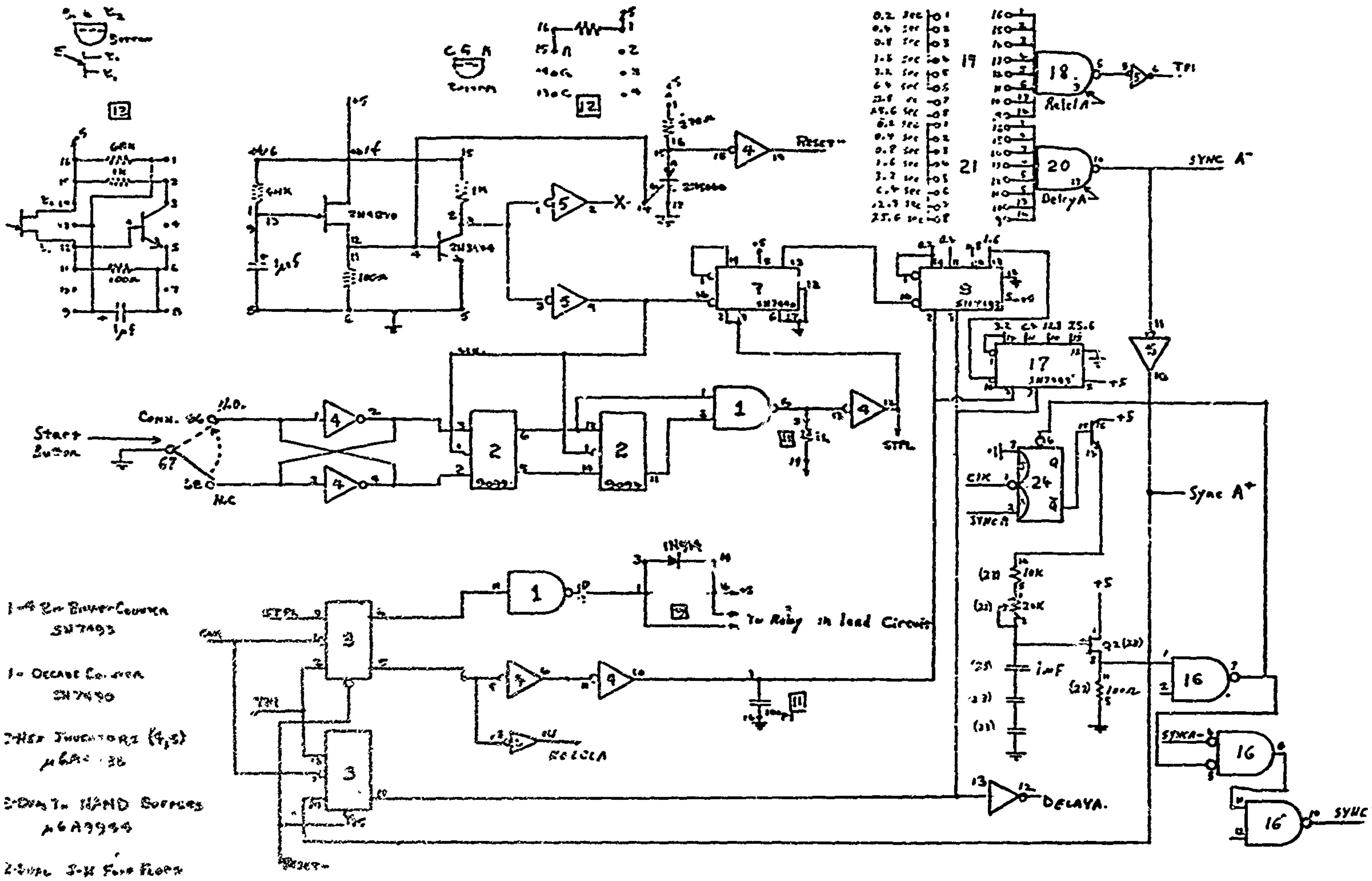


FIGURE 5

Timing and Control Circuit .

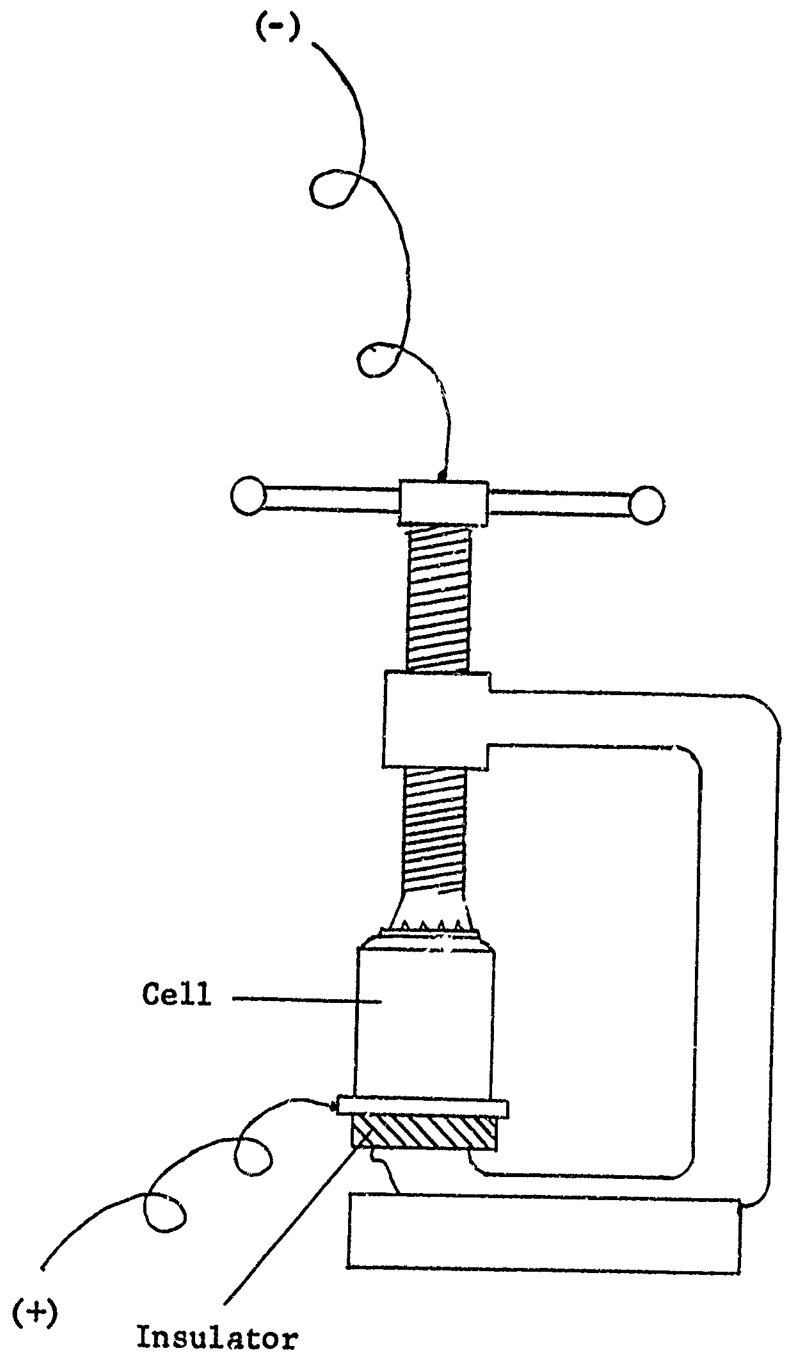


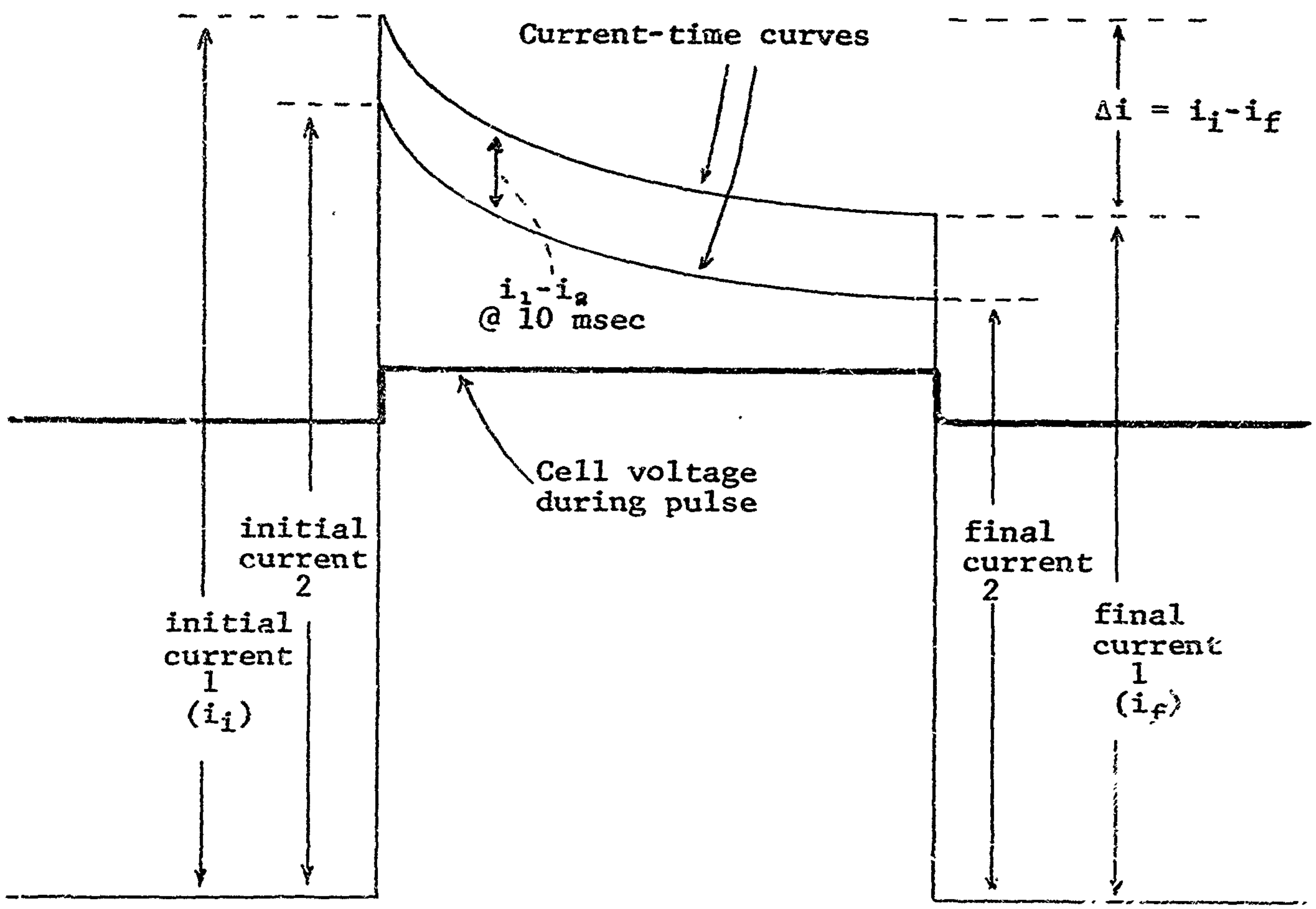
FIGURE 6

Cell Holder

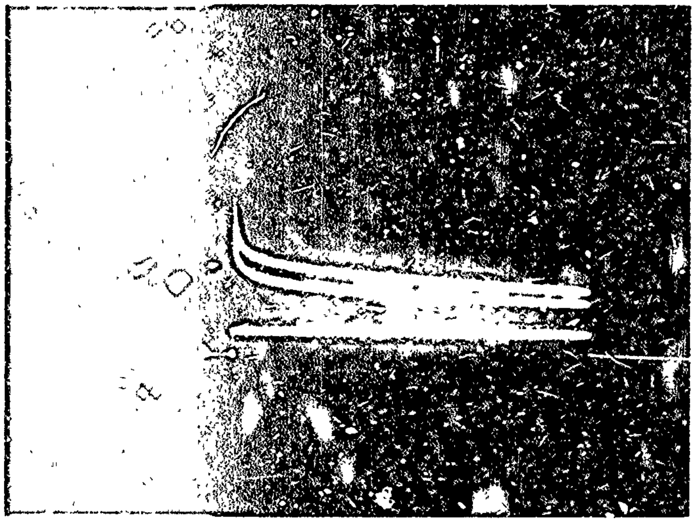
conjunction with other measurements it can prove useful as a "screening" method. This will be discussed in detail in a later section.

The remainder of the test data for a particular cell is collected in the form of a Polaroid picture of voltage-time and current-time traces during the two charging pulses. Figure 7 shows the type of data obtained during each test. The voltage of the test cell before, during, and after each charging pulse is shown, as is the charging current before, during, and after each pulse. Since the cell is polarized to 1.50 volts during each pulse only one voltage-time trace (heavy line) is apparent during the pulse, but this actually represents two superimposed traces. Two current traces are shown. Before and after the pulse the current is zero, so the two current traces are superimposed during those periods. During the pulse, however, the current-time traces are different, the first pulse invariably being the higher current pulse. It can be seen from Figure 7 that there are a number of parameters relating to the current-time traces, and all of these were found to vary with state-of-charge. The only ones which varied in a regular manner, however, were Δi, the initial current of trace 1 minus the final current of trace 1, and i_1-i_2, the current of trace 1 at 10 milliseconds minus the current of trace 2 at 10 milliseconds.

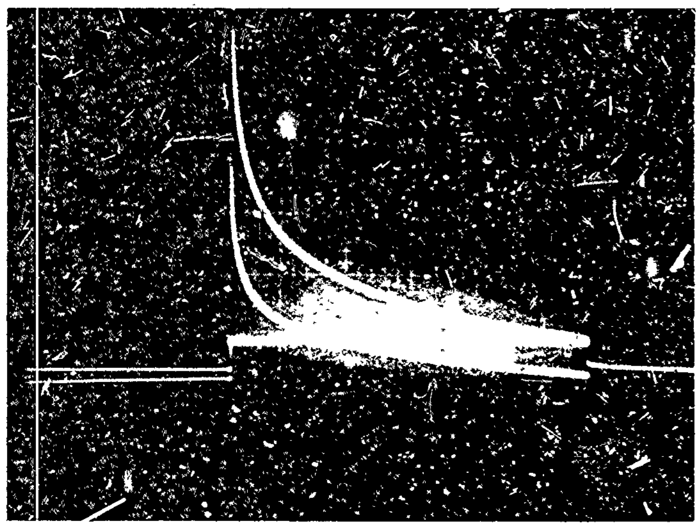
Some actual photographs of test data are shown in Figure 8. Picture (a) shows an old RM1NCMC cell at 14% discharge. Picture (b) shows a fully discharged RM1NCMC cell. In both of these pictures, the voltage is 0.5 volts/div, the current is .0715 amp/div, and the time is 10 msec/div. Picture (c) shows a battery composed of ten old RM1NCMC cells at 18% discharge. Picture (d) shows a battery composed of nine good cells at full charge and one bad cell. In these pictures, the voltage is 5.0 volts/div and the current and time are the same as above.



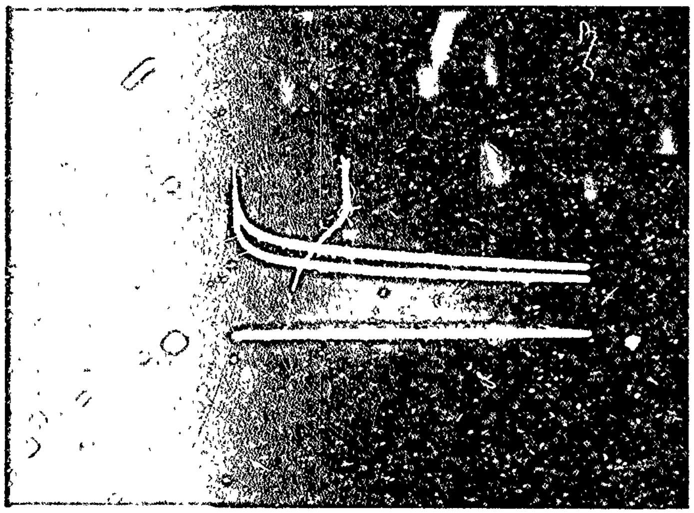
Test Results
FIGURE 7



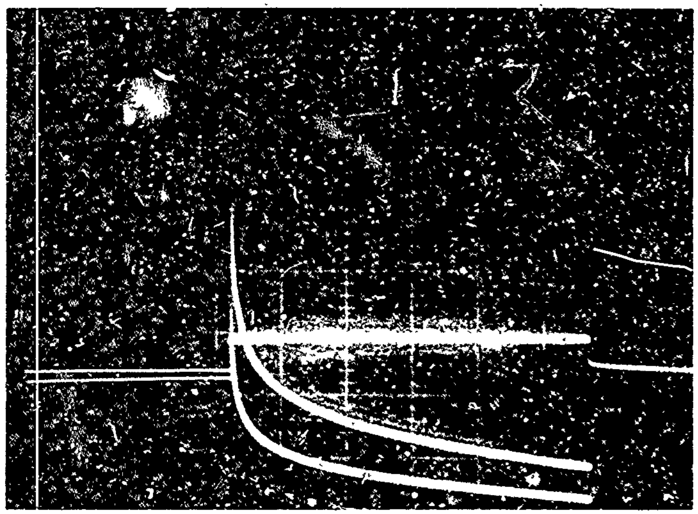
(a)



(b)



(c)



(d)

FIGURE 8

Photographs of Test Results

D. Discharge Parameters and Discharge Circuit

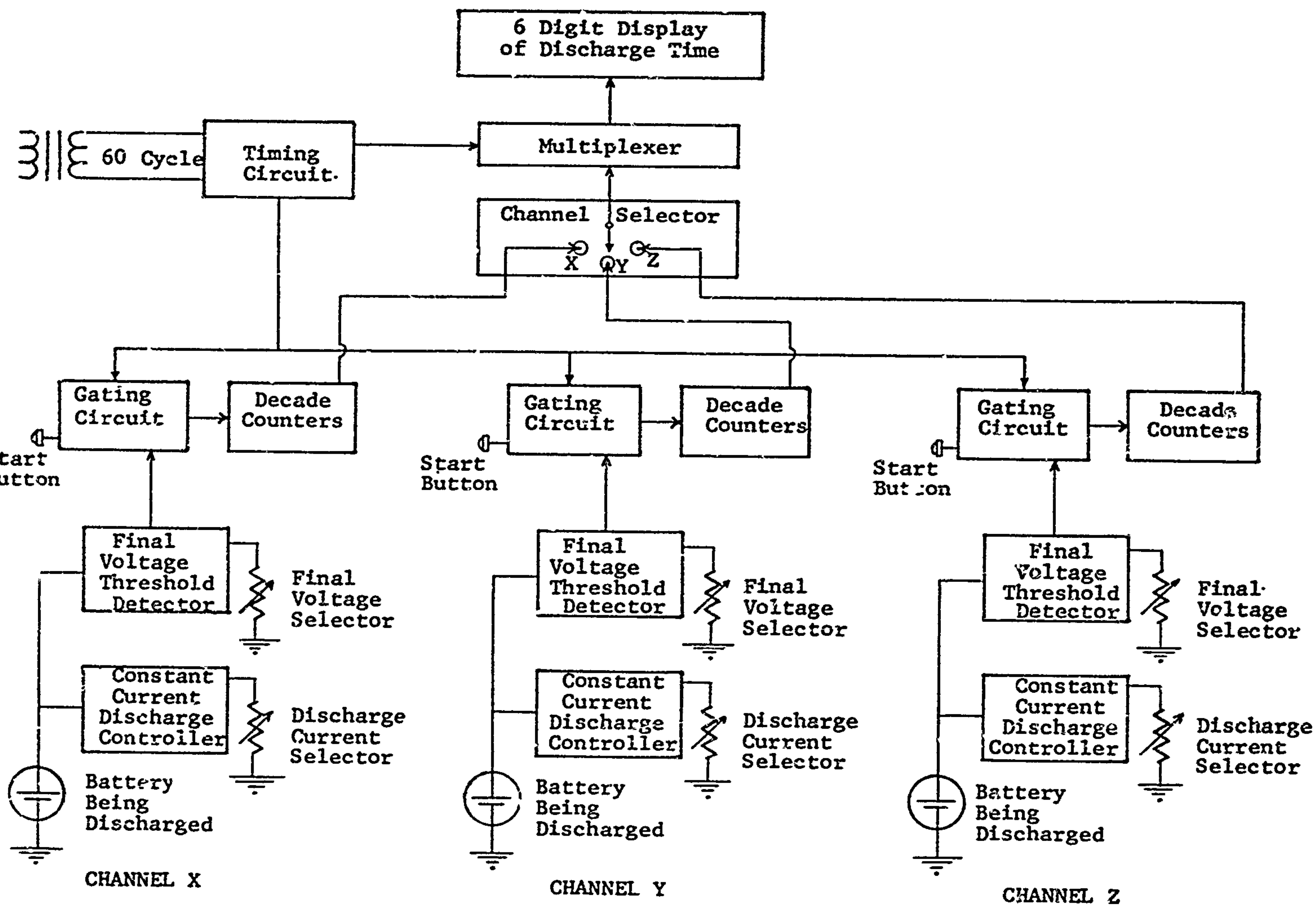
The following discharge parameters were specified for the cells used in this study.

RM828 - 55 mA constant current discharge to an end voltage of 1.00 volts per cell.

RM3WA - 85 mA constant current discharge to an end voltage of 1.00 volts per cell.

RM1NCMC - 60 mA constant current discharge to an end voltage of 1.08 volts per cell.

A discharge circuit was devised and constructed for discharging one or ten cell batteries at any desired constant current discharge, with a cut-off at any desired end point voltage. This circuit has three channels so that three cells can be discharged simultaneously, each with its own required discharge current and end point voltage. A block diagram of this circuit is shown in Figure 9. This is basically a digital circuit whose detailed circuit diagram is given in Appendix I. The discharge current can be set with an accuracy of 0.1 milliamp and the end point voltage can be set with an accuracy of 1 millivolt. This circuit requires external power supplies of +5 DC, ±15 DC, and 115 AC. This apparatus was particularly useful since the decade counters store the discharge time required to reach the end point voltage. Thus batteries could be put on to discharge during the night and the discharge times could be recorded the next morning.



Discharge Circuit

FIGURE 9

E. Construction of Standard Curves

Once a parameter has been found which varies in a regular manner with state-of-charge, a graph of this parameter as a function of state-of-charge can be prepared and used to predict the state-of-charge of unknown cells which are subsequently tested. This is done by measuring the parameter of interest for the unknown cell, plotting this value on the graph, and noting the percent discharge at which this plotted point lies.

The graphs or "standard curves" for the cells of interest in this study were prepared as follows.

1. Standard Curves for Single Cells

Three sets of new cells were used. One cell in each set was not discharged. One cell in each set was discharged at the specified constant current for one hour, another for two hours, another for three hours, and so on until the end point voltage was reached on the last cell before its specified number of hours of discharge was complete. All three sets of cells were then allowed to stand at 70°F for at least a week. Each cell was then tested as described in section A. The cells were then allowed to stand at least 24 hours at 32°F, and within 15 seconds after being removed from the cooler each cell was tested again as described in section A. The test results for the three series of cells were averaged for each discharge point, e.g., the results for the three cells discharged one hour were averaged, and these averaged results were plotted versus percent discharge to yield a 70°F standard curve and a 32°F standard curve. Actually three lines occur on each graph, Δi, $i_1 - i_2$, and E_d versus state-of-charge. The cells which made up these curves had not been discharged to determine their true state-of-charge at the time they were tested. The standard curves thus reflected the apparent state-of-charge of the cells based on their initial discharge time. Because of this, these curves are referred to as "uncorrected standard curves".

Next, all cells were discharged on the discharge apparatus described in section D to determine their actual state-of-charge at the time they were tested. For each cell, the actual discharge time was added to the initial discharge time to obtain a total discharge time or total "life" for that particular cell. This value was used as a check on the quality of that cell. Any cell exhibiting a total discharge time significantly lower than the other cells was judged substandard, and the test points (Δi, $i_1 - i_2$, E_d) collected from that cell were not used. The test data collected earlier were replotted on the basis of actual discharge times to yield "corrected" standard curves. The data from each cell of the three series was plotted individually. Cells which were all initially discharged the same length of time often did not plot at the same percent discharge due to differences in actual discharge time. The 100% discharge time was defined by the cell which exhibited the longest life during a continuous discharge from full charge to the end point voltage. Six cells were discharged in this manner during collection of data from the three series of cells. Only the corrected standard curves were used in predicting the state-of-charge of unknown cells.

