LEVEL II

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PRIMARY LITHIUM THIONYL-CHLORIDE CELL EVALUATION

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A test program was conducted to evaluate the Altus 1350AH cell performance against the Minuteman Survival Ground Power requirements. Twelve cells of the 17 inch diameter, 1-3/8 inch heights were fabricated and tested during this study. Under discharge rates varying from C/100 to C/400 at ambient temperature, thevolumetric and gravimetric energy density performance requirements of 15 watt hours per cubic inch and 150 watt hours per pound were exceeded in all cases. All other performance requirements of voltage, current, configuration, capacity volume, weight, electrolyte leakage (none), and

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maintainability (none required), were met or exceeded.

The abuse testing demonstrated the Altus Cell's ability to safely withstand short circuit by external shorting, short circuit by penetration with a conductive object, forced discharge, and forced charging of a cell.

Disposal of discharged cells by incineration is an environmentally safe and efficient method of disposal.

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SECTION 1

INTRODUCTION

A test program has been conducted to evaluate the Altus Corporation 1350 amp hour cell performance against the Minuteman Survival Ground Power requirements. Twelve cells of the 17-inch diameter, 1-3/8 inch height were fabricated and tested during this study. The major performance parameters of interest were identified as operational safety and minimum volume per unit of energy.

The abuse testing conducted demonstrated the cell's ability to safely withstand short circuit by penetration of a fully charged cell, short circuit of a fully charged cell by external shorting, and forced discharge to 150% of the 3.0 volt nominal capacity of 1350 AH. During these tests, no overheating, venting, or explosions occurred. During incineration of two discharged cells, the cells safely vented gas after the internal pressure buildup caused separation at the inner 3 inch diameter ring weld within 4 to 5 minutes resulting in approximately 10 square inches of venting surface area. The intact inert stainless steel case with charred inert contents remained. Incineration appears to offer the most simple safe method of disposal.

Under discharge rates varying from C/100 to C/400 at ambient temperature, the volumetric and gravimetric energy density performance requirements of 15 watt hours per cubic inch and 150 watt hours per pound were exceeded in all cases. All other performance requirements of voltage, current, configuration, capacity, volume, weight, electrolyte leakage (none), and maintainability (none required) were also met or exceeded.

SECTION 2

CELL ACCEPTANCE TESTS

Prior to program testing, the cells were subjected to an Inspection and Acceptance Procedure by the Test Engineer. The manufacturing documentation is reviewed for completeness for problems which might have occurred during assembly or fill of the cell and for the amount of electrolyte introduced into the cell. A visual inspection of the cell is made to judge the workmanship of the welds and to catch any notable anomalies. Finally, a polarization scan of the cell is taken.

In Table 1 are listed the total weights, after fill of the cells, tested for this program. Table 2 lists the polarization data for these cells. Figure 1 shows the polarization curves of three cells which represent the range of polarization behavior of all the cells.

TABLE 1

CELL WEIGHTS

Cell S/N	Weight grams	Weight lbs.	Note *with pressure transducer
152	13366	29.47	
154	13375	29.49	
157	13636	30.06	*
158	13352	29.44	
159	13175	29.05	
160	13825	30.48	*
161	13471	29.70	
163	13530	29.83	*
164	13646	30.08	*
166	14043	30.96	*
168	13912	30.67	*
169	13790	30.40	*

*Weight of pressure transducer is about 350 gms.

TABLE 2

POLARIZATION DATA

Cell S/N	Voltage	Current (amps)	Cell S/N	Voltage	Current	Cell S/N	Voltage	Current
152	3.09	25.5	154	3.12	25.0	157	3.19	25.8
	3.27	14.6		3.30	14.4		3.33	14.8
	3.32	12.2		3.34	12.0		3.37	11.9
	3.35	10.5						
	3.42	6.5		3.43	6.6		3.44	6.5
	3.46	4.5		3.47	4.6		3.47	4.5
	3.64	0.0		3.64	0.0		3.62	0.0
158	3.18	26.0	159	3.16	25.7	160	3.12	25.5
	3.32	14.5		3.31	14.8		3.28	14.7
	3.36	11.8		3.35	12.2		3.33	12.1
	3.43	6.5		3.43	6.5		3.42	6.5
	3.46	4.5		3.46	4.5		3.45	4.5
	3.62	0.0		3.62	0.0		3.62	0.0
161	3.18	25.5	163	3.13	25.5	164	3.13	25.6
	3.33	14.5		3.31	14.6		3.30	14.6
	3.37	11.6		3.34	12.2		3.35	11.5
	3.44	6.5		3.44	6.6		3.43	6.6
	3.47	4.5		3.47	4.6		3.46	4.6
	3.63	0.0		3.64	0.0		3.64	0.0
166	3.14	26.1	168	3.14	26.1	169	3.16	26.0
	3.30	14.9		3.28	15.0		3.31	15.0
	3.35	12.0		3.32	12.2		3.34	12.3
	3.43	6.6		3.40	6.6		3.42	6.5
	3.47	4.6		3.44	4.5		3.46	4.5
	3.64	0.0		3.62	0.0			

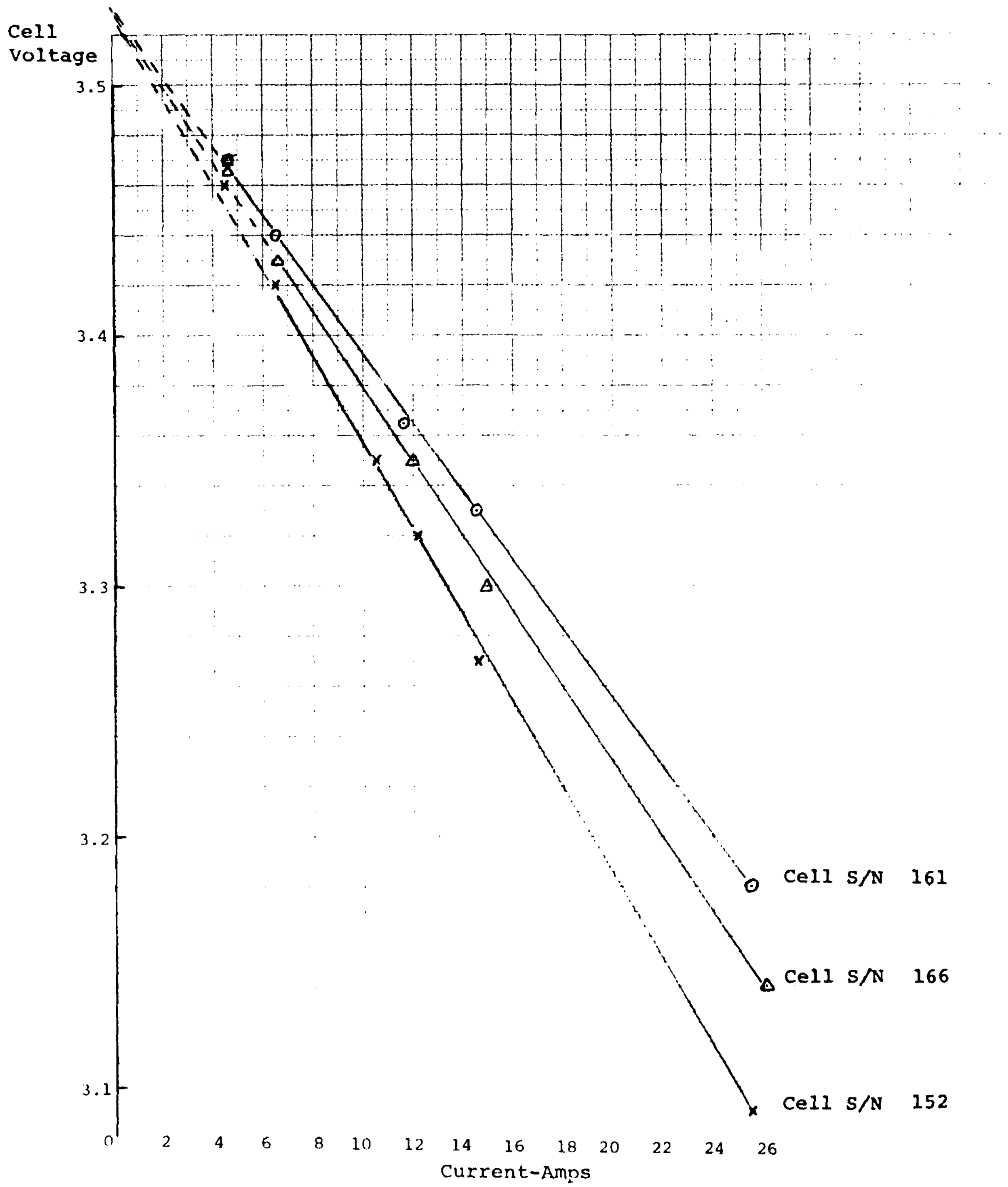


Figure 1. Polarization Curves

TEST 4.3.1 - NAIL PENETRATION

Purpose

The object of this test was to observe the effect, upon a fresh cell, of a nail driven in normal to the electrodes by a nail-set gun so that the cell was fully penetrated

The test was performed upon S/N 154 at an open test range under ambient conditions.

Description

The fresh, unclamped cell was mounted on the test fixture with its cylindrical axis oriented horizontally (Figure 2). Leads for monitoring the cell voltage were connected to the positive and negative terminals. An iron/constantan thermocouple was attached to the cell case within an inch of the site of penetration on the face opposite the fixture.

The nail-set gun was loaded, attached to the fixture, cocked and fitted with a lanyard for pulling the trigger. A safety net of chain-link fence was placed over the cell and fixture.

Cell voltage and temperature were recorded on a dual-pen strip chart recorder at a chart speed of 2 inches/minute. A digital multimeter.

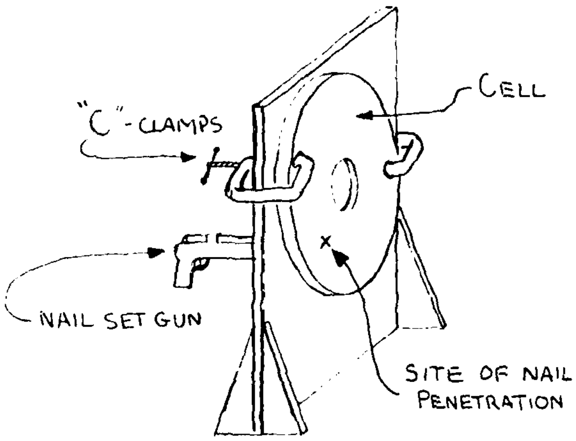


Figure 2. Cell In Nail Set Fixture

was used to cross-reference the recorder for cell voltage.

A visual record of the test was made on video tape and 8mm film.

Results

The nail-set gun was fired and the nail was driven into the cell so that the point protruded from the case. The cell voltage dropped immediately upon penetraion (Figure 3) and recovered within two seconds to 3.3 volts. It then fell to 2.96 volts one minute after penetration before it began a steady climb to 3.51 volts, where it stabilized.

The uncompensated thermocouple registered a slow rise in temperature from approximately 61°F, before penetration, to a maximum temperature of approximately 127°F after 8.30 minutes. After reaching the maximum, the temperature was erratic but declining so that a low of approximately 86°F was recorded 30 minutes after penetration.

Visually, there was nothing to be seen, with the exception of a nail protruding from the case, after or during penetration. There was no fire, smoke or electrolyte leakage to be seen.

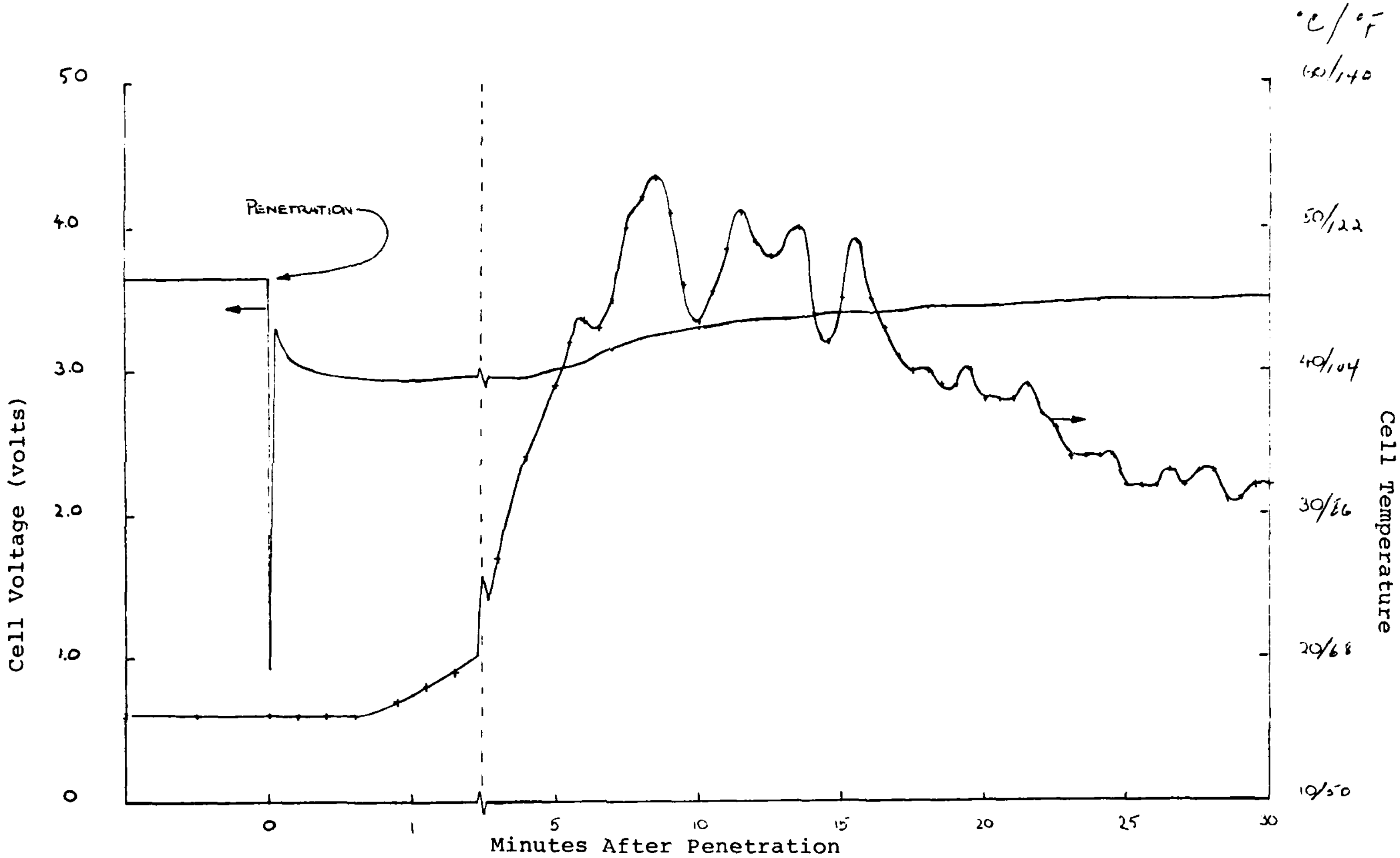


Figure 3. Temperature and Voltage Behavior of S/N 154 After Nail Penetration

Disposal

Approximately 43 minutes after penetration, S/N 154 was shot, still clamped to the fixture, with three 30-06 caliber bullets (Figure 4).

The first bullet caused the cell voltage to spike downwards, from 3.51 volts but it recovered immediately to approximately 2.8 volts. No temperature change was recorded. The second bullet again caused a downward spike in cell voltage with rapid recovery to 2.7 volts. A temperature drop of 4°F was recorded following the second bullet. The third bullet initiated a local reaction which ruptured the inner ring weld and destroyed the cell. There was no fragmentation during the disposal.

TEST 4.3.2 - EXTERNAL SHORT CIRCUIT

Purpose

The purpose of this test was to observe the effect of an external short circuit with a total impedance of not more than 0.002 ohms on a fresh cell.

This test was performed upon S/N 161 in a test chamber at ambient temperature.

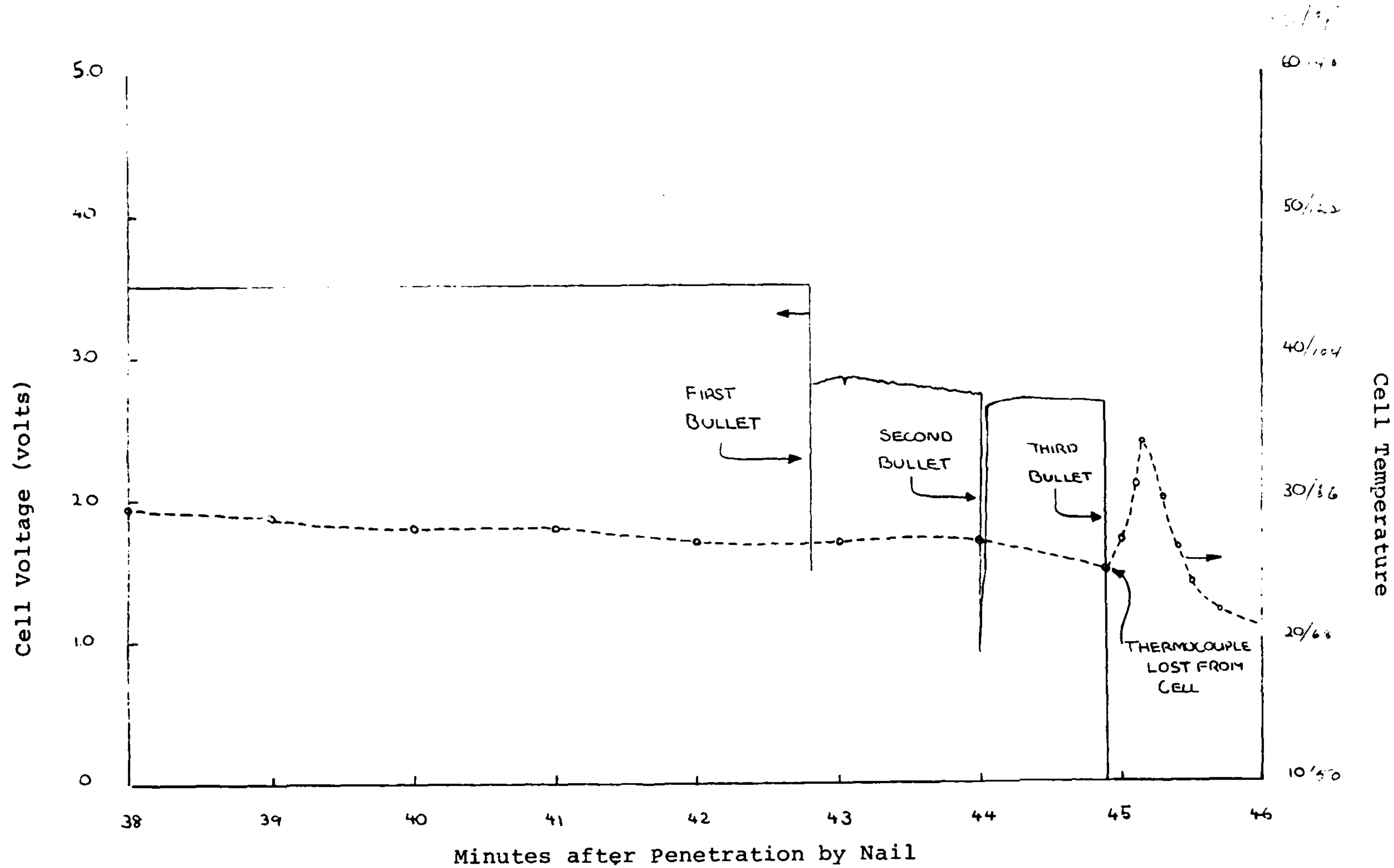


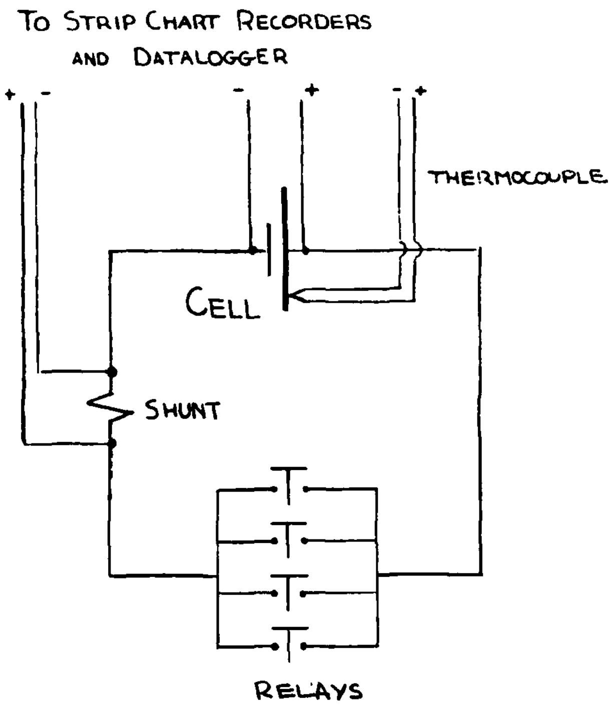
Figure 4. Temperature and Voltage of S/N 154 During Disposal by Bullet Penetration

Procedure

The fresh, unclamped cell, S/N 161, was placed on edge against sandbags on a table in the chamber. The short-circuit fixture (Figure 5) (consisting of four relays, a 500 amp/50 mV shunt, copper bars and terminal connections -- total resistance 0.00043 ohms) was clamped to the cell, and electrical connections were made to the instrumentation. Temperature (from an iron/constantan thermocouple), current (from the shunt) and cell voltage were recorded on strip chart recorders with an initial chart speed of 6 inches/minute, later switched to 1 inch/minute. Cell voltage was also recorded by a Fluke datalogger scanning continuously until the cell voltage dropped to zero. The short circuit was closed by activating the relays remotely.

