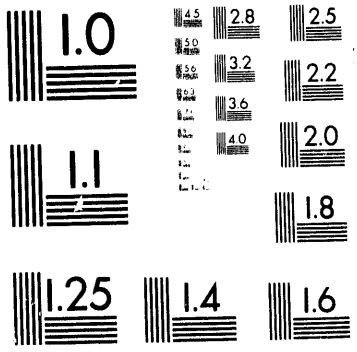
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CHARACTERISTICS AND DEVELOPMENT REPORT FOR THE T1576 POWER SUPPLY AND THE MC3935 BATTERY

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Abstract

This report describes the requirements, designs, performance, and development histories for the T1576 power supply and the MC3935 rechargeable battery. These devices are used to power Permissive Action Link (PAL) ground controllers. The T1576 consists of a stainless steel container, one SA3553 connector, and one MC3935 battery. The MC3935 is a vented nickel/cadmium battery with 24 cells connected in series. It was designed to deliver 5.5 Amp-hours at 25#C and the one-hour rate, with a nominal voltage of 28 V. The battery was designed to operate for 5 years or 500 full charge/discharge cycles. The power supply is expected to last indefinitely with replacement batteries and hardware.

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INTRODUCTION

This report describes the development and characteristics of the T1576 power supply. It is used to power PAL (Permissive Action Link) ground controllers. The T1576 (P/N 368509) consists of one MC3935 (P/N 410083) nickel/cadmium battery, a stainless steel container (P/N 382196), and one SA3553 (P/N 411293) connector. This equipment was designed to replace the aging T436B (P/N 338991) PAL power supply and MC1605C (P/N 319222) battery. Development of the MC1605 and MC1605B was described in earlier reports (1, 2).

The primary goal of the T1576 development project was to design a power supply that was capable of storing more energy than the MC1605 in the same weight and volume. Other key objectives were to design a battery that was simple, easy to maintain, and able to provide power over a wide temperature range. An adequate level of electromagnetic interference (EMI) shielding was also desired. Finally, long life and low purchase cost were additional objectives.

After a review of available battery technologies, the vented nickel/cadmium system was selected as best able to satisfy the majority of the application requirements. Eagle-Picher (EP), Colorado Springs was chosen as the industrial developer through a competitive procurement. Prototypes were built by EP and evaluated at Sandia. Allied Signal Aerospace, Kansas City Division (Bendix), assumed production responsibility for these components. The first production units (FPU) of the T1576 were delivered on schedule on March 31, 1988.

The T1576 was designed to be charged in the field by the T1577 (P/N 368510) battery changer. The T1577 was developed in parallel with the T1576 by the Command and Control Division (5126). A separate report describes its development and characteristics. The T1576 may also be charged by the T431A (P/N 331323) battery charger/monitor, but due to its poor charge control features, this is not recommended.

In this report, the design requirements of the T1576 and related components will be reviewed. This will be followed by a description of the power supply characteristics. A summary of the history of the development project will be included. Results of tool made sample (TMS) testing will also be presented. Finally, life and performance testing conducted at Sandia will be reviewed.

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T1576 DESIGN REQUIREMENTS

The T1576 is used by the Armed Forces with eight different PAL ground controllers. The controllers are the T1533/34/35/36/39/54/55/63. It will also be used with several new controllers presently being developed.

The specific requirements for the T1576 were developed jointly by the Command and Control Division and the Storage Batteries Division. They are documented in Compatibility Drawing CD368509 (Appendix 1). The primary design objectives are summarized in Table 1. The battery must operate during discharge over the range of 26.8-33 volts. A key requirement was for the unit to discharge between -40 and 71°C. The minimum capacity was initially specified as 2.6 Ah at 25°C and the one-hour rate. The minimum capacity requirement was later changed to 5.5 Ah. A low self-discharge rate and long shelf and operating lives were required. A minimum of battery maintenance was a high priority. The environmental (mechanical shock, vibration, humidity, temperature shock, etc.) requirements were selected to match those of the controllers. EMI shielding specifications were set through discussions with the Electromagnetic Testing Division (7555).

These requirements were used to prepare the Product Specification (PS). It is attached as Appendix 2. Included in the PS are details for electrical testing, environmental testing, and visual inspection of production units. All batteries must pass a 30-day charged-stand test. Samples are chosen for Engineering (E) and Destructive (D) tests. All batteries must pass the applicable PS tests before a lot of batteries is accepted. The PT3515 tester, built and maintained by search and change everywhere to Allied Signal, Kansas City Division, the approved device for acceptance testing of this product. Allied-Signal Aerospace also supplied the GA8556 gauge for dimensional acceptance of the T1576 stainless steel container.