2. Standard Curves for Ten-Cell Batteries

Three ten-cell batteries were prepared using new cells. Each battery was tested at 70°F and 32°F (as described in section A) in the full charge condition, discharged one hour and allowed to stand four days, tested again, discharged another hour, etc., until the end point voltage of the battery was reached. The total discharge time of the battery which lasted the longest defined the 100% discharge time. The delay between discharging the battery and testing it was to allow the battery to stabilize after the discharge. It was found that if tested shortly (e.g., less than a day) after being discharged for one hour, the battery would appear (based on Δi) to be more discharged than it actually was.

The test values for Δi, $i_1 - i_2$, and E_d were plotted for each battery at each discharge point (based on actual discharge time) to yield standard curves at both 32°F and 70°F. Since all the data points did not fall on a single line, two dotted lines were drawn to show the "spread" of the data. A solid line was drawn between these to show average behavior, and this line (Δi) was used to predict the state-of-charge of unknown batteries.

F. Test Cells and Batteries

New cells were obtained from the Mallory Battery Company. Old cells were obtained from the Radio, Beacons, and Batteries Group at Kelly Air Force Base, San Antonio, Texas.

III. EXPERIMENTAL RESULTS

A. Optimization of Test Parameters

The test procedure which evolved from this study was outlined in section II-A. The tests by which that procedure was devised are described here.

It had been observed in earlier work that a brief discharge prior to pulse charging the battery was advantageous. This conditioning procedure presented three parameters to be optimized, namely, the resistance (R_L) through which the cell would be discharged, the length of time (t_{dis}) the cell would be discharged, and the delay time (t_{del}) between the end of the discharge and the initiation of the charging pulse. The charging pulse itself also presented two parameters to be optimized, the voltage to which the cell would be polarized (E_p) and the length of time the charging pulse would be applied to the cell (t_p).

When it was decided to add a second charging pulse, an additional parameter was added, namely, the delay time between the end of the first pulse and the beginning of the second (Δt).

Before any of the above test parameters could be optimized, some variable must be known whose response to changes in the above test parameters would be monitored. This variable must of course vary with state-of-charge, and the optimization actually consists of getting the maximum change in this variable as a function of state-of-charge. To express this another way, if a plot of some variable versus state-of-charge yields a line whose slope is not zero, the optimization of the test parameters consists of finding those particular test conditions which yield a maximum value for the slope of that line.

Earlier work had shown that several of the variables relating to the current-time trace did exhibit a variation with state-of-charge. The first step was to determine which of these was most promising as a state-of-charge indicator. Referring back to Figure 7 on page 14, the variables which were examined were:

(1) initial current of pulse 1 - i_i

(2) final current of pulse 1 - i_f

(3) initial current of pulse 1 minus final current of pulse 1 - Δi

(4) current at time t during pulse 1 minus current at time t during pulse 2 - i_1-i_2.

It is noteworthy that the second charging pulse was not added to the test until after the optimization of the other test parameters had been completed. Thus (4) above was not originally considered in the optimization.

To summarize, there were originally five test parameters (R_L, t_{dis}, t_{del}, E_p and t_p) to optimize to obtain the maximum response in one of the three test variables (i_i, i_f, and Δi).

It is noteworthy that there are other considerations besides getting the optimum response in the test variables when it comes to choosing the range through which the test parameters might be evaluated. For example, the smaller R_L is and the longer t_{dis} is, the greater the quantity of charge removed from the battery by the test itself. Since it is clearly desirable to minimize the "draining" of the battery, a charge removal of one half of one percent of the total charge output capability of the cell was selected as the maximum allowable discharge. At the specified discharge conditions, all of these cells have a capacity near 3000 amp-seconds. Thus the discharge should remove less than 15 amp-seconds from the cell.

In the case of the delay time t_{del}, the circuit itself imposed a lower limit of 200 milliseconds.

The greater E_p is and the longer t_p is, the greater the amount of charge which will be put into the battery. Since the zinc-mercuric oxide reaction is not readily reversible (the battery may be damaged by extended charging), it was considered desirable to minimize this charging of the battery. Actually, the charging pulse is so brief that very little charge is put into the battery. For example, a fully charged cell might typically receive only 0.004 amp-seconds charge during a 1.5 volt, 55 millisecond charging pulse. Nevertheless, it seemed desirable to minimize the pulse voltage E_p to avoid triggering some irreversible, damaging change in the cell.

In light of the above considerations, the following range of parameters was evaluated.

R_L - 20Ω to 1Ω

t_{dis} - 1 sec to 16 sec

t_{del} - 6 sec to 0.2 sec

E_p - 1.4 volts to 1.6 volts

t_p - 20 milliseconds to 110 milliseconds

One series of cells, discharged in one hour intervals, was prepared for each of the three types of cells.

For the purposes of this feasibility study, the time and expense required to conduct a statistically designed experiment to simultaneously optimize all the test parameters was not justifiable. Instead, the following approach was adopted. The parameters relating to the charging pulse (E_p and t_p) were optimized first, using no prior discharge. After values for E_p and t_p had been selected, the parameters relating to the discharge (R_L, t_{dis}, t_{del}) were optimized. Next the charging pulse parameters were varied in each direction from the values chosen earlier, using the optimized discharge, to see if the test was improved, i.e., the charge parameters were re-optimized using the selected discharge parameters.

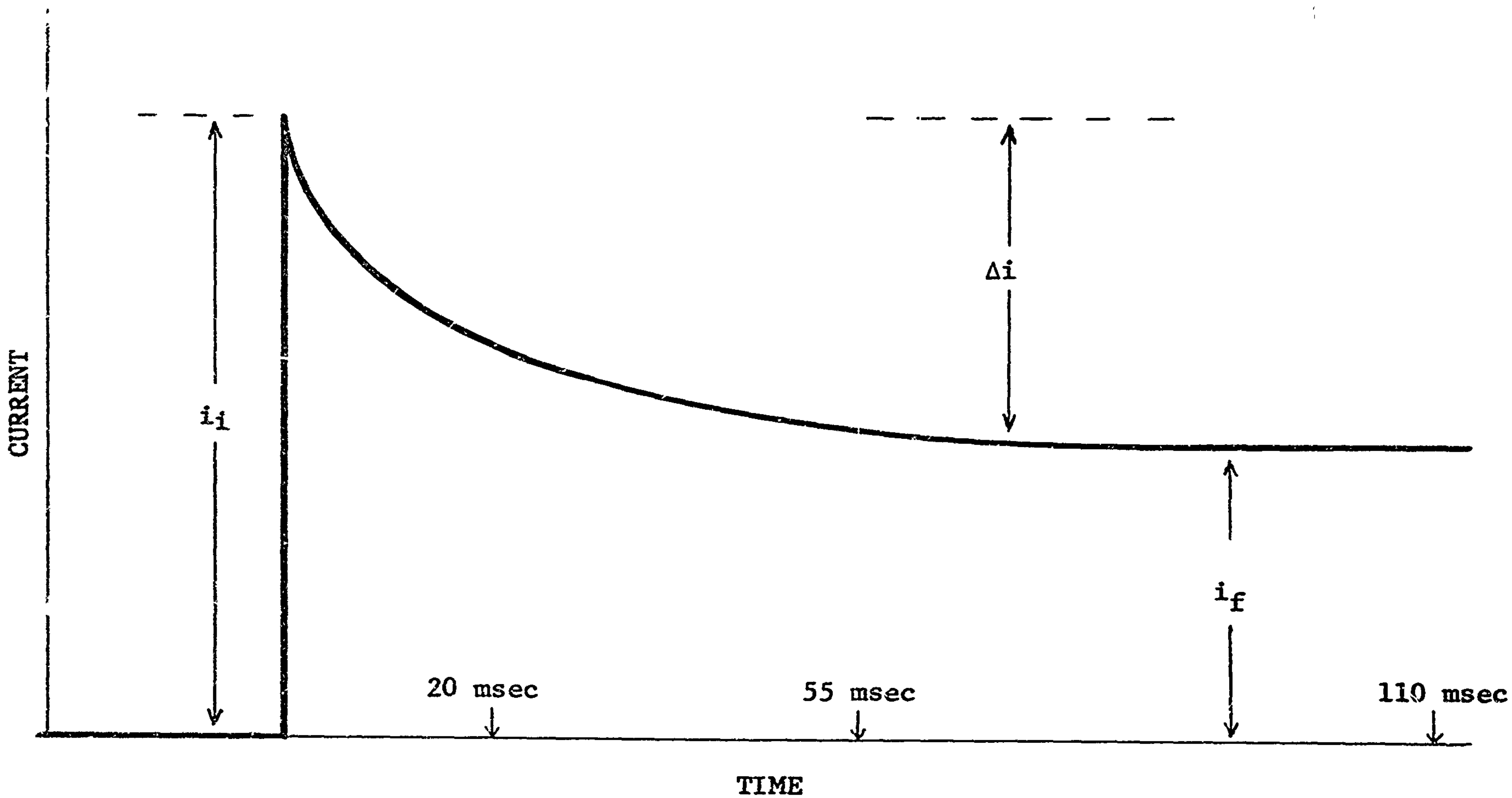
After it was decided to add a second charging pulse, the parameter Δt was optimized without varying the previously chosen test parameters. The variable of primary interest during this particular optimization was i_1-i_2.

The optimization was begun by determining the optimum test parameters for one type of cell at 70°F using the approach outlined above. After the optimum values for the test parameters had been found for this type cell, these values were used as starting points for the optimization of this type cell at 32°F and the other two type cells at 70°F and 32°F. Specifically, the test parameters were varied one at a time in each direction from the selected values to determine if the test results were improved for the cell and temperature involved.

The optimized parameters obtained with the single cells were used as starting points for the optimization of the ten-cell battery test parameters in that an attempt was made to make each of the ten cells see the environment it would see if it were being tested alone. Since the ten cells were in series, R_L was multiplied by ten, t_{dis} was unchanged, t_{del} was unchanged, E_p was multiplied by ten, t_p was unchanged, and Δt was unchanged. The parameters were then varied one at a time in each direction from the starting values to see if the test results were improved.

The optimization was begun using the series of RM828 cells. The combination of E_p and t_p was optimized first. Three E_p values were examined, 1.40, 1.50, and 1.60 volts. Three t_p values also were examined, 20 msec, 55 msec, and 110 msec. It was found when examining the pulse time (t_p) that the current-time trace eventually reaches a steady state for any E_p value. This is illustrated in Figure 10. Once the current-time trace stabilizes, no additional information can be gained by continuing the charging pulse. Also, as discussed earlier, it is desirable to minimize the area under the current-time curve. With these considerations, the optimum value for t_p was found to be 55 milliseconds.

As expected, i_i, i_f, and Δi increased with pulse voltage E_p. The rate of change as a function of state-of-



Current-Time Curve
FIGURE 10

charge for these variables was more erratic at 1.4 volts than at 1.5 volts or 1.6 volts, the latter two being much more regular and approximately equal in rate of change. Therefore, in line with the earlier policy of minimizing the charge put into the battery, 1.5 volts was selected as the optimum pulse voltage.

Given an E_p of 1.5 volts and a t_p of 55 milliseconds, initial discharge parameters of $R_L = 20\Omega$, $t_{dis} = 1$ sec, and $t_{del} = 6$ sec were chosen. As R_L was decreased, the results of the test improved, likewise, as t_{dis} was increased the test improved, and as t_{del} decreased, the test improved. The restrictions discussed earlier on the quantity of charge which could be removed from the cell limited the decrease in R_L to a final value of 1Ω and the increase in t_{dis} to a final value of 16 seconds. The minimum t_{del} which could be achieved with the test circuit was 0.20 seconds. Thus considerations other than obtaining the maximum response in the variables of interest fixed the optimum discharge parameters at $R_L = 1\Omega$, $t_{dis} = 16$ seconds, and $t_{del} = 0.2$ seconds. It is noteworthy that the response obtained in the variables of interest using the test parameters given above, while possibly not the very optimum, was certainly sufficient for the purposes of this feasibility study.

The optimized test parameters given above were used as starting points for the RM828 cell at 32°F. Again the 1.50 volt pulse (E_p) and 55 millisecond duration (t_p) were found to be best. Because of the same limitations on discharge and circuitry discussed above, $R_L = 1\Omega$, $t_{dis} = 16$ seconds, and $t_{del} = 0.2$ seconds were again selected as the optimum discharge parameters.

These same test parameters were used as starting points for the RM3WA and RM1NCMC cells at both 70°F and 32°F. In every case, a 1.5 volt E_p and a 55 millisecond t_p were selected. The same considerations discussed above led to optimum values of $R_L = 1\Omega$, $t_{dis} = 16$ sec, and $t_{del} = 0.2$ sec being chosen.

After it was decided to add a second charging pulse, another parameter (Δt) had to be optimized. It became quickly apparent with all three types of cells that minimizing Δt yielded the greatest variation in $i_1 - i_2$ as a function of state-of-charge. Because of limitations in the circuitry, the minimum Δt which could be obtained was 105 milliseconds. This value was used for all cells.

In developing the optimum test parameters for ten cell batteries, an attempt was made to make each cell of the battery "see" the same test environment as if it were being tested as a single cell. Accordingly, initial test parameters of $R_L = 1\Omega$, $t_{dis} = 16$ sec, $t_{del} = 0.2$ sec, $E_p = 15$ volts, $t_p = 55$ msec, and $\Delta t = 105$ msec were chosen. It can be seen that all time intervals are the same as for single cells, while R_L and E_p have both been increased by a factor of ten to accommodate the ten cell batteries. The current-time trace was stabilized for both batteries after 55 msec, so this time was chosen for t_p. To minimize charging of the cells, an E_p of 15.0 volts was chosen. R_L, t_{dis}, t_{del}, and Δt each could only be varied in one direction because of the limitations discussed earlier. In each case, such a variation did not improve the test results for the two types of batteries tested (RM3WA and RM1NCMC).

B. RM828 Single Cell Results

1. Standard Curves

Considerable problems were encountered in obtaining high quality cells for use as standards. Of the first batch of fifty new cells, only six cells exhibited the proper open circuit voltage, while twelve cells had an open circuit voltage below 1.2 volts. None of this batch of cells was used. The next batch of cells received all exhibited the proper open circuit voltage, however, the lack of uniformity in the capacity of these cells was disappointing. Six of these cells exhibited discharge times ranging from 740 minutes to 795 minutes when discharged at 55 milliamps to an end point voltage of 1.00 volts, a variation of approximately 7%.

Table I shows the discharge data for the first three series of cells prepared for the construction of standard curves. Table II shows the 70°F test data for these cells. It can be seen that only Δi, i_1-i_2, and E_d are listed in this test data. i_i and i_f were found to vary in an irregular manner with state-of-charge for all the types of cells, rendering them useless for prediction of state-of-charge. i_1-i_2 was found to vary in a fairly regular manner for new cells, however, the slope of i_1-i_2 versus state-of-charge was so low that this curve was of limited usefulness in predicting state-of-charge. E_d varied in a regular manner with state-of-charge for new cells which had been recently discharged. As will be seen, however, old cells which had "run down" over a long period of time exhibited wide variations in E_d.

The data in Tables I and II were used to construct an uncorrected standard curve as outlined in section II.E.1.

TABLE I

RM828 Discharge Data - Standard Cells

Discharge Data - 1st Series of Cells

(55MA Constant Current Discharge, 1.00 End-Point Voltage)

Cell No.	0	1	2	3	4	5	6	7	8
Disch. Time	0	60	120	180	240	300	420	600	762
End Voltage	1.42	1.29	1.19	1.18	1.16	1.15	1.10	1.05	1.00

Discharge Data - 2nd Series of Cells

Cell No.	0	1	2	3	4	5	6	7	8
Disch. Time	0	60	120	180	240	300	420	600	740
End Voltage	1.41	1.30	1.20	1.18	1.17	1.15	1.12	1.06	1.00

Discharge Data - 3rd Series of Cells

Cell No.	0	1	2	3	4	5	6	7	8
Disch. Time	0	60	120	180	240	300	420	600	742
End Voltage	1.41	1.30	1.20	1.19	1.15	1.16	1.13	1.11	1.00

(Note: All times in minutes)

TABLE II

RM828 - 70° Test Data - Standard Cells

Test Data - 1st Series

Cell No.	0	1	2	3	4	5	6	7	8
Δi (amps)	.075	.062	.10	.13	.13	.14	.16	.20	.24
Disch. Voltage	.74	.63	.60	.60	.57	.55	.56	.55	.45
$i_1 - i_2$ (amps)	.019	.019	.036	.046	.045	.050	.055	.057	.055

Test Data - 2nd Series

Cell No.	0	1	2	3	4	5	6	7	8
Δi (amps)	.066	.058	.075	.12	.13	.12	.16	.18	.27
Disch. Voltage	.73	.61	.60	.58	.58	.56	.55	.55	.40
$i_1 - i_3$ (amps)	.026	.023	.027	.035	.035	.040	.056	.053	.050

Test Data - 3rd Series

Cell No.	0	1	2	3	4	5	6	7	8
Δi (amps)	.060	.058	.072	.110	.105	.119	.18	.18	.22
Disch. Voltage	.73	.62	.60	.59	.58	.57	.52	.45	.49
$i_1 - i_2$ (amps)	.031	.025	.026	.032	.042	.048	.053	.055	.050

This curve, shown in Figure 11, was not used for the evaluation of unknown cells, but does illustrate the variation of Δi, E_d, and i_1-i_2 with state-of-charge. Table III shows the test data for the three series of standard cells at 32°F. This data was used to construct the uncorrected standard curve given in Figure 12. These uncorrected curves were not used for the evaluation of unknown cells.

To permit construction of corrected standard curves, the cells described in Table I were all discharged to obtain their actual state-of-charge at the time the test data was collected from them, as discussed in Section II.E.1. The results of this discharge are given in Table IV. The cells with a total discharge time below 700 minutes were thrown out (total time underlined). Because so many cells were thrown out, a new series of cells was discharged to replace numbers 2 through 7 in series one and 5 through 7 in series two. The discharge data and test data for this new series is given in Table V. The actual discharge time in Tables IV and V plus the test data in Tables II and V were used to construct a corrected standard curve for RM828 cells at 70°F. This curve is shown in Figure 13. It can be seen that for each of the three parameters of interest (Δi, E_d and i_1-i_2) the spread of the data is given by dashed lines while the average behavior is noted by a solid line. Only the Δi solid line was used for the evaluation of unknown cells since the slope of the i_1-i_2 line is so low. It can be seen that the Δi curve exhibits a good variation with state-of-charge through the range of greatest interest, namely, 0 to 30% discharge. Any cell which is known to be more than 20% discharged will in all probability be judged unfit for use in survival gear.

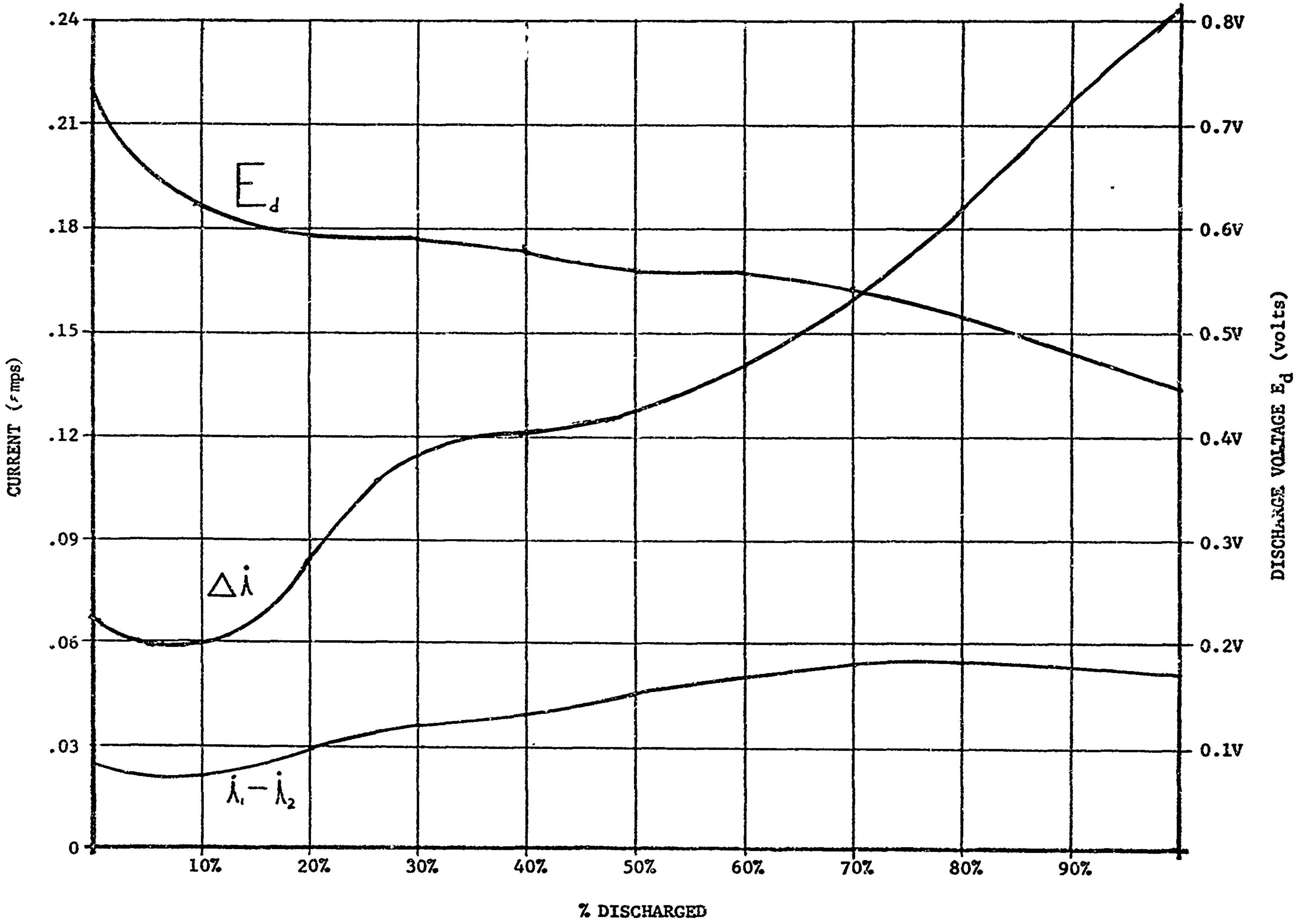


FIGURE 11
Uncorrected Standard Curve for RM828 - 70°F

TABLE III

RM828 - 32° Test Data - Standard Cells

Test Data - 1st Series of Cells

Cell No.	0	1	2	3	4	5	6	7	8
Δi (amps)	.058	.049	.081	.094	.10	.12	.13	.16	.22
Disch. Voltage	.64	.50	.48	.49	.47	.47	.45	.44	.43
i_1-i_2 (amps)	.015	.015	.016	.015	.016	.018	.019	.021	.023

Test Data - 2nd Series of Cells

Cell No.	0	1	2	3	4	5	6	7	8
Δi (amps)	.064	.047	.090	.10	.12	.10	.13	.17	.19
Disch. Voltage	.61	.53	.48	.48	.45	.47	.46	.43	.40
i_1-i_2 (amps)	.015	.015	.016	.015	.020	.019	.019	.015	.023

Test Data -3rd Series of Cells

Cell No.	0	1	2	3	4	5	6	7	8
Δi (amps)	.061	.048	.070	.11	.10	.11	.15	.17	.24
Disch. Voltage	.63	.52	.48	.48	.46	.47	.46	.42	.38
i_1-i_2 (amps)	.015	.016	.015	.014	.016	.018	.015	.018	.020