Results

The moment the short circuit was activated, the cell voltage dropped to approximately 0.07 volts from an initial OCV of 3.63 volts (Figures 6 and 7). This voltage was maintained for three seconds before stepping down to zero where it stayed until the short circuit was opened. The short circuit current rose rapidly to over 170 amps, peaked at 175 amps and stepped down to zero with the voltage after three seconds. The capacity drained was 0.14 AH.



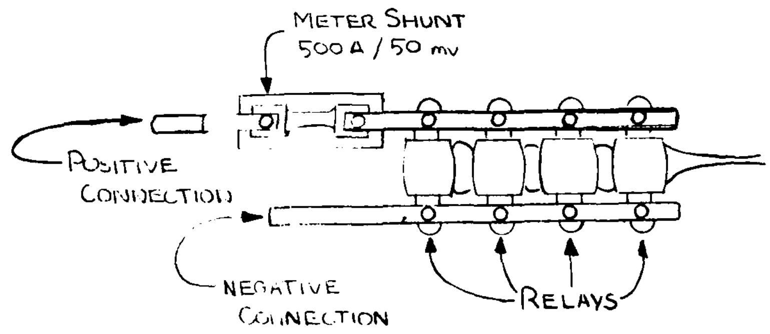


Figure 5. Short Circuit Apparatus

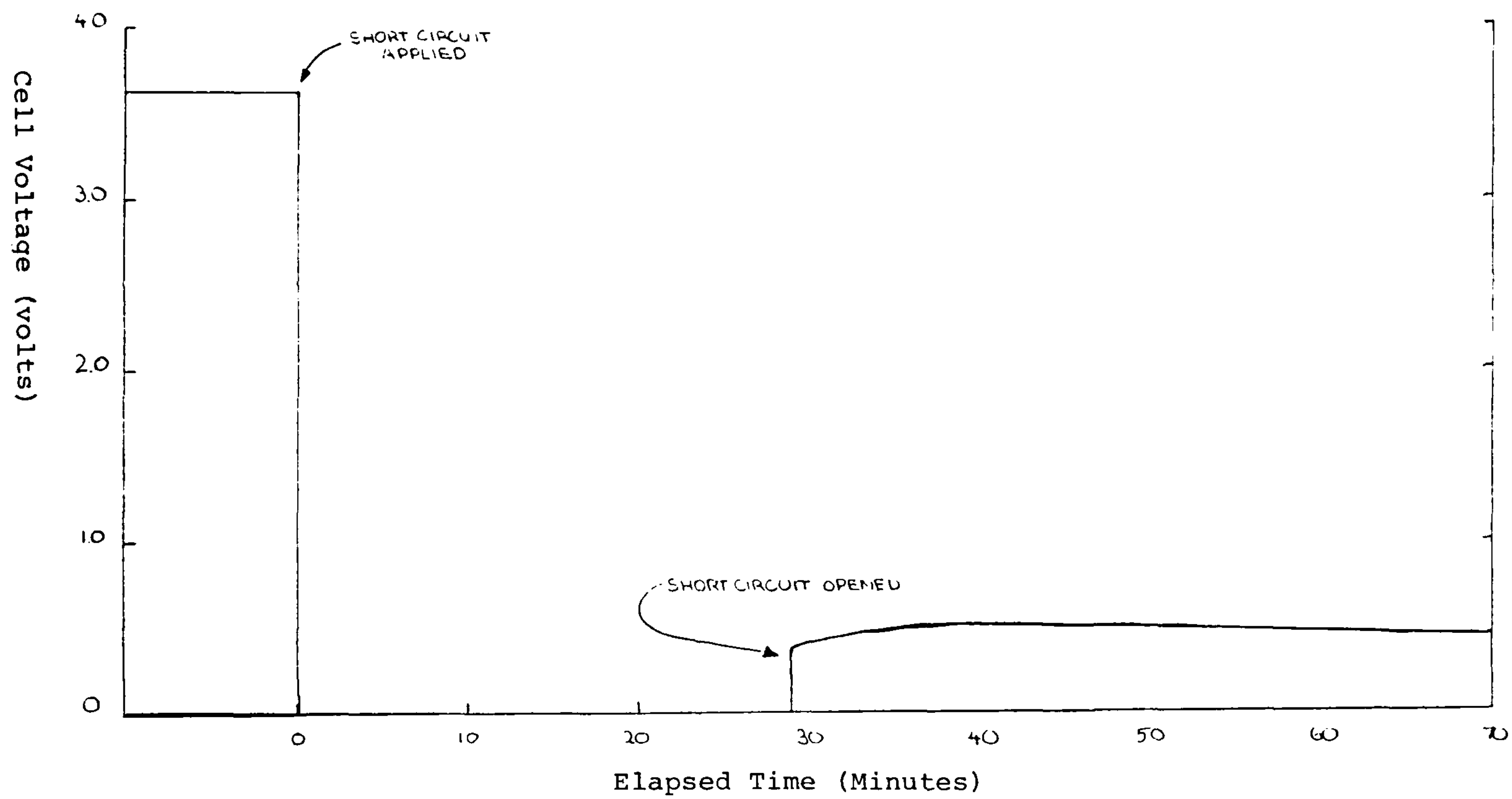


Figure 6. Cell Voltage of S/N 161 During Short Circuit Test

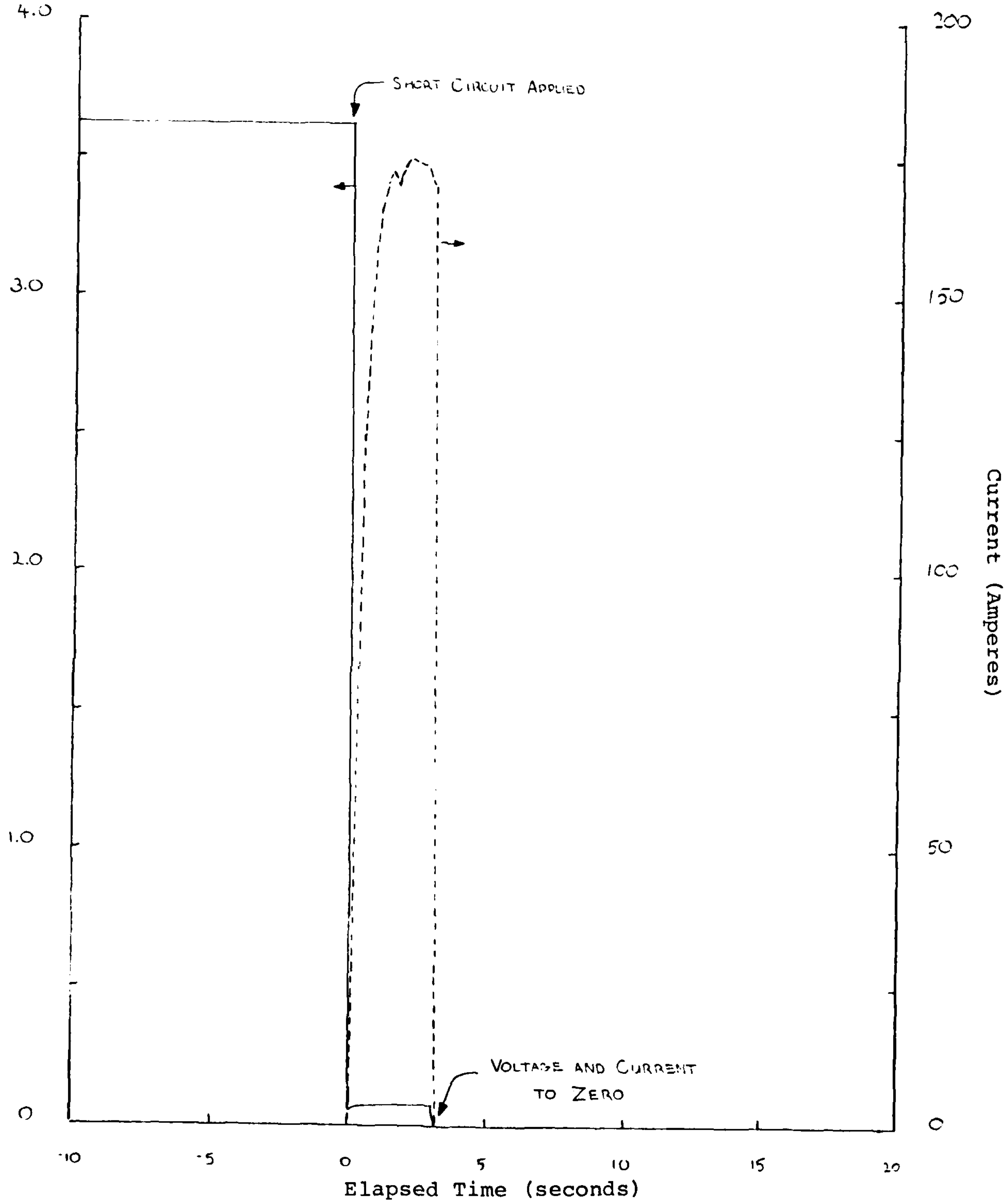


Figure 7. Voltage and Current of S/N 161 External Short Circuit

The short circuit was opened 29 minutes after it was closed and the cell voltage stepped up to 0.35 volts and increased gradually to 0.50 volts in thirteen minutes before it started a slow decline, stabilizing at approximately 0.42 volts.

During the test, the recorded temperature of the cell case rose from 61°F to 64°F over 45 minutes.

Disposal

Cell 161 was shot where it was at the end of the test. The first bullet caused the cell voltage to drop to zero from 0.42 volts. Some smoke was observed but the cell remained otherwise intact. Afterwards, the cell voltage began to recover but was quite erratic.

The second bullet initiated a reaction which destroyed the cell. The inner ring weld and part of the outer ring weld were opened but the cell case did not come apart.

CELL DISCHARGE TESTS 4.3.3 THROUGH 4.3.8

These various tests each require cell discharge through a constant impedance load such that the average current to a 3.0 volt level is given by the rate requirement C/400, C/250, C/200, C/133, or C/100, where the capacity, C, is taken to be a constant nominal value of 1350 ampere hours. The required average current values for the various rates are, therefore, as follows:

C/400 = 3.375 amps

C/250 = 5.400 amps

C/200 = 6.750 amps

C/133 = 10.150 amps

C/100 = 13.500 amps

In actual practice, one can only estimate the required impedance load from a predicted estimate of the average voltage of the cell above 3.0 volts divided by the required average current (given above). The achieved average current for each test together with the hour duration of the discharge to 3.0 volts is given for each test since these are the important absolute values which only approximate the test requirements.

TEST 4.3.3 - C/250 DISCHARGE TEST

Test Purpose

The purpose of this test is to demonstrate the capacity of the cell operating at approximately a C/250 discharge rate at 70°F after being soaked at 150°F for four hours.

Test Procedure

Cell S/N 158 was clamped between aluminum plates to a final torque value on the bolt-nut components of 25 ft.-lbs. The cell assembly was then placed in an oven at 150°F and the assembly left in the oven for four hours subsequent to the cell assembly attaining 150°F temperature. A thermocouple monitored cell surface temperature.

The oven was then readjusted for 70°F and the cell was electrically connected to the datalogger instrument to monitor cell voltage, circuit current, cell surface temperature and time. The circuit resistance had previously been adjusted by a variable resistance in circuit to a value of 0.653 ohms.

When the cell assembly had attained 70°F, the circuit relay was energized and the discharge test commenced. Data was automatically acquired at one-hour intervals. Test was terminated when the cell voltage dropped below 2.7 volts.

Data

Figure 8 is a plot of the cell voltage and cell surface temperature as a function of time. The temperature plot shows the daily temperature variation within the oven during the discharge test and gives a maximum temperature of 24.3°C (75.7°F) after 242 hours and a minimum of 19.9°C (67.8°F) after 182 hours. The average temperature throughout the first 180 hours of test is approximately 70°F. There is an indication that during the last 100 hours of test the cell itself may be contributing to a gradual temperature increase of about 3°F as the cell voltage decays to below 3 volts.

The cell voltage attains a maximum of 3.495 volts after 25 hours when delivering 5.35 amps and steadily falls to 3.0 volts (4.59 amps) after a total of 288.2 hours. The small voltage humps correspond directly with the oven temperature fluctuations and suggest about 2 mV cell voltage change per °F change in cell surface temperature.

The voltage profile clearly shows that the cell has delivered its useful energy to about 3.1 volts when the voltage drops rapidly. The 3.0 volt cut-off level is in accord with the cell characteristics at this rate and temperature.

The cell capacity to 3.0 volts, integrated hourly, totals 1501.2 amp hours for 288.2 hours. Further cell characteristics can be found in the following table (Table 3). In particular, the high energy densities of 173 watt hours/pound and 16.7 watt hours /cu. in. are noteworthy.

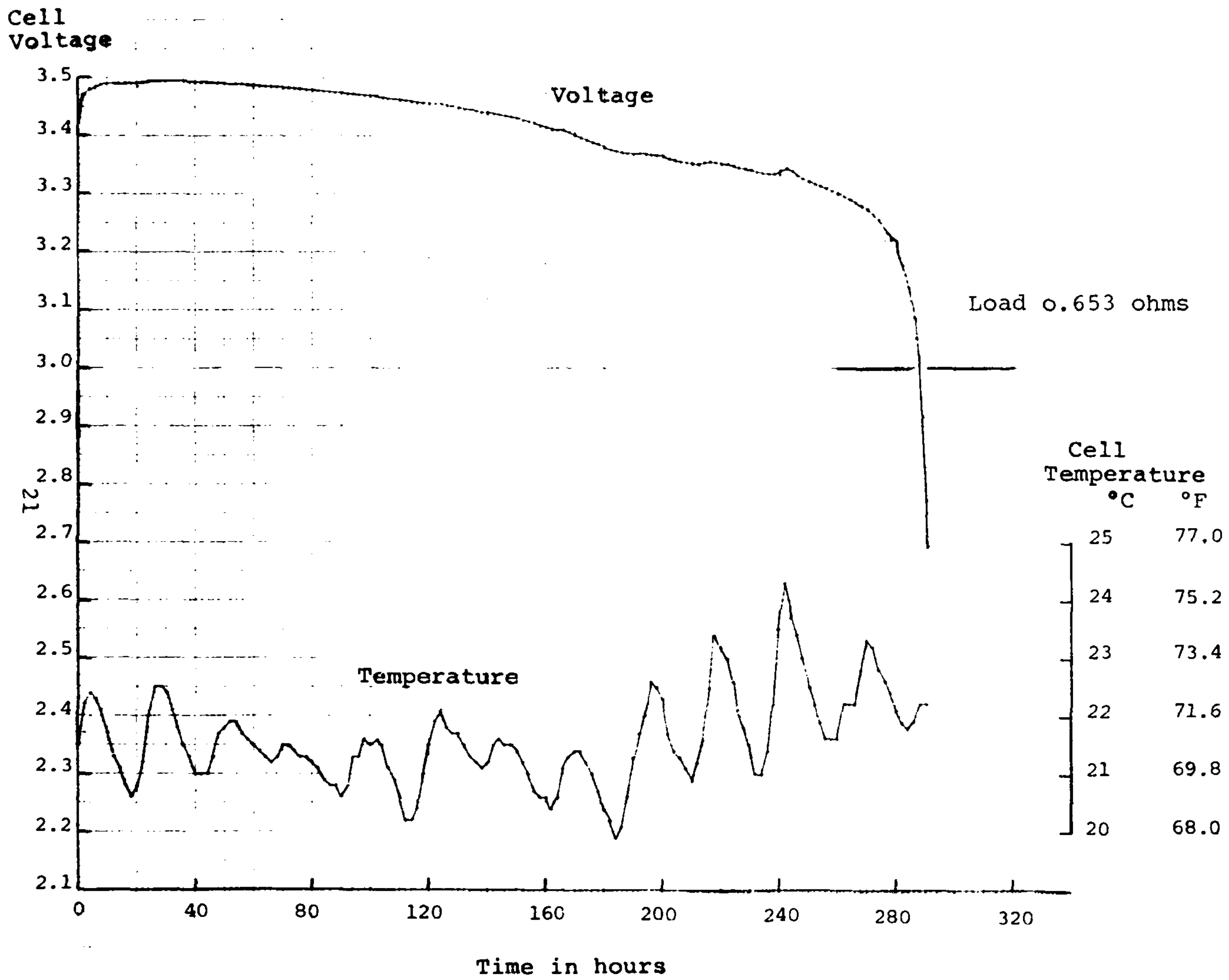


Figure 8. Cell No. 158 Voltage vs. Time and Temperature Under 0.653 OHM Load

TABLE 3

CELL NO. 158 PERFORMANCE DATA

Cell S/N	158
Cell Weight	29.44 lbs.
Load resistance	0.653 ohms
Total hours to 3.0 volts	288.2 hours
Capacity to 3.0 volts	1501 amp-hours
Average current to 3.0 volts	5.21 amps
Average voltage to 3.0 volts	3.400 volts
Average power output to 3.0 volts	17.7 watts
Energy above 3.0 volts	5.1 kwh
Energy density above 3.0 volts	173 wh/lb.
or	16.7 wh/cu. inch
Maximum voltage	3.495 volts
Maximum current	5.35 amps
Minimum current at 3.0 volts	4.59 amps

TEST 4.34 - C/250 DISCHARGE AND FORCED DISCHARGE

Purpose

The purpose of the test was to demonstrate the capacity of the cell operating at a C/250 discharge rate at 70°F. Further, to demonstrate the safety of the cell when forced discharged, with the cell at a reverse potential condition, to an additional 150% of the original capacity to the three volt level. This test significantly exceeds the conditions that might occur within a multi-cell battery system.