T1576 CHARACTERISTICS

The T1576 is illustrated in Figure 1. It consists of a stainless steel container and cover, one MC3935 battery, and one SA3553 connector. The container is 31.2 cm (12.3 in.) long, 18.8 cm (7.4 in.) wide including side brackets, and 14.0 cm (5.5 in.) high to the top of the connector. The weight of the T1576 is approximately 9.5 kg (20.9 lbs). The container and cover are built by EP, and are made of .050 inch thick type 304 stainless steel. The cover is attached to the container with a hinge that is welded to both parts. A neoprene gasket in the cover contacts the top of the battery and holds it in place. A conductive gasket, also in the cover, insures electrical continuity between the cover and container and provides optimum shielding effectiveness for the T1576. The exteriors of the container and cover are sand blasted to enhance their appearance. A rope handle is used to carry the power supply.

The SA3553 connector consists of a stainless steel shell, to resist corrosion by the battery electrolyte, a 13-4S insert, and a captive cover. Solder cups attach four leads to the back of the connector. The back of the connector is encapsulated with Hysol to protect the solder joints mechanically and to prevent corrosion. The battery-ends of the four wires are crimped to flag terminals.

Please note on Table 1, the T1576 power supply includes MC3935 battery, a battery container, and a connector.

TABLE 1
T1576 Power Supply and
MC3935 Rechargeable Battery Design Requirements

Parameter	Design Requirement*
Voltage Range	26.8 - 33, nominal 28 V
Battery Weight (maximum)	12 lb (5.4 kg)
T1576 Weight (maximum)	20 lb (9.1 kg)
Battery Volume (maximum)	0.3 ft^3 (8.5 liters)
T1576 Volume (maximum)	0.5 ft^3 (14.2 liters)
Temperature Range	-40 to 160°F (-40 to 71°C)
Capacity (minimums)	
initial @ 25°C	2.6 Ah @ ~1 hr rate, load=15 + 2 ohms
initial @ -40°C	0.8 Ah @ ~1 hr rate, load=15 $\pm$ 2 ohms
Peak Current	12 A for 200 msec
Charged Storage Capacity (minimum)	1.0 Ah @ ~1 hr rate @ 25°C load = 15 $\pm$ 2 ohms , after 30 days @ 43°C (110°F) open curcuit
Operating Life (minimum)	500, 100% DOD cycles or 5 years
Shelf Life	10 years - no trickle charging
Environmental	Requirements for temperature and mechanical shock, vibration, electromagnetic radiation, and nuclear radiation.
Shielding (container)	50 dB at frequencies of 100 kHz-200 MHz
Maintenance	Minimal, except recharge and periodic complete discharge, if necessary
Duty Cycle	Each operation: 1 A-min at various rates - 60 operations required per charge (1 Ah)
Recharge Time	Max. 8 hours @ 25°C - goal: 4 hours

* Refer to latest version of CD368509 for present requirements.