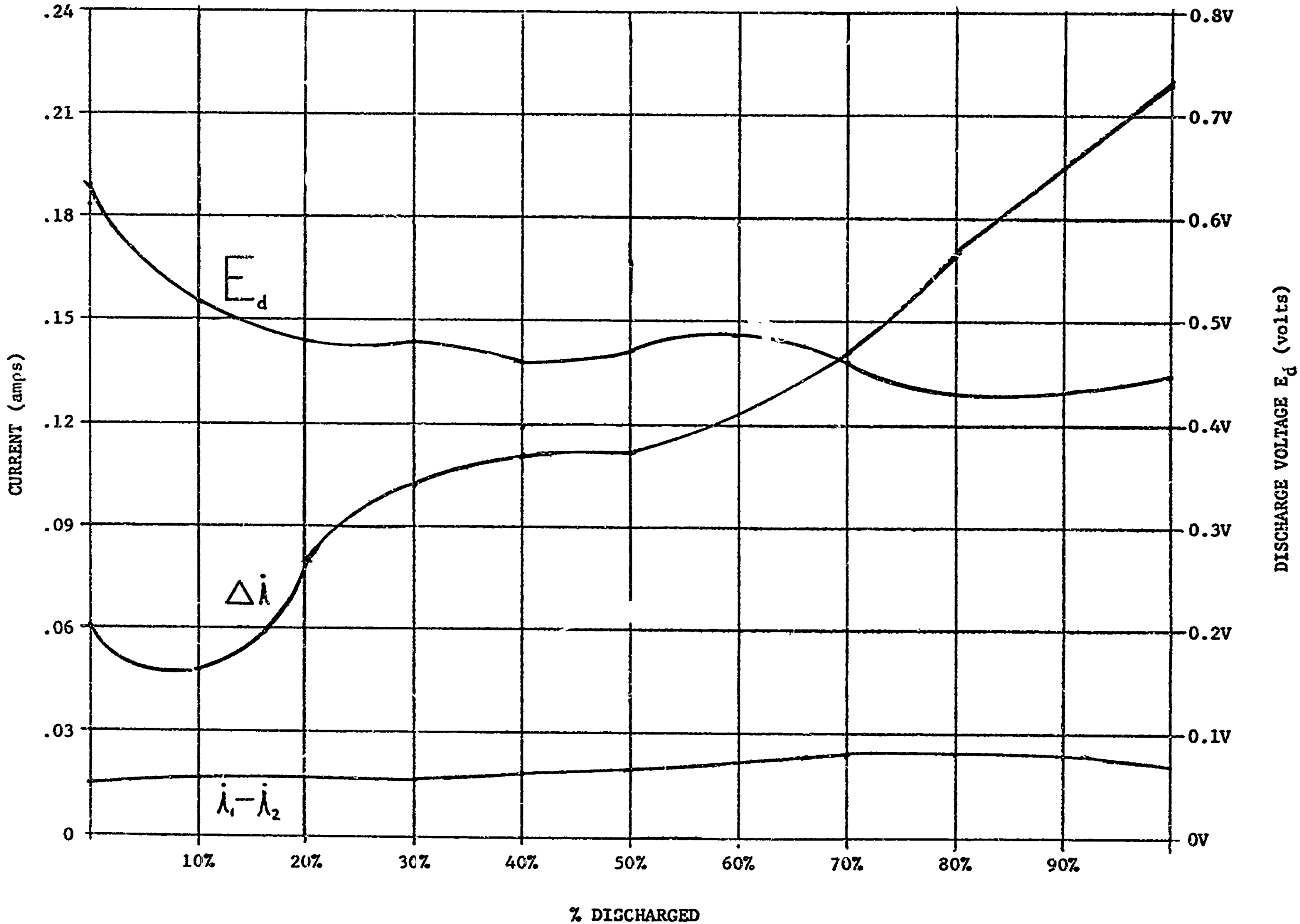


FIGURE 12

Uncorrected Standard Curve for RM828 - 32°F

The spread of the data is considerably greater than desirable, but is not surprising considering the lack of uniformity in the new cells. The Δi curve is double valued in the 0 to 8% discharge region, rendering Δi values in that region uncertain by as much as 8%. Because E_d exhibits its greatest variation in that same region, it was originally hoped that the E_d value could be used to accurately place the Δi values in that region. As will be seen, however, E_d values from old cells do not permit such accurate placement.

The actual discharge times in Tables IV and V plus the test data in Tables III and V were used to construct a corrected standard curve for RM828 cells at 32°F. The curve is shown in Figure 14. Again, the Δi curve is double valued from 0 to 8% discharge. Also, the slope of the $i_1 - i_2$ curve is too low to permit prediction of state-of-charge using this curve.

2. Test of Unknown Cells

a) Temperature of 70°F

The old RM828 cells which were tested were obtained by dismantling PRC-90 batteries. The age and environmental history of these batteries is unknown. Not more than four cells were taken from any one battery.

The cells were tested as outlined in section II-A, and subsequently discharged to determine their actual state-of-charge at the time of the test as discussed in section II-d. The Δi value obtained from the test was matched to the Δi solid line on the corrected standard curve in Figure 13 to obtain a predicted state-of-charge.

TABLE V

RM828 Discharge and Test Data - Standard Cells

Discharge Data

Cell No.	2	3	4	5	6	7	5'	6'	7'
Initial Disch. Time	120	180	240	300	420	600	300	420	600
Actual Disch. Time	700	645	560	476	381	199	440	310	190
Total Disch. Time	820	825	800	776	801	799	740	730	790

Test Data - 70°F

Cell No.	2	3	4	5	6	7	5'	6'	7'
Δi (amps)	.10	.13	.17	.22	.24	.23	.26	.28	.24
E_d (volts)	.60	.60	.56	.50	.48	.49	.48	.47	.47
i_1-i_2 (amps)	.025	.030	.034	.046	.048	.040	.505	.050	.052

Test Data - 32°F

Cell No.	2	3	4	5	6	7	5'	6'	7'
Δi (amps)	.080	.12	.15	.20	.22	.23	.20	.24	.20
E_d (volts)	.48	.47	.46	.42	.38	.34	.44	.42	.40
i_1-i_2 (amps)	.025	.030	.040	.045	.040	.045	.035	.045	.040

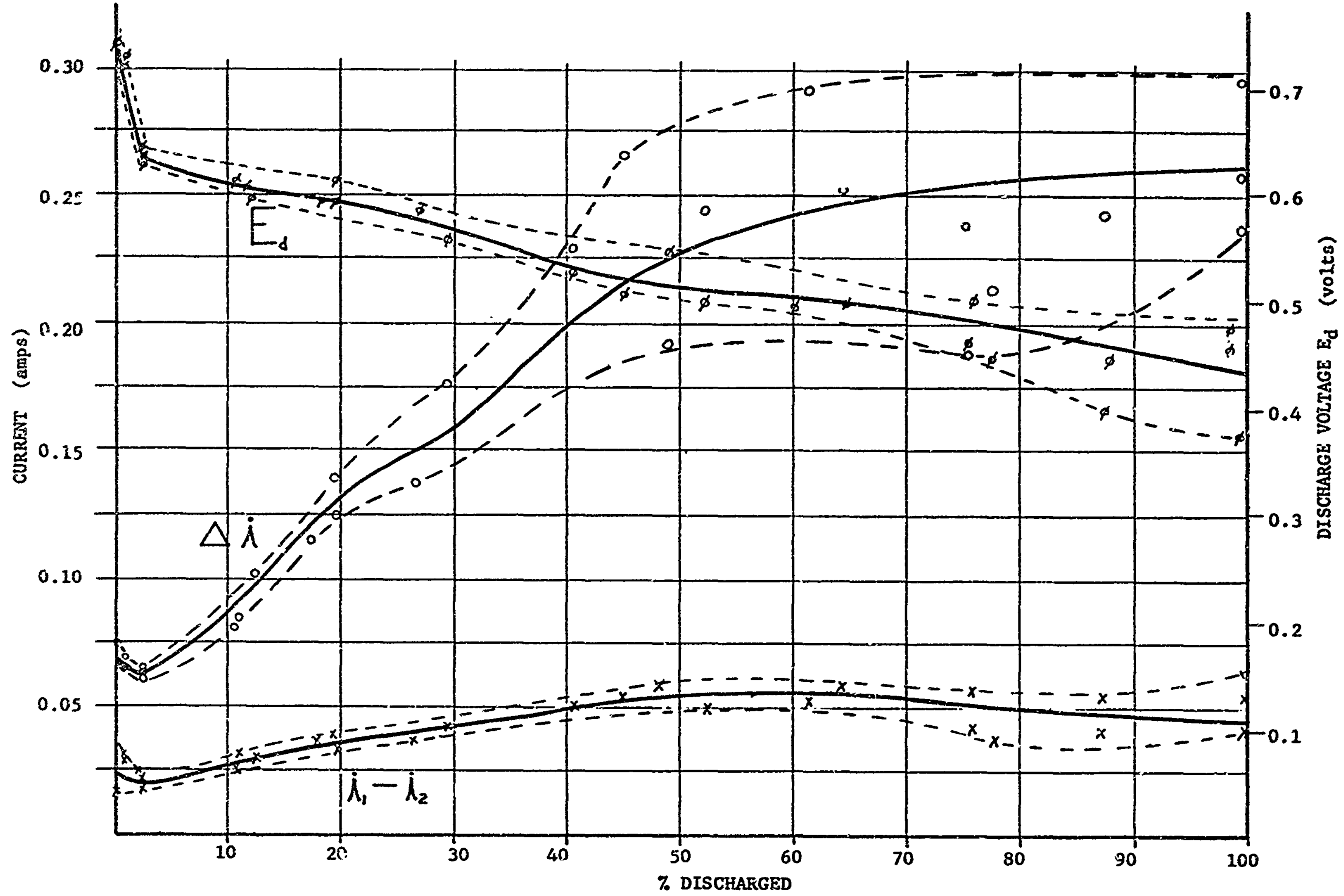


FIGURE 13

Corrected Standard Curve for RM828 - 70°F

The spread of the data is considerably greater than desirable, but is not surprising considering the lack of uniformity in the new cells. The Δi curve is double valued in the 0 to 8% discharge region, rendering Δi values in that region uncertain by as much as 8%. Because E_d exhibits its greatest variation in that same region, it was originally hoped that the E_d value could be used to accurately place the Δi values in that region. As will be seen, however, E_d values from old cells do not permit such accurate placement.

The actual discharge times in Tables IV and V plus the test data in Tables III and V were used to construct a corrected standard curve for RM828 cells at 32°F. The curve is shown in Figure 14. Again, the Δi curve is double valued from 0 to 8% discharge. Also, the slope of the i_1-i_2 curve is too low to permit prediction of state-of-charge using this curve.

2. Test of Unknown Cells

a) Temperature of 70°F

The old RM828 cells which were tested were obtained by dismantling PRC-90 batteries. The age and environmental history of these batteries is unknown. Not more than four cells were taken from any one battery.

The cells were tested as outlined in section II-A, and subsequently discharged to determine their actual state-of-charge at the time of the test as discussed in section II-d. The Δi value obtained from the test was matched to the Δi solid line on the corrected standard curve in Figure 13 to obtain a predicted state-of-charge.

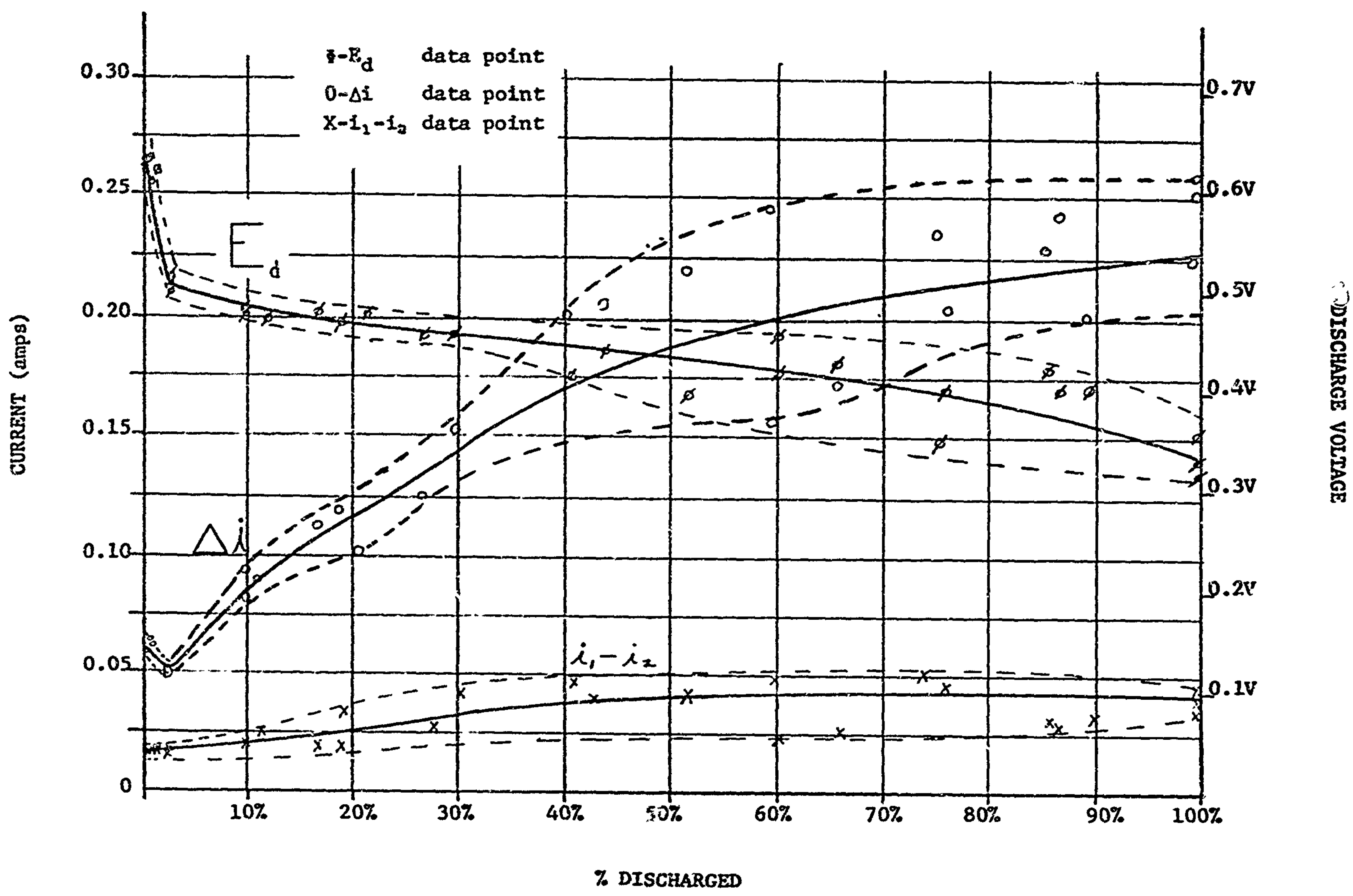


FIGURE 14

Corrected Standard Curve for RM828 - 32°F

Thirty-nine cells were tested, however, no actual state-of-charge was obtained for two of these, leaving a total of thirty-seven test results. The test data and test results for these cells are shown in Table VI.

An examination of Table VI reveals that neither E_d or i_1-i_2 is a reliable indicator of state-of-charge. However, it appears that E_d may prove useful as a "screening value". The three cells in which the predicted state-of-charge is in greatest error (24, 25, 29) all have low E_d values. If one adopts a policy of automatically rejecting any cell with an E_d value below, e.g., 0.585 volts, no matter what its Δi value, then the results are improved. Rejecting all cells with an E_d value below 0.585 volts would eliminate cell numbers 24, 25, 29, 37, and 39. Among these, only number 37 is an acceptable cell. It is noteworthy that old cells often seem to somehow lose capacity without losing the ability to exhibit a good discharge voltage during a brief discharge, e.g., numbers 5 and 6. Thus it is not unreasonable to reject a cell which cannot even exhibit a good discharge voltage.

The results of an error analysis for the test data both with and without use of a screening value is given in Table VII. The low mean error is misleading since errors in the positive and negative directions are cancelling each other. The standard deviation more clearly illustrates the accuracy of the test. It can be seen that use of a screening value reduces the standard deviation from 11.4 to 6.6% (at the expense of rejecting one good cell).

The two-sided tolerance limits are calculated by the method of Natrella.[a] It is noteworthy that a much greater number of samples is needed to obtain a really accurate representation of the tolerance limits.

TABLE VI

Test Results for RM828 Unknown Cells at 70°F

Cell No.	E_d(volts)	Δi(amps)	$i_1 - i_2$(amps)	Actual Discharge time(min)	State-of-charge (as % discharged) Predicted	Actual	Error
1	.637	.100	.034	658	14	17	-3
2	.620	.128	.032	650	19	18	+1
3	.636	.100	.029	754	14	5	+9
4	.654	.135	.046	719	21	10	+11
5	.641	.128	.038	521	19	34	-15
6	.642	.121	.038	598	18	24	-6
7	.648	.096	.032	753	12	5	+7
8	.634	.117	.034	638	17	20	-3
9	.678	.130	.023	---	20	--	--
10	.659	.075	.023	774	7	3	+4
11	.645	.069	.019	778	5	2	+3
12	.630	.117	.036	671	17	16	+1
13	.636	.130	.040	614	20	22	-2
14	.617	.117	.036	616	17	22	-5
15	.614	.088	.023	655	10	17	-7
16	.650	.092	.029	785	11	1	+10
17	.667	.096	.032	761	12	4	+8
18	.675	.102	.036	718	14	10	+4
19	.658	.088	.034	700	10	12	-2
20	.657	.100	.036	664	14	16	-2
21	.640	.088	.027	719	10	10	0
22	.624	.092	.027	721	11	9	+2
23	.657	.092	.034	---	11	--	--
24	.547	.138	.021	400	22	48	-25
25	.485	.155	.025	362	28	54	-26
26	.637	.054	.021	820	3	0	-3
27	.640	.054	.021	770	3	3	0
28	.623	.071	.029	686	6	13	-7
29	.579	.050	.021	425	3	46	-43
30	.593	.075	.021	708	9	11	-2
31	.602	.092	.029	718	11	10	+1
32	.603	.105	.029	762	15	4	+11
33	.640	.105	.034	772	15	3	+12
34	.612	.117	.032	771	17	3	+14
35	.638	.105	.032	692	15	13	+2
36	.635	.088	.029	793	10	0	+10
37	.584	.109	.034	706	15	11	+4
38	.632	.071	.021	808	6	0	+6
39	.034	.441	.044	1	100	100	0

mean - 0.865

standard deviation - 11.42

TABLE VII

Error Analysis for RM828 at 70°F

Without Screening Value		With Screening Value	
Mean	-0.86	Mean	+1.8
Standard Deviation	11.4	Standard Deviation	6.6

Tolerance Limits

Gamma is percent confidence that P percent of the test values lie within the maximum error limits L_1 and L_2.

		Without screening value		With screening value	
gamma	P	L_1	L_2	L_1	L_2
75	75	-15.5	+13.7	-6.8	+10.5
75	95	-25.8	+24.0	-12.9	+16.6
95	75	-17.5	+15.8	-8.1	+11.8
95	95	-29.2	+27.5	-15.1	+18.8

It also should be noted that whenever the test predicted a cell to be less than 18% discharged, and when a screening value was used, that cell was never more than 22% discharged (26 cells). Only one cell was below 18% discharge and was predicted to be greater than 18%.

b) Temperature of 32°F

The Δi solid line in the corrected standard curve in Figure 14 was used to predict state-of-charge. Twenty-three cells were tested at 32°F. The test data and test results are given in Table VIII.

Again, use of E_d as a screening value can improve the test results. Rejecting any cell with an E_d value below 0.520 volts eliminates numbers 4, 5, 6, 7, 12, 13, 17, 21, and 23. Only numbers 13 and 21 are acceptable cells.

The results of the error analysis both with and without use of a screening value is given in Table IX. Again, use of a screening value considerably improves the test results, this time at the expense of rejecting two good cells. It can be seen that the accuracy of the test is remarkably similar at 70°F and 32°F.

It is important to note that for the 13 cells that the test predicted to be less than 18% discharged utilizing a screening value, no cell was more than 14% discharged. One other cell was actually less than 18% discharged, but was predicted to be greater than 18% discharged.

TABLE VIII

Test Results for RM828 Unknown Cells at 32°F

Cell No.	E_d(volts)	Δi(amps)	$i_1 - i_2$(amps)	Actual Discharge Time	State-of-charge (as% discharged) Predicted	Actual	Error
1	.545	.075	.023	835	8	0	+8
2	.526	.075	.025	719	8	10	-2
3	.524	.075	.023	721	8	10	-2
4	.451	.210	.012	410	>50	48	✓
5	.384	.147	.021	362	31	54	-23
6	.420	.235	.029	132	>50	83	✓
7	.332	.222	.012	117	>50	85	✓
8	.553	.033	.021	706	3	11	-8
9	.549	.063	.019	820	7	0	+7
10	.574	.071	.021	770	8	3	+5
11	.560	.071	.023	686	8	14	-6
12	.509	.058	.019	425	6	46	-40
13	.497	.054	.019	708	3	11	-8
14	.545	.067	.023	718	7	10	-3
15	.542	.088	.025	762	11	4	+7
16	.557	.096	.023	772	12	3	+9
17	.426	.290	.010	300	>50	62	--
18	.592	.113	.031	771	19	3	+16
19	.558	.088	.023	692	11	13	-2
20	.567	.075	.025	793	8	1	+7
21	.502	.088	.023	706	11	11	0
22	.544	.067	.019	808	5	0	+5
23	.035	.441	.021	1	100	100	✓
						mean -	-1.3

TABLE IX

Error Analysis for RM828 at 32°F

Without Screening Value		With Screening Value	
mean	-1.3	mean	+2.9
standard deviation	11.4	standard deviation	6.7

Tolerance Limits

Gamma is percent confidence that P percent of the test values lie within the maximum error limits L_1 and L_2.

		without screening value		with screening value	
Gamma	P	L_1	L_2	L_1	L_2
75	75	-16.4	+13.8	-6.6	+12.5
75	95	-27.1	+24.3	-13.3	+19.2
95	75	-19.2	+16.6	-9.1	+14.9
95	95	-31.8	+29.2	-17.5	+23.3

It is noteworthy that in terms of the personnel in the field who actually use a state-of-charge tester, no "harm" results from relying on a predicted state-of-charge that is less than the actual state-of-charge (+ error). It is the (-) errors which are of real concern. In terms of economics, the larger the average (+) error, the greater the rejection rate of cells that are actually acceptable. However, most of these will have already been close to the acceptable-unacceptable border line. Finally it can be seen that by "shifting" the standard curve on the % discharge axis, the relative proportions of (+) and (-) errors can be changed.

C. RM1NCMC Single Cell Results

1. Standard Curves

Problems in obtaining high quality cells for use as standards were also encountered with the RM1NCMC cells. The first batch of new cells received all exhibited the expected open circuit voltage. Three series of standard cells were prepared using these cells. The discharge data for these cells is given in Table X. It can be seen that the three cells which were completely discharged lasted 375, 300 and 352 minutes. The test data for these cells at 70°F is given in Table XI. An uncorrected standard curve was prepared using the data in Tables X and XI, and is shown in Figure 15.

A separate set of standards was prepared for collection of the 32°F data. The discharge data for these cells are given in Table XII. Note the discharge times of 395, 363, and 373. The test data at 32°F are given in Table XIII. An uncorrected standard curve was prepared using the data in Tables XII and XIII, and is shown in Figure 16.