Procedure

The cell, S/N 169, was clamped between two metal plates with the bolts torqued, arbitrarily, to 25 foot-lbs. The cell was electrically connected across a regulated power supply with the positive terminal of the power supply connected to the negative (lithium anode) terminal of the cell and the power supply negative terminal connected to the cell positive (carbon cathode) terminal. A 50 mV/50 amp shunt was included in the circuit for current measurement. The cell had been constructed to include a pressure transducer in order to monitor the cell internal pressure throughout the test, and a surface thermocouple to monitor the cell temperature. The Fluke data-logger system tabulated the cell voltage, circuit current, cell temperature and internal pressure at hourly intervals continuously. The power supply was adjusted to deliver 5.38 amps constant current independent of the varying cell voltage. The cell discharge was started and the experiment allowed to proceed for the required term of the test. The cell discharge test was conducted within a temperature controlled chamber for about the first 190 hours and at that point the test was continued with the cell at an uncontrolled 'ambient' temperature.

Results

Figures 9 and 10 show the cell parameters of voltage, pressure, temperature as a function of time. The cell current was constant at 5.38 amps ± 0.04 amps throughout the test and therefore is not plotted. Figure 9 depicts the normal discharge voltage profile from start of test to 1.8 volts over the 285 hour period. The cell displayed an initial 3.465 volt plateau and then steadily dropped to about 3.3 volts before a rapid decline to the 3.0 volt capacity cut-off and a following steeper decline to zero volts.

During the first 190 hours with the temperature controlled to 180° C ± 3°C (64°F ± 6°F) only slight diurnal temperature influence on the cell voltage is preceivable. Once removed from the controlled environment, 30°C (54°F) temperature variations caused significant voltage fluctuations in the cell output in the order of 0.06 volts.

Corresponding daily cycles can be observed in the pressure profile which otherwise shows the rapid drop from the enforced 35 psi clamping pressure to a 2.5 psi operationg value. As the voltage declines rapidly, the pressure internally slowly increases to about 10 psi at zero volts.

The cell achieved a capacity of 1485 amp-hours to 3.0 volts over a 276-hour period with an average cell voltage of

3.40 volts. Within a further 9 hours, the cell voltage fell to 1.0 volts for a further 47 amp-hours expended. The voltage curve between 1.0 volts and zero volts has not been plotted but the data showed less than one hour for this to occur at the continuous 5.38 amp rate.

Figure 10 shows the data plotted for the period commencing with the cell at +0.08 volts and the subsequent reverse voltage condition. The zero on the time axis corresponds to the 386th hour into the discharge test, and the time now represents hours spent below zero volt output for the cell.

The data shows that the cell temperature was constant throughout the reverse-voltage test but for the 20 to 25°C diurnal contributions. The cell internal pressure attained a maximum of about 20 psi after 80 hours of reverse voltage condition and then remained constant. Temperature fluctuations of the ambient environment caused the 15 psi pressure changes within the cell.

The cell voltage fell rapidly from zero volts to -0.085 mV within one hour and from then on maintained a very low negative potential in the 0.06 to 0.08 volt range continuously. The data plotted shows the cell characteristics for 470 hours below zero volts which corresponds to 2518 amp-hours of forced discharge in a negative voltage condition without any indication of potential cell malfunction or safety hazard. In practice, this test was conducted for 826 hours and 4,465 amp-hours with the cell in reverse-voltage mode which demonstrated extreme resistance to reverse-voltage abuse. The electrical data for this test is summarized in Table 4.

TABLE 4

TEST DATA

Cell S/N.	169
Cell Weight (less transducer)	29.63 lbs.
Current	5.38 ± 0.04 amps.
Total hours to 3.0 volts	276 hours
Capacity to 3.0 volts	1485 amp-hours
Total hours to zero volts	286 hours
Capacity to zero volts	1536 amp-hours.
Average voltage to 3.0 volts	3.40 volts
Average power to 3.0 volts	18.3 watts
Energy above 3.0 volts	5.0 Kwh.
Energy density above 3.0 volts	170 wh/lb. or 16.6 wh/cu. inch
Hours discharged in reverse-voltage	826 hours
Amp.-hours expended in reverse-voltage	4,465 amp-hours.
Nominal discharge rate	C/250
Nominal cell temperature	70°F

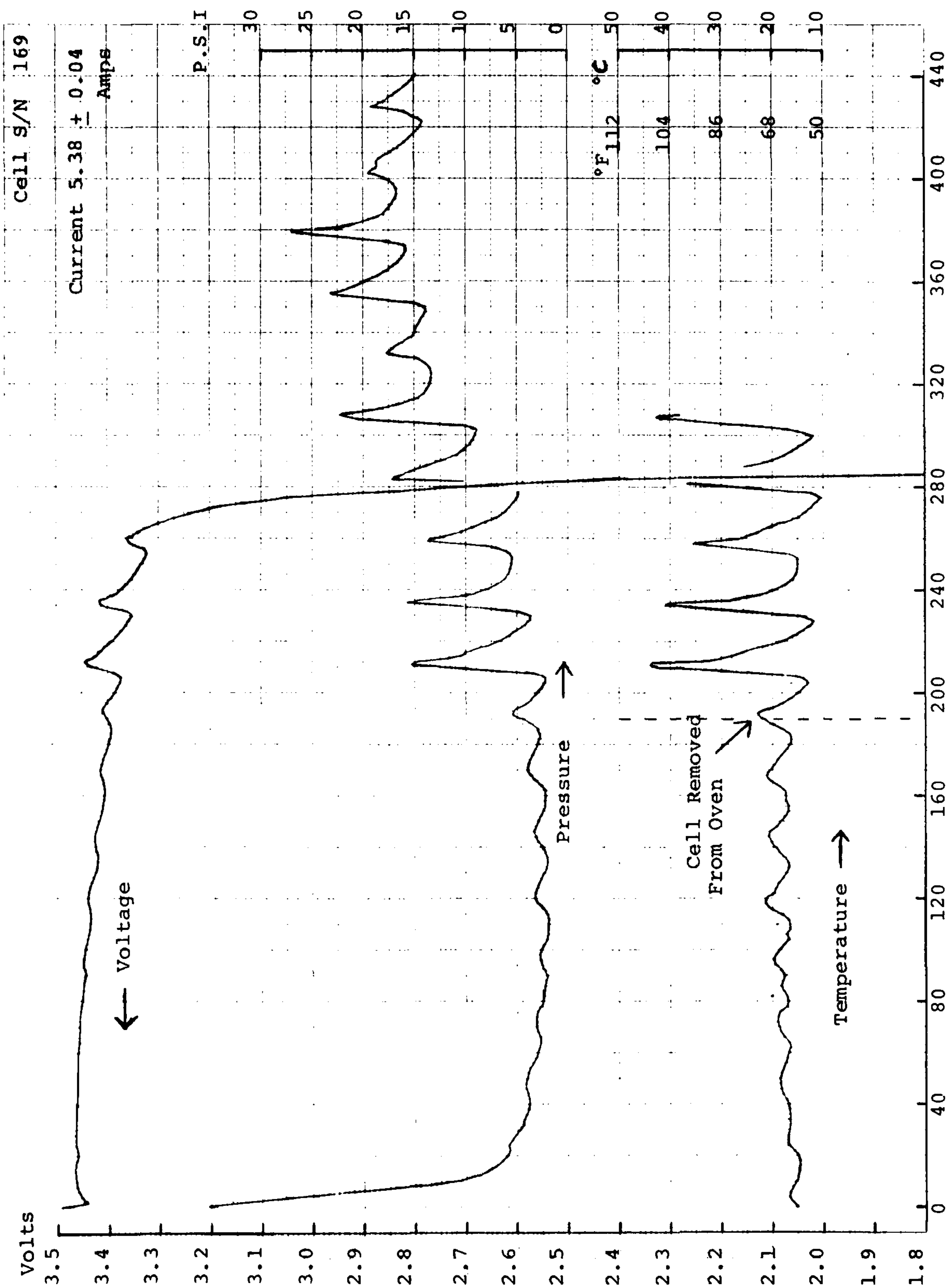


Figure 9. Cell No. 169 Pressure, Temperature, Voltage vs. Time

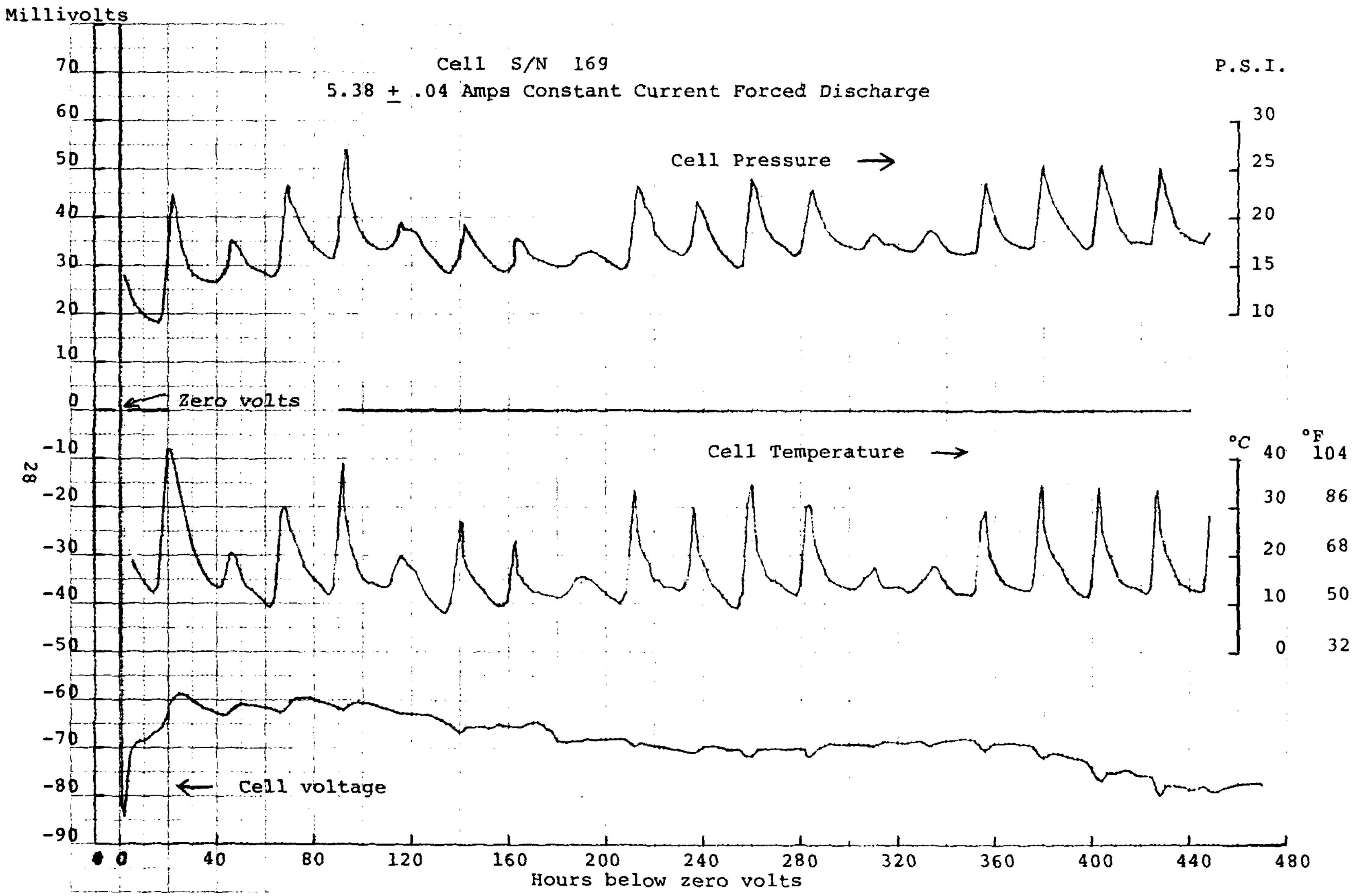


Figure 10. Cell No. 169 Pressure, Temperature, Voltage vs. Time Under Constant Current Forced Discharge

TEST 4.3.5 - C/400, C/200, C/133, C/100 DISCHARGE TESTS

Test Purpose

The purpose of this series of tests is to demonstrate the capacity of the cell at various discharge rates at 70°F.

Test Procedure

Four cells with S/N's 160, 157, 164 and 166, all fitted with pressure transducers, were individually clamped between aluminum plates with 25 ft.-lbs. of torque applied to the bolt-nut components. Each cell assembly was placed in an oven at 70°F and electrical connections to the cell terminals, circuit current shunt, thermocouple, and pressure transducer were made (Figure 11). Each current resistance had previously been adjusted to be that necessary for the particular test requirement.

Nominal Rate	Resistance	Cell Serial No.
C/400	1.025 ohms	160
C/200	0.517 ohms	157
C/133	0.361 ohms	164
C/100	0.252 ohms	166

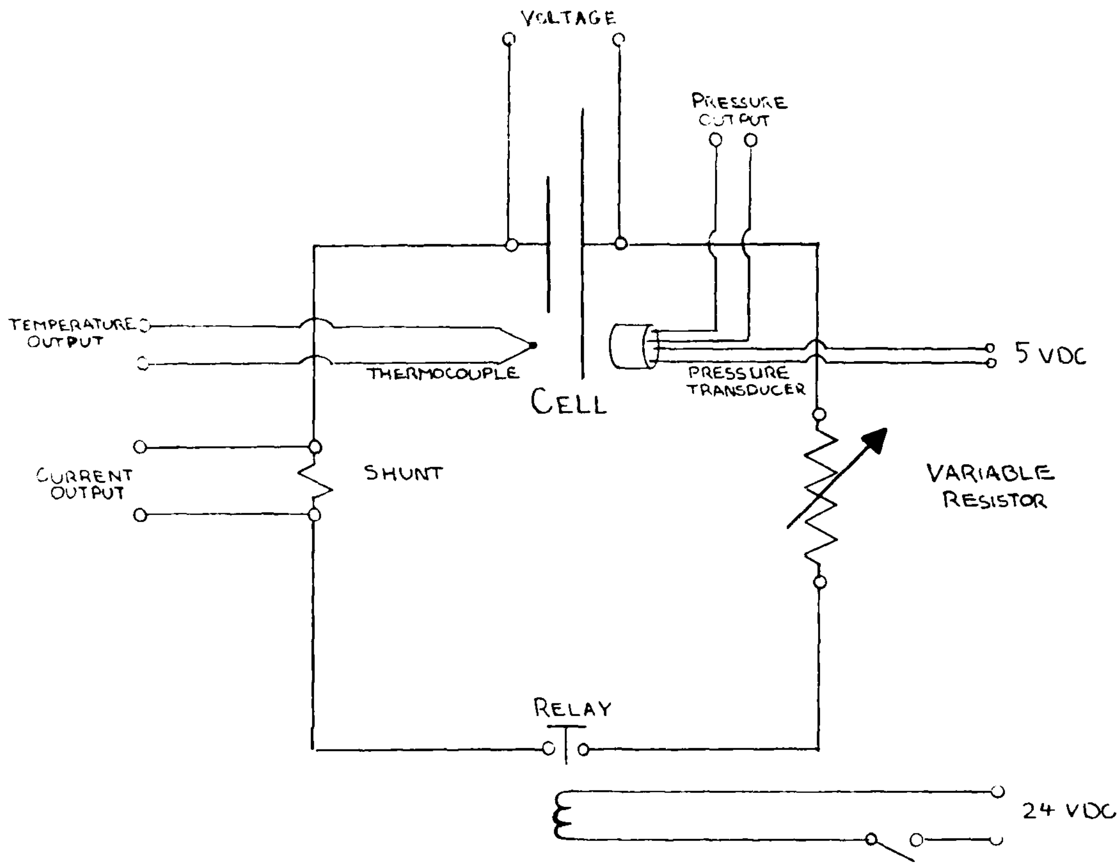


Figure 11. Circuit For Capacity Tests

When the cell assembly had attained 70°F, the circuit relay was energized and the discharge test started. Data was automatically acquired at one hour intervals using a Fluke 2240B datalogger. Data recorded included time, cell voltage, circuit current, cell internal pressure, and cell surface temperature. Each test was terminated when the cell voltage had dropped below 2.0 volts.