T1576 POWER SUPPLY

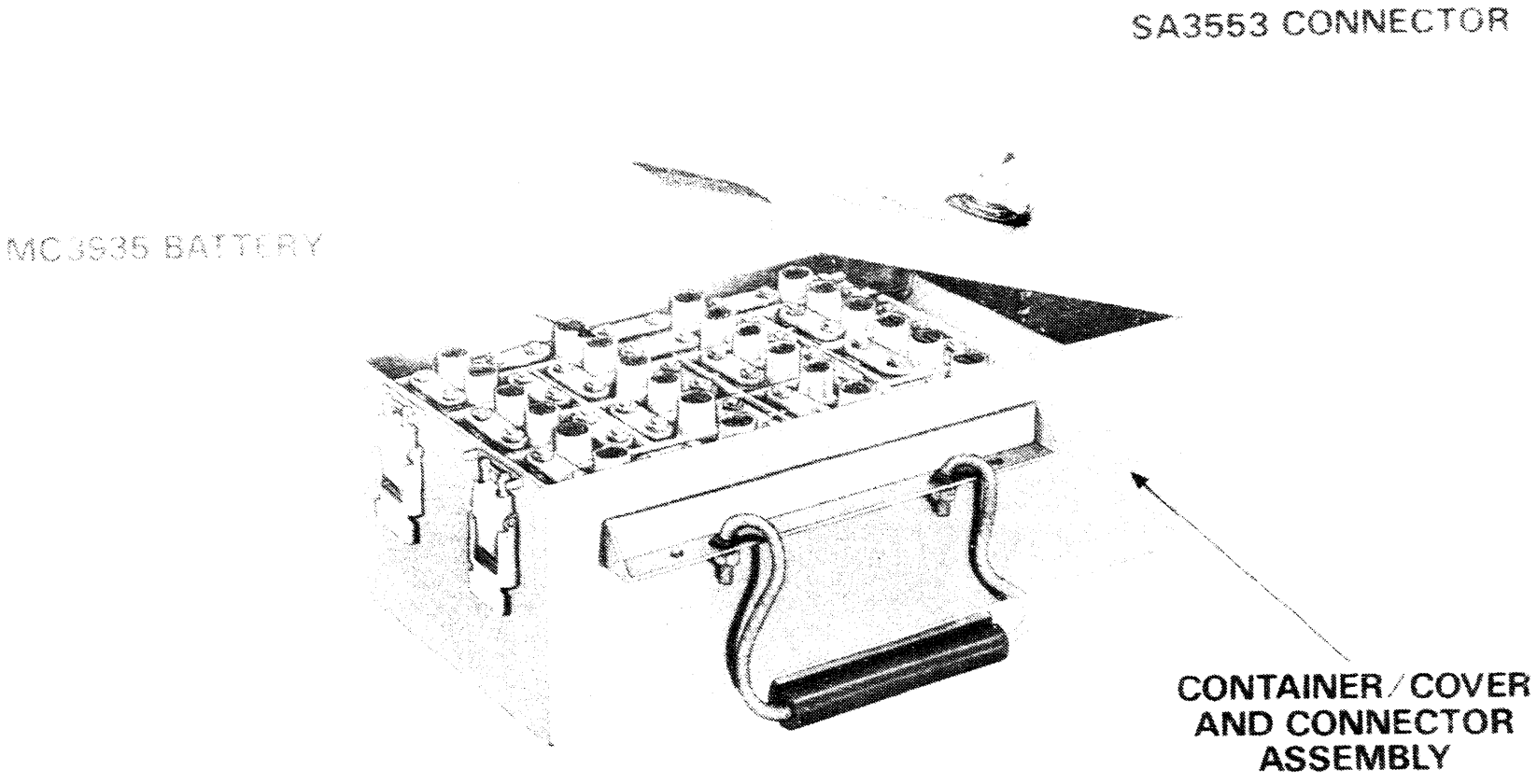

FIGURE 1. ILLUSTRATION OF THE T1576 POWER SUPPLY

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MC3935 CHARACTERISTICS

The MC3935 vented nickel/cadmium battery consists of 24 series-connected cells. The cells are taped together into a unit. Figure 2 shows the MC3935 battery. A single cell is illustrated is Figure 3. The electrochemistry of the nickel/cadmium couple is described in several reference books (3, 4, 5).

Each cell has a rated capacity of 5.5 Ah at 25°C and the one-hour rate. Each contains 10 positive (nickel) plates and 10 negative (cadmium) plates. The electrodes are made of nickel using the dry-sinter process. Vacuum impregnation is used to load the active materials on the electrodes. The precise electrode and plate manufacturing processes are considered proprietary by EP and are not specified in the drawing package. The plates are separated by two layers of nylon around one layer of Celguard. The cell case and cover material are nylon. A thermal fusion bonding technique is used to seal the cover to the body of the cell case. Nickel tabs are welded to each plate, and then all positive tabs and all negative tabs are respectively welded together. The appropriate tabs are then welded to the positive and negative cell terminal studs.

The cells contain approximately 30 milliliters of 30 wt.% potassium hydroxide electrolyte. Periodically, deionized or distilled water must be added to the cells to maintain a sufficient amount of electrolyte to cover the plates.

Table 2 summarizes the chemical constituents of the MC3935 and MC1605 batteries.

TABLE 2
Chemical Constituents of MC3935 and MC1605 Batteries

CHEMICAL	QUANTITY MC1605	QUANTITY MC3935	NOTES
Potassium hydroxide KOH, 30 wt% solution, specific gravity=1.3	330 mL	720 mL	Liquid is absorbed by electrodes when battery is discharged.
Nickel Ni	0.9 kg	2.7 kg	Electrode substrate and hardware.
Nickel hydroxide $Ni(OH)_2$	0.3 kg	0.9 kg	Positive active material.
Cadmium hydroxide $Cd(OH)_2$	0.3 kg	0.9 kg	Negative active material.

The balance of these batteries is plastic.