TABLE X

RM1NCMC Discharge Data - Standard Cells

Discharge Data - 1st Series of Cells

Each cell number represents a separate cell.
60 MA Constant Current Discharge, 1.08 Cut-Off Voltage

Cell No.	0	1	2	3	4	5	6
Disch. Time (min.)	0	60	120	180	240	300	375
End Point Voltage	1.35	1.20	1.15	1.15	---	1.12	1.08

Discharge Data - 2nd Series of Cells

Cell No.	0	1	2	3	4	5
Disch. Time (min.)	0	60	120	180	240	300
End Point Voltage	1.35	1.20	1.16	1.15	1.14	1.08

Discharge Data - 3rd Series of Cells

Cell No.	0	1	2	3	4	5	6
Disch. Time (min.)	0	60	120	180	240	300	352
End Point Voltage	1.35	1.21	1.16	1.14	1.14	1.11	1.08

TABLE XI

RM1NCMC - 70° Test Data - Standard Cells

Test Data - 1st Series

Cell No.	0	1	2	3	4	5	6
Δi (amps)	.053	.062	.075	.080	.104	.099	.13
Discharge Voltage	.724	.66	.65	.64	.62	.57	.50
$i_1 - i_2$ (amps)	.014	.020	.025	.037	.045	.055	.055

Test Data - 2nd Series

Cell No.	0	1	2	3	4	5
Δi (amps)	.053	.060	.080	.078	.090	thrown out
Discharge Voltage	.725	.66	.64	.61	.60	thrown out
$i_1 - i_2$ (amps)	.012	.017	.032	.037	.044	thrown out

Test Data - 3rd Series

Cell No.	0	1	2	3	4	5	6
Δi (amps)	.055	.064	.076	.085	.095	.095	.11
Discharge Voltage	.726	.67	.63	.60	.61	.50	.51
$i_1 - i_2$ (amps)	.010	.016	.030	.031	.036	.044	.057

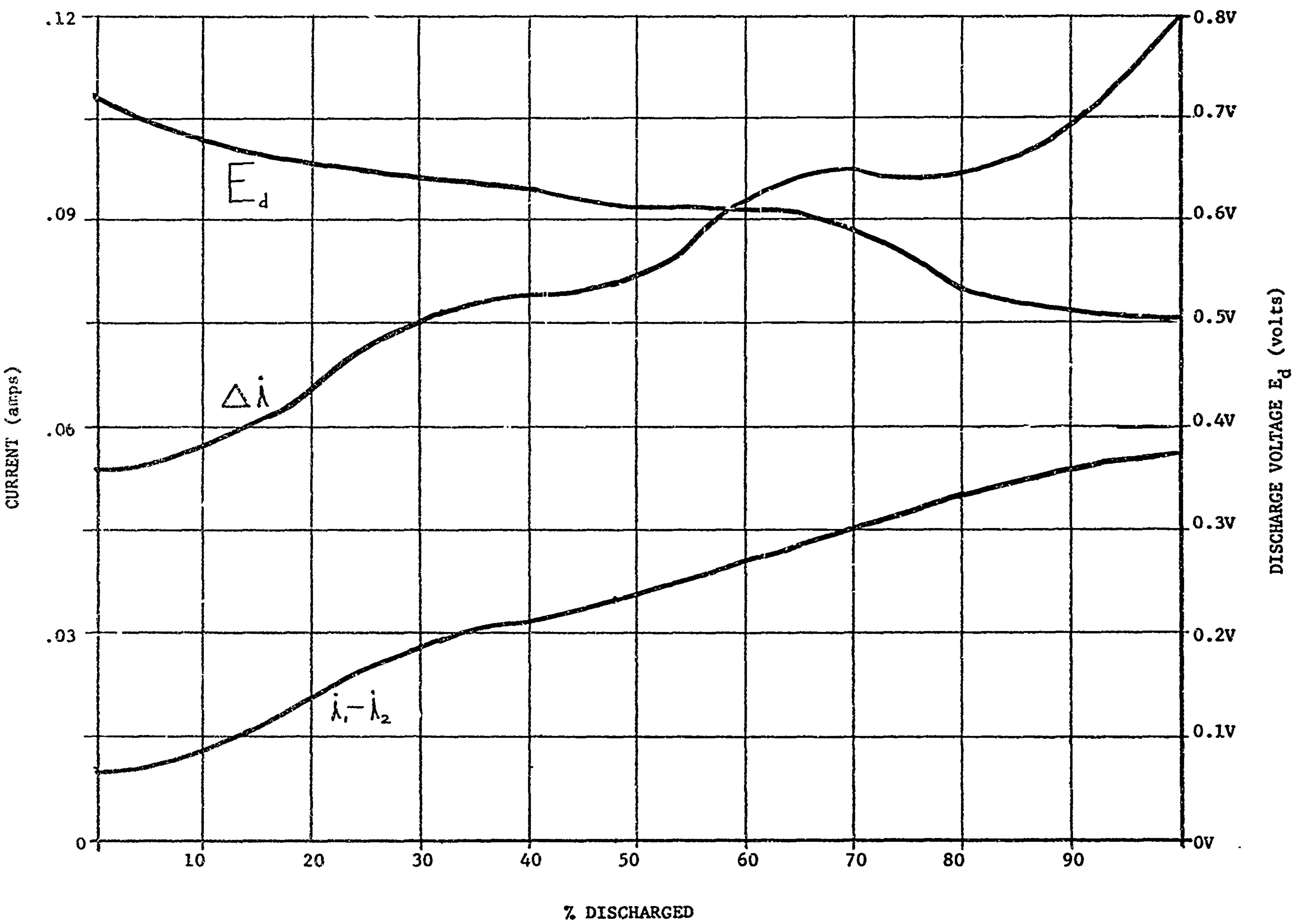


FIGURE 15

Uncorrected Standard Curve for RM1NCMC - 70°F

TABLE XII

RM1NCMC Discharge Data - Standard Cells

Discharge Data - 1st Series of Cells

Cell No.	0	1	2	3	4	5	6	7
Discharge Time	0	60	120	180	240	300	360	395
End Point Voltage	1.35	1.20	1.16	1.15	1.14	1.12	1.10	1.08

Discharge Data - 2nd Series of Cells

Cell No.	0	1	2	3	4	5	6	7
Discharge Time	0	60	120	180	240	300	360	363
End Point Voltage	1.35	1.21	1.15	1.15	1.14	1.12	1.10	1.08

Discharge Data - 3rd Series of Cells

Cell No.	0	1	2	3	4	5	6	7
Discharge Time	0	60	120	180	240	300	360	373
End Point Voltage	1.35	1.21	1.16	1.14	1.14	1.11	1.09	1.08

TABLE XIII

RM1NCMC Test Data - 32°F - Standard Cells

Test Data - 1st Series

Cell No.	0	1	2	3	4	5	6	7
Δi (amps)	.050	.055	.062	.065	.080	.094	.11	.13
Disch. Voltage	.55	.42	.48	.47	.42	.45	.42	.43
$i_1 - i_2$ (amps)	.002	.011	.013	.016	.014	.022	.024	.026

Test Data - 2nd Series

Cell No.	0	1	2	3	4	5	6	7
Δi (amps)	.045	.053	.065	.066	.075	.075	.095	.13
Disch. Voltage	.54	.50	.50	.45	.43	.44	.44	.41
$i_1 - i_2$ (amps)	.007	.009	.012	.016	.018	.020	.020	.025

Test Data - 3rd Series

Cell No.	0	1	2	3	4	5	6	7
Δi (amps)	.044	.051	.060	.070	.070	.083	.090	.12
Disch. Voltage	.52	.44	.46	.49	.35	.43	.42	.38
$i_1 - i_2$ (amps)	.005	.010	.011	.013	.018	.018	.026	.027

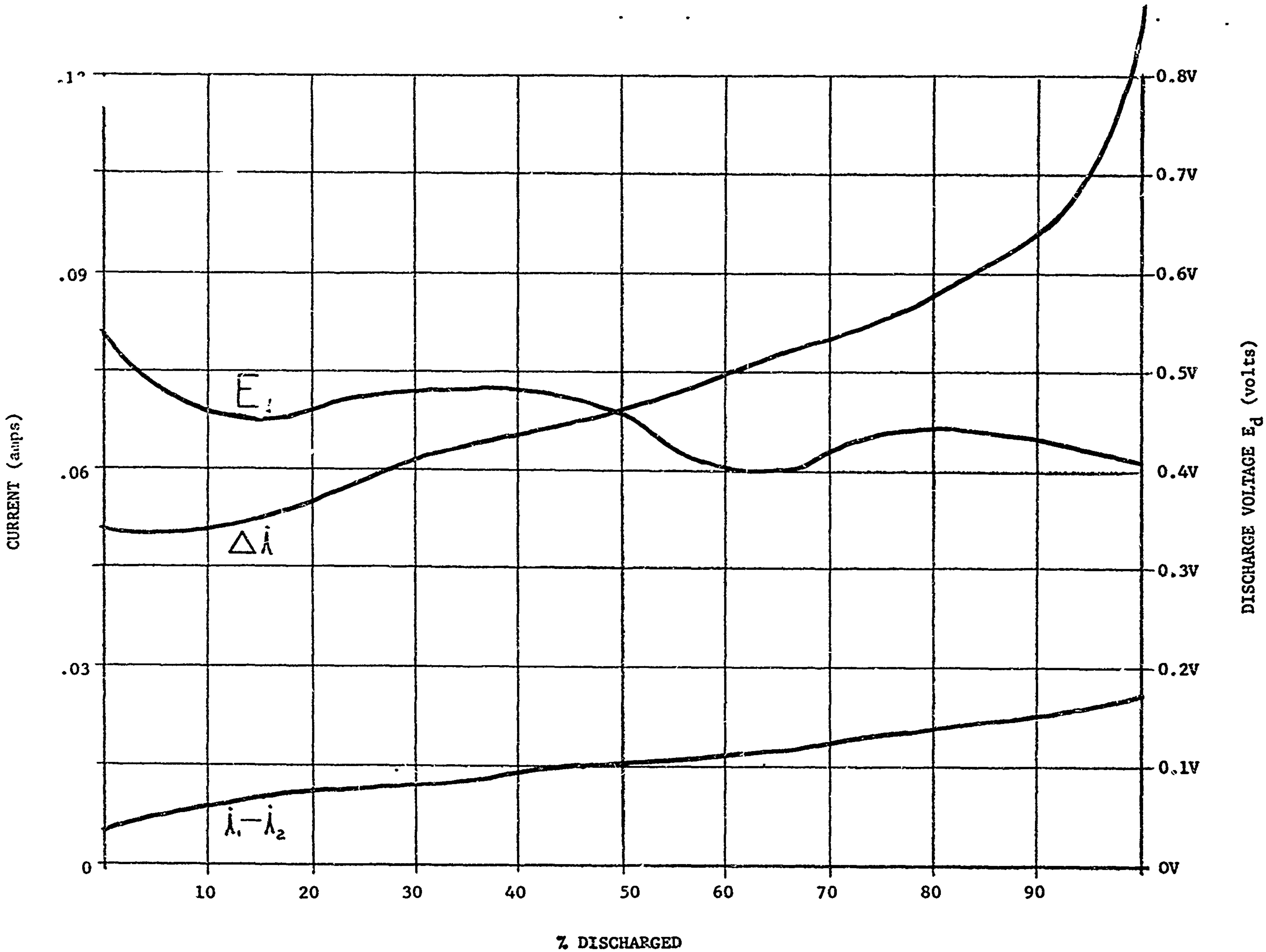


FIGURE 16

Uncorrected Standard Curve for RM1NCMC - 32°F

By this stage of the investigation, several old RT-10 batteries had been obtained from Kelly AFB. It was decided to discharge a few of these to determine how badly degraded they were. The first six old cells lasted 514, 483, 494, 491, 519, and 535 minutes, i.e., longer than the new cells. It was clear that the new cells were substandard, so another batch of new cells was ordered.

Three new series of standard cells were prepared using these cells. The initial, actual, and total discharge data for these cells is given in Table XIV. Cells with a total discharge time below 695 minutes were judged substandard. The range of discharge times for the six cells which were continuously discharged is 790 to 722 minutes. The test data for these cells at 70°F is given in Table XV, and for 32°F in Table XVI.

The data in Tables XII and XIII was used to prepare a corrected standard curve at 70°F. This curve is given in Figure 17. (No uncorrected standard curve was prepared for this latest batch of cells.) An examination of Figure 17 reveals that the Δi curve for RM1NCMC cells is not double valued at any point, however, the spread of the data for the new cells is considerably larger than for the RM828. Considering the extreme spread of discharge times observed with various new cells this is not surprising.

The data in Tables XII and XIV was used to prepare a corrected standard curve at 32°F, which is given in Figure 18. Again, no uncorrected standard curve was prepared.

TABLE XIV

RM1NCMC - Discharge Data - Standard Cells

Series 1

Cell No.	0	1	2	3	4	5	6	7	8	9	10	11	12	14
Initial Discharge Time	0	60	120	180	240	304	360	420	480	500	600	660	730	720
Actual Discharge Time	776	598	611	602	426	397	340	299	243	265	166	90	51	60
Total Discharge Time	776	658	731	782	666	701	700	719	723	765	766	750	781	780

Series 2

Cell No.	0	1	2	3	4	5	6	7	8	9	10	11	12	14
Initial Discharge Time	0	60	120	180	240	300	360	420	480	540	600	660	720	775
Actual Discharge Time	741	590	592	468	468	398	343	55	55	148	161	70	98	54
Total Discharge Time	741	650	712	648	708	698	703	475	535	688	761	740	818	829

Series 3

Cell No.	0	1	2	3	4	5	6	7	8	9	10	11	12	14
Initial Discharge Time	0	60	120	180	240	300	360	420	480	540	600	660	720	722
Actual Discharge Time	790	704	651	585	458	360	354	245	252	233	142	93	63	38
Total Discharge Time	790	764	771	765	698	660	714	665	732	773	742	753	783	760

(Note: 790 minutes = 100% discharge)

TABLE XV

RM1NCMC Standard Cell Test Data - 70°F

Series 1

Cell No.	0	1	2	3	4	5	6	7	8	9	10	11	12	14
Δi (amps)	.059	(.10)	.13	.14	(.16)	.25	.28	.31	.29	.37	.36	.37	.41	.60
E_d (volts)	.79	(.70)	.65	.64	(.60)	.60	.54	.52	.51	.52	.49	.48	.44	.37
i_1-i_2 (amps)	.017	(.021)	.056	.069	(.059)	.079	.092	.084	.084	.10	.096	.12	.12	.13

Series 2

Cell No.	0	1	2	3	4	5	6	7	8	9	10	11	12	14
Δi (amps)	.084	(.11)	.11	(.17)	.15	.24	.28	(.29)	(.31)	(.32)	.34	.40	.41	.43
E_d (volts)	.80	(.66)	.66	(.63)	.64	.54	.55	(.56)	(.54)	(.53)	.51	.49	.49	.45
i_1-i_a (amps)	.012	(.021)	.021	(.044)	.069	.079	.096	(.096)	(.10)	(.090)	.092	.11	.12	.12

Series 3

Cell No.	0	1	2	3	4	5	6	7	8	9	10	11	12	14
Δi (amps)	.042	.080	.080	.096	.20	(.20)	.25	(.29)	.29	.31	.34	.32	.46	.51
E_d (volts)	.75	.75	.70	.65	.61	(.61)	.54	(.51)	.50	.50	.49	.49	.43	.43
i_1-i_2 (amps)	.017	.021	.021	.034	.096	(.088)	.088	(.096)	.092	.10	.10	.10	.13	.12

TABLE XVI

RM1NCMC Standard Cell Test Data - 32°F

Series 1

Cell No.	0	1	2	3	4	5	6	7	8	9	10	11	12	14
Δi(amps)	.050	(.088)	.10	.17	(.19)	.23	.18	---	.28	.37	.37	.38	.44	.60
E_d(volts)	.69	(.60)	.51	.49	(.40)	.43	.39	---	.39	.41	.37	.37	.34	.29
i_1-i_2(amps)	.012	(.19)	.054	.057	(.054)	.063	.075	---	.067	.092	.100	.100	.109	.151

Series 2

Cell No.	0	1	2	3	4	5	6	7	8	9	10	11	12	14
Δi(amps)	.054	(.096)	.088	(.180)	.202	.193	.256	(.302)	(.328)	(.353)	.369	.457	.461	.436
E_d(volts)	.68	(.51)	.55	(.48)	.49	.40	.43	(.42)	(.38)	(.39)	.37	.37	.36	.34
i_1-i_2(amps)	.012	(.189)	.029	(.048)	.073	.058	.086	(.092)	(.096)	(.094)	.096	.109	.111	.126

Series 3

Cell No.	0	1	2	3	4	5	6	7	8	9	10	11	12	14
Δi(amps)	.046	.071	.075	.113	.168	(.231)	.227	(.290)	.319	.294	.394	.378	.483	.550
E_d(volts)	.66	.61	.53	.50	.46	(.40)	.43	(.41)	.36	.37	.34	.35	.34	.30
i_1-i_2(amps)	.012	.021	.029	.050	.071	(.075)	.071	(.075)	.096	.100	.117	.109	.117	.138

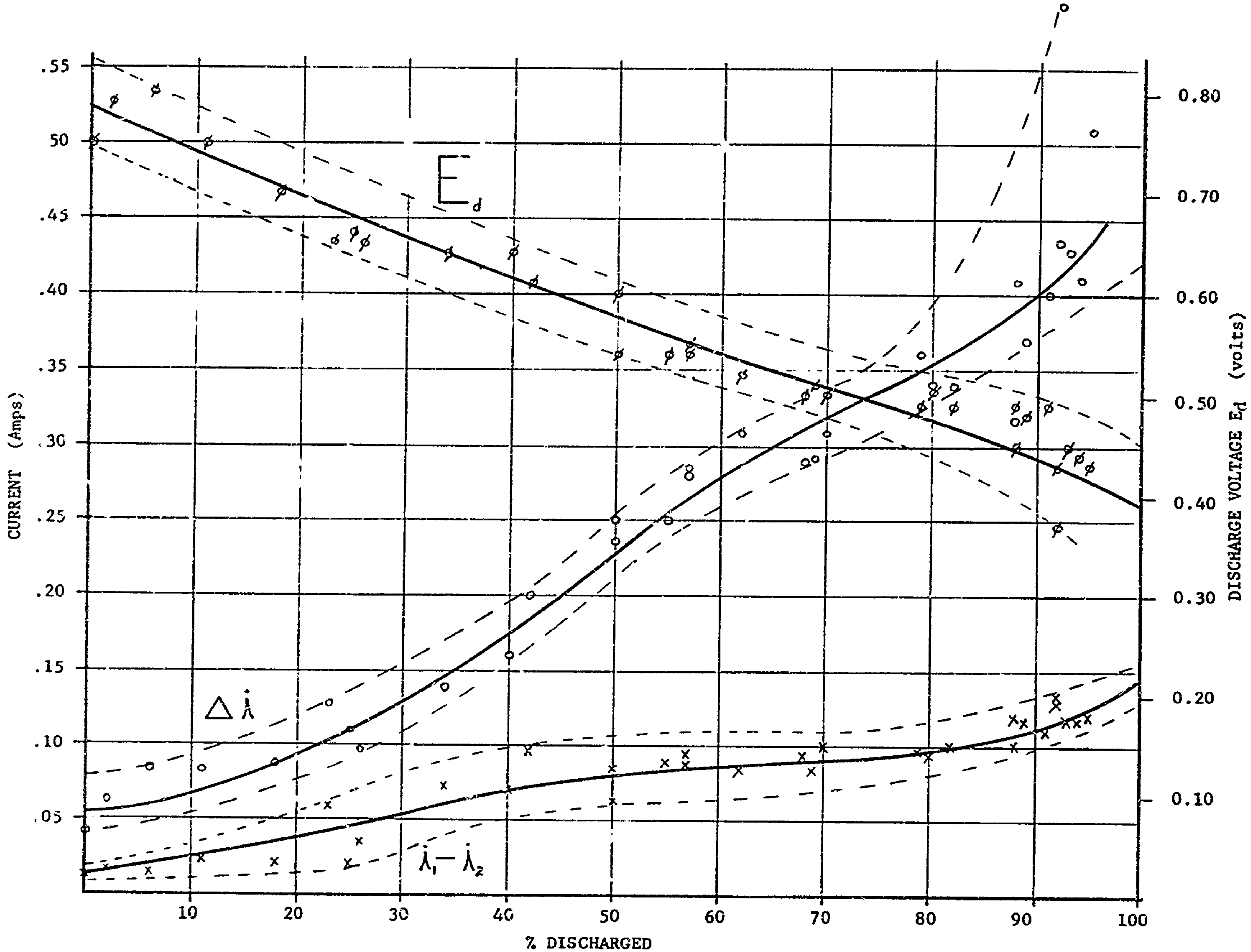


FIGURE 17
Corrected Standard Curve for RM1NCMC - 70°F

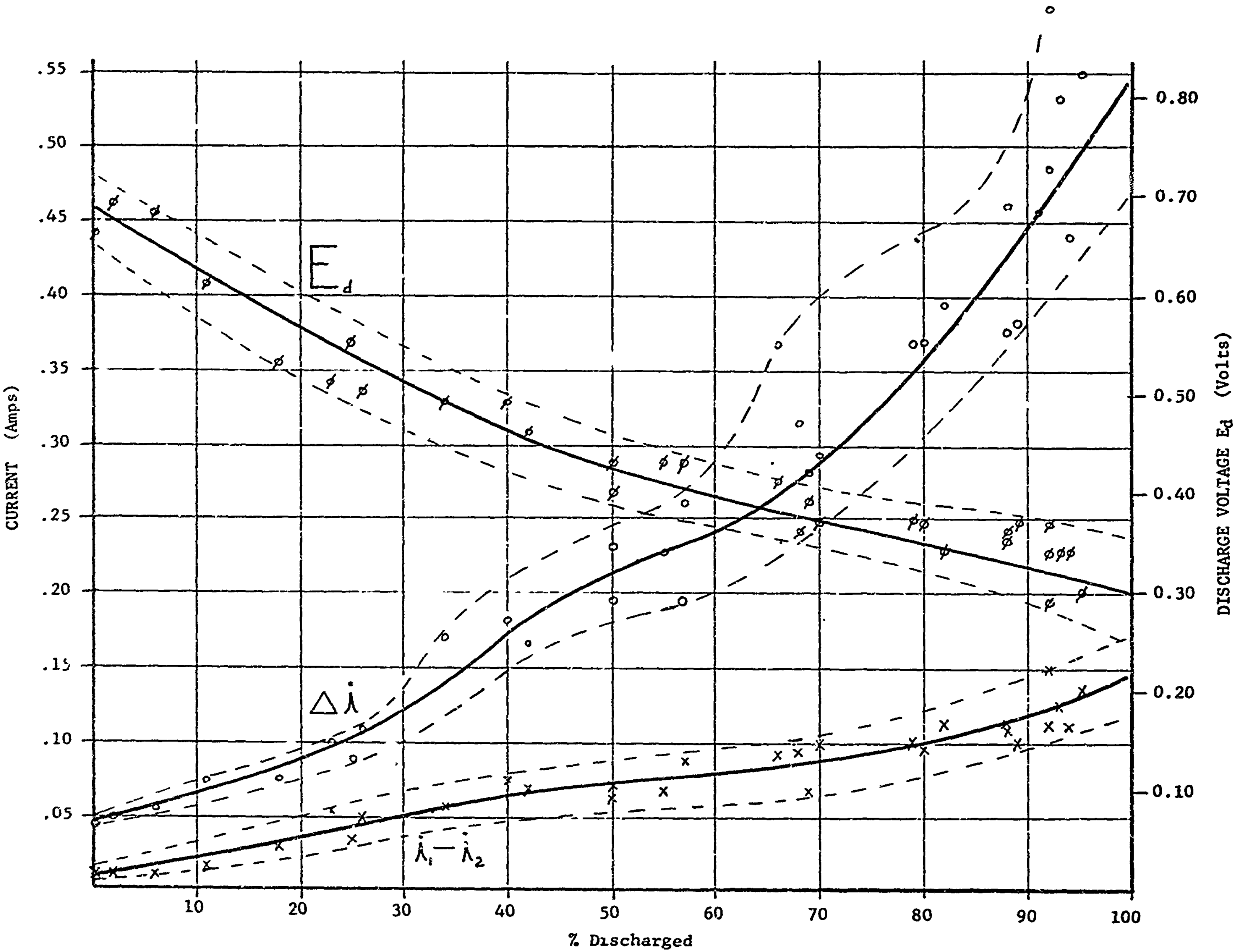

CURRENT (Amps)
.55
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
DISCHARGE VOLTAGE E_d (Volts)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
E_d
Δi
$i_1 - i_2$
10
20
30
40
50
60
70
80
90
100
% Discharged

FIGURE 18

2. <u>Test of Unknown Cells</u>

a) 70°F

The old RM1NCMC cells which were tested were obtained by dismantling RT-10 batteries. These batteries had a month and year painted on them, all being in 1968 or 1969. Possibly this was the date of manufacture. Their environmental history was unknown. The Δi value obtained from the test was matched to the solid Δi line in Figure 17 to obtain a predicted state-of-charge. Thirty-eight cells were tested at 70°F. The test data and test results are shown in Table XVII.

Again, E_d and i_1-i_2 provide a poor indication of state-of-charge. However, E_d is again useful as a screening value to eliminate some of the cells which are not eliminated on the basis of their Δi value. Rejecting all cells with an E_d value below 0.75 volts eliminates cell numbers 11, 14, 16, 24, 27, and 35. None of these are actually good cells.