Data

4.3.5.1 - C/400 NOMINAL DISCHARGE RATE

Figure 12 is a plot of the performance of cell S/N 160. Curves shown are for cell voltage, cell internal pressure and cell surface temperature as a function of time. The temperature plot shows the influence of the diurnal temperature cycle due to the limited temperature control of the oven and its influence on both cell pressure and voltage are clearly depicted by a vertical time correspondence. The average temperature for the first 350 hours of test is approximately 68°F with a maximum diurnal excursion to 78°F and minimal to 57°F. Loss of temperature regulation from 350

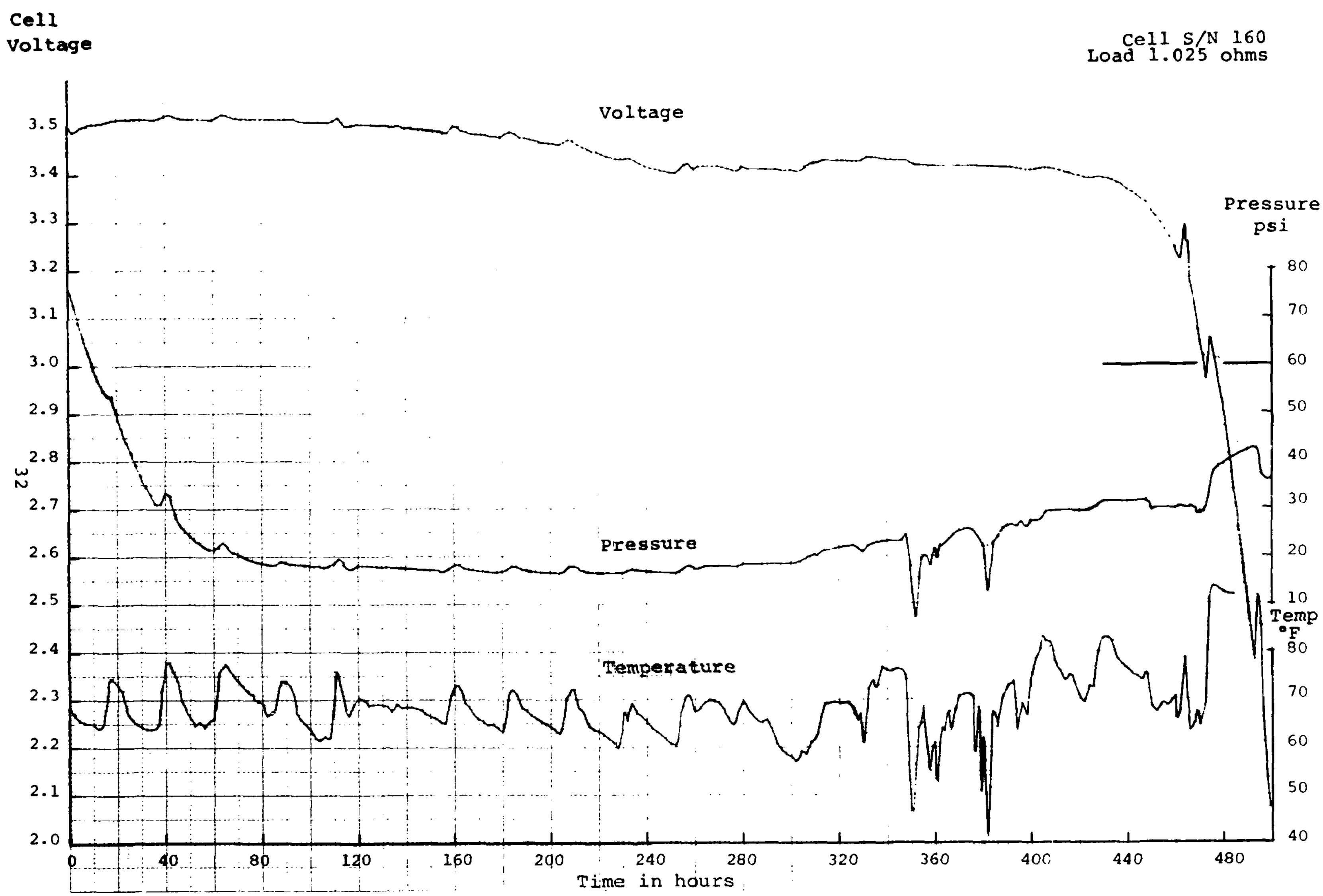


Figure 12. Cell No. 160, Pressure, Temperature, Voltage vs. Time

hours to 400 hours caused some negative temperature spikes to 42°F minimum and a further loss of regulation after 470 hours allowed a temperature increase to 94°F. Both severe temperature fluctuations caused pressure surges within the cell and the corresponding voltage fluctuations in the cell output. In particular, three voltage spikes can be observed on the steep voltage decline.

The cell voltage attained a maximum of 3.525 volts after 64 hours when delivering 3.45 amps and then steadily falls to 3.0 volts after a total of 472 hours of discharge. The voltage profile indicates the presence of two plateaus with the second commencing half way through the discharge test.

The pressure profile showed that the internal "hydraulic" pressure of the electrolyte caused by the clamping of the cell fell rapidly from 76 psi to 19 psi in the first 77 hours of discharge presumably due to the production of more dense discharge products. The pressure then went through a very shallow minimum of 16.4 psi slowly increasing to about 30 psi (at 70°F) as the cell was depleted. It should be noted that the pressure values given are psi above atmospheric pressure and, therefore, are not absolute values.

The cell capacity calculated by integration on an hourly basis totalled to 1584 amp hours for the 472 hours of discharge at an average current of 3.36 amps and average voltage of 3.443 volts. At this discharge rate, the energy density exceeded 180 wh/lb. and attained 18 wh/cu. in. Further characteristics of cell S/N 160 can be found in Table 5. The test was terminated when the cell voltage reached 2.0 volts, the cell having delivered a further 32 amp hours.

4.3.5.2 - C/200 NOMINAL DISCHARGE RATE

Figure 13 shows the voltage, pressure and temperature profiles for cell S/N 157 as a function of time. As in previous tests, the influence of the diurnal temperature cycle on both cell pressure and voltage output under load is evident to the same minor extent. The temperature in this test was maintained at a 70°F average and there is no indication of any thermal contribution from the cell throughout the discharge period. Maximum temperature excursion was to 78.4°F with a minimum temperature of 61.4°F.

The cell internal pressure dropped rapidly from its initial 47.8 psi above atmospheric to a constant pressure of about 15 psi. During the final 1/3 of the cell life, the pressure showed a gradual increase to about 25 psi.

The voltage profile for the cell under constant resistance load of 0.517 ohms attained a broad maximum of 3.486 volts at 6.76 amps and slowly declined to 3.0 volts after 220 hours. Below three volts, the voltage fell rapidly to 2.0 volts within a further 5.5

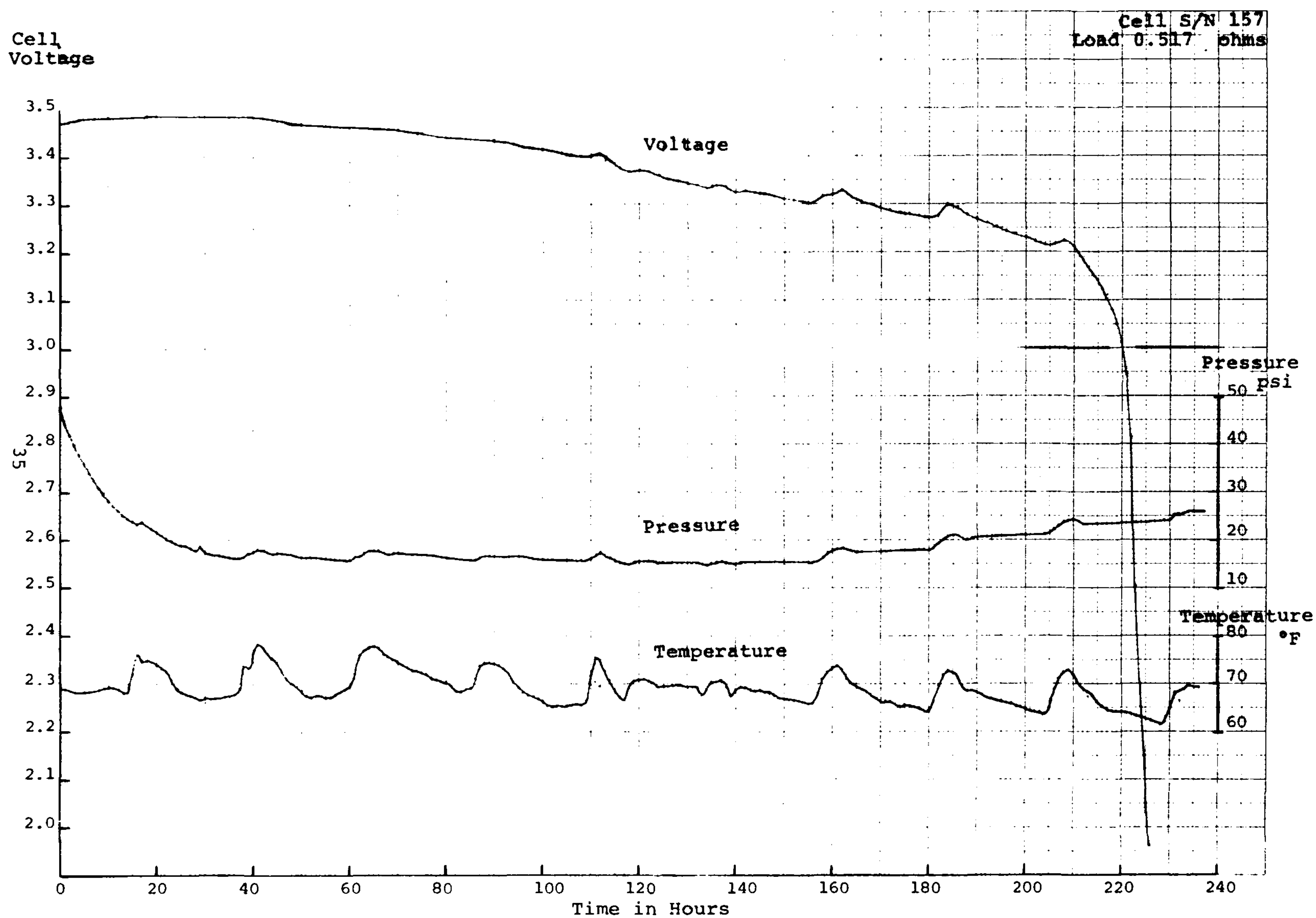


Figure 13. Cell No. 157, Pressure, Temperature, Voltage vs. Time

hours to yield a further 21 amp hours when the test was terminated.

The capacity for this cell totalled 1434 amp hours to 3.0 volts delivering an average current of 6.52 amps. Other performance data is given in Table 5 on Page 41.

4.3.5.3 - C/133 NOMINAL DISCHARGE RATE

The voltage, pressure and temperature characteristics for cell S/N 164 are plotted in Figure 14.

The temperature control of the oven in this test was less than desired mostly due to poor weather conditions and power outages during this period of testing. The mean temperature was about 70°F with a maximum excursion to 84°F and a minimum to 50.5°F.

The effect of the initial clamping pressure of 72.3 psi above atmospheric rapidly disappeared and the cell operated at an internal pressure of 16 psi to the 100th hour when the pressure slowly increased to 30 psi at the 3.0 volt cut-off level.

The cell discharged through a constant resistive load of 0.362 ohms, delivering an average current of 9.20 amps with a maximum drain of 9.48 amps at 3.415 volts. The voltage profile displayed a steady decline to 3.0 volts when the voltage dropped rapidly to

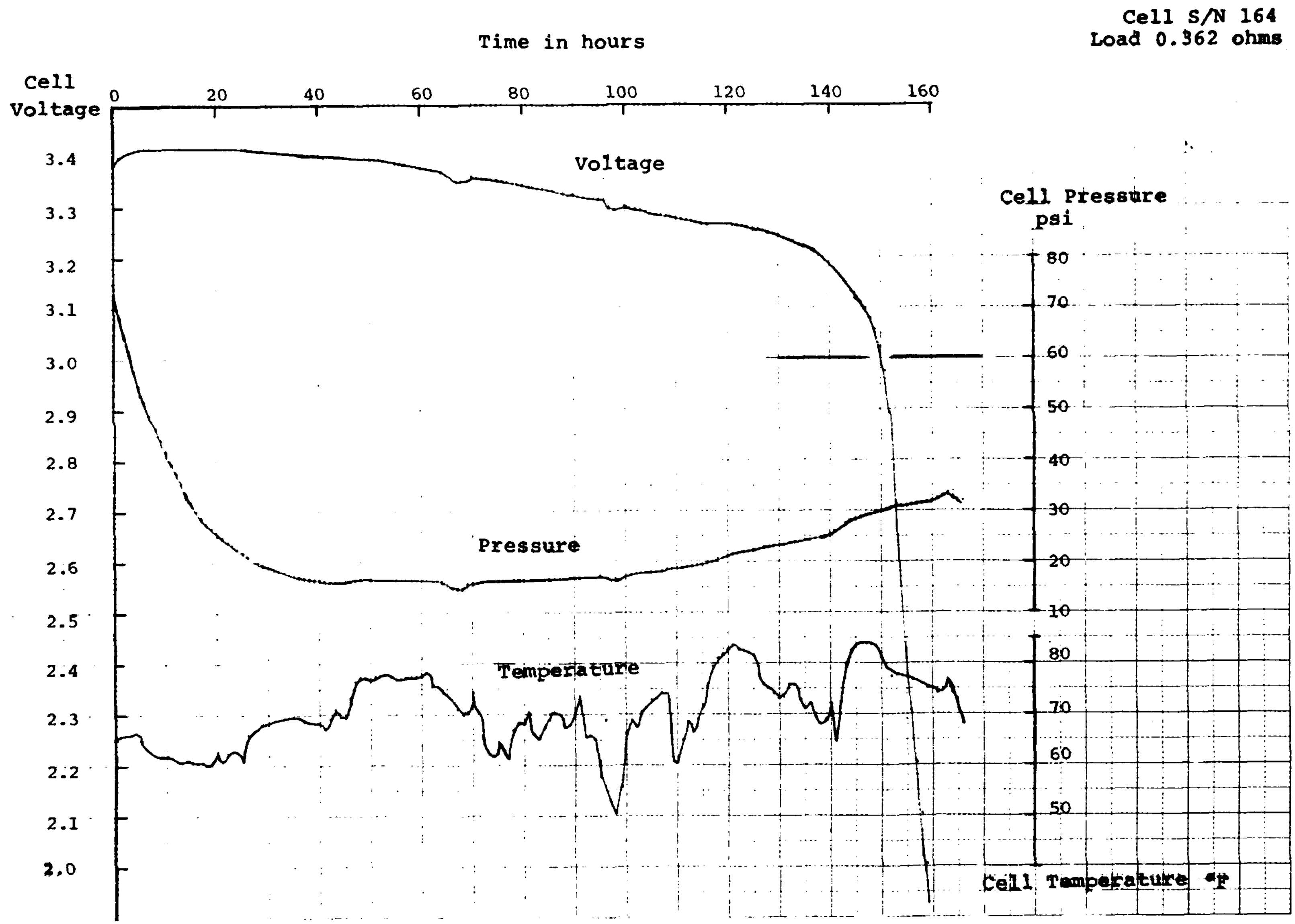


Figure 14. Cell No. 164, Pressure, Temperature, Voltage vs. Time

below 2.0 volts and the test was terminated. The small 0.02 volt discontinuities correspond to temperature fluctuations in the test environment, as do the similar 1 to 2 psi internal pressure changes.

Integration of the hourly data provides a total capacity of 1380 amp hours for the 150 hours of discharge to 3.0 volts. Only 68 amp hours further capacity was delivered between 3.0 and 2.0 volts confirming that a 3.0 volt cut-off is a good selection at 70°F temperature. Table 5 shows further data for this test.

4.3.5.4 - C/100 NOMINAL DISCHARGE RATE

The performance curve for cell S/N 166 discharged through 0.252 ohms resistance load are shown in Figure 15.

The environmental temperature as measured by the thermocouple at the cell outer surface assumed diurnal variations from 66°F to 73°F about the nominal 70°F for this test.

The cell internal pressure dropped rapidly from the initial clamping pressure of 104.3 psi to a minimum operating pressure of 16.4 psi with a gradual increase to 18.8 psi at the 3.0 volt cut-off.

The cell voltage attained its maximum plateau of 3.39 volts after five hours and then fell steadily to the 3.0 volt level. The

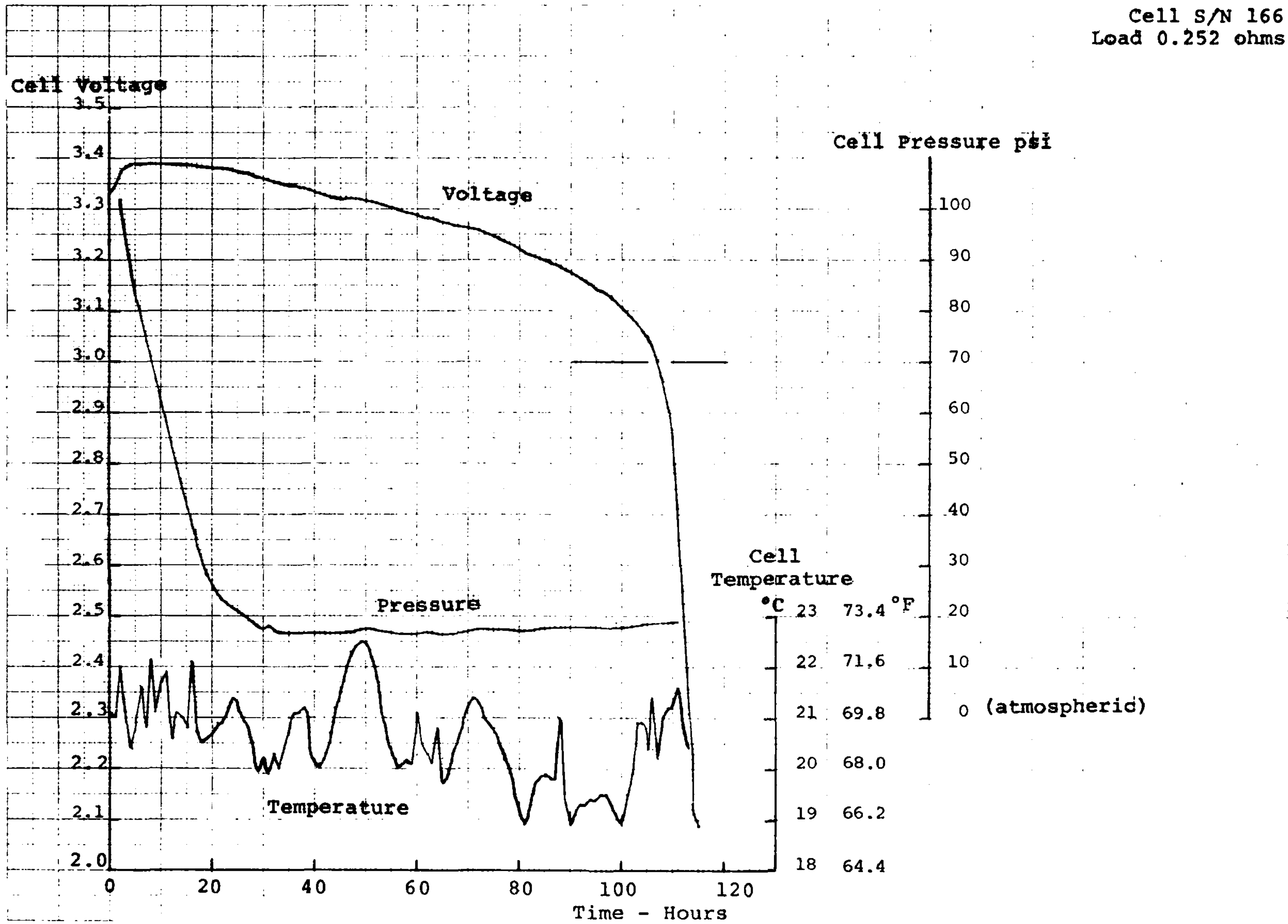


Figure 15. Cell No. 166, Pressure, Temperature, Voltage vs. Time

average current to three volts was 13.01 amps with a 13.48 amp maximum and a lowest value at 3.0 volts of 11.93 amps. Capacity integration yields 1394 amp hours above 3.0 volts during the 107 hours of discharge. The data is compiled in Table 5.

TEST 4.3.6 - C/100 DISCHARGE TEST AT 110°F AND 40°F

Test Purpose

The purpose of this test is to demonstrate the capacity of the cell at a C/100 nominal discharge rate at two selected temperatures of 40°F and 110°F.