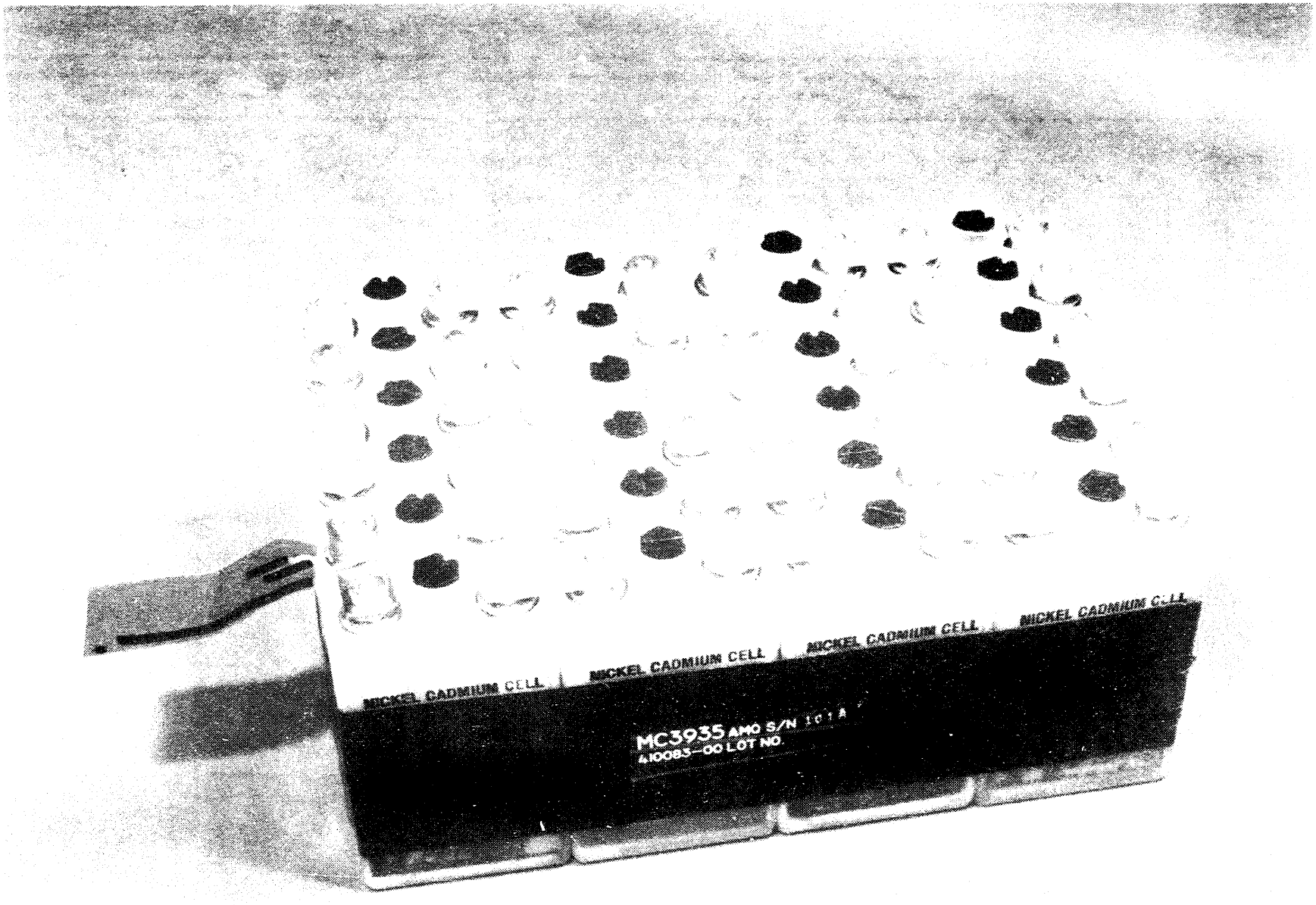

FIGURE 2. MC3935 NI/CADMIUM BATTERY, 24 CELLS IN SERIES

MC 3935 CELL DESIGN

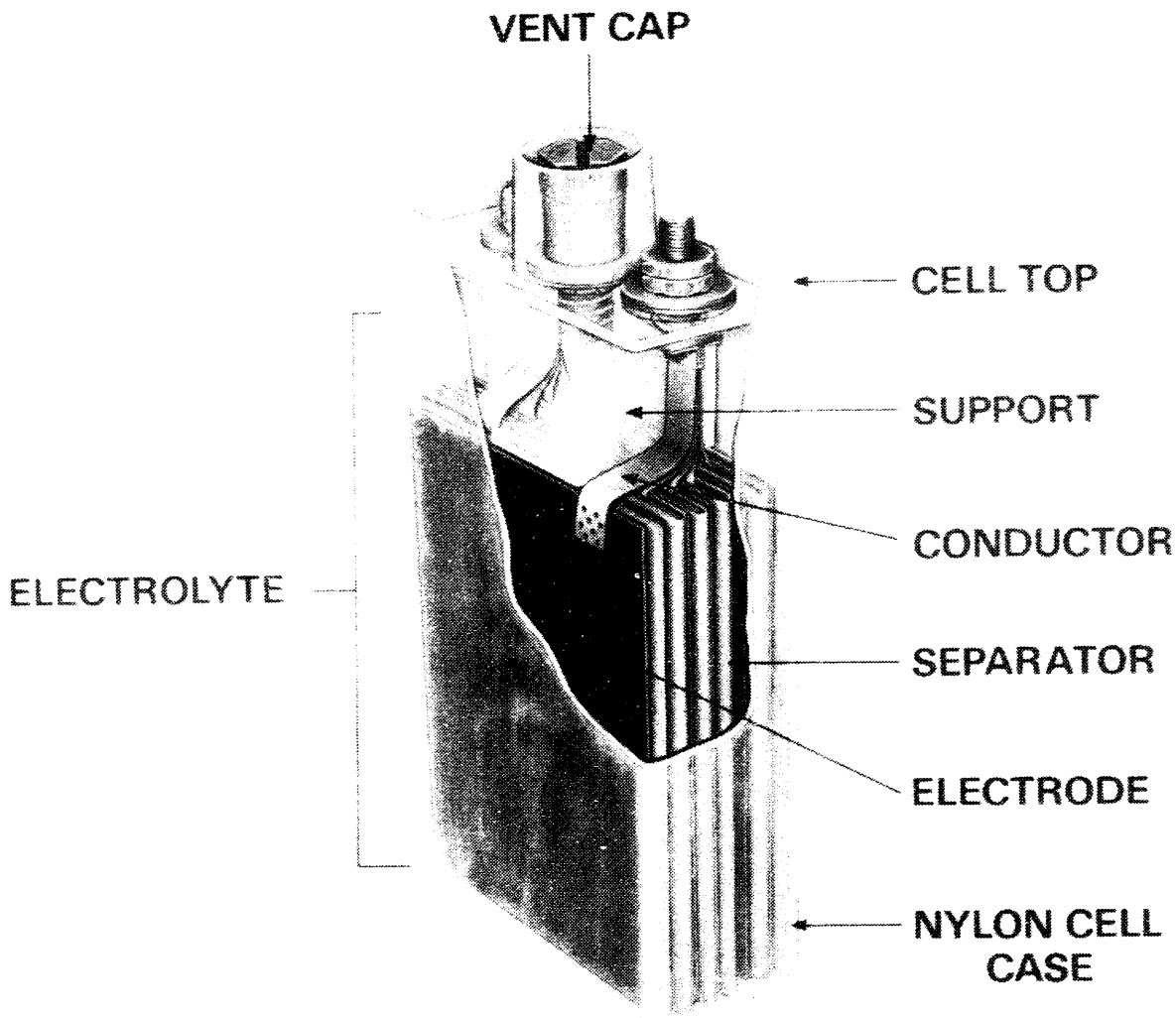

FIGURE 3. ILLUSTRATION OF THE MC3935 SINGLE CELL

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DEVELOPMENT HISTORY

The need to replace the aging T436B power supply and MC1605 battery had long been recognized by the Armed Forces. Numerous problems were encountered in the field with the T436B components. The MC1605 cells were prone to crack and leak electrolyte resulting in short life. The cells were rated at 1.3 Ah, a relatively low capacity for the PAL application. This characteristic resulted in frequent battery recharging and watering. The MC1605 had several design features which complicated manufacturing and increased product cost. The battery container was coated with a non-conductive epoxy which was very difficult to apply. A specialized electrical cable connected the battery to the MC1676 interconnect/fuse device in the T436B. This cable was extremely costly and difficult to manufacture. The MC1676 itself was an additional cost item, and blown fuses were occasionally a source of trouble. Because of the low capacity of the MC1605, two batteries were used in parallel in the T436B. Any imbalance in the two batteries resulted in blown fuses and additional maintenance requirements.

During the late 1970's, several studies were conducted in an attempt to determine which electrochemical technologies would best meet the PAL controller requirements. In 1984, at the request of the Department of Energy, Albuquerque Operations Office, the Command and Control Division solicited the design of a new power supply and battery to replace the T436B and MC1605. The Storage Batteries Division (2525) was assigned to respond to the request. A project plan was developed and accepted in March 1984. Table 3 presents a summary of the key dates during the development project.