The results of the error analysis for the test data both with and without a screening value is given in Table XVIII. It can be that the use of a screening value is not as effective with the RM1NCMC as with the RM828. Generally speaking, the unknown RM1NCMC cells were in rather poor condition since only five of thirty-eight cells were less than 20% discharged.

Only one cell was predicted to be less than 18% discharged when a screening value was used. This cell plus three others were actually less than 18% discharged.

TABLE XVII

Test Results for RM1NCMC Unknown Cells at 70°F

Cell No.	E_d(volts)	Δi(amps)	$i_1 - i_2$(amps)	Actual Discharge time(min)	State of Charge (as % discharged) Predicted	Actual	Error
1	0.897	0.117	.021	610	26	23	+3
2	0.879	0.134	.021	375	31	52	-21
3	0.846	0.105	.019	681	23	14	+9
4	0.922	0.147	.025	520	34	34	0
5	0.834	0.113	.017	598	25	24	+1
6	0.909	0.138	.021	570	32	28	+4
7	0.872	0.126	.023	782	28	1	+27
8	0.793	0.126	.013	625	28	21	+7
9	0.788	0.202	.013	442	45	44	+1
10	0.788	0.071	.015	658	10	17	-7
11	0.085	0.349	.008	1	79	100	-21
12	0.818	0.088	.019	600	19	24	-5
13	0.832	0.101	.019	620	22	21	+1
14	0.723	0.080	.015	485	17	38	-21
15	0.772	0.084	.013	674	18	15	+3
16	0.740	0.088	.017	39	19	95	-76
17	0.827	0.096	.019	59	22	92	-70
18	0.774	0.210	.008	408	47	48	-1
19	0.844	0.159	.011	419	37	47	-10
20	0.860	0.113	.015	420	25	47	-22
21	0.766	0.180	.006	429	42	46	-4
22	0.812	0.113	.017	614	25	22	+3
23	0.771	0.201	.008	404	45	49	-4
24	0.678	0.260	.006	372	56	53	+3
25	0.884	0.130	.017	243	30	70	-40
26	0.875	0.155	.015	593	36	25	+11
27	0.700	0.155	.008	293	36	63	-27
28	0.846	0.121	.021	592	26	25	+1
29	0.848	0.121	.017	439	26	45	-19
30	0.756	0.130	.008	610	30	23	+7
31	0.846	0.117	.019	573	26	28	-2
32	0.865	0.088	.015	526	19	33	-14
33	0.806	0.096	.015	651	22	18	+4
34	0.811	0.143	.023	472	33	38	-5
35	0.741	0.176	.034	347	40	54	-14
36	0.830	0.130	.017	551	30	27	+3
37	0.757	0.122	.015	557	28	26	+2
38	0.868	0.143	.021	594	33	22	+11
						mean	-7.4
						standard deviation	20.1

TABLE XVIII

Error Analysis for RM1NCMC at 70°F

Without Screening Value		With Screening Value	
Mean	-7.4	Mean	-4.6
Standard Deviation	20.1	Standard Deviation	17.7

Tolerance Limits

Gamma is percent confidence that P percent of the test values lie within the maximum error limits L_1 and L_2.

		without screening value		with screening value	
gamma	P	L_1	L_2	L_1	L_2
75	75	-33.2	+18.2	-27.6	+18.3
75	95	-51.3	+36.4	-43.8	+34.5
95	75	-36.8	+21.9	-31.1	+21.9
95	95	-57.4	+42.6	-49.8	+40.5

The results in general are not as good as was obtained with the RM828 cells. The reason for this is not clear, but it is noteworthy that the geometry of the cells is different. The RM828 is a "sandwiched wafer" construction, while the RM1NCMC is a "concentric cylinder" construction. Because of the difference in cell construction, perhaps some failure mechanism occasionally occurs with the RM1NCMC which does not occur with the RM828, and this failure is not reflected by Δi. (The RM3WA has still another construction, a spiral anode configuration.)

b) 32°F

The Δi value obtained from the test of the unknown cell was matched to the solid Δi line in Figure 18 to obtain a predicted state-of-charge. Thirty-three cells were tested at 32°F. The test data and results are given in Table XIX. Using a screening value of $E_d = 0.735$, cells number 3, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 22, 23, 24, 27, 30, and 33 are rejected. Of all these cells, only 3, 10, 15, and 33 are actually acceptable. The error analysis for the 32°F test results is given in Table XX. The large negative mean error indicates there is a systematic error in the test, i.e., the standard curve is not in the optimum position insofar as obtaining the minimum error is concerned. It can be seen that in this case the use of a screening value does not greatly improve the test results.

It can be seen that for 32°F as well as 70°F, the old cells frequently exhibit a higher discharge voltage than did new undischarged cells or new cells discharged to the same extent as the old cell of interest. The reason for this is not

TABLE XIX

Test Results for RM1NCMC Unknown Cells at 32°F

Cell No.	E_d(volts)	Δi(amps)	i_1-i_2 (amps)	Actual Discharge time(min)	State of Charge (as % discharged) Predicted	Actual	Error
1	0.776	0.096	.013	610	24	23	+1
2	0.746	0.092	.013	375	23	52	-29
3	0.710	0.084	.011	681	20	14	+6
4	0.820	0.100	.019	520	24	34	-10
5	0.756	0.100	.015	598	24	24	0
6	0.790	0.130	.021	570	32	28	+4
7	0.785	0.096	.017	782	24	1	+23
8	0.785	0.100	.013	625	24	21	+3
9	0.702	0.172	.011	442	39	44	-5
10	0.638	0.046	.008	658	0	17	-17
11	0.052	0.298	.004	1	72	100	-28
12	0.633	0.050	.006	600	2	24	-22
13	0.689	0.063	.008	620	6	21	-15
14	0.566	0.050	.004	485	2	38	-36
15	0.611	0.050	.008	674	2	15	-13
16	0.733	0.059	.008	39	5	95	-90
17	0.681	0.067	.006	59	9	92	-81
18	0.695	0.176	.013	408	40	48	-8
19	0.752	0.117	.013	419	28	47	-19
20	0.831	0.105	.017	420	24	47	-23
21	0.736	0.159	.008	429	38	46	-8
22	0.702	0.088	.013	614	21	22	-1
23	0.684	0.151	.008	404	36	49	-13
24	0.648	0.239	.006	372	58	53	+5
25	0.740	0.084	.011	243	20	70	-50
26	0.790	0.113	.015	593	27	25	+2
27	0.669	0.143	.006	293	35	63	-28
28	0.762	0.100	.015	592	24	25	-1
29	0.747	0.096	.013	439	24	45	-21
30	0.666	0.113	.008	610	27	23	+4
31	0.772	0.096	.017	573	24	28	-4
32	0.789	0.080	.013	526	19	33	-14
33	0.716	0.071	.013	651	10	18	-8

TABLE XX

Error Analysis for RM1NCMC at 32°F

Without Screening Value		With Screening Value	
Mean	-15.0	Mean	-9.9
Standard Deviation	23.2	Standard Deviation	17.1

Tolerance Limits

Gamma is percent confidence that P percent of the test values lie within the maximum error limits L_1 and L_2.

		Without Screening Value		With Screening Value	
gamma	P	L_1	L_2	L_1	L_2
75	75	-45.1	+15.0	-33.8	+13.9
75	95	-66.3	+36.2	-50.6	+30.8
95	75	-49.7	+19.7	-39.6	+19.2
95	95	-74.2	+44.1	-60.6	+40.7

apparent. It would not be particularly surprising for an old cell to exhibit a higher E_d than a new cell discharged to that same extent because (a) the new cell was discharged more recently, and (b) the new cell was discharged at a relatively high current for a short period while the old cell "ran down" over a long period of time. It does not seem reasonable, however, that this same old cell could also exhibit an E_d value higher than that of an undischarged new cell. One possible explanation is that the new cells used as standards are not as good as the old cells were when they were new. However, the relative discharge times of the new versus the old cells does not bear this out. It is noteworthy that old RM828 cells did not exhibit higher E_d values than did new undischarged cells, but a particular old cell usually did exhibit a higher E_d than a new cell discharged to the same extent. It is interesting that the old RM828 cells were generally only slightly discharged and did not exhibit a high E_d whereas the old RM1NCMC cells were on the average considerably more discharged and did exhibit a high E_d value.

D. RM1NCMC Ten Cell Batteries

1. Standard Curves

RM1NCMC cells were not originally scheduled to be used for the ten cell battery tests. However, the unavailability of old RM3WA cells (URC-64 batteries) dictated a change to RM1NCMC cells. Because the construction of standard curves is a lengthy procedure for ten cell batteries (see section II.E.2), and because the decision to switch to RM1NCMC ten cell batteries was not made until the last month of the contract period, it was not possible to obtain complete standard curves for the RM1NCMC batteries. These curves were completed for the state-of-charge region of greatest interest, namely 0 to 30% discharged. Of course, to use these curves it is necessary to assume that the curve does not "double back" at higher levels of discharge. Based on past experience with all the single cells and with the new ten cell RM3WA batteries, this is a safe assumption.

The discharge data for the new batteries used in the construction of the standard curves are given in Table XXI.

The test data for 70°F are given in Table XXII, while the test data for 32°F are given in Table XXIII.

The corrected standard curve for 70°F prepared from Tables XXI and XXII is given in Figure 19. The Δi curve is remarkably straight when compared to the single cell RM1NCMC behavior. It is probable that some averaging effects occur since all the cells are in series. It can be seen that i_1-i_2 exhibits a good slope as a function of state-of-charge.

The corrected standard curve for 32°F prepared from Tables XXI and XXIII is given in Figure 20. The Δi curve is not nearly so straight as at 70°F, and the i_1-i_2 curve has a poor slope.

2. <u>Test Results of Unknown Batteries</u>

a) 70°F

Ten cell batteries were prepared from old RT-10 batteries. Where possible, ten cells of an original series of cells were used.

TABLE XXI

Ten Cell RM1NCMC Battery

Standard Discharge Data

Series 1

Battery No.	A0	A1	A2	A3	A4
Initial Disch. Time	0	60	120	180	240
Actual Disch. Time	--	--	--	--	509
Total Disch. Time	--	--	--	--	749

Series 2

Battery No.	B0	B1	B2	B3	B4
Initial Disch. Time	0	60	120	180	240
Actual Disch. Time	--	--	--	--	520
Total Disch. Time	--	--	--	--	760

(Note: 760 minutes = 100% discharge)

Series 3

Battery No.	C0	C1	C2	C3	C4
Initial Disch. Time	0	--	--	--	--
Actual Disch. Time	--	--	--	--	--
Total Disch. Time	--	--	--	--	--

Battery No. C was accidentally shorted and completely discharged.

TABLE XXII

Ten Cell RM1NCMC Battery
Standard Test Data - 70°F

Series 1

Battery No.	A0	A1	A2	A3	A4	A4'
Δi	.092	.122	.155	.185	.218	0.55
E_d	8.06	6.72	6.01	5.81	5.65	6.15
i_1-i_2	.012	.024	.036	.055	.080	.138

Series 2

Battery No.	B0	B1	B2	B3	B4	B4'
Δi	.084	.109	.138	.168	.193	0.48
E_d	8.13	6.93	6.15	6.01	5.72	5.70
i_1-i_2	.012	.021	.034	.055	.076	.121

Series 3

Battery No.	C0	C1	C2	C3	C4	C4'
Δi	.084	---	---	---	---	---
E_d	8.12	---	---	---	---	---
i_1-i_2	.012	---	---	---	---	---

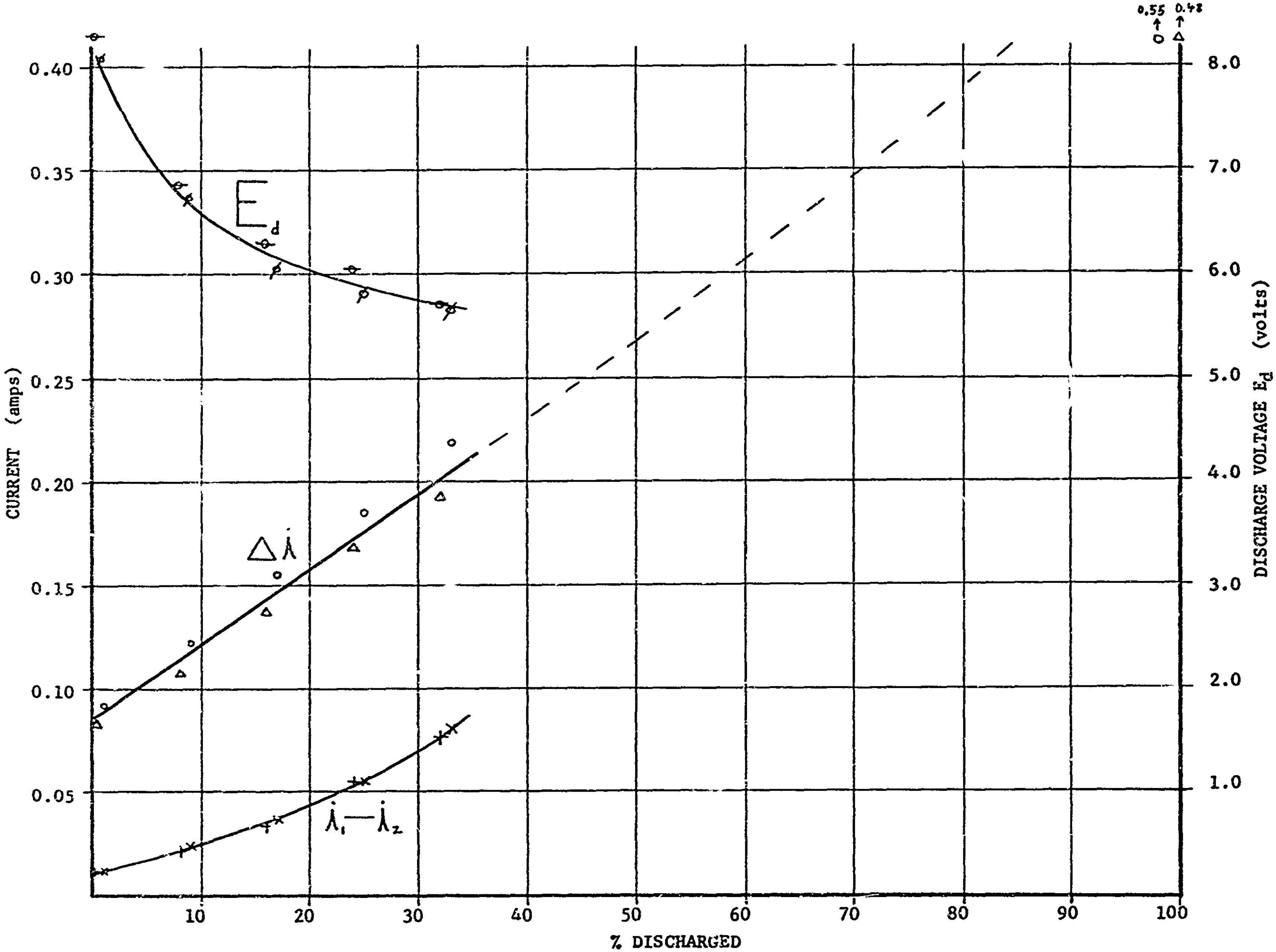


FIGURE 19
Standard Curve for RM1NCMC Ten Cell Battery - 70°F

TABLE XXIII

Ten Cell RM1NCMC Battery

Standard Test Data - 32°F

Series 1

Battery No.	A0	A1	A2	A3	A4
Δi (amps)	.117	.100	.122	.138	.159
E_d (volts)	4.90	3.92	3.78	3.64	3.50
$i_1 - i_2$ (amps)	.023	.019	.029	.036	.038

Series 2

Battery No.	A0	A1	A2	A3	A4
Δi (amps)	.092	.096	.113	.134	.160
E_d (volts)	4.80	3.90	3.75	3.60	3.44
$i_1 - i_2$ (amps)	.025	.025	.029	.038	.042

Series 3

Battery No.	C0	C1	C2	C3	C4
Δi (amps)	.096	--	--	--	--
E_d (volts)	4.95	--	--	--	--
$i_1 - i_2$ (amps)	.025	--	--	--	--

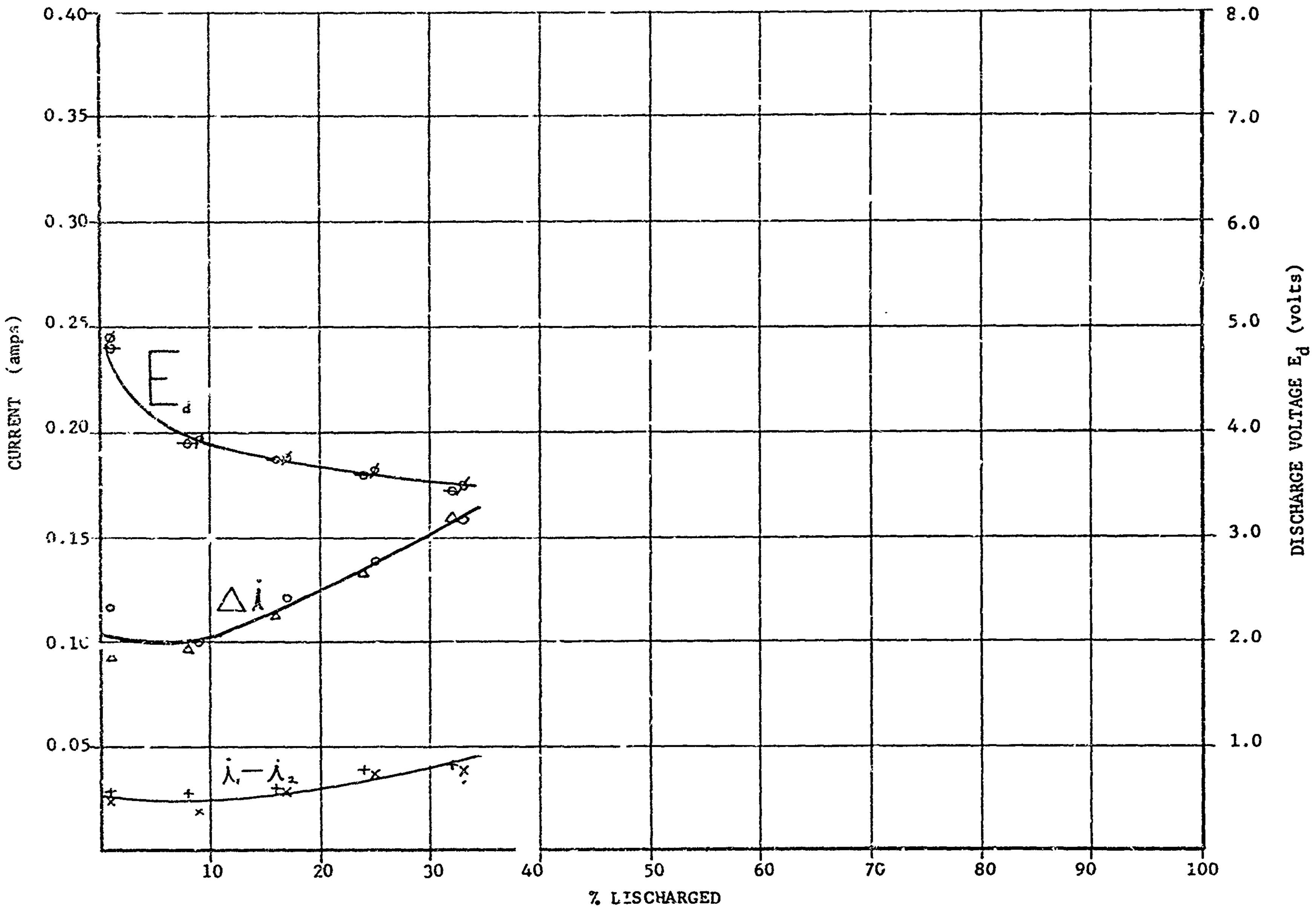


FIGURE 20

Standard Curve for RM1NCMC Ten Cell Battery - 32°F

The Δi value obtained from the test was matched to the solid Δi line in Figure 19 to obtain a predicted state-of-charge. Twenty-four batteries were tested at 70°F. The test data and test results are shown in Table XXIV.

The E_d values are particularly useless as an indicator of state-of-charge for ten cell batteries. For example, battery number 7 exhibited a higher discharge voltage than the new cells used as standards, yet was 98% discharged at the time of the test. Conversely, no screening value of E_d could be found which appeared to improve the test results. As with the RM1NCMC single cell tests, old batteries frequently exhibited a higher discharge voltage than did new undischarged batteries.

Although i_1-i_2 varied in a regular manner with new batteries, old batteries appeared to vary almost randomly in their i_1-i_2 values.

The results based on Δi were either quite good or very bad. The error analysis for the results are given in Table XXV. It is particularly noteworthy that the accuracy of the RM1NCMC ten cell tests is almost identical to the accuracy of the RM1NCMC single cell tests as given in Table XVIII on page 62. There had been some concern that if one bad cell was in series with nine good cells, the good cells would "mask" the bad cell during the test. This does not seem to be the case since in all cases where a battery exhibited a short life, that early failure was due to one cell failing while the others were still in good condition.

It is noteworthy that whenever the test predicted a battery to be less than 18% discharged, that battery was never more than 21% discharged (13 batteries). (Two batteries were

TABLE XXIV

Test Results for Unknown RM1NCMC
Ten Cell Batteries - 70°F

Cell No.	E_d(volts)	Δi(amps)	$i_1 - i_2$(amps)	Actual Discharge time(min)	State-of-charge (as % discharged) Predicted	Actual	Error
1	8.64	0.155	0.023	590	19	22	-3
2	6.26	0.319	0.124	1	>35	100	✓
3	8.66	0.168	0.029	255	23	66	-43
4	7.43	0.206	0.017	635	33	16	+17
5	5.06	0.239	0.021	1	>35	100	✓
6	2.79	0.285	0.105	1	>35	100	✓
7	8.50	0.176	0.025	10	25	98	-73
8	8,04	0.168	0.013	538	23	29	-6
9	8.59	0.134	0.021	603	14	20	-6
10	8.37	0.130	0.019	599	12	21	-9
11	8.36	0.134	0.021	610	14	19	-5
12	9.09	0.164	0.025	606	22	20	+2
13	8.77	0.147	0.023	611	17	19	-2
14	8.71	0.155	0.025	637	19	16	+3
15	8.21	0.155	0.025	475	19	37	-18
16	8.11	0.189	0.025	465	29	39	-10
17	8.44	0.117	0.019	697	8	8	0
18	8.20	0.180	0.017	550	27	27	0
19	8.15	0.109	0.019	742	6	2	+4
20	8.16	0.117	0.019	685	9	10	-1
21	8.43	0.117	0.019	717	9	5	+4
22	8.35	0.143	0.015	648	16	15	+1
23	8.55	0.139	0.019	628	15	17	-2
	8.42	0.143	0.023	688	16	9	+7

mean -5.8
standard deviation 17.8

TABLE XXV

Error Analysis for Ten Cell

RM1NCMC Batteries at 70°F

Mean	-5.8
Standard Deviation	17.8

Tolerance Limits

Gamma is the percent confidence that P percent of the test values lie within the maximum error limits L_1 and L_2.

gamma	P	L_1	L_2
75	75	-29.5	+17.8
75	95	-46.1	+34.4
95	75	-33.7	+22.0
95	95	-53.2	+41.6

less than 18% discharged which were not predicted to be.) It is with the more discharged batteries that large errors are encountered.

b) 32°F

The Δi value obtained from the test was matched to the solid Δi line in Figure 20 to obtain a predicted state-of-charge. Twenty batteries were tested at 32°F. The test data and test results are shown in Table XXVI.

For the 32°F data, choosing a screening value of E_d = 0.620 volts results in considerable improvement of the test results. Cells number 2, 3, 4, 11, 15, 19, and 20 are rejected on this basis. Of these, only 3 and 15 are acceptable cells. The error analysis is given in Table XXVII.

It can be seen that the test results at 32°F are considerably better than the 70°F results. Due to the limited numbers of batteries tested at both temperatures, it is not possible to tell whether this is a coincidence.

It is important that whenever the test predicted a battery to be less than 18% discharged, that battery was never more than 22% discharged (8 batteries). One battery was below 18% discharge, but was not predicted to be.