TEST 4.3.6.1 - 110°F, C/100

Test Procedure

Cell S/N 163 was clamped to 25 foot-lbs. of torque applied to the bolts securing the cell between two aluminum plates and the internal pressure of the cell noted to be 82.7 psi at ambient temperature. The cell assembly was then placed in an oven and the temperature raised to 110°F. The cell was electrically connected into its discharge circuit and the cell voltage, circuit current, thermocouple and pressure transducer, fully instrumented. The cell was soaked at 110°F for 47 hours before the discharge test

TABLE 5

PERFORMANCE DATA, FOUR DISCHARGED CELLS

Test	4.3.5.1	4.3.5.2	4.3.5.3	4.3.5.4
Nominal Rate	C/400	C/200	C/133	C/100
Cell S/N	160	157	164	166
Cell Weight (less pressure transducer)	29.7 lbs.	29.3 lbs.	29.3 lbs.	30.2 lbs.
Load resistance	1.025 ohms	0.517 ohms	0.362 ohms	0.252 ohms
Total hours to 3 volts	472 hrs.	220 hrs.	150 hrs.	107 hrs.
Capacity to 3 volts	1584 amp-hrs.	1434 amp-hrs.	1380 amp-hrs.	1394 amp-hrs.
Average current to 3 volts	3.36 amps	6.52 amps	9.20 amps	13.01 amps
Average voltage to 3 volts	3.443 volts	3.371 volts	3.332 volts	3.282 volts
Average power to 3 volts	11.6 watts	22.0 watts	30.7 watts	42.7 watts
Energy above 3 volts	5.45 kwh	4.83 kwh	4.60 kwh	4.58 kwh
Gravimetric energy density to 3 volts	183 wh/lb.	165 wh/lb.	157 wh/lb.	152 wh/lb.
Volumetric energy density to 3 volts	17.9 wh/in^3	15.9 wh/in^3	15.1 wh/in^3	15.0 wh/in^3
Maximum voltage	3.525 volts	3.486 volts	3.415 volts	3.390 volts
Maximum current	3.45 amps	6.76 amps	9.48 amps	13.48 amps
Nominal temperature	70°F	70°F	70°F	70°F

was started causing the cell pressure to increase to 124.7 psi. The datalogger system recorded the four sets of data every hour until the test was terminated at a voltage below 3.0 volts.

Data

Figure 16 shows the plots of voltage, pressure and temperature for this test using cell S/N 163.

The temperature shows fluctuations about the required 110°F with a maximum recorded temperature of 116°F and a brief minimum of 90°F. These excursions transmit their effect to a minor extent in both the pressure and voltage profiles. In particular, at the 50th hour, a drop of 14°F contributed to a 4 psi change in cell pressure and a voltage fluctuation of about 0.01 volts.

The cell internal pressure behaved normally and showed the rapid decline from initial 124.7 psi to a 38 psi plateau and then a gradual increase to 43 psi at 3.0 volts.

The cell was discharged through a resistive load of 0.268 ohms and the resultant voltage profile attained a maximum of 3.426 volts slowly dropping to the 3.0 volt cut-off value and then a rapid decline to 2.0 volts within a further three hours. The average current delivered over the 109.3 hours to 3.0 volts, was 12.48 amps. The integrated capacity over the discharge period to three volts

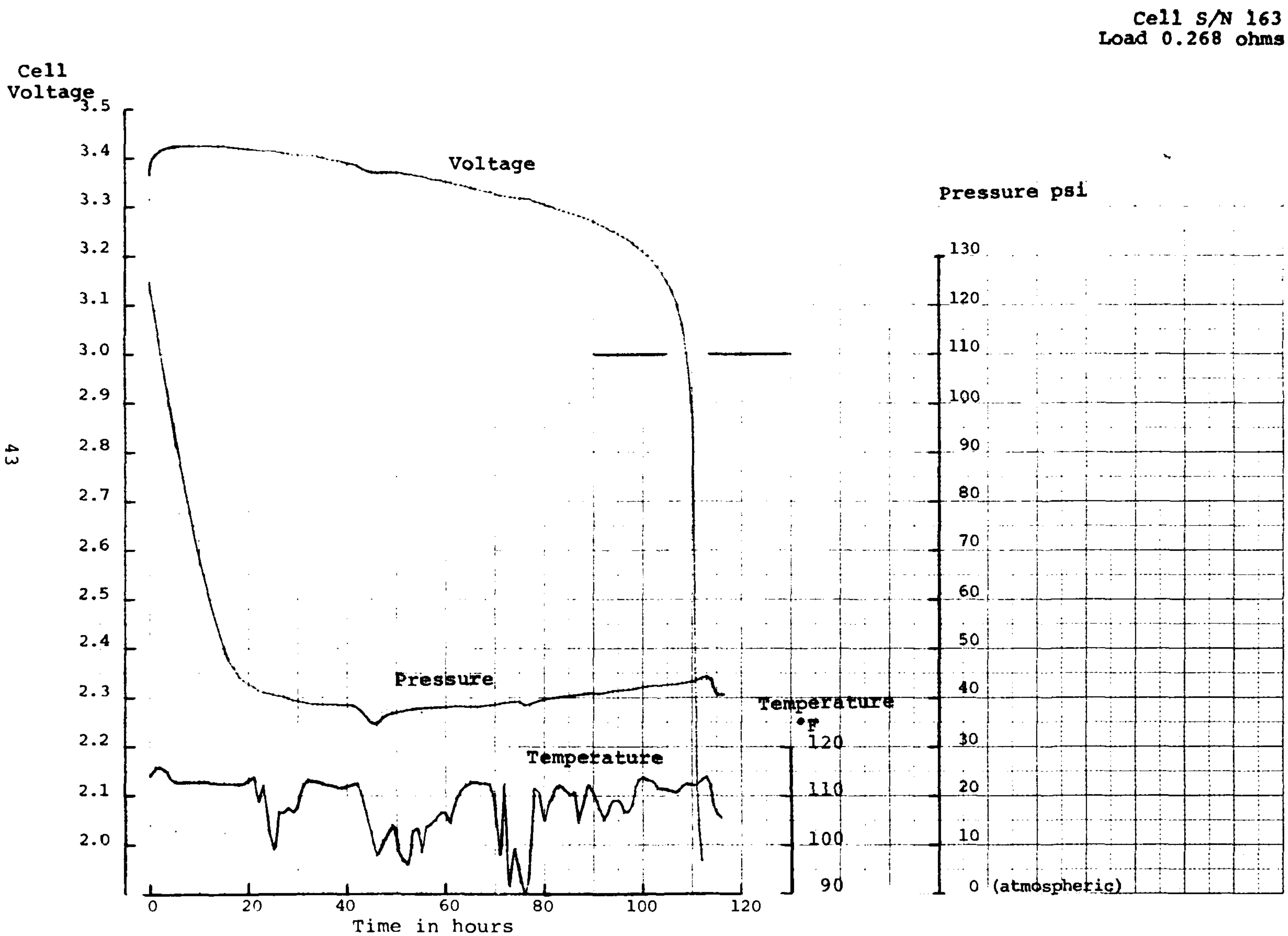


Figure 16. Cell No. 163, Pressure, Temperature, Voltage vs. Time
High Temperature
Discharge

totals 1364 amp hours with only a further 26 amp hours residing in the three volt to two volt tail.

Further data is supplied in Table 6.

TEST 4.3.6.2 - 40°F, C/100

Test Procedure

Cell S/N 168 was clamped to 25 ft. lbs. of torque applied to the bolts securing the cell between two flat aluminum plates and the internal pressure of the cell increased from atmospheric by 65.5 psi. The cell was connected into the discharge circuit and placed in a 40°F freezer for 21 hours of soaking at that temperature, prior to commencing the discharge test through a resistive load of 0.239 ohms. Due to the lowering of the cell temperature, the internal pressure dropped to 17.8 psi prior to start of discharge.

Data

Three of the test parameters monitored during cell discharge are plotted in Figure 17.

The temperature regulation at 4.5°C ± 1.5°C (40°F ± 3°F) was very good. The pressure curve shows the monatonic decrease from 17.8 psi to 3.5 psi as the discharge proceeded.

TABLE 6

PERFORMANCE DATA, HIGH AND LOW TEMPERATURE DISCHARGE

Test #	4.3.6.1	4.3.6.2
Cell S/N	163	168
Test temperature	110°F	40°F
Nominal rate	C/100	C/100
Cell weight (less pressure transducers)	29.06 lbs.	29.90 lbs.
Load resistance	0.268 ohms	0.239 ohms
Total hours to 3 volts	109.3 hrs.	54.2 hrs.
Capacity to 3 volts	1364 amp-hrs.	716 amp-hrs.
Average current to 3 volts	12.48 amps	13.20 amps
Average voltage to 3 volts	3.341 volts	3.155 volts
Average power to 3 volts	41.7 watts	41.6 watts
Energy above 3 volts	4.56 kwh	2.26 kwh
Gravimetric energy density to 3 volts	157 wh/lb.	76 wh/lb.
Volumetric energy density to 3 volts	15.0 wh/in^3	7.4 wh/in^3
Maximum voltage	3.426 volts	3.311 volts
Maximum current	13.23 amps	13.78 amps

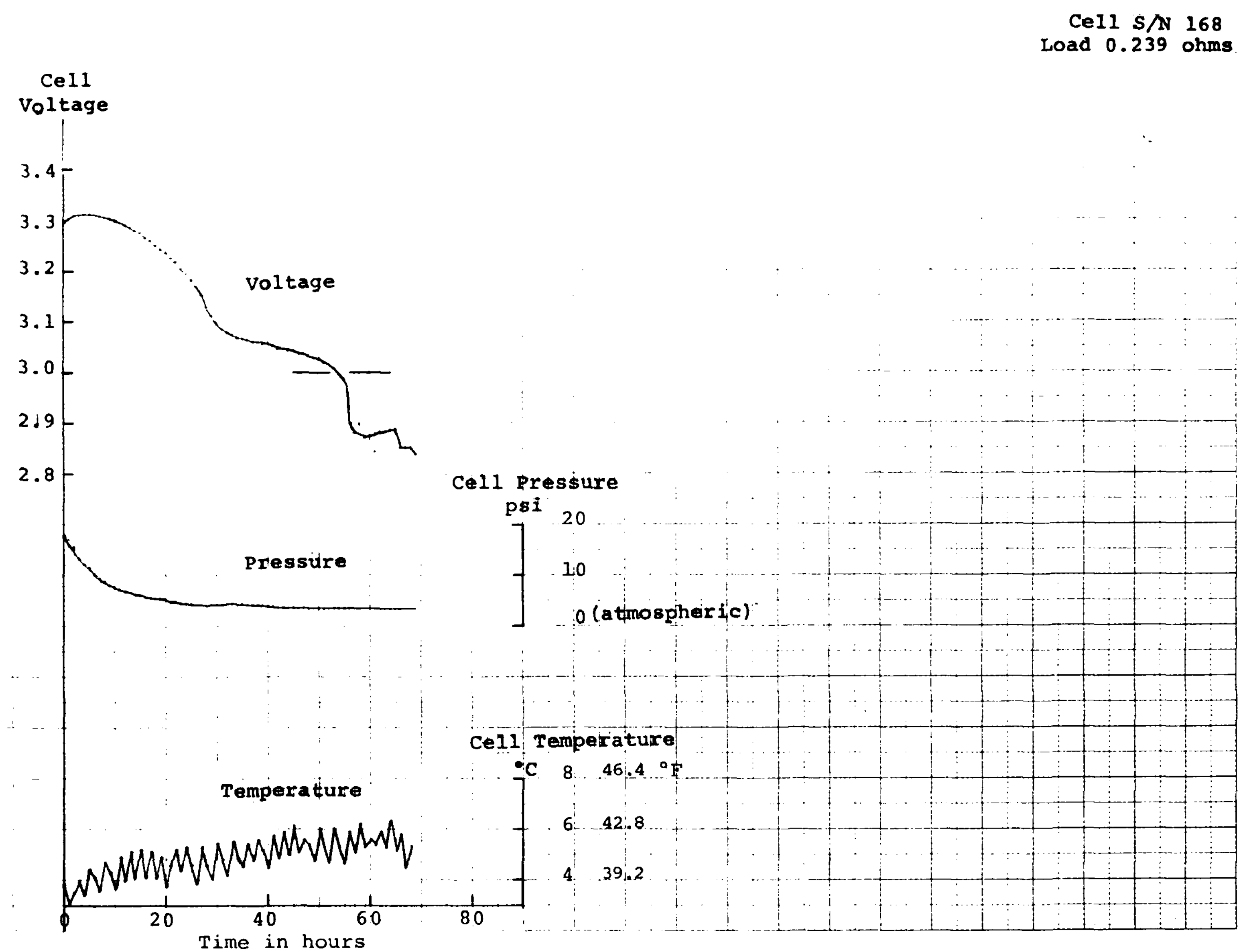


Figure 17. Cell No. 168, Pressure, Temperature, Voltage vs. Time, Low Temperature Discharge

The cell voltage fell rapidly from a 3.31 volt maximum at 13.8 amps to the 3.0 volt level 54.2 hours into the test. The average current during the test period was 13.20 amps and the average voltage 3.155 volts. The capacity to three volts totalled only 716 amp hours at this lower temperature and high current rate.

The results are tabulated in Table 6.

TEST 4.3.7 - CURRENT CYCLE DISCHARGE TESTS

Test Purpose

The purpose of this test is to demonstrate the effect of a varying load profile on the performance of the cell.

Test Procedure

Cell S/N 159 was clamped between aluminum plates to a final torque of 25 ft.-lbs. on the bolt-nut components. The cell was placed in an oven at 70°F and electrical connections were made. The load cycling apparatus consisted of a cam-timer which switched power on and off to the three load relays and their respective loads, each of which had been previously adjusted to give nominal C/133, C/200 and C/400 rates respectively.

Data

The voltage and temperature data for cell S/N 159 is given in plotted form in Figure 18.

The voltage curve displays the changes in voltage every three hours when the cell switches from one resistive load to another. The three loads were 0.970, 0.507 and 0.331 ohms. The highest voltage segments correlate to the highest resistance load and the lowest circuit current. The cycle commenced with the 0.970 ohm load, then 0.507 ohms, followed by 0.331 ohms and then continuously repeated. Total cycle time was 9.0 hours with 3.0 hours spent at each load.

Into the 0.970 ohm load, the cell attained a maximum voltage of 3.53 volts and completed 23 full cycles of three hours each. The integrated capacity totalled 245.6 amp hours for the 69 hours under test at this load. The average current and voltage during this time were 3.56 amps and 3.454 volts respectively which represents an average power delivery of 12.3 watts. A total of 848 watt hours of energy were expended into the 0.97 ohm load.

During the discharge through the 0.507 ohm load, the cell reached a maximum of 3.465 volts and yielded 458.9 amp hours of capacity during the 23 full test cycles of three hours each duration. The average current, voltage and power during the 69 hours at this

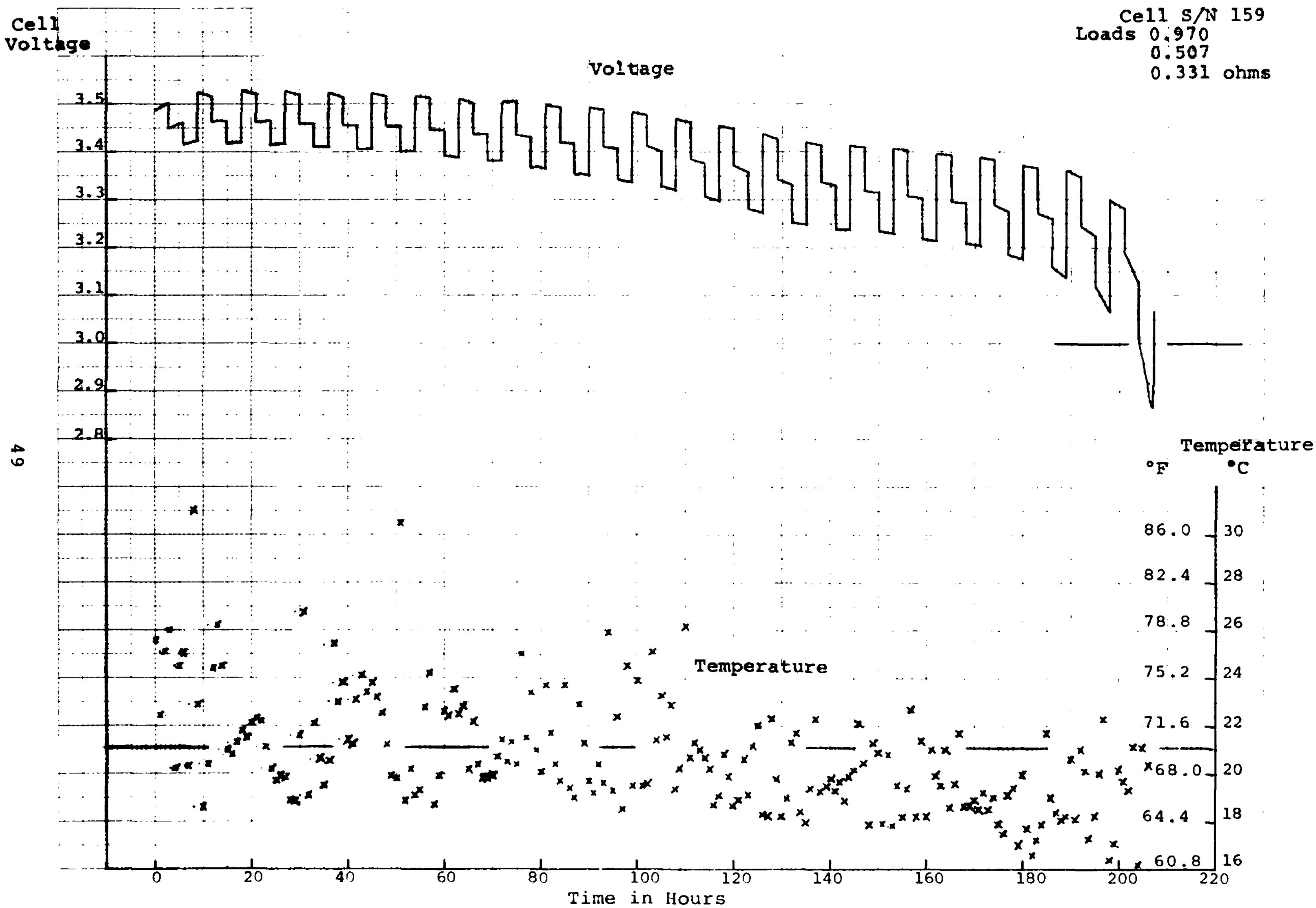


Figure 18. Cell No. 159, Cycle Load Discharge, Voltage and Temperature vs. Time

load were 6.65 amps, 3.372 volts and 22.4 watts respectively. A total energy of 1547 watt hours were expended at this rate.

The highest discharge rate through 0.331 ohms gave a maximum voltage of 3.42 volts and slowly declined to 3.0 volts after 204 total hours of testing. Capacity integration yields 659.7 amp hours for the 22 full cycles of three hours each duration. The average current, voltage and power during the 66 hours on the 0.331 ohm load were 10.00 amps, 3.307 volts and 33.06 watts respectively. 2182 watt-hours of energy were expended during this part of the cyclic test.

The total capacity to 3.0 volts for this cyclic discharge test totalled 1364 amp hours for the 204 hours. The average current and voltage were 6.69 amps and 3.379 volts which represents an average load of 0.505 ohms. The energy output of the cell to the first drop below 3.0 volts was 4.58 kwh.

The temperature recorded each hour by the thermocouple is plotted in Figure 18 and shows a scatter of data points about the 21°C (70°F) line. Temperature control is about ±5°C (±9°F). Since this cell S/N 159 as placed in the same oven as cell S/N 166 and both tests commenced at the same time, one can refer to the temperature data of Figure 15 and observe the diurnal cycles with greater clarity.

Further computations of the data for this test are shown in Table 8.