Initially, a thorough review of available battery technologies was performed. Appendix 3 presents a memo which summarizes the review process and results. Table 4 summarizes the advantages and disadvantages of each battery type considered.

Four candidates were selected from this list for further study. Of the four, three were rechargeable: sealed and vented nickel/cadmium, sealed lead-acid; one was non-rechargeable (primary): lithium/sulfur dioxide. While the vented nickel/cadmium technology was proven in the MC1605, it was also the cause of several operational problems observed in that battery. Several improvements were suggested for a new battery relative to the MC1605, such as increased capacity, improved separators, and nylon cell cases.

The sealed nickel/cadmium battery offered the promise of very little maintenance. However, this system suffered from poor capacity at low temperature and also had relatively poor capacity retention during charged stand. Sealed lead-acid batteries also would have required little maintenance, but had the disadvantage of poor shelf life without periodic recharge and poor high-discharge rate performance.

The lithium non-rechargeable battery was considered because it could meet most of the requirements if enough parallel strings were included in the design. However, on a life cycle cost basis, this technology was not competitive with the rechargeable types if the batteries were heavily used, i.e., discharged more than a few times a year. Since the batteries receive heavy use in training exercises and in recoding operations, this option was not economically promising.

T1576/MC3935 DEVELOPMENT HISTORY

COMPONENT REQUEST	1/84
VENTED Ni/Cd CELL DESIGN SELECTED	6/85
DEVELOPMENT CONTRACT WITH EPI	8/85
T1576 BATTERY CONTAINER DESIGN	5/86
FIRST PROTOTYPE DELIVERED TO SANDIA	10/86
DRAWINGS TRANSFERRED TO BKC	2/87
BKC PURCHASE AGREEMENT WITH EPI	7/87
FPU	3/88