TABLE XXVI

Test Results for Unknown
RM1NCMC Ten Cell Batteries - 32°F

Cell No.	E_d(volts)	Δi(amps)	i_1-i_2(amps)	Actual Discharge time(min)	State of Charge (as % discharged) Predicted	Actual	Error
1	6.25	0.105	.021	590	12	22	-10
2	4.80	0.197	.042	1	>35	100	✓
3	5.44	0.193	.029	635	>35	16	+19
4	4.32	0.239	.029	10	>35	98	✓
5	6.83	0.122	.021	603	18	20	-2
6	6.48	0.113	.023	599	15	21	-6
7	6.59	0.109	.023	670	14	19	-5
8	7.11	0.122	.027	606	18	20	-2
9	7.07	0.122	.025	611	18	19	-1
10	6.84	0.105	.023	637	12	16	-4
11	5.76	0.134	.023	475	23	37	-14
12	7.01	0.147	.021	465	28	39	-11
13	6.94	0.092	.013	692	6	8	-2
14	6.51	0.122	.017	550	18	27	-9
15	6.09	0.096	.019	742	6	2	+4
16	6.61	0.096	.019	685	6	10	-4
17	6.45	0.100	.019	628	8	17	-9
18	6.40	0.096	.017	688	6	9	-3
19	6.17	0.122	.021	261	18	66	-48
20	5.98	0.138	.017	540	25	29	-4
						mean	-5.5
						standard deviation	12.0

TABLE XXVII

Error Analysis for Ten Cell
RM1NCMC Batteries at 32°F

Without Screening Value		With Screening Value	
Mean	-5.5	Mean	-5.3
Standard Deviation	12.0	Standard Deviation	3.4

Tolerance Limits

Gamma is the percent confidence that P percent of the test values lie within the maximum error limits L_1 and L_2.

		Without Screening Value		With Screening Value	
gamma	P	L_1	L_2	L_1	L_2
75	75	-21.8	+10.7	-10.1	+0.3
75	95	-33.2	+22.1	-13.5	+3.1
95	75	-25.0	+13.9	-11.4	+1.0
95	95	-38.8	+27.7	-15.8	+5.3

E. RM3WA Single Cell Results

1. Standard Curves

As with the other types of cells, the first batch of RM3WA cells was sub-standard. Mallory Battery Company specifies a 26 hour lifetime for the RM3WA when discharged through a 25Ω resistor to an end voltage of 0.9 volt at 70°F. Several cells selected at random from the first batch of cells lasted less than 22 hours. A new batch of RM3WA cells was obtained and found to be acceptable, and three series of standard cells were prepared.

An uncorrected standard curve at 70°F was prepared using these new cells, but it was discovered that the discharge relay (see Figure 4) had not been working properly at the time the test data for this curve was collected. This relay was replaced, and test data was obtained for the three series of cells at 70°F and 32°F. Table XXVIII gives the initial, actual, and total discharge times for these cells. Table XXIX and XXX give the test data at 70°F and 32°F, respectively.

Figure 21 shows a 70°F corrected standard curve prepared from the data in Tables XXVIII and XXIX. It can be seen that the slope of this curve is zero between 0% and 13% discharge, thus the state-of-charge of a cell whose Δi lies in this region will be uncertain by as much as 13%. The i_1-i_2 curve has too low a slope for the prediction of state-of-charge. For new cells, E_d changes in a regular manner with state-of-charge.

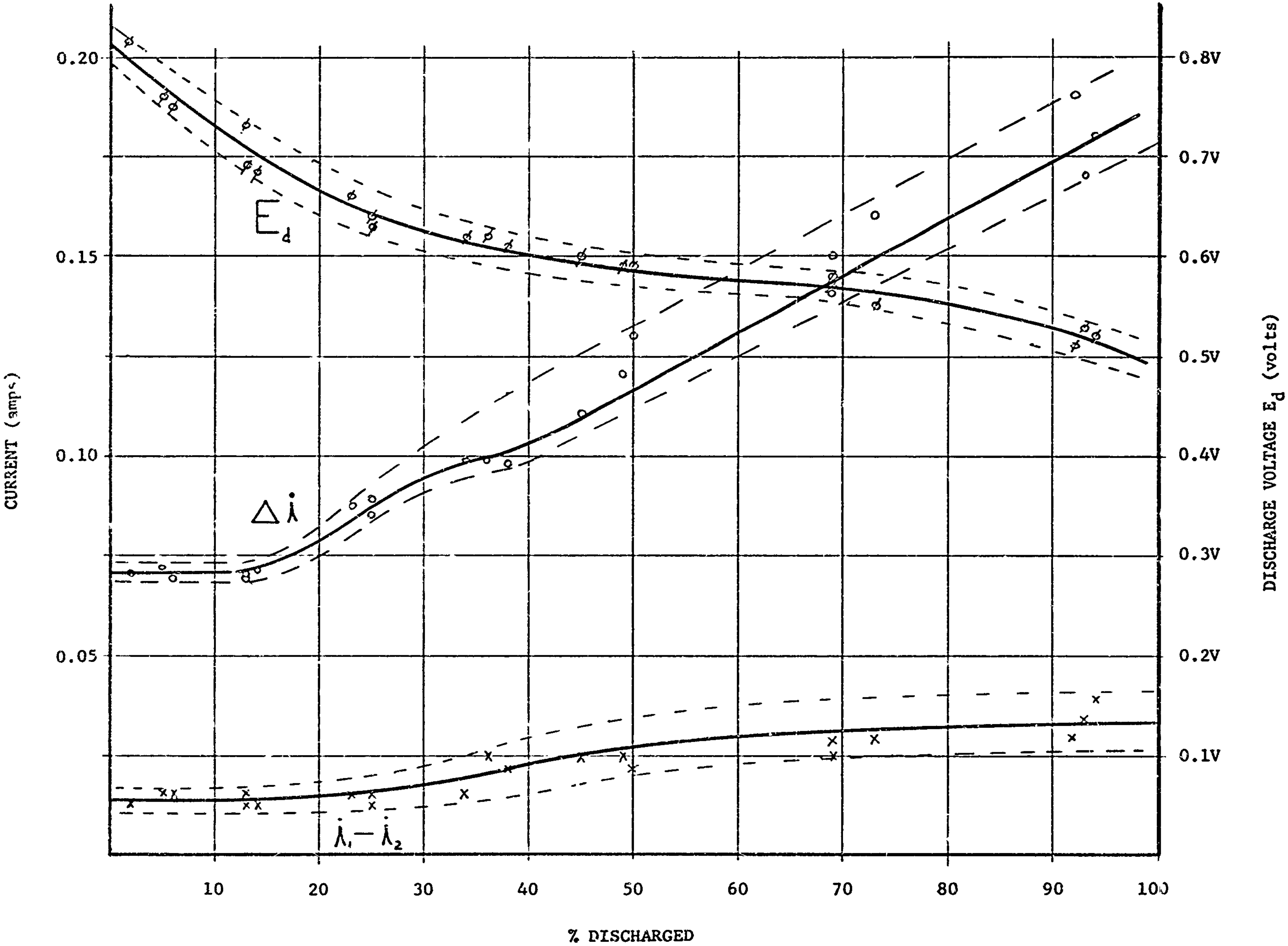


FIGURE 21
Corrected Standard Curve for RM3WA - 70°F

TABLE XXVIII

Discharge Data for RM3WA Standard Cells

1st. Series

Cell Number	0	1	2	3	4	5	6
Initial Disch. Time	0	60	120	180	240	360	504
Actual Disch. Time	493	430	390	319	252	154	35
Total Disch. Time	493	490	510	499	492	514	539

(Note: 504 minutes = 100% discharge)

2nd. Series

Cell Number	0	1	2	3	4	5	6
Initial Disch. Time	0	60	120	180	240	360	490
Actual Disch. Time	479	436	379	332	278	135	30
Total Disch. Time	479	496	499	512	518	495	520

3rd. Series

Cell Number	0	1	2	3	4	5	6
Initial Disch. Time	0	60	120	180	240	360	494
Actual Disch. Time	473	433	375	310	256	157	42
Total Disch. Time	473	493	495	490	496	517	536

TABLE XXIX

Test Data for RM3WA Standard Cells - 70°F

1st. Series

Cell Number	0	1	2	3	4	5	6
Δi (amps)	.070	.070	.088	.098	.13	.14	.17
E_d (volts)	.81	.73	.66	.62	.59	.58	.53
$i_1 - i_2$ (amps)	.012	.017	.017	.025	.021	.029	.034

2nd. Series

Cell Number	0	1	2	3	4	5	6
Δi (amps)	.071	.069	.085	.098	.11	.16	.18
E_d (volts)	.76	.69	.64	.62	.60	.55	.52
$i_1 - i_2$ (amps)	.017	.012	.017	.017	.025	.029	.038

3rd. Series

Cell Number	0	1	2	3	4	5	6
Δi (amps)	.069	.071	.088	.098	.12	.15	.19
E_d (volts)	.75	.68	.63	.61	.59	.56	.51
$i_1 - i_2$ (amps)	.017	.012	.012	.021	.025	.025	.029

TABLE XXX

Test Data for RM3WA Standard Cells - 32°F

1st Series

Cell No.	0	1	2	3	4	5	6
Δi(amps)	.050	.055	.064	.077	.10	.13	.20
E_d(volts)	.68	.52	.51	.48	.45	.42	.38
i_1-i_2(amps)	.012	.016	.017	.018	.027	.027	.050

2nd Series

Cell No.	0	1	2	3	4	5	6
Δi(amps)	.052	.057	.064	.077	.097	.14	.19
E_d(volts)	.67	.54	.50	.48	.46	.40	.37
i_1-i_2(amps)	.012	.016	.016	.017	.020	.032	.040

3rd Series

Cell No.	0	1	2	3	4	5	6
Δi(amps)	.051	.055	.067	.080	.092	.14	.18
E_d(volts)	.66	.52	.50	.48	.45	.42	.39
i_1-i_2(amps)	.012	.012	.017	.020	.020	.030	.040

Figure 22 shows a 32°F corrected standard curve for RM3WA cells. This curve was prepared from the data in Tables XXVIII and XXX. It can be seen that this curve exhibits a more favorable slope of Δi versus state-of-charge. Again, the slope of the i_1-i_2 curve is too low to permit prediction of state-of-charge.

2. <u>Tests of Unknown Cells</u>

No old URC-64 batteries could be located during this investigation, thus precluding any tests of unknown cells.

F. <u>RM3WA Ten Cell Batteries</u>

1. <u>Standard Curves</u>

Standard curves were prepared by the techniques outlined in Section II.E.2.

The discharge data for the three standard batteries are given in Table XXXI. The test data are given in Tables XXXII and XXXIII for 70°F and 32°F, respectively.

Figure 23 shows a 70°F standard curve which was prepared from the data in Tables XXXI and XXXII. Figure 24 shows a 32°F standard curve which was prepared from the data in Tables XXXI and XXXIII. In both of these curves, the i_1-i_2 slope is too low to be of use in predicting state-of-charge. The large drop in E_d as a function of discharge is surprising when compared to the single cell behavior (Figure 21). It can

TABLE XXXI

Discharge Data for Standard Ten Cell RM3Wa Battery

1st Series (Battery A)

Battery No.	A0	A1	A2	A3	A4	A5	A6	A7	A8
Initial Disch. Time	0	60	120	180	240	300	360	420	480
Actual Disch. Time	--	--	---	---	---	---	---	---	168
Total Disch. Time	--	--	---	---	---	---	---	---	648

(Note: 648 minutes = 100% discharge)

2nd Series (Battery B)

Battery No.	B0	B1	B2	B3	B4	B5	B6	B7	B8
Initial Disch. Time	0	60	120	180	240	300	360	420	480
Actual Disch. Time	--	--	---	---	---	---	---	---	143
Total Disch. Time	--	--	---	---	---	---	---	---	623

3rd Series (Battery C)

Battery No.	C0	C1	C2	C3	C4	C5	C6	C7	C8
Initial Disch. Time	0	60	120	180	240	300	360	420	480
Actual Disch. Time	--	--	---	---	---	---	---	---	152
Total Disch. Time	--	--	---	---	---	---	---	---	632

TABLE XXXII

Test Data for Standard Ten Cell RM3WA Battery - 70°F

1st Series

Battery No.	A0	A1	A2	A3	A4	A5	A6	A7	A8
Δi(amps	.060	.070	.090	.095	.15	.19	.23	.24	.28
E_d(volts)	8.2	6.8	5.5	4.9	5.1	4.8	4.9	5.0	4.5
i_1-i_2(amps)	.008	.012	.017	.021	.029	.040	.054	.064	.080

2nd Series

Battery No.	B0	B1	B2	B3	B4	B5	B6	B7	B8
Δi(amps)	.060	.074	.090	.11	.15	.20	.24	.26	.30
E_d(volts)	8.1	7.0	5.8	5.2	5.2	5.1	5.0	5.0	4.5
i_1-i_2(amps)	.012	.021	.025	.029	.035	.040	.040	.070	.090

3rd Series

Battery No.	C0	C1	C2	C3	C4	C5	C6	C7	C8
Δi(amps)	.060	.075	.090	.11	.15	.21	.24	.27	.28
E_d(volts)	8.2	7.1	5.8	5.3	5.2	5.0	4.9	4.9	4.6
i_1-i_2(amps)	.012	.012	.017	.029	.029	.037	.050	.064	.080

TABLE XXXIII

Test Data for Standard RM3WA Battery - 32°F

<u>1st Series</u>

Battery No.	A0	A1	A2	A3	A4	A5	A6	A7	A8
Δi(amps)	.045	.051	.055	.085	.13	[illegible]	.21	.23	.28
E_d(volts)	6.0	5.3	4.2	3.8	3.0	2.9	3.0	2.9	2.8
i_1-i_2(amps)	.008	.012	.008	.017	.025	[illegible]	.055	.065	.075

<u>2nd Series</u>

Battery No.	B0	B1	B2	B3	B4	B5	B6	B7	B8
Δi(amps)	.045	.055	.065	.10	.15	.17	.22	.25	.30
E_d(volts)	6.1	5.4	4.4	4.1	3.2	3.0	3.2	3.0	2.8
i_1-i_2(amps)	.012	.017	.021	.021	.029	.045	.045	.065	.075

<u>3rd Series</u>

Battery No.	C0	C1	C2	C3	C4	C5	C6	C7	C8
Δi(amps)	.050	.060	.065	.11	.13	.16	.23	.26	.30
E_d(volts)	6.1	5.5	4.4	3.9	3.3	3.1	3.0	3.0	2.6
i_1-i_2(amps)	.012	.017	.017	.021	.021	.040	.050	.070	.085

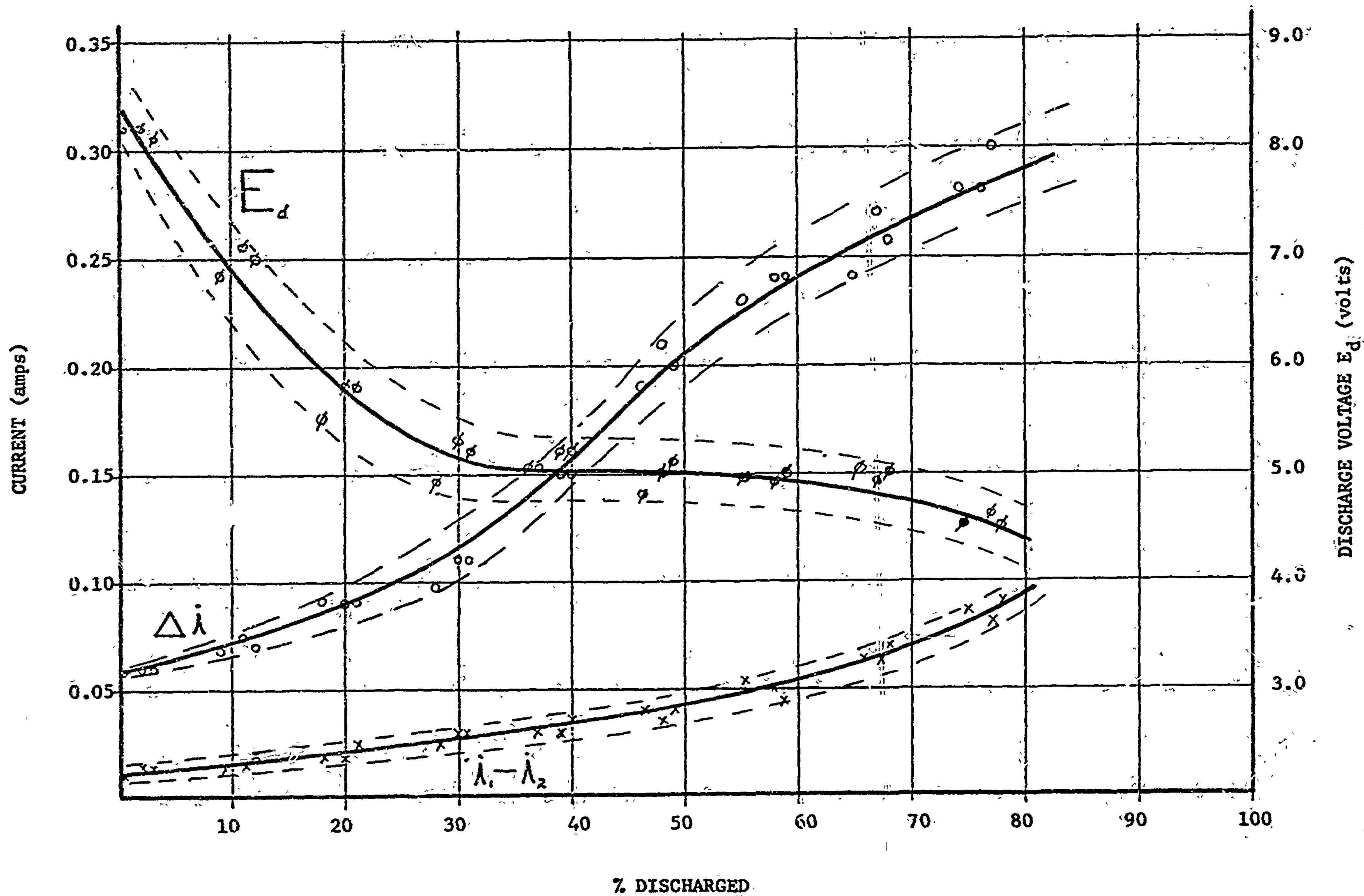


FIGURE 23

Corrected Standard Curve for Ten Cell RM3WA Battery - 70°F

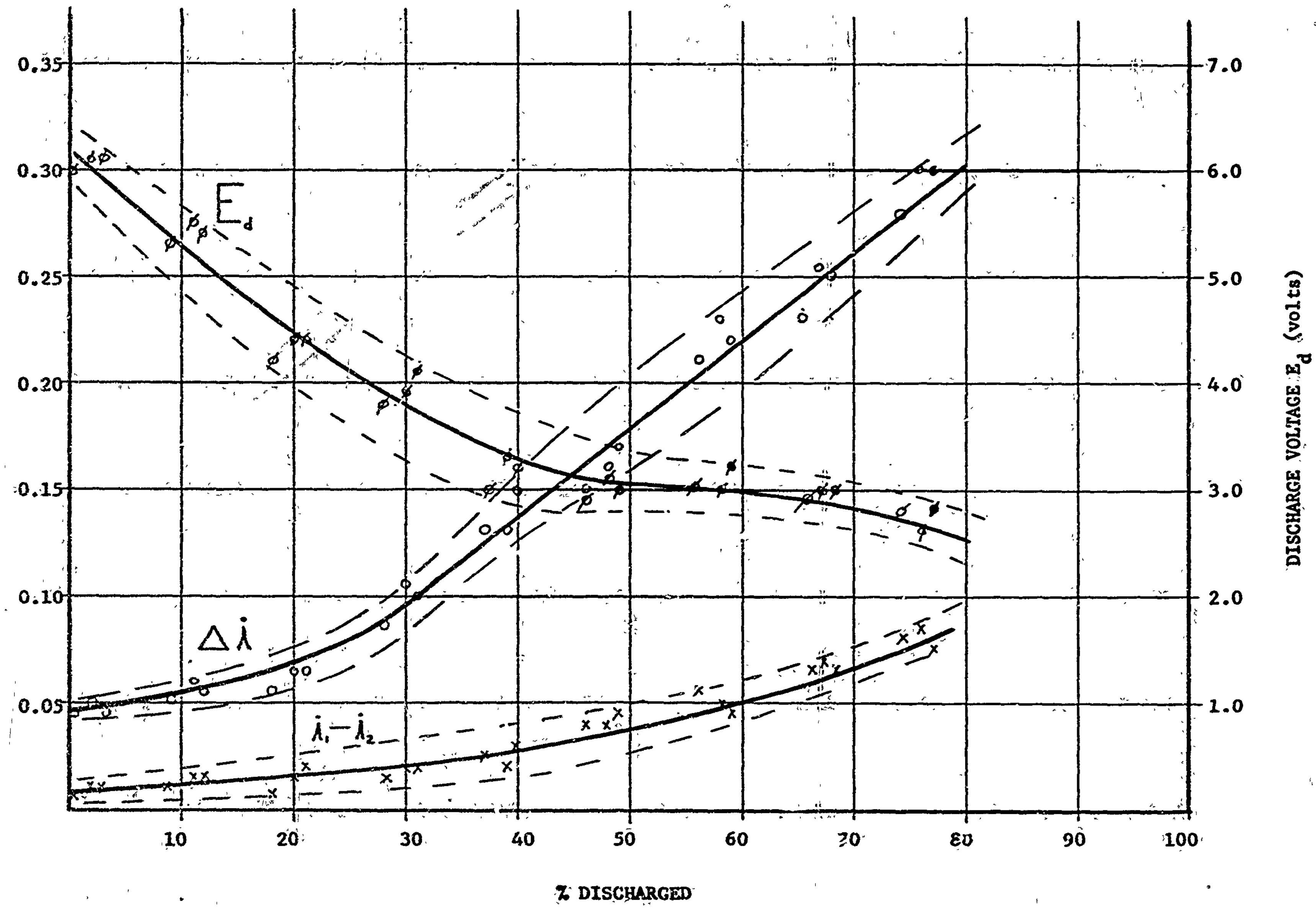


FIGURE 24

Corrected Standard Curve for Ten Cell RM3WA Battery - 32°F

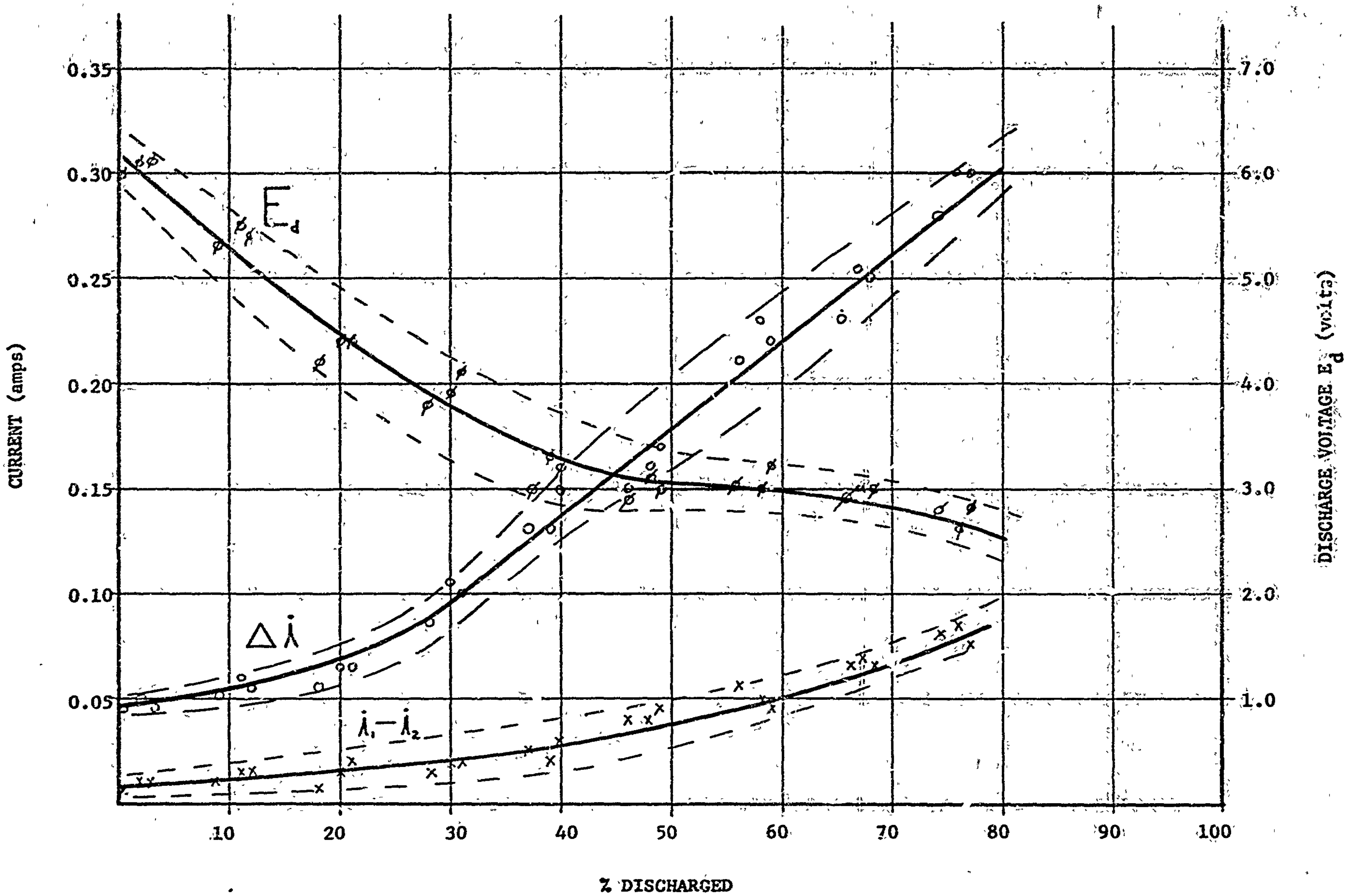


FIGURE 24

Corrected Standard Curve for Ten Cell RM3WA Battery - 32°F

be seen that the slopes of the Δi curves in Figures 23 and 24 are lower than desirable in the low discharge region.