TABLE 7

CELL NO. 169, TOTAL EFFECT OF CYCLIC DISCHARGE

Cell S/N 159 Test 4.3.7	0.970 ohm cycle	0.507 ohm cycle	0.331 ohm cycle	Total effect of cyclic discharge
Total hours on discharge	69	69	66	204
Capacity	245.6 amp-hrs.	458.9 amp-hrs.	659.7 amp-hrs.	1364 amp-hrs.
Average current	3.56 amps	6.65 amps	10.00 amps	6.69 amps
Average voltage	3.45 volts	3.37 volts	3.31 volts	3.38 volts
Average power	12.3 watts	22.4 watts	33.1 watts	22.6 watts
Energy delivered	848 watt-hrs.	1547 watt-hrs.	2182 watt-hrs.	4.58 kwh to 3 volts
Gravimetric energy density to 3.0 volts	-	-	-	158 watt-hours per pound
Volumetric energy density to 3.0 volts	-	-	-	15.0 watt-hrs. per cu. inch
Maximum voltage	3.53 volts	3.47 volts	3.42 volts	3.53 volts
Average load resistance	0.970 ohms	0.507 ohms	0.331 ohms	0.505 ohms
Nominal temperature	70°F	70°F	70°F	70°F

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TEST 4.3.8 - PERIODIC DISCHARGE AT C/250

Test Purpose

The purpose of this test is to demonstrate the capacity of the cell during operational circumstance where the cell is discharged for a period of time, then allowed to remain in a standby condition for two weeks before discharging again.

Test Procedure

Cell S/N 152 was clamped between two flat plates held together with bolts and nuts torqued down to 25 foot-lbs. The electrical circuit for discharge is similar to previous discharge tests. The cell in this test was not instrumented for pressure measurement. The cell voltage, circuit current and cell surface temperature were monitored and recorded by the data-logger at hourly intervals until the cell voltage dropped to 2.2 volts at which time the test was terminated. The cell was discharged through a constant resistive load of approximately 0.64 ohms from one discharge cycle test to another. The objective of the electrical circuit was to cause an average discharge current of 5.4 amps over the entire test to the 3.0 cell voltage cut-off.

The cell during this test was not placed in a temperature controlled environment but assumed ambient temperature of 40 to 68°F. The objective of the test was to subject the cell to a C/250 discharge rate until about 20% of its capacity is removed after about 50 hours and then disconnect the cell from the load for a two week period. Following the storage period, the cell was to be further discharged at the same C/250 rate until a further 20% capacity is removed and then stored at open circuit condition for an additional two weeks. This process was to be repeated until the cell voltage dropped below the three volt level. The test objectives were adhered to closely.

Data

Figure 19 shows the voltage and cell surface temperature throughout the discharge periods of the test. Six test cycles were completed before the cell voltage steadily dropped to below three volts. The effect of the diurnal temperature variations are exhibited in the voltage profile especially as the cell is depleted. The cell voltage varies approximately 2.5 mV per °F temperature change.

The discharge cycles were as follows:

Cycle I:

Discharged	49.1 hours
Stored	17 days
Capacity	270.6 amp-hours
Average current	5.51 amps
Average voltage	3.474 volts

Cycle II:

Discharged	49.8 hours
Stored	14 days
Capacity	265 amp-hours
Average current	5.32 amps
Average voltage	3.422 volts

Cycle III:

Discharged	52.0 hours
Stored	19 days
Capacity	274.9 amp-hours
Average current	5.29 amps
Average voltage	3.349 volts

Cycle IV:

Discharged	50.2 hours
Stored	14 days
Capacity	250.8 amp-hours
Average current	5.00 amps
Average voltage	3.281 volts

Cycle V:

Discharged	56 hours
Stored	12 days
Capacity	295.1 amp-hours
Average current	5.27 amps
Average voltage	3.285 volts

Cycle VI:

Discharged	22.9 hours
Test complete	3.0 volts
Capacity	107.1 amp-hours
Average current	4.68 amps
Average voltage	3.186 volts

The total effect of the periodic discharge was to deliver a total capacity of 1464 amp-hours during the 280 hours on load and within the 85 days test period. The results of this test can be compared directly with test 4.3.3 in which a similar cell was discharged continuously at a similar C/250 rate. The differences in cell performance are negligible. Continuous discharge gave 1501 amp-hours compared to 1464 for periodic discharge. The 2% drop in capacity probably resulted from the significantly lower average temperature of the periodic discharge test. The temperature difference in the two tests is thought to be the dominant effect in lowering the average voltage 3.400 volts in test 4.3.3 to 3.346 volts in this test.

The total energy, gravimetric and volumetric energy densities at C/250 are unaffected by the periodic discharge and are 4900 watts, 166 watt-hours per pound and 16.1 watt-hours per cubic inch respectively as shown in the compiled data of Table 4.3.8.

TABLE 8

CELL NO. 152, PERIODIC CYCLE DISCHARGE DATA

	Cycle 1 (I)	Cycle 2 (II)	Cycle 3 (III)	Cycle 4 (IV)	Cycle 5 (V)	Cycle 6 (VI)	Total Result
Nominal Rate Temperature Cell S/N	C/250 7.5 to 17°C -	C/250 10 to 16.5°C -	C/250 6.5 to 15°C -	C/250 5 to 14°C -	C/250 11 to 20°C -	C/250 18 to 20°C -	C/250 5 to 20°C -
Cell weight (lbs)	-	-	-	-	-	-	29.5
Load resistance (ohms)	0.63	0.64	0.63	0.66	0.62	0.68	0.64
Hours on discharge	49.1	49.8	52.0	50.2	56.0	22.9	280
Subsequent Storage *period*	17 days	14 days	19 days	14 days	12 days	Test Complete	-
Capacity (amp-hrs)	270.6	265.0	274.9	250.8	295.1	107.1	1463.5
Average current (amps)	5.51	5.32	5.29	5.00	5.27	4.68	5.23
Average voltage	3.474	3.422	3.349	3.281	3.285	3.186	3.346
Average power (watts	19.1	18.2	17.7	16.4	17.3	14.9	17.5
Energy (watt-hrs)	940	907	921	823	969	341	4900
Gravimetric energy density (watt-hrs/lb)	-	-	-	-		-	166
Volumetric energy **density** (watt-hrs/cu inch)	-	-	-	-	-	-	16.1

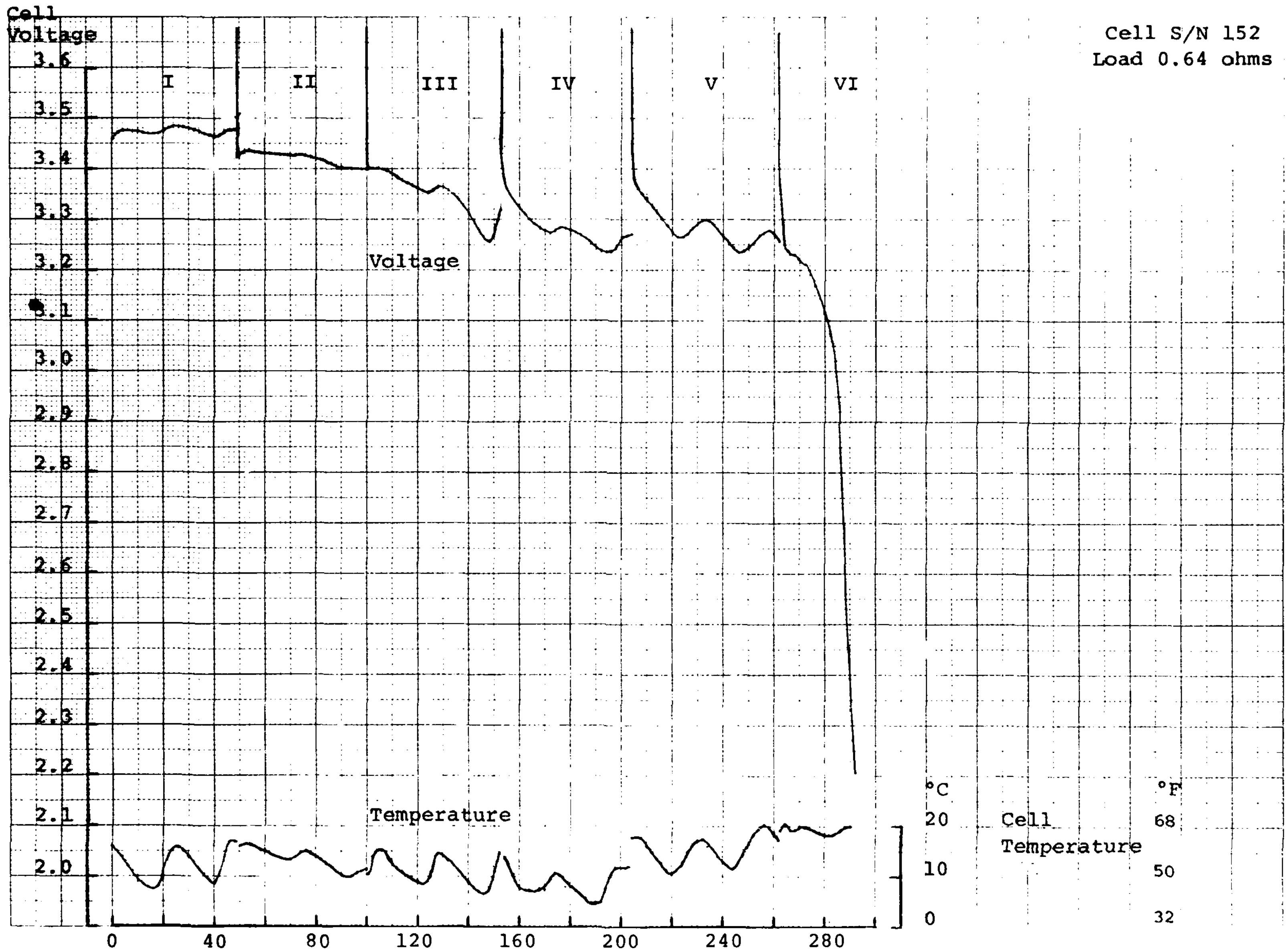


Figure 19. Cell No. 152, Periodic Cycle, Voltage and Temperature vs. Time

Test Conclusions

The cell discharge tests 4.3.3 through 4.3.8 demonstrate the high performance characteristics of the Altus lithium-thionyl chloride cell. In particular features such as the inherent high energy density, the stable output voltage with a slow monatonic decrease from 3.4/3.5 down to 3.0 volts, and the low internal cell pressure attributed to very low generation of gaseous discharge products, are brought out. It should be noted that the small (millivolt) voltage fluctuations in the discharge profiles which correspond to the dicernal temperature cyles are not totally due to changes of load resistance with temperature. Calculations show that only 50% of the voltage fluctuation is in general due to load variation and the remaining change is an electrochemical contribution. The constant current condition of test 4.3.4 demontrates the true temperature effect on the cell output voltage since here the load varies only slowly with time and does not change appreciably with temperature.

Typically there is no voltage delay when the cell is put on load and the operating voltage is achieved instantly as can be shown by comparing the voltage expected for the intended current from the polarization curve with the starting voltage of the discharge profile. The cell voltage does further increase under load by 10-20 mV during the first 5-10 hours of operation as the internal cell resistance decreases slightly.

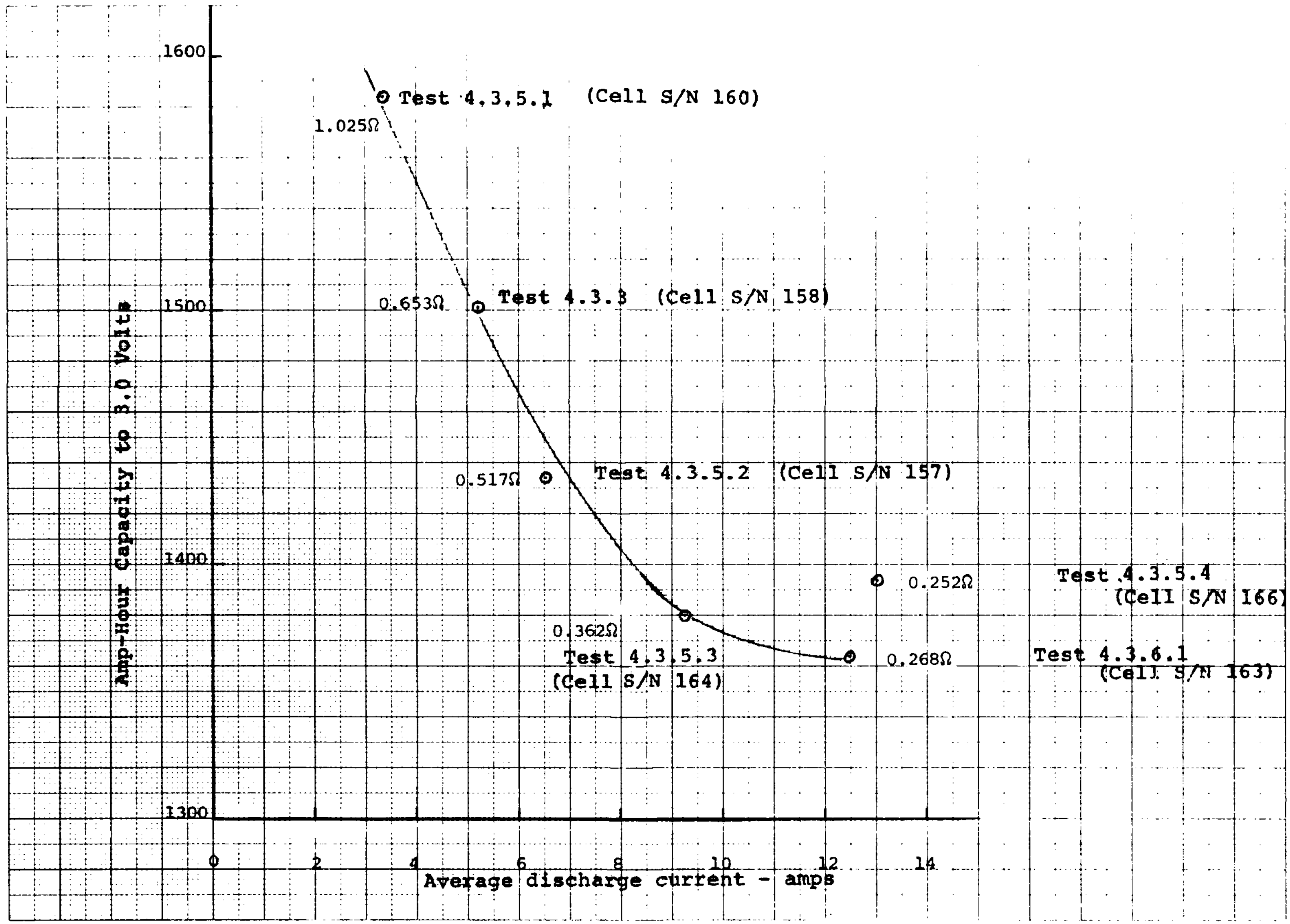


Figure 20. Capacity vs. Average Discharge Current

Figure 20 is a plot of the capacity values of the cell attained at the various discharge rates above 70°F and it is evident that a high capacity of 1584 amp hours is achievable at a rate of C/400 at 3.4 amps and this value is only slightly reduced to the range 1364 to 1394 amp hours at C/100 and 12.5 to 13.0 amps.

The energy density of the cell displayed a high of 183 watt hours per pound and 17.9 watt hours per cubic inch for the 3.4 amp discharge rate which corresponds to an internal energy density (heavy steel case not considered) of 347 watt hours per pound and 21 watt hours per cubic inch.

The effect of raising the temperature to 110°F during discharge or pre-soaking at 150°F appears to have little or no effect on the cell performance compared to that expected at 70°F. Comparison of the sets of data at C/100 (13 amps) from test 4.3.6.1 at 110°F (Page 45) and test 4.3.5.4 at 70°F (Page 41) show excellent agreement for the capacities 1364 amp hours, 1394 amp hours, and energy available 4.56 KWH, 4.58 KWH at 110°F and 70°F respectively.

However, lowering the temperature to 40°F during discharge caused a surprisingly poor cell performance with a capacity of only 716 amp hours compared with the anticipated 880 amp hours which has been achieved as an average of previous tests on similar cells at 12 amps discharge current at 32°F. The 3.0 volt cut-off for low temperature operation is a significant constraint on capacity and a figure of 2.7 volts usually permits a capacity of 1130 amp hours to be extracted from the cell before rapid voltage decay. The low total energy output at 40°F is compounded by both the low capacity, cut-off voltage constraint and low average cell voltage of about 3.1 volts. It should also be noted that this cell design was not optimized for low temperature operation.

The current cycle test (4.3.7) in which the load was varied continuously yielded 1364 amp hours capacity compared to the 1434 amp hours for a similar average current of 6.5 amps in test 4.3.5.2. The difference of 70 amp hours probably would have been recovered above the 3.0 volt level of the cycle test had been allowed to continue, since the cell voltage for two of the loads was still above 3.0 volts at the termination of the test. The varying load condition tested appears to have little effect on predicted cell performance compared to steady discharge.

The three data sets from cells tested at C/250 in test 4.3.3, (Page 22), test 4.3.4 (Page 26) and test 4.3.8 (Page 56) show very close agreement in electrical performance despite the varying test conditions.

Test	4.3.3	4.3.4	4.3.8
Load (ohms)	0.65	-	0.64
Hours to 3 volts	288	276	280
Capacity (amp-hours)	1501	1485	1464
Average current (amps)	5.21	5.38	5.23
Average cell voltage (volts)	3.40	3.40	3.35
Power delivery (watts)	17.7	18.3	17.5

Test	4.3.3	4.3.4	4.3.8 (cont.)
Available energy density	5.1	5.0	4.9
Gravimetric energy density	173	170	166
Volumetric energy density	16.7	16.6	16.1

This demonstrates that the cell performance is unaffected by whether the discharge is through a constant resistive load or under constant current conditions or whether the discharge is continuous or periodic. The results also indicate a consistency in the performance from cell to cell.

The inherent capability of the cell to withstand forced discharge in revere voltage to limits well beyond any conditions that could conceivably arise in a battery system is brought out in test 4.3.4. The cell was forced discharged at 5.4 amps for 826 hours and 4465 amp hours beyond the point at which the cell had dropped to zero volts and then the test was voluntarily terminated. The results show no internal pressure build-up indicating no generation of gaseous products by electrolysis and no surface temperature increase as would be expected from the minimal 0.4 watt power dissipation.

The abuse testing in both cases of short circuit, by total puncture with a nail and by direct external connection of anode and cathode terminals, demonstrated the inherent inertness of the cell design to such severe abuse. The disposal of the cell by rifle fire further demonstrated the basic resilience to extreme conditions.

The incineration in a gasoline fire of cell discharged in this program has been very effective as a cell neutralization method in which the cell vents within five minutes without any separation of cell components.

SECTION 5

SYSTEM SAFETY ANALYSIS

5.1 Design Safety

The disc cell design of the lithium-thionyl chloride cell contains significant design safety features. The design simplicity provides a high degree of manufacturing reliability. The Altus cell does not generate large amounts of SO_2, other high vapor pressure substances or free sulphur. The amount of lithium present at the end of discharge is minimal.

Certain safety features inherent in the design are considered proprietary by Altus Corporation.