TABLE 3

TABLE 4
Extended Candidate Battery List for MC3935

TECHNOLOGY	KEY ISSUES ADVANTAGES	DISADVANTAGES
Flooded lead-acid	Long-Life Low Cost High cell voltage	Poor high rate perf. Maintenance required Poor portability
Sealed lead-acid	No maintenance High cell voltage	Poor high rate perf. Poor cycle life Short shelf life
Flood nickel/ cadmium (sintered electrode)	Good low temp. perf. Good charge retention Good high rate perf.	Maintenance required
Sealed nickel/ cadmium (sintered electrode)	Good high rate perf. No maintenance Good low temp. perf.	Short charge retention Long recharge time Cells can't be reversed
Flooded nickel/ cadmium (pocket plate)	Mod. high rate perf. Long life-shelf & active No memory effect	Maintenance required Very poor portability Mod. low temp. perf. Stationary application Built >10 Ah capacities
Nickel/iron	Long shelf-life & active Withstands abuse	Poor low temp. perf. Poor high rate perf. Very poor portability Extensive maintenance Poor charge retention
Nickel/zinc	Good high rate perf. Good portability	Very poor cycle life Poor charge retention Maintenance required Difficult to charge
Silver/zinc	Good high rate perf. Good portability	Long charge times Very poor cycle life Poor shelf life Poor low temp. perf.
Silver/cadmium	Good high rate perf. Good portability	Poor low temp. perf. Poor cycle life Poor shelf life High cost Long charge times
Nickel/hydrogen	Long life High reliability	Very poor portability Poor charge retention Poor low temp. perf. Very high cost

TABLE 4
Extended Candidate Battery List for MC3935 - cont.

TECHNOLOGY	KEY ISSUES ADVANTAGES	DISADVANTAGES
Lithium/sulfur dioxide primary	High voltage Maintenance free No charger Long shelf life Good portability	Mod. high rate perf. Extensive supply system needed Uncertain life cycle cost
Alkaline manganese dioxide primary	Good portability Maintenance free No charger	Mod. high rate perf. Extensive supply system needed Short shelf life Mod. low temp. perf.
Mercury/zinc primary Silver/zinc primary	Long shelf life Maintenance free No charger Good portability	Disposal problem Mod. low temp. perf. Small sizes only Susceptible to shock High cost

Simultaneous with the review of possible battery technologies, an advertisement was placed in the Commerce Business Daily (CBD) notifying industrial firms of the T1576 and MC3935 development project. Approximately 20 firms responded to the ad. A Request for Proposal (RFP) was then issued to these firms with an outline of battery requirements and the development plans. Proposals were received from two divisions of Eagle-Picher Industries; one in Colorado Springs and one in Joplin. Colorado Springs proposed an improved vented nickel/cadmium battery while Joplin proposed a sealed nickel/cadmium battery. Following a technical rating of the proposals and the review of the possible battery types described above, the Colorado Springs proposal and the vented nickel/cadmium technology were selected for this project. The selection was based on the use of the best electrochemical system for this application and a competitive proposal from the contractor.

A development contract (P.O. 51-1417) was placed with EP in August, 1985. Its period of performance was 2 years. The contract Statement of Work is included in Appendix 4. The contract tasks included cell design, container development, prototype fabrication, design optimization, final prototype fabrication, and documentation.

The orignal EP design proposal for the T1576 consisted of a steel battery box inside a fiberglass container. Because of the low probability of damaging mechanical shock and the desire to minimize cost, weight, and volume, a single steel box was chosen as the container. However, to maintain the option of using the outer fiberglass container if it were ever deemed necessary, it and the special connectors required for its use were designed. The power supply including the fiberglass box was designated the T1581 (P/N 368522).

Two special connectors with stainless steel shells were developed for the fiberglass container option. The SA3478 (P/N 410876) was designed to mount on the fiberglass outer box while the SA3479 (P/N 410877) was to mount on the inner stainless steel container. The two connectors were designed to mate when the lid of the fiberglass container was closed. When the container design was changed to the single steel box, the SA1671-11 (P/N 359040) connector was considered. It met all of the application requirements except that it contained butt-welded contacts. Solder cups were desired for the T1576 for reasons of low cost and simplicity. Thus, the SA3553 was designed for this application. It was configured with a stainless steel shell, to resist corrosion by the caustic electrolyte, a 13-4S insert, and a captive cover.

In late October, 1985, the Command and Control Division slightly modified the requirements for the T1576. The modifications included the addition of EMI shielding requirements described in Table 1. Also, the ability to install two MC1605 batteries in the T1576 stainless steel container was required. With two MC1605s in the container instead of the MC3935, the power supply is designated the T436C (P/N 368521). This component is described in Appendix 6.

With these changes in the design requirements, the development project was delayed slightly. A prototype container design was proposed in May 1986, which satisfied the revised requirements. The MC3935 battery was held in the steel container with plastic shims and the compressive force of the cover gasket. The ability to firmly hold the battery in place was important. As these cells age, the electrodes, or plates, inside the cells tend to swell. Without a rigid container, the plates will eventually grow large enough to burst the cell case. Therefore, the battery was intended to be tightly held in the container.

The MC3935 battery design was based on an existing hardware used by EP in other products. A cell design (designated "5A06" by EP) was modified by using one layer of Celguard in place of cellophane in the separator. The original EP proposal indicated that the active material would be loaded on the electrodes using a new process called electrochemical impregnation. However, prototype cells were fabricated and tested and found to perform poorly. Therefore, the proven vacuum impregnation process was instead selected for this product.