2. Test of Unknown Batteries

No unknown batteries were tested since no old URC-64 batteries could be located.

IV. CONCLUSIONS

The two most important conclusions to be drawn from this feasibility study are the following.

(1) A test procedure has been developed to yield a test variable, Δi, which varies in a regular manner with the state-of-charge of mercury cells and batteries.

(2) This test variable can be used in conjunction with a screening technique based on discharge voltage, E_d, to predict with a high degree of confidence whether a cell or battery is less than 17% discharged.

Other conclusions which can be drawn from this study include the following:

(3) Of all the test variables examined (Δi, $i_1 - i_2$, i_i, i_f, E_d) only Δi proved to be suitable for the prediction of state-of-charge. E_d proved to be useful for screening out the cells for which the test exhibited the largest error (these cells were almost always considerably discharged).

(4) The test becomes less accurate as the % discharge of the cell or battery being tested increases.

(5) The test is more accurate for RM828 cells than for RM1NCMC cells.

(6) The accuracy of the test for ten cell RM1NCMC batteries is equal to or greater than the accuracy for RM1NCMC single cells.

(7) The test is considerably more accurate for ten cell batteries at 32°F than it is at 70°F.

(8) Because of limitations in the test circuitry which was used, the test parameters used in this study probably were not the optimum.

(9) Overall, the test results did not meet the specified goal of predicting the state-of-charge within 5% of the actual state-of-charge with a confidence level of 98%.

The standard deviation of the error between predicted and actual state-of-charge was only 6.6% (70°F) and 6.7% (32°F) for the RM828 cells and only 3.4% (32°F) for the ten cell RM1NCMC battery, however. Considering the very limited scope of this investigation, these are believed to be excellent results. In addition, when the test predicted that a cell or battery was less than 18% discharged, in no case did the actual percent discharge exceed that value by more than 5%. This result is extremely important in terms of building a practical state-of-charge indicator for life support missions.

As a final point, it should be noted that statistical evaluations based on the small numbers of test results reported in this study are somewhat suspect. Much larger numbers of batteries need to be tested to obtain a true picture of the accuracy and precision of the predicted results.

(10) It is believed that the success achieved in this limited investigation warrants a further development of this test procedure. This investigation should proceed in four areas.

(a) Alter the test circuitry to permit optimization of the test parameters over a wider range.

(b) Include other types of cells (batteries) in the evaluation.

(c) Evaluate other types of pulse charging techniques.

(d) Test much larger numbers of cells and batteries.

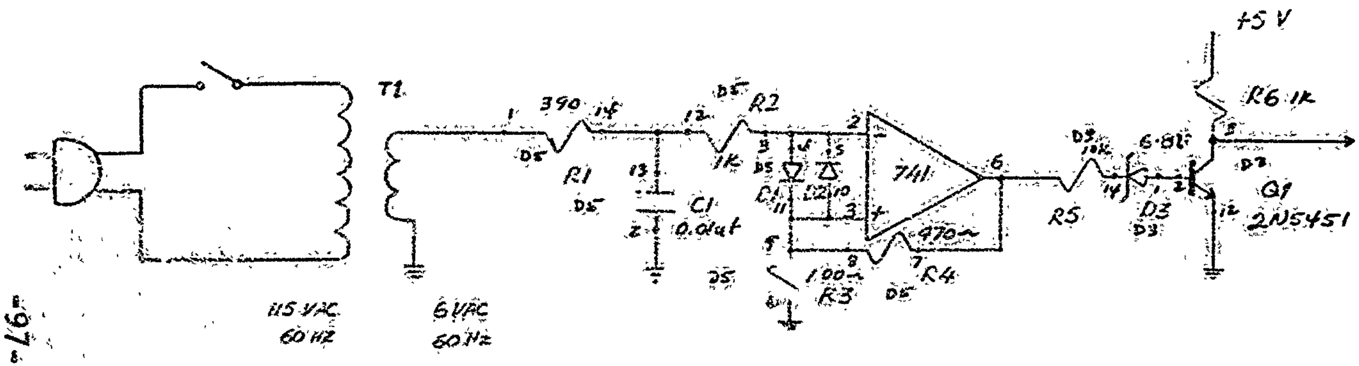
REFERENCES

(1) D. C. Jones, Unsolicited Proposal submitted to Wright-Patterson Air Force Base, Radian Corporation Proposal No. 484-019-71, April 1971.

(2) M. G. Natrella, Experimental Statistics, National Bureau of Standards Handbook 91, U. S. Government Printing Office, Washington, D. C., page 2-13 (1963).

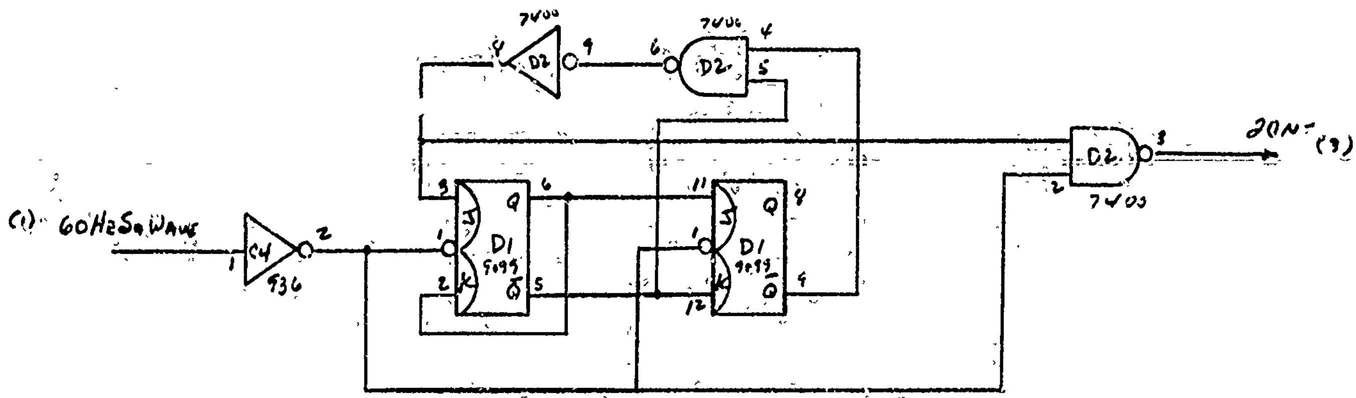
APPENDIX

Circuit Diagrams for Discharge Apparatus



T1
390 1/4
R1
R2
1K
C1
0.01uf
D1
D2
741
R3
100
R4
470
R5
6.8V
D3
R6 1K
+5 V
Q1
2N5451
115 VAC
60 HZ
6 VAC
60 Hz

60 Hz Sq. Wave


(1) 60HzSqWave
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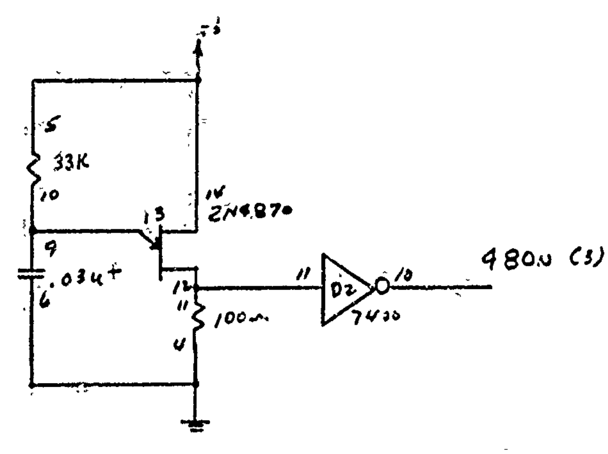
936
D1
D2
7400
20N (3)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2N4870
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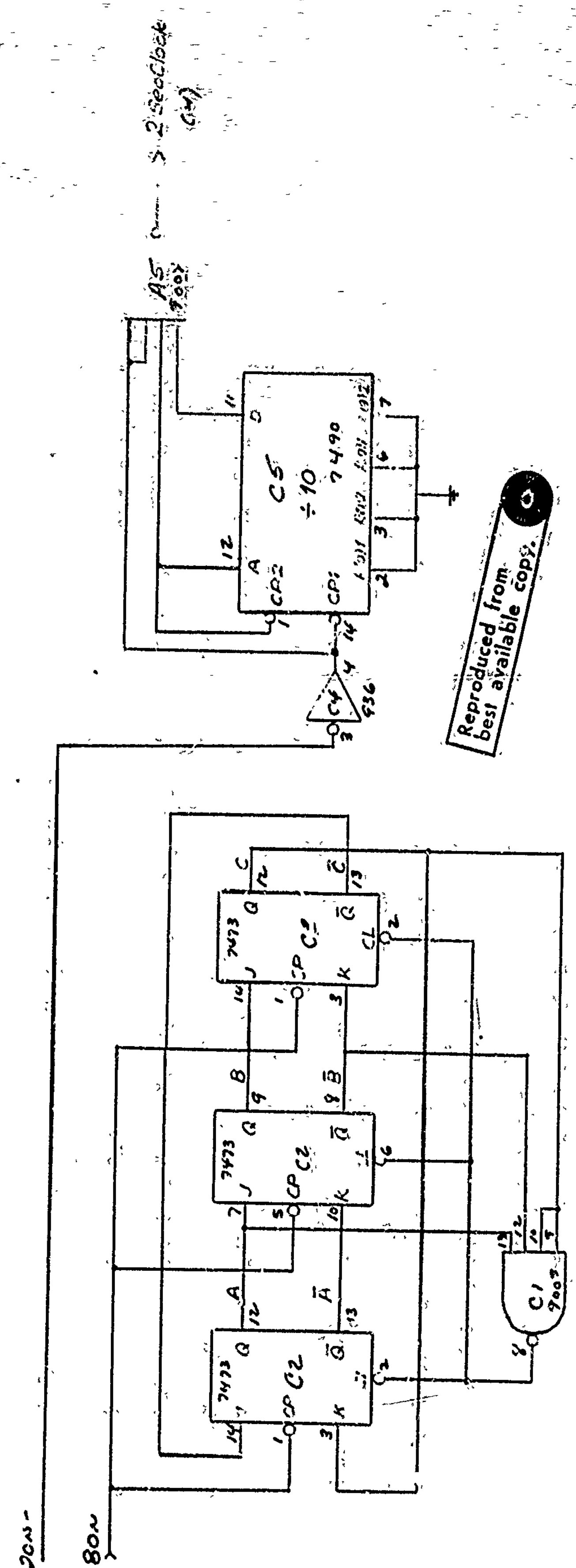
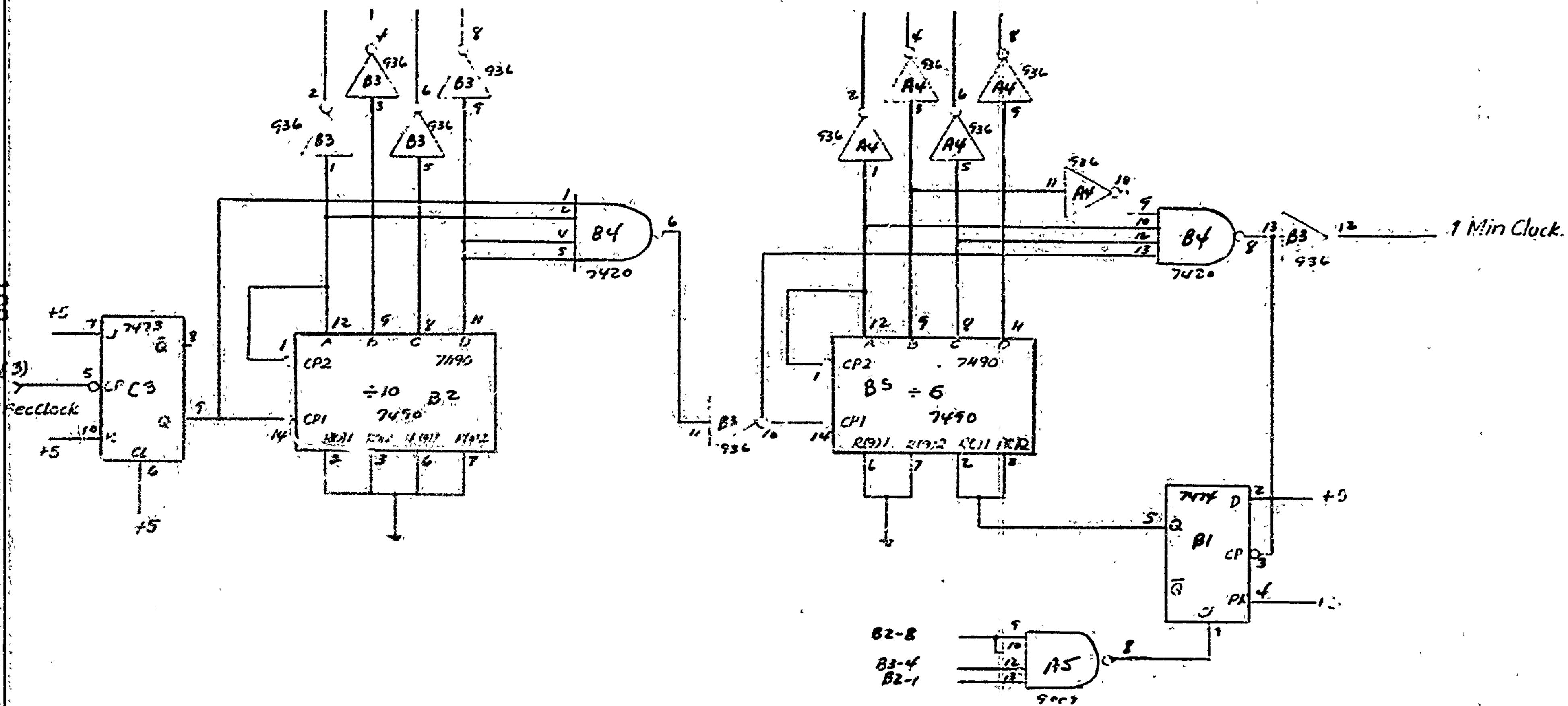
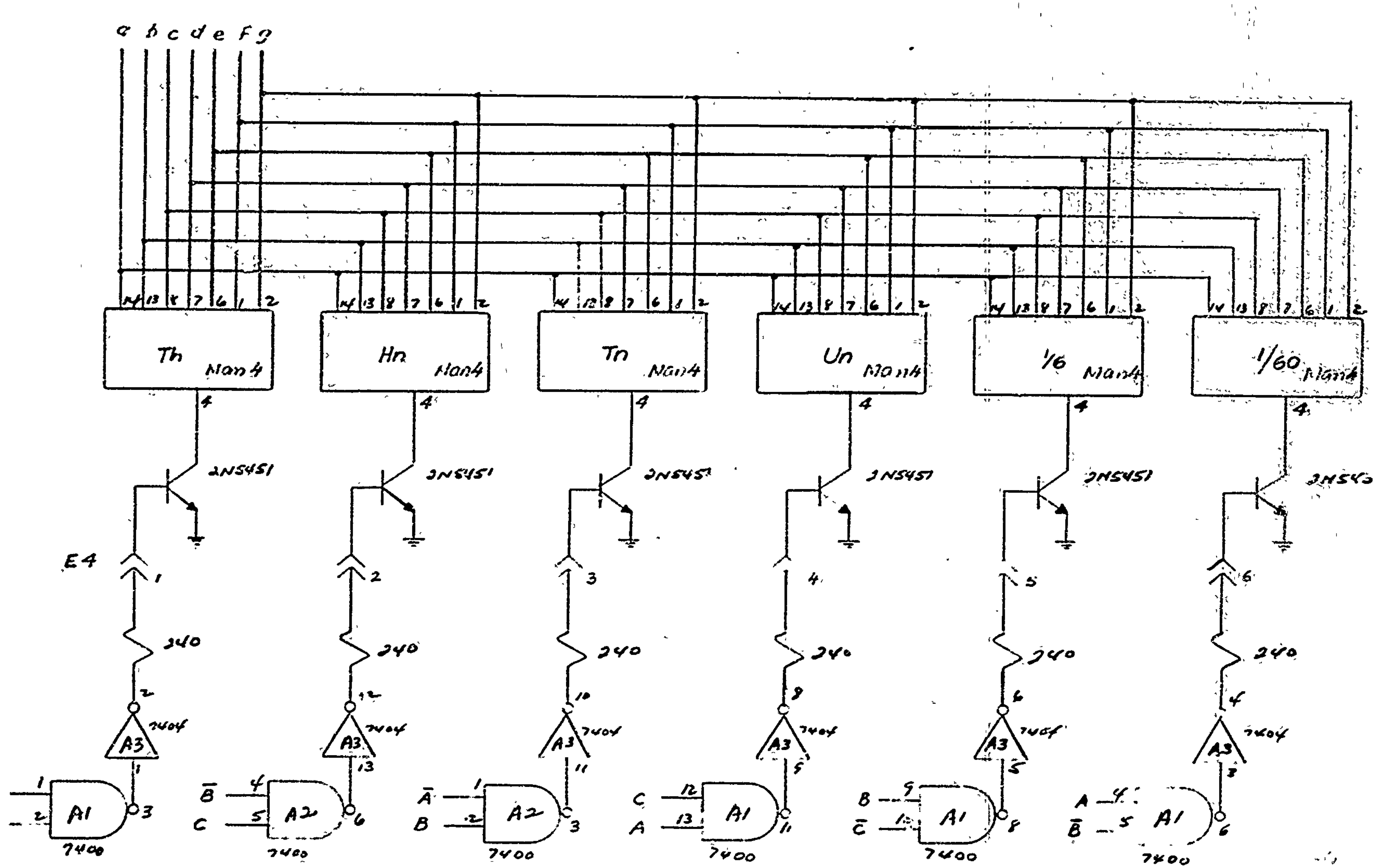
100
D2
7400
480N (3)

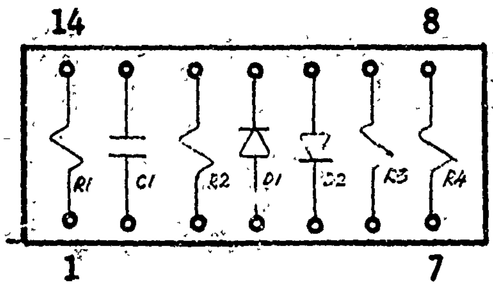

2 SecClock
A5
C5
÷10
7490
C4
936
7473
C2
C1
(3) 480N

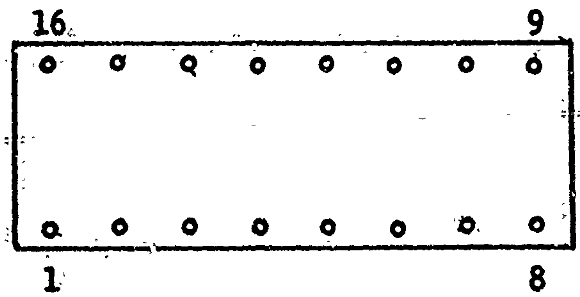


1 Min Clock.
Sec Clock
C3
7473
B2
÷10
7490
B5 ÷ 6
B4
7420
B1
7474
A5
B2-8
B3-4
B2-1
+5



a b c d e F g
Th Man4
Hn Man4
Tn Man4
Un Man4
1/6 Man4
1/60 Man4
2N5451
240
7404
A3
A1
A2
7400
E4

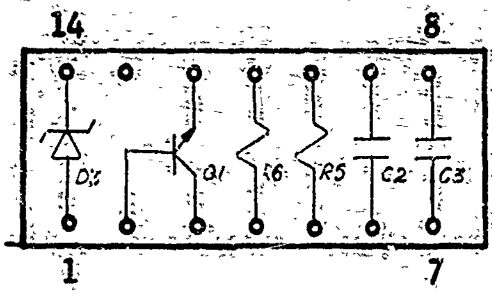


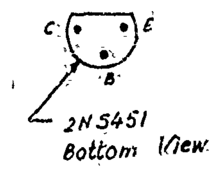


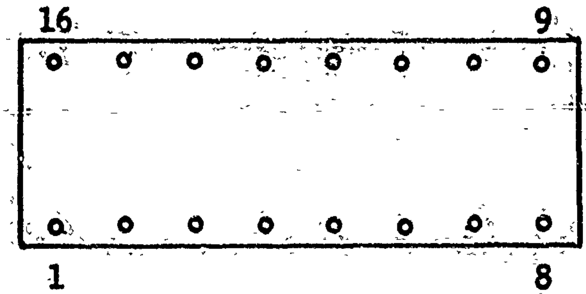
Board #1

Socket D-5

MATERIAL LIST			
Ref. Design.	Qty.	Specifications	Manu.
R1	1	390 KΩ	Any
R2	1	1 KΩ	
R3	1	100 KΩ	
R4	1	470 KΩ	
C1	1	.01 µf	
D1	1	1N914	
D2	1	1N914	