5.2 Hazard Analysis

In this preliminary hazard analysis, the test results from 137 Altus 17" diameter, 1-3/8" height cells manufactured from 1 May 1979, to present were reviewed.

A review of this data reveals that no Altus cells have ever exploded or exhibited unsafe characterstics under the following conditions:

- o Discharge
- o Handling

- o Transportation
- o Storage
- o Shock
- o Vibration
- o Short circuit
- o Crush up to 18,000 psi
- o Incineration
- o Drop

Altus cells exhibit greatly enhanced resistance under extreme abusive conditions.

- o Nail penetration - All cells of the 1350 amp hour nominal rating have been completely uneventful when penetrated (except for leakage of electrolyte around the nail). Thirteen out of the fifteen 1350 amp hour cells survived penetration without venting.

- o Incineration - All sizes of Altus cells have been subjected to incineration (over 1000°C). No explosions occur, only venting and occasional cracking welds and blow out of insulators.

- o Bullet penetration - Under some conditions, bullet penetration can be sufficiently destructive as to cause disruption of certain safety features. When this happens, fires and/or explosions can occur. The effect, however, is localized to the small volume disrupted by the bullet. The resultant explosion or fire is much less severe than would be the case in a complete runaway explosion which might normally result from such a test. Recently, improvements in cell construction have exhibited increased resistance to bullet penetration, and cells have survived two and three bullets before localized fire or low order venting occurred.

- Reverse voltage - Altus has developed a very effective reverse voltage safety system which is incorporated in the internal design of the cell.

- Breaching - Drop tests have demonstrated that the 316 stainless steel hermetically sealed case is extremely resistant to puncture or breaching.

The following matrix of safety critical areas was developed with recommended precautions indicated.

Safety Critical Areas	Hazards	Severity	Probability of Occurrence	Precautions*
1. Transportation	1. Shock	low	low	1
	2. Vibration	low	high	2
	3. Crush	low	low	3
	4. Puncture	medium	low	4
2. Storage	1. Corrosion	low	low	5
	2. Heat/fire	high	low	6
3. Handling	1. Short circuit	low	high	7
	2. Drop	low	high	8
	3. Crush	low	low	9
	4. Puncture	medium	low	10
4. Discharge	1. Reverse voltage	low	high	11
	2. Reverse current (forced charge)	low	high	12
5. Disposal	1. Incineration	low	high	13
	2. Bullet penetration	low	high	14

Precautions List

1. Ship in wood packing crate with styrofoam packing.

2. Same as 1 above; comply with DOT regulations.

3. Use handling, storage precautions to avoid crushing.

4. Use of shipping container, employment of handling precautions.

5. Monitor storage visually for evidence of corrosion on periodic basis.

6. Monitor storage temperature, store at ambient, avoid flammable hazards.

7. Adequate handling procedures, training.

8. Adequate handling procedures, training.

9. Same as 3 above.

10. Same as 4 above.

11. Reverse voltage safety feature incorporated in cell.

12. Employ non-interchangeable terminal connectors.

13. Use containment facility with scrubber for gas or remote facility.

14. Use remote site or containment as in 13 above.

5.3 Other Safety Provisions

The hazards related to the chemical materials used in the lithium-thionyl chloride battery are of concern principally when the cell case is mechanically breached.

The control and containment is achieved by the rugged case design. However, special protective equipment in areas of sustained storage or use is recommended. This includes protective equipment for personnel such as self-contained breathing apparatus, chemically resistant clothing, boots, neutralizer for the electrolyte, such as ammonium carbonate or lime, and Lithex to extinguish any lithium fires.

Thionyl chloride is a liquid at room temperature. Upon contact, it causes skin irritation. In addition, it readily hydrolyzes in moist air to generate hydrochloric acid gas and sulfur dioxide, both toxicants by inhalation.

Lithium metal will cause skin burns on contact in its raw state. The principal concern is from the flammability of lithium, which when ignited, produces a very hot flame similar to magnesium, and will extract oxygen out of most compounds to sustain the combustion.

A hazard related to systems interfacing would include fire in adjacent equipment. While such a fire could raise the gas pressure in a cell to the level at which venting occurred, Altus' unique internal chemistry would keep the lithium from producing a general conflagration. The principal control approach is to design the whole launcher system to minimize the risk of fire.

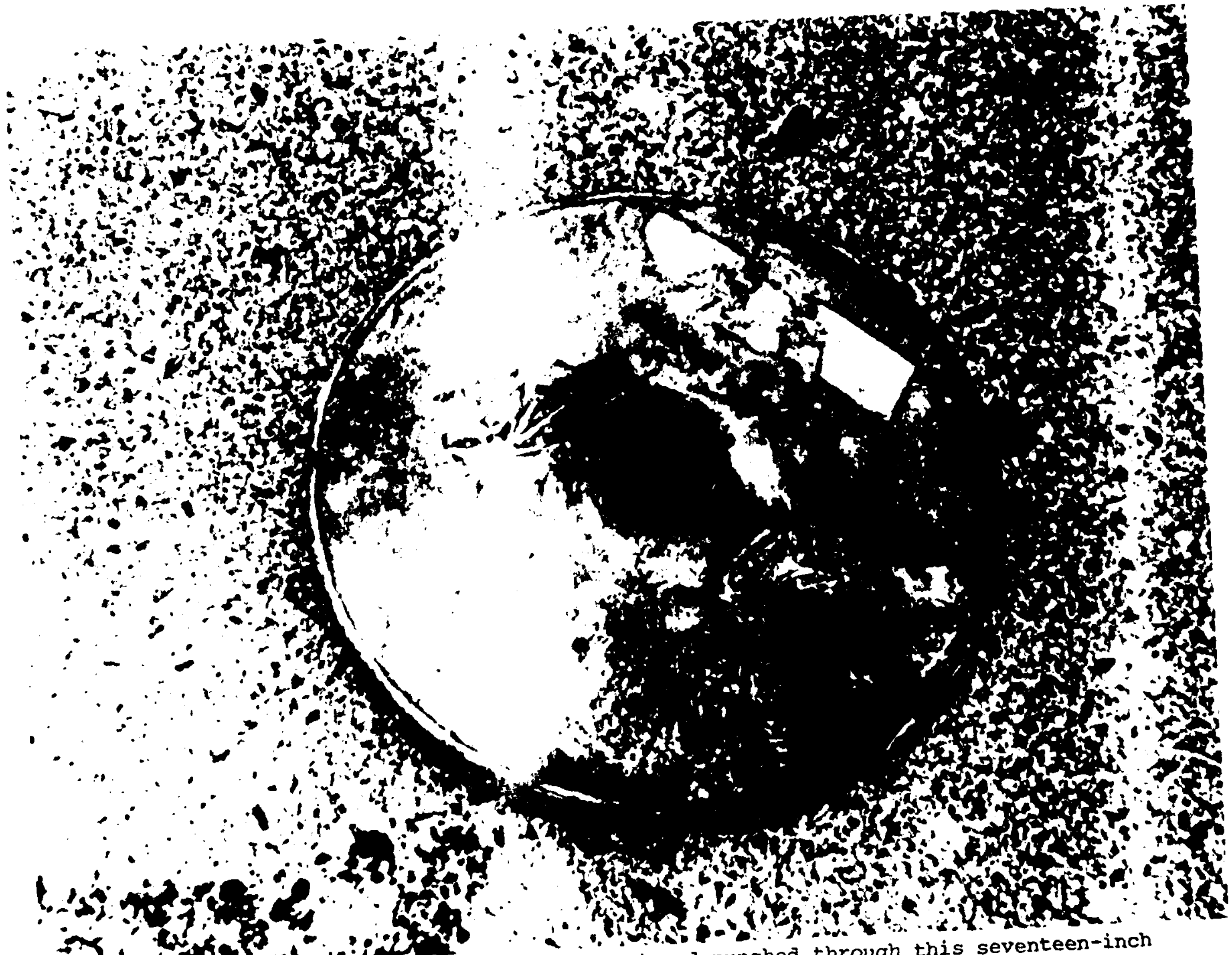
The environmental hazards of shock and vibration are present during transportation, installation, and maintenance. However, the cells have proven extremely resistant to these environments.

Control measures include proper packing, warning labels and routine training of personnel.

External short circuits at a battery system level may generate considerable heat, but do not generally cause venting of a battery. Control measures include insulating covers for terminals. Training of handling personnel will emphasize the dangers of dropping tools across terminals and shorting of batteries with rings and watch bands.

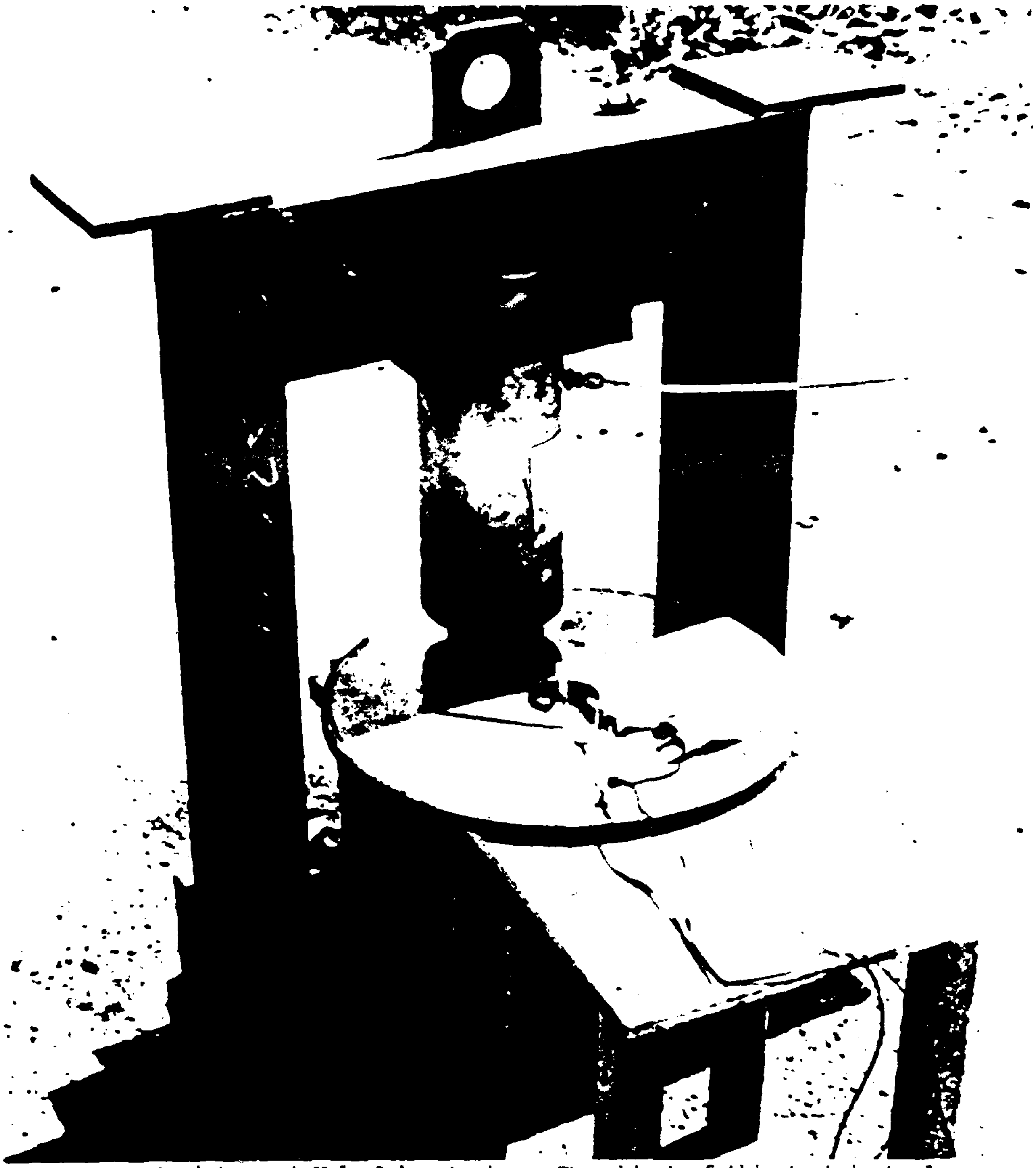
At the system level, fire outside a battery system represents a serious, but not insuperable hazard as previously noted. The Altus cells can withstand a large heat input. Measures should be taken to isolate the batteries as much as possible from potential outside conflagrations.

Operational and support hazards range from personnel injuries from dropping heavy batteries onto feet and hands to accidental puncturing with mechanical lifting equipment and concommitant venting. These hazards can be mitigated by adequate training of personnel.



Pressure Test. A one-inch ram exerted 18,000 psi and *punched through* this seventeen-inch diameter cell. No high order explosion or fragmentation occurred in spite of the massive puncture shown at 4 o'clock on cell's case.

Figure 21. Typical Cell After Pressure Test

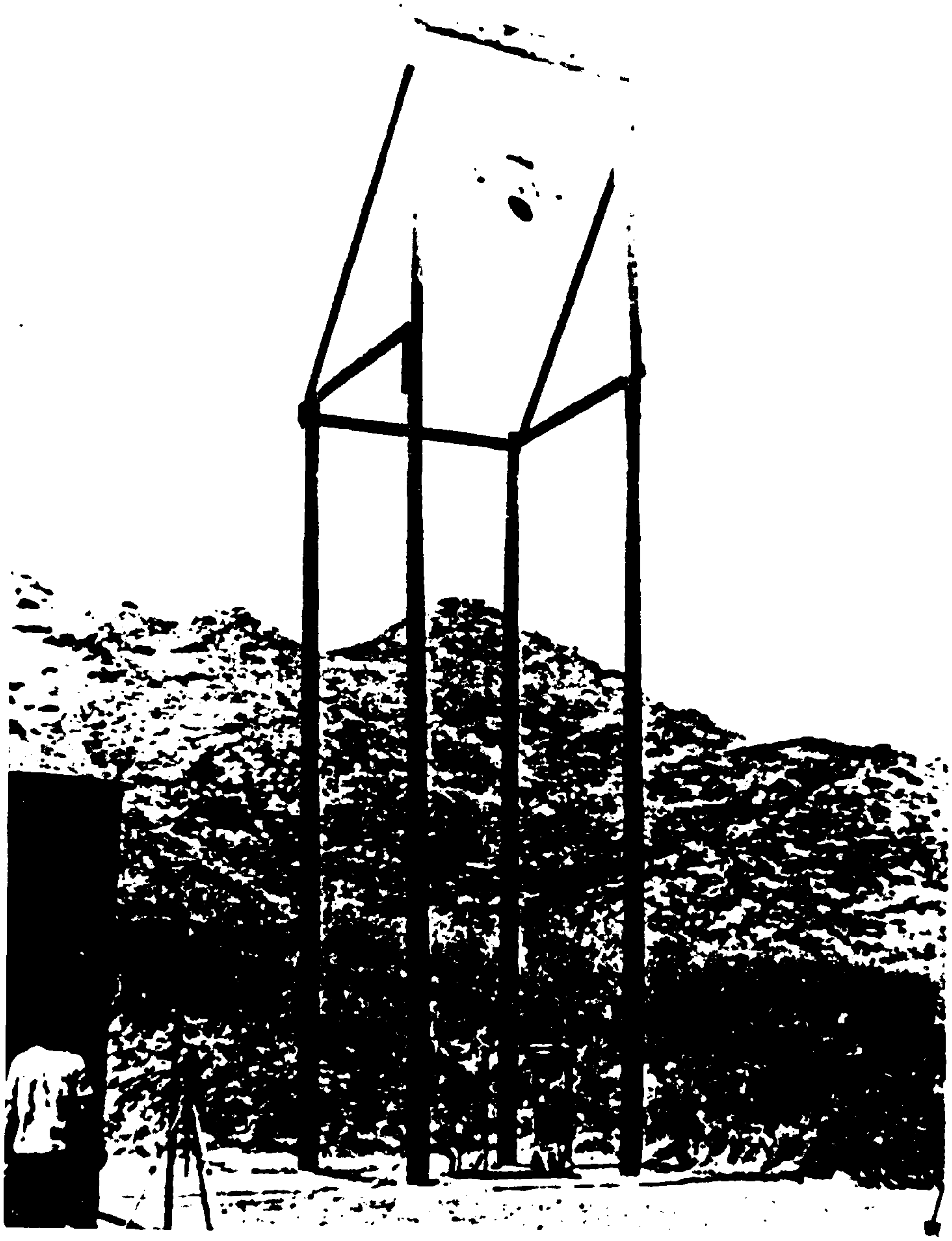


Pressure Test Fixture at Wyle Laboratories. The object of this test is to demonstrate that cell does not explode and is safe during crush. This ram exerted 18000 psi on the cell while the voltage and current were continuously monitored. In this test, no internal shorts, failures or interruptions of electrical characteristics occurred.

Figure 22. Typical Cell Crush Test

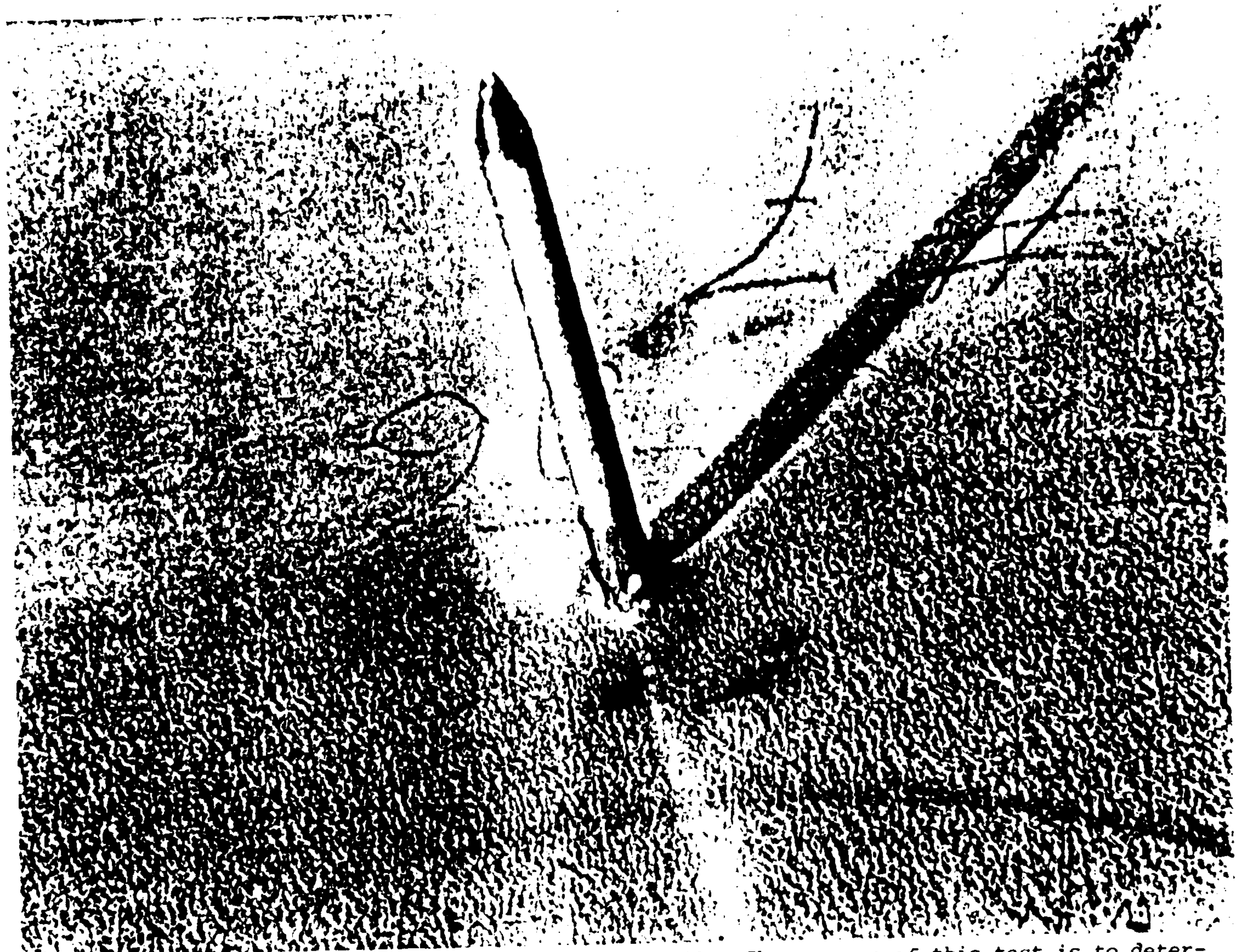
Bonfire Test of 17-Inch Diameter Cells. In this test, JP-4 fuel is ignited to provide a rapid rise of temperature of the cell, suspended above the fire. The object of this test is to determine if the cells will detonate in a high order explosion or start a lithium fire. These cells merely vented with no explosion or fire.