Once the container design was established and the cell fabrication method was selected, six T1576 prototypes were built at EP and sent to Sandia for evaluation. They arrived at Sandia in November, 1986. The power supplies were electrically tested to verify proper capacity. Several of the planned Product Specification (PS) acceptance tests were run to determine if the batteries could pass the proposed tests. One of the batteries was subjected to extreme mechanical shock tests to determine the survivability of the container. One prototype container was evaluated for the effectiveness of the EMI shielding.

During initial tests of the first group of prototypes, a significant decline in capacity was observed after several charge/discharge cycles. This loss was related to inadequate charging. EPI and others were consulted concerning optimized charging procedures. A modified procedure was selected and proven to be adequate in tests with the prototypes. This method represented a compromise between providing full battery capacity and the extra undesirable maintenance (cell watering) needed when significant overcharge was applied to a battery.

Several tests described in a draft of the Product Specification were run on the prototypes during the charge optimization studies described above. The batteries met the requirements of the constant resistance discharge test, low temperature discharge test, high temperature stand test, and a shortened version of the 30-day stand test. Because of the reduced discharge capacity noted above, the batteries demonstrated less capability than was expected. However, the requirements were still satisfied.

One battery was put through a series of mechanical shock tests. The initial shock requirements were based on general, worst case expectations for handling of portable equipment. The tests were designed to simulate a 48-inch drop onto a concrete surface. The power supply was dropped on six sides using a shock table. It was also dropped by hand on the connector (top of the container) to simulate a worst case situation. While the battery and connector survived these shocks, the stainless steel box was damaged. The integrity of the EMI shielding was compromised, although the lid of the box could still be forced to a closed position.

Based on these results, the mechanical shock requirements were revised. It was determined that the shock specifications for the PAL controllers were applicable to the power supply. The physical environments for controllers are specified in SB343825. The drop test was changed to one, 36-inch drop on the container bottom according to the requirements of this document. Shock table tests were redefined to consist of 3, 150 g shocks for 1.7 msec. One shock each would be performed in the direction of the three axes of the battery container (see Appendix 2, Figure 1). This test is very similar to the requirement for the MC1605C battery (PS319222).

A prototype stainless steel container with two MC1605C batteries was evaluated to determine the effectiveness of the EMI shielding. The test data indicated that excellent shielding effectiveness was provided by the container.

Following resolution of the charging and shock test specifications, EP fabricated the final 12 prototype T1576 power supplies. These units were delivered to Sandia in April 1987. A Tool Made Sample (TMS) test plan, prepared by the Electromechanical Structure/TPV Quality Assurance Division (7253) was implemented. The plan was based on the PS (Appendix 2). Although the margin of passing certain tests was not as large as anticipated, the TMS plan was successfully completed without a failure. The PS was modified slightly to accomodate the reduced performance observed in these tests.

The Complete Engineering Release (CER) was issued in September, 1987. EP began production of the first production lot of the T1576 at that time. This lot was accepted and shipped in late March, 1988. This date satisfied the program schedule, and was only three months later than the first estimate made in mid-1984.

Simultaneous with the fabrication of this lot, Sandia prepared a technical manual for use by the Armed Forces which described the maintenance and operation of the T1576. An issue developed concerning the ease of removing single cells from the T1576 for replacement. Although this capability was never specified in the CD, it was requested informally after the design of the T1576 was completed. The economic benefit of replacing individual failed cells and continuing to use the remaining cells was obvious. Because of the need to tightly restrain the cells during use (see above), removing cells was not intended to be easy. After considerable discussion, a cell pulling tool, simply made from fabric and brass eyelets, was accepted for use. All maintenance procedures were proven and documented in TPT 1576-2.

Evaluation of several T1576 units continued at Sandia to determine their useful life. These data will be discussed in the Test and Evaluation section.

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TEST AND EVALUATION

Prototype Testing

Tests were conducted on six prototype T1576 batteries shipped to Sandia in the Fall of 1986. The objective of these evaluations was to verify the rated capacity of the batteries. In addition, battery performance was determined using the proposed product acceptance tests.

Initial electrical tests run on the prototypes consisted of 12 cycles of charge and discharge, using the EP-recommended charge regime, and a 3 A constant current discharge. The preliminary recommended charge profile was a constant current charge of 3 A to a voltage limit of 37.2 volts. Charging then switched to a constant potential mode at 37.2 volts, and the current was allowed to taper. Total charge time was limited to 3 hours. When this test was implemented at Sandia on the prototypes, available battery capacity declined drastically during the 12 cycles. See Figure 4 for a plot of capacity versus cycle number. This decline was traced to a corresponding drop in charge acceptance. These data strongly indicated that the MC3935 batteries required a different charge method. Following the 12 cycles, full battery discharge capacity was not recovered by a single complete discharge. Full capacity was recovered only after several cycles and a constant current overcharge (cycles 17-21) applied to the batteries.

A modified charge regime was developed based on recommendations from EP, Sandia, and others. It consisted of a 5 amp, constant current charge until the battery voltage reached 37.4 V, or a maximum of 2.5 hours. Then, the charge was continued at 1.5 amps for 1 hour, or until the battery reached 41 V.

The 12-cycle test regime was repeated on a battery from the same group, using the modified charge regime described above. This battery's performance is shown in Figure 5 for two consecutive sets of 12 cycles. The battery was completely discharged and shorted out for 24 hours between each set. In this case, the discharge capacity initially declined and then stabilized at acceptable levels. This performance was comparable to that observed with the MC1605B when tested under similar conditions. A plot of voltage, current, and temperature for a typical cycle with the improved charge regime is included in Figure 6.

Some of the proposed acceptance tests were conducted on these batteries. The results of the tests are presented in Table 5.

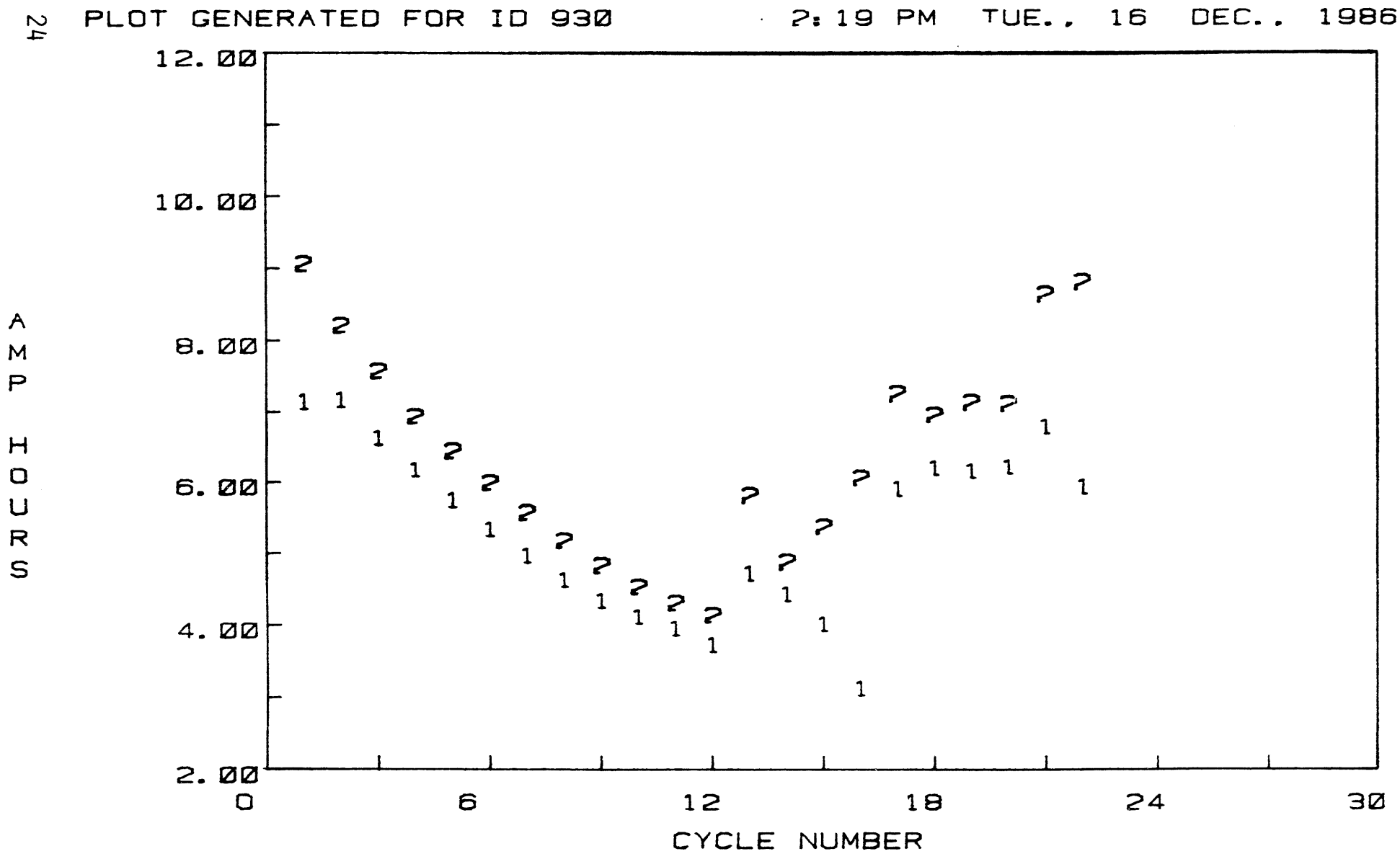

FIGURE 4: CHARGE (2) AND DISCHARGE (1) AMP-HOURS VS. CYCLE NUMBER FOR PROTOTYPE T1576 # 930 USING PRELIMINARY CHARGE REGIME