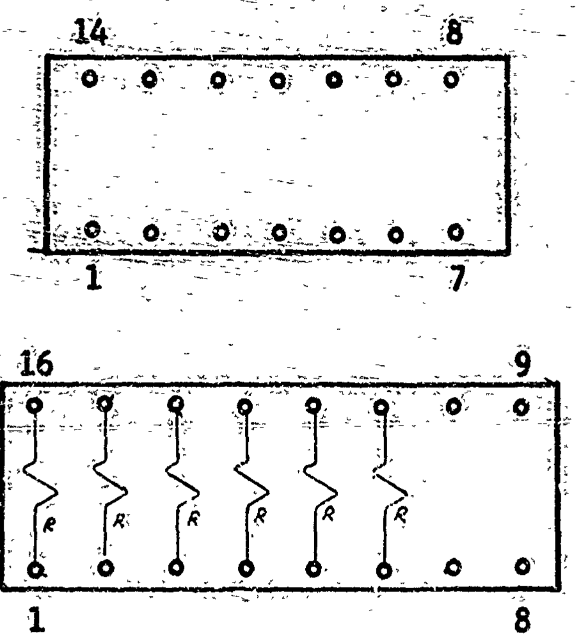




Board #1

Socket D3

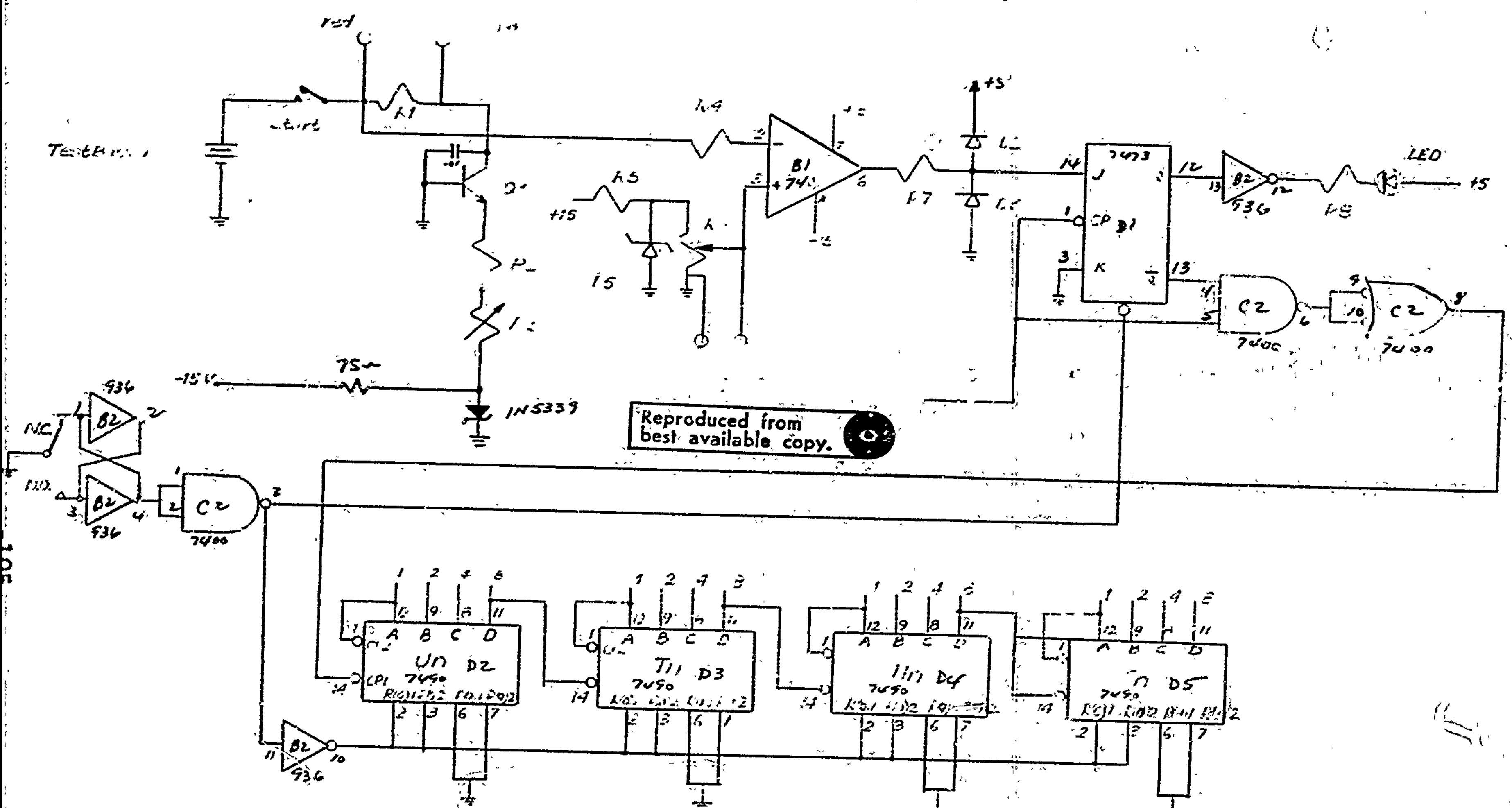
MATERIAL LIST			
Ref. Design.	Qty.	Specifications	Manu.
R5	1	10 KΩ	Any
R6	1	1 KΩ	
C2	1	1000 pf	
C3	1	1000 pf	
D3	1	1N5235 Motorola	
Q1	1	2N5451 TI	



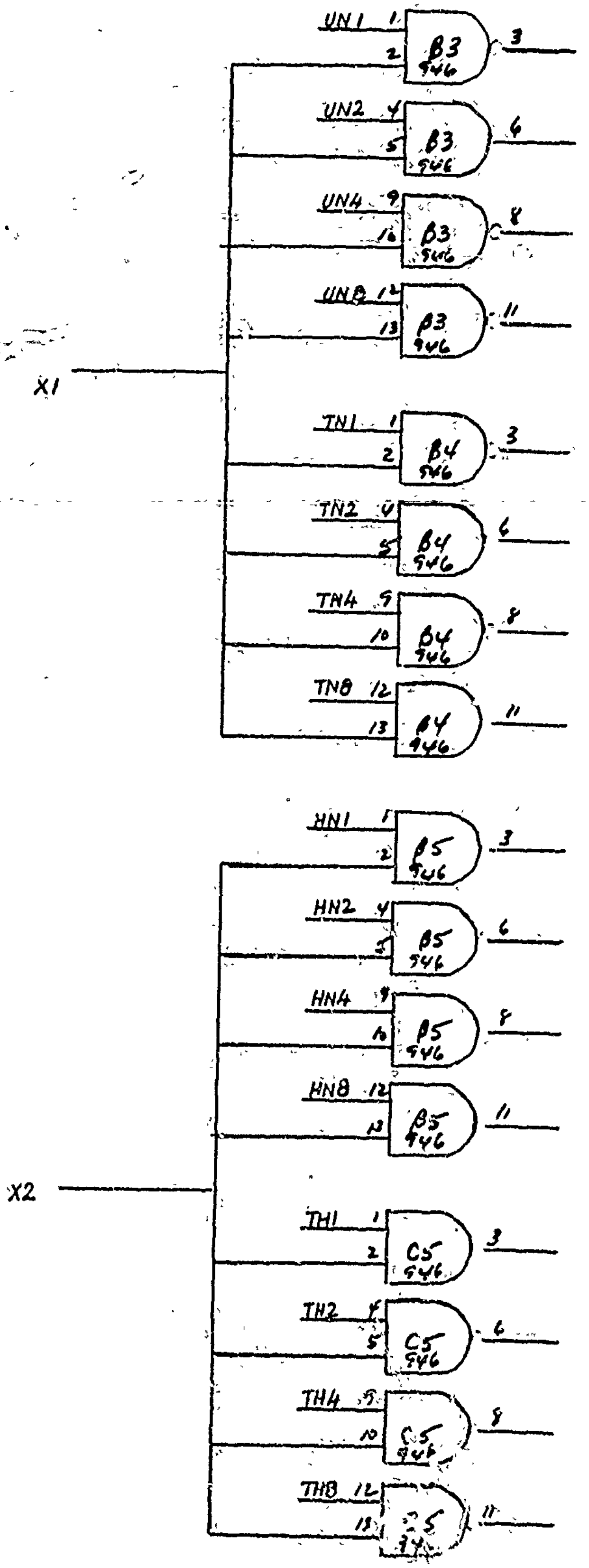
Board #1

Socket S-3

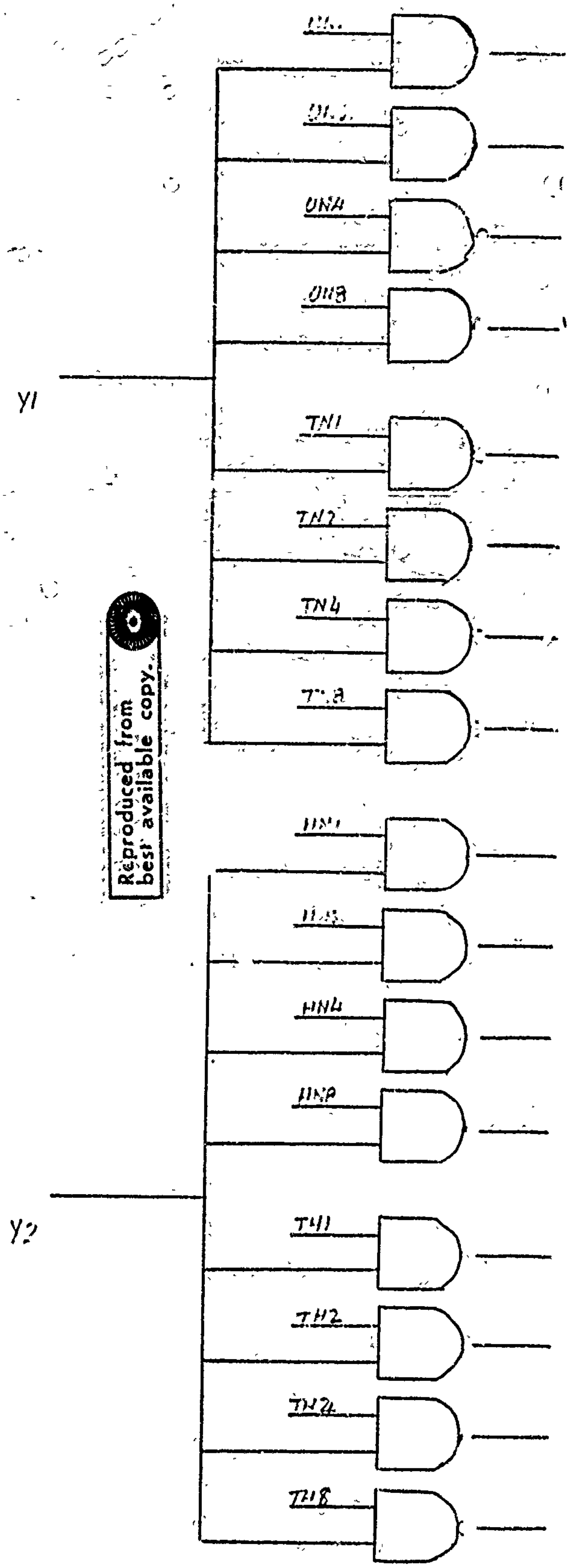
MATERIAL LIST			
Ref. Design.	Qty.	Specifications	Manu.
R	6	240Ω ¼w ±5%	Any



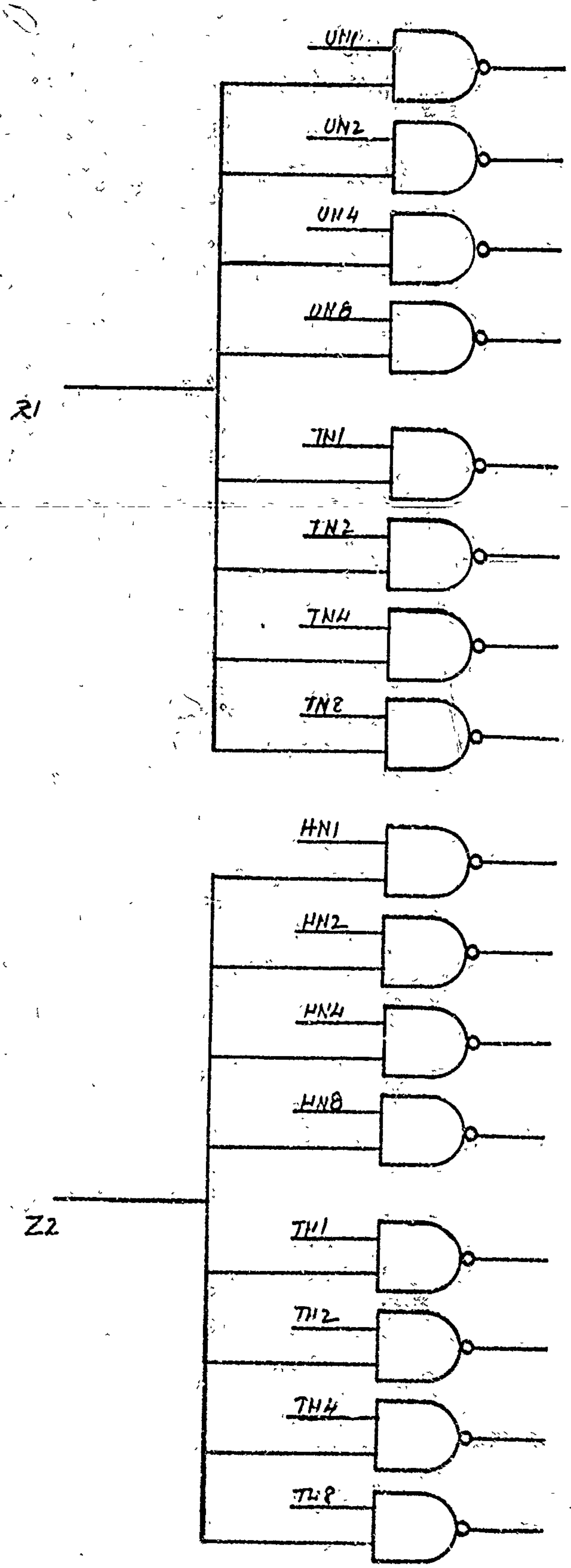
LED
+5
+15
B1
741
B2
936
934
C2
7400
7473
7490
D2
D3
D5
1N5339
75
-15V
N.C.
N.O.



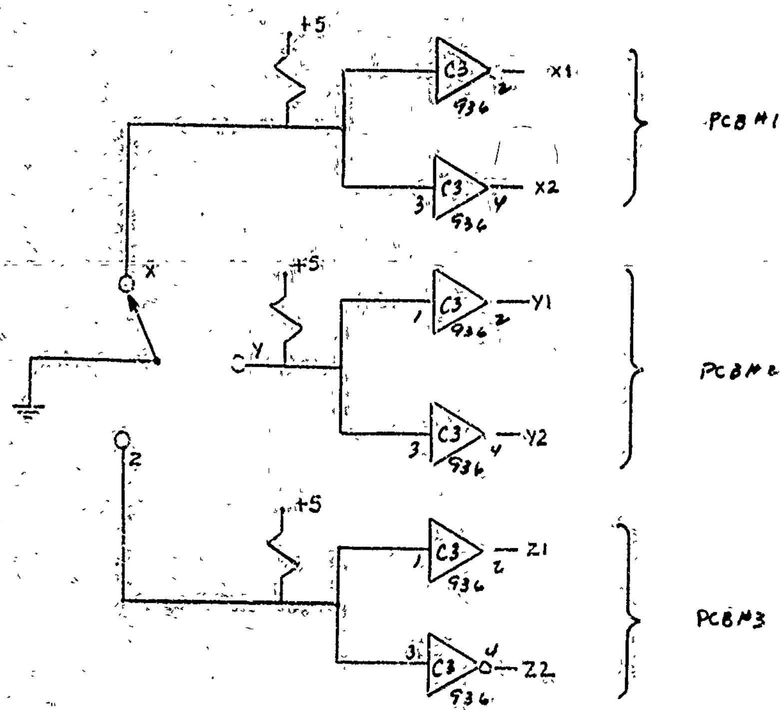
Outputs of Each Gate
Tied to Similar Output
on PCB #2,3, and 4

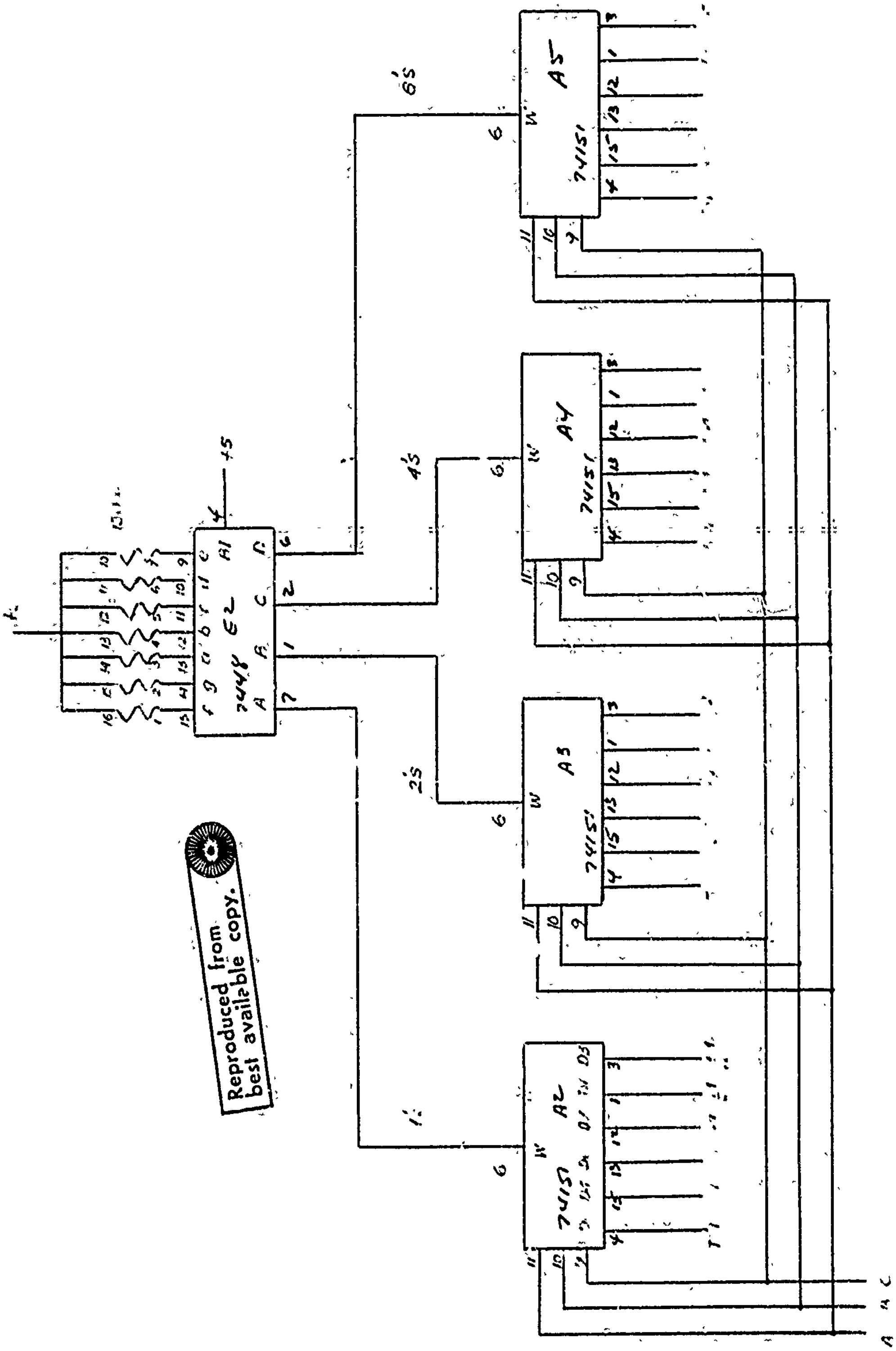


946-all
Circuit Location - same as previous sheet except on board #2



946-a11
circuit location same
as previous sheet
except on board #3


+5
C3
936
X1
X2
PCB #1
X
Y
+5
Y1
Y2
PCB #2
Z
+5
Z1
Z2
PCB #3



INTEGRATED CIRCUIT PARTS LIST

I. Board 1

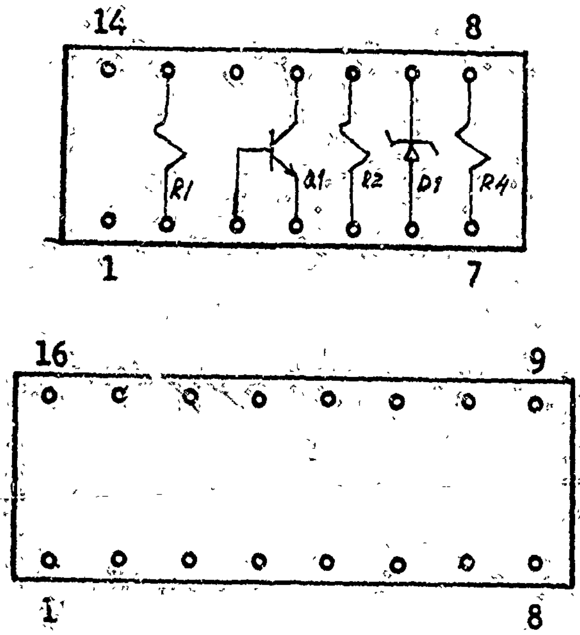
Reference Designation	Description	Manufacturer	Part Number
1A, 2A, 1D, 2D	Quad 2 in nand/nor gate	Fairchild	u6A740059X
3A	Hex inverter	Fairchild	u6A740459X
4A, 3B, 4C	Hex inverter	Fairchild	u6A993659X
5A, 4B, 1C	Dual 4 in nand/nor gate	Fairchild	u6A742059X
1B	Dual D-type flipflop	Fairchild	u6A747459X
2B, 5B, 5C	Decade Counter	Fairchild	u6A749059X
2C, 3C	Dual J-K master slave edge triggered flipflop	Fairchild	u6A747359X
4D	Operational amplifier	T. I.	SN72741P

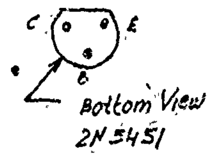
II. Board 2 Only

Reference Designation	Description	Manufacturer	Part Number
A2, A3, A4, A5	8 in multiplexer	T. I.	SN74151-N
E2	7 segment decoder driver	T. I.	SN7448N

III. Board 2, 3, 4

Reference Designation	Description	Manufacturer	Part Number
B1	Operational amplifier	T. I.	SN72741P
B2, C3	Hex inverter	Fairchild	u6A993659X
B3, B4, B5, C5	Quad 2 in nand/nor gate	Fairchild	u6A994659X
D1	Dual J-K master slave edge triggered flipflop	Fairchild	u6A747359X

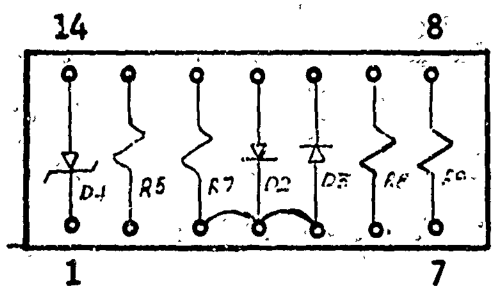


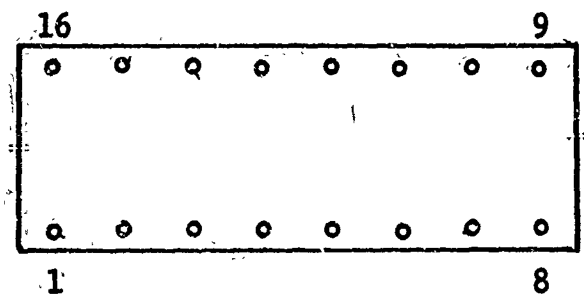


Board # 2,3 and 4

Socket A-1

MATERIAL LIST			
Ref. Design.	Qty.	Specifications	Manu.
R1	1	1Ω	
R2	1	27Ω	
R4	1	150 kΩ	
D1	1	1N5239B	
Q1	1	2N5451	

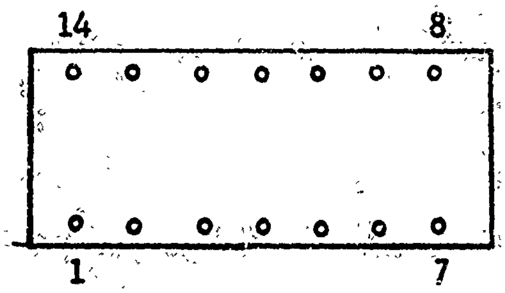


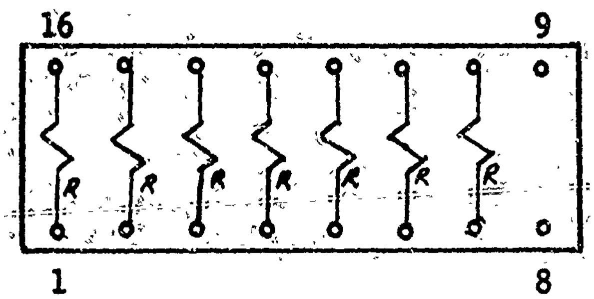


Board # 2, 3 and 4

Socket C-1

MATERIAL LIST			
Ref. Design.	Qty.	Specifications	Manu.
D2	1	1N914	Any
D3	1	1N914	
D4	1	1N5233B	
R5	1	2.2 kΩ	
R7	1	10 kΩ	
R8	1	270Ω	
R9	1	3.9kΩ	





Board # 2 only

Socket E-3

MATERIAL LIST			
Ref. Design.	Qty.	Specifications	Manu.
R	7	150 Ω	Any