Figure 23. Incineration of Typical Cell



Forty Foot Drop Fixture with Altus Cell. The purpose of this test is to demonstrate the safety of the cell against a free fall drop from extreme heights. A seventeen-inch cell, hoisted to the top of the fixture, was instrumented to measure voltage and current. The cell was dropped onto a heavy steel plate. In this test, the cell was damaged but remained fully functional after the test. The voltage and current were not affected at or after the moment of impact. In drops to date, all cells have demonstrated complete safety.

Figure 24. Forty-Foot Drop Test



Nail Penetration Test on a Seventeen-Inch Diameter Cell. The purpose of this test is to determine safety boundaries upon penetration by a conductive metal object. Typically, there are no explosions and venting.

Figure 25. Typical Nail Penetration Test

Application to Minuteman Requirement

The Altus 17 inch diameter cell with 1-3/8 inch height examined in this program has demonstrated safety during normal handling and abnormal abuse as well as achieving high energy density.

In addition, Altus is demonstrating, in another program, that a cell 2 inches thick with a nominal 2250 AH capacity achieves the optimum energy density for this cell design. The 2 inch thick cell also exhibits the same inherent safety features as the 1-3/8 inch cell. Therefore, for the Minuteman Survival Ground Power Battery application, Altus recommends the 2 inch height cell. The 17 inch diameter, 2 inch height cell can be packaged in a battery configuration to provide 10,000 AH nominal capacity, 305 KWH of energy at the required 31.5 to 28.0 volt operating range and Minuteman discharge profile. This battery is shown in Figures 6-1 and 6-2, and conforms to the Minuteman lithium module volumetric envelope and weight requirement.

Thirty-six of the 17 inch diameter, 2 inch height cells are packaged in a 2 x 3 x 6 inches deep cell array comprised of three each identical 2 x 6 inches deep submodules. The cells are electrically interconnected in units of four parallel cells, nine units in series.

This configuration would retain all of the demonstrated safety, performance, and reliability features of the basic large 2250 AH cell. Because the tooling and production facility now exists for these cells, the battery or submodules can be produced for engineering evaluation and demonstration with non-recurring engineering effort required only for the submodule case and electrical interconnecting components.

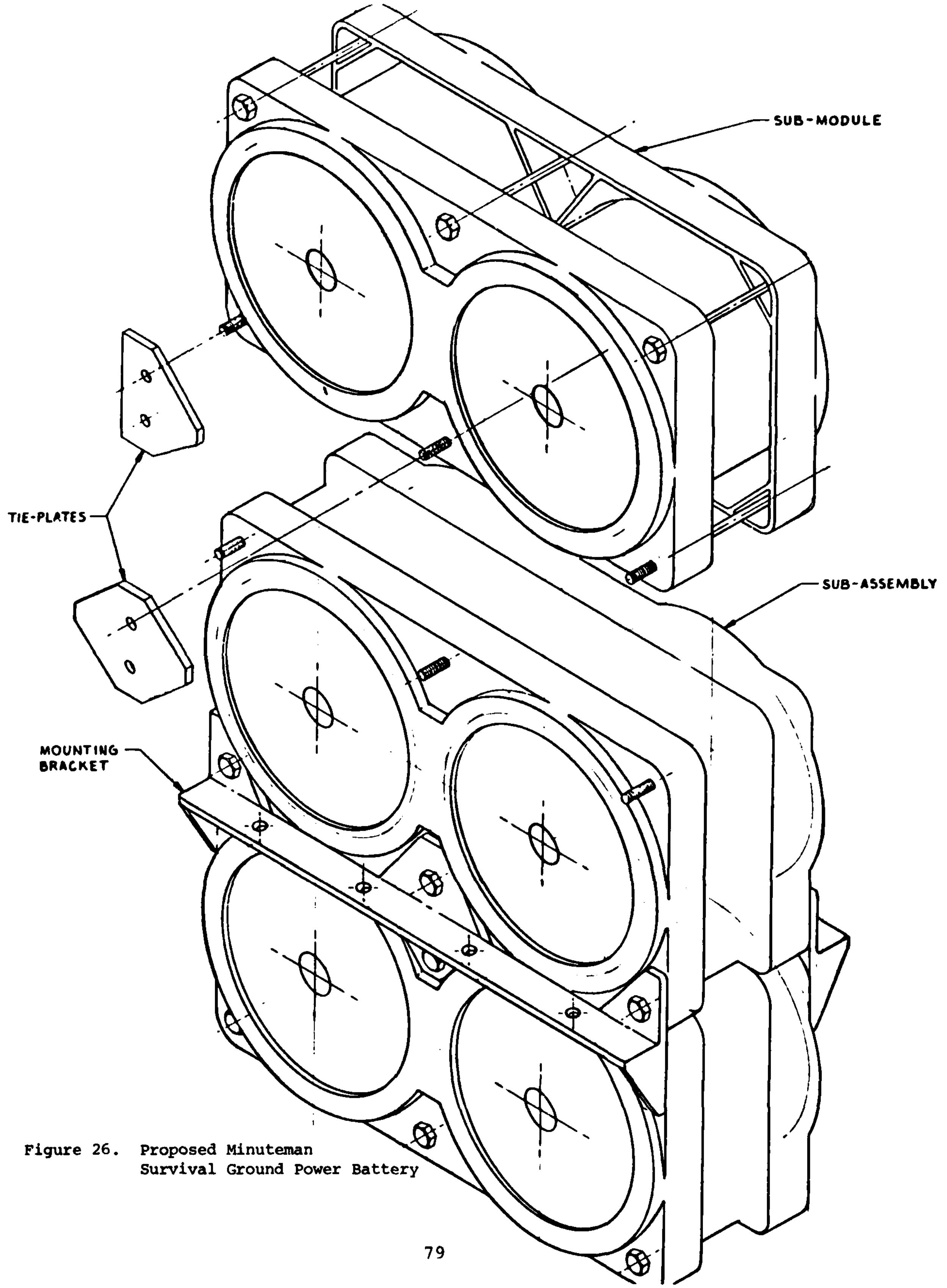


Figure 26. Proposed Minuteman
Survival Ground Power Battery

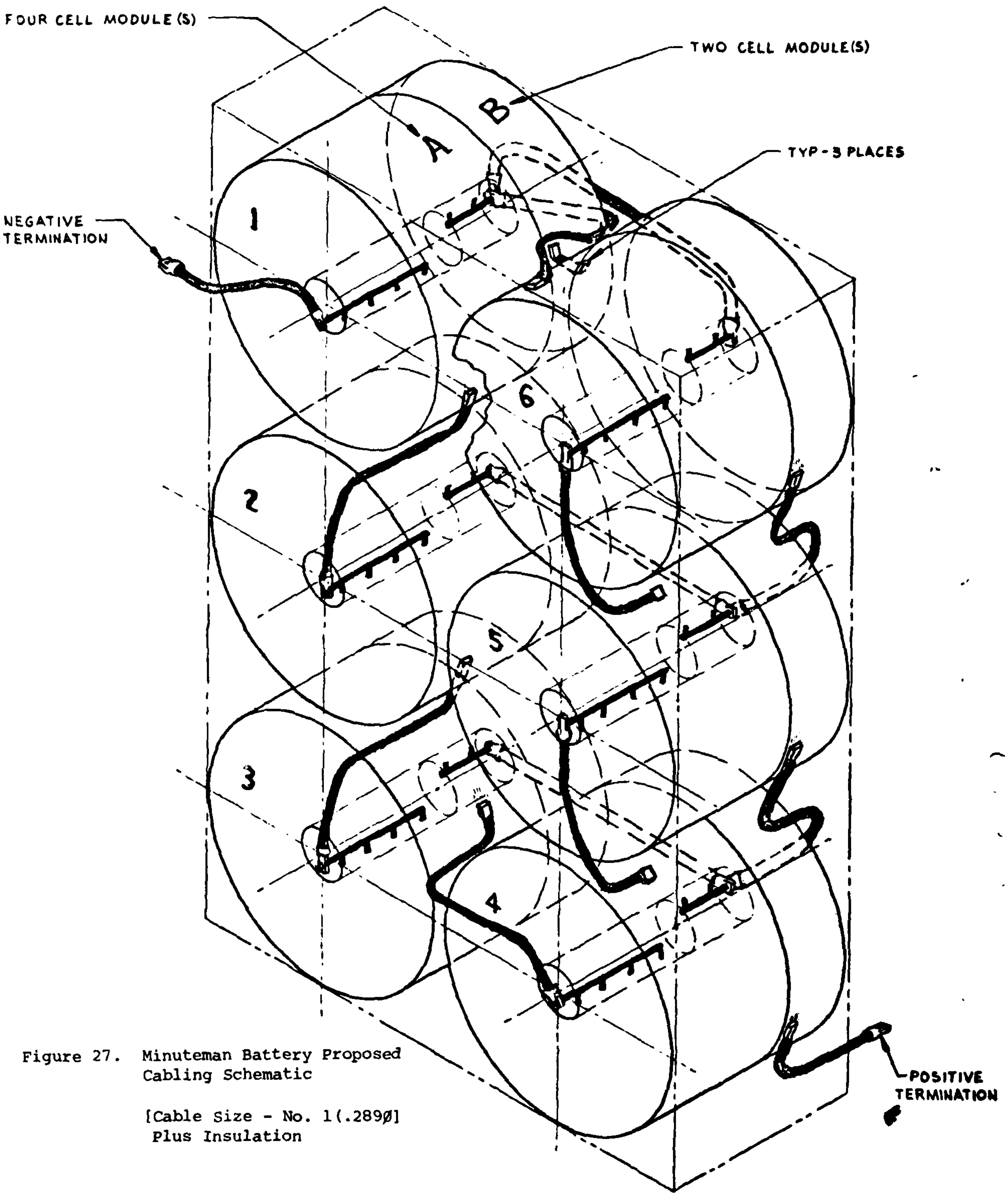


Figure 27. Minuteman Battery Proposed Cabling Schematic

[Cable Size - No. 1(.289Ø] Plus Insulation

APPENDIX

R & D TEST PLAN
Contract No: F33615-79-C-2072
Project No: Nr. 3145

Cell Test and Evaluation

Twelve (12) experimental test cells are to be built with the performance characteristics as outlined in paragraph 6.0 of the subject contract. The following is the test plan by contract paragraph number for these cells.

4.3.1 Cell Short Circuit-Nail Penetration

A. Test Purpose

The purpose of this test is to demonstrate the safety of the cell when penetrated by a sharp object such as might occur during packing or handling of the cell.

B. Test Description

One fully charged cell will be penetrated by a nail of sufficient length to pass through the entire cell. The nail will be fired at point blank range from an "Omack" nail set.

C. Test Data

During the test, the cell voltage and temperature will be monitored by means of a strip chart recorder and the data recorded for the final test report.

D. Test Equipment

1. OMACK nail set gun for nail penetration.
2. Fluke model 2240B datalogger.
3. Datamack model SR6252 strip recorder.

E. Test Schedule

This test will be conducted at the leased Altus facility at Tracy, California during the month of February 1980.

4.3.2 Cell Short Circuit, Externally Shorted Circuited.

A. Test Purpose

The purpose of this test is to demonstrate the safety of the cell, when externally short circuited such as might occur through handling, faulty use or external equipment malfunction.

B. Test Description

One fully charged cell shall be subjected to an external short circuit across the terminals by closure of relay contacts, such that the circuit has a resistance of less than .01 ohms. The short circuit shall be applied until the cell output current is less than 0.1 amp and the cell voltage is less than .001 volts or for a period not exceeding one hour.

C. Test Data

During this test the cell voltage, short circuit current and cell temperature will be monitored by means of a strip chart recorder. The physical condition of the cell after short circuit will also be recorded. All data will be recorded. All data will be presented in the final report.

D. Test Equipment

1. 500 amp relay
2. Strip chart recorder DATAmark model SR6252
3. Fluke model 2240B data logger
4. 500 amp shunt
5. Power supply for remote operation of relay

E. Test Schedule

This test will be conducted at the Altus facility at Watsonville during the month of February 1980.

4.3.3 C/250 Discharge Test

A. Test Purpose

The purpose of this test is to demonstrate the capacity of the cell operating characteristics at C/250 discharge rate at 70^{o}C after being soaked at 150^{o}F for four hours.

B. Test Description

One fully charged cell will be soaked at ambient temperature of 150^{o}F for four hours.

The cell will then be allowed to equilibrate to 70^{o}F for one day. The cell will then be discharged at a constant current rate of 5.4 amperes or at average current of 5.4 amps through a constant load resistor until the cell has discharged to a 3.0 volt level.

C. Test Data

During this test the cell voltage, current and temperature will be recorded every 30 minutes by a datalogger until the cell reaches a 3.0 volt level. This data will be tabulated for the final report.

D. Test Equipment

1. Fluke model 2240B datalogger
2. Load resistor (1%)
3. 10 amp constant current power supply (optional)

E. Test Schedule

This test will be conducted at the Altus facility at Watsonville, Calif. during the month of March 1980.

4.3.4 C/250 Discharge Test - Forced Discharge

A. Test Purpose

The purpose of the test is to demonstrate the capacity of the cell operating at a C/250 discharge rate at 70°F. Further the test demonstrates the safety of the cell when put into a forced discharge condition to 150% of the 3.0 volt capacity exceeding the conditions that might occur during a battery malfunction in operation.

B. Test Description

One fully charged cell will be discharged at a constant current rate of 5.4 amperes at 70°C until the cell has reached the 3.0 volt output level. The cell will continue under the same forced discharge condition of 5.4 amperes and discharged for a further 2025ah or 150% of the 3.0 volt capacity.

C. Test Data

The cell voltage, current and temperature will be recorded every 30 minutes until the completion of the test.

D. Test Equipment

1. Fluke model 2240B datalogger
2. 10 amp constant current power supply
3. Load resistor

E. Test Schedule

This test will be conducted at the Altus facility at Watsonville, Calif. during the month of February 1980.

4.3.5 C/100, C/133, C/200, C/400 Discharge Test

A. Test Purpose

The purpose of this test is to demonstrate the capacity of the cells at the discharge rates listed above.

B. Test Description

Four fully charged cells will be discharged to a 3.0 volt level at the following rates using either a forced constant current by means of a power supply or through a fixed constant load.

1 - C/400 rate
1 - C/200 "
1 - C/133 "
1 - C/100 "

C. Test Data

The cell voltage, current and temperature of each cell will be recorded at 30 minute intervals. Additionally, the internal cell pressure will be monitored with a Sensometics Inc. SP91KFS-150g-4-16 pressure transducer. The cell pressure will be monitored every 30 minutes by a Fluke datalogger.

D. Test Equipment

1. Sensometics Inc. SP91KFS-150g-4-16 pressure transducer
2. Fluke 2240B datalogger
3. Load resistor
4. Power supply (optional)

E. Test Schedule

This test will be conducted at the Altus facility at Watsonville, Calif. during the month of February 1980.

4.3.6 Discharge Versus Temperature Testing

A. Test Purpose

The purpose of this test is to demonstrate the capacity of the cell at a C/100 discharge rate at both 40^{o}F and 110^{o}F cell soak temperature.

B. Test Description

One fully charged cell will be soaked at 40^{o}F for 4 hours and then discharged at 40^{o}F at a C/100 rate (13.5 amperes), constant current or load, until the 3.0 volt cutoff. The second fully charged cell will be soaked at 110^{o}F for 4 hours and discharged at 110^{o}F at a C/100 rate (13.5 amperes) constant current or load until the 3.0 volt cutoff.

C. Test Data

The cells temperature, pressure, voltage at current will be logged at 30 minute intervals and the results included in the final test report.

D. Test Equipment

1. Fluke 2240B datalogger
2. Sensometics Inc. SP91KFS-150g-4-16 pressure transducer
3. Load resistor
4. Power supply (optional)

E. Test Schedule

This test will be conducted at the Altus facility at Watsonville, Calif. during the month of March 1980

4.3.7 Capacity Versus Discharge Rate Test

A. Test Purpose

The purpose of this test is to demonstrate the capacity of the cell when subjected to cyclic variation in the discharge rate of C/400, C/200 and C/133 as may happen under operational use.

B. Test Description

One fully charged cell will be connected via a mechanical relay switching device to three different constant loads demanding 3.4, 6.75 and 10 amperes sequentially, which simulate discharge rates of C/400, C/200 and C/133. The cell will be discharged as follows: three hours at the C/400 rate, three hours at the C/200 rate, three hours at the C/133 rate. The cell will continuously be recycled through this sequence until the three volt cutoff voltage is reached.

C. Test Data

The cell voltage, current and temperature will be monitored every 30 minutes during this test and the results tabulated for the final report.

D. Test Equipment

1. Fluke 2240B datalogger
2. Load resistor

E. Test Schedule

This test will be conducted at the Altus facility at Watsonville, Calif. during the month of March 1980.

4.3.8 Cell Capacity vs Time

A. Test Purpose

The purpose of this test is to demonstrate the capacity of the cell during operational circumstance where the cell is discharged for a period of time, then allowed to remain in a standby condition for two weeks before discharging again.

B. Test Description

One fully charged cell will be subjected to a C/250 discharge rate of a constant current or load demanding 5.4 amperes until 20% of its total energy is removed ($\approx$ 50 hrs) at which time the cell will be disconnected from the load and stored for two weeks. After the two week interval the cell will again be subjected to a C/250 rate until another 20% of its total energy is removed ($\approx$ 50 hrs) at which time it will be removed from test and stored an additional two weeks. This process will be repeated until the cell voltage drops below the three volt level.

C. Test Data

The cell voltage, current and temperature will be monitored every 30 min. by a Fluke datalogger. The results of this test will be recorded and included in the final report.

D. Test Equipment

1. Fluke 2240B datalogger
2. Load resistor

E. Test Schedule

This test will be performed at the Altus facility in Watsonville, Calif. during the month of February 1980.

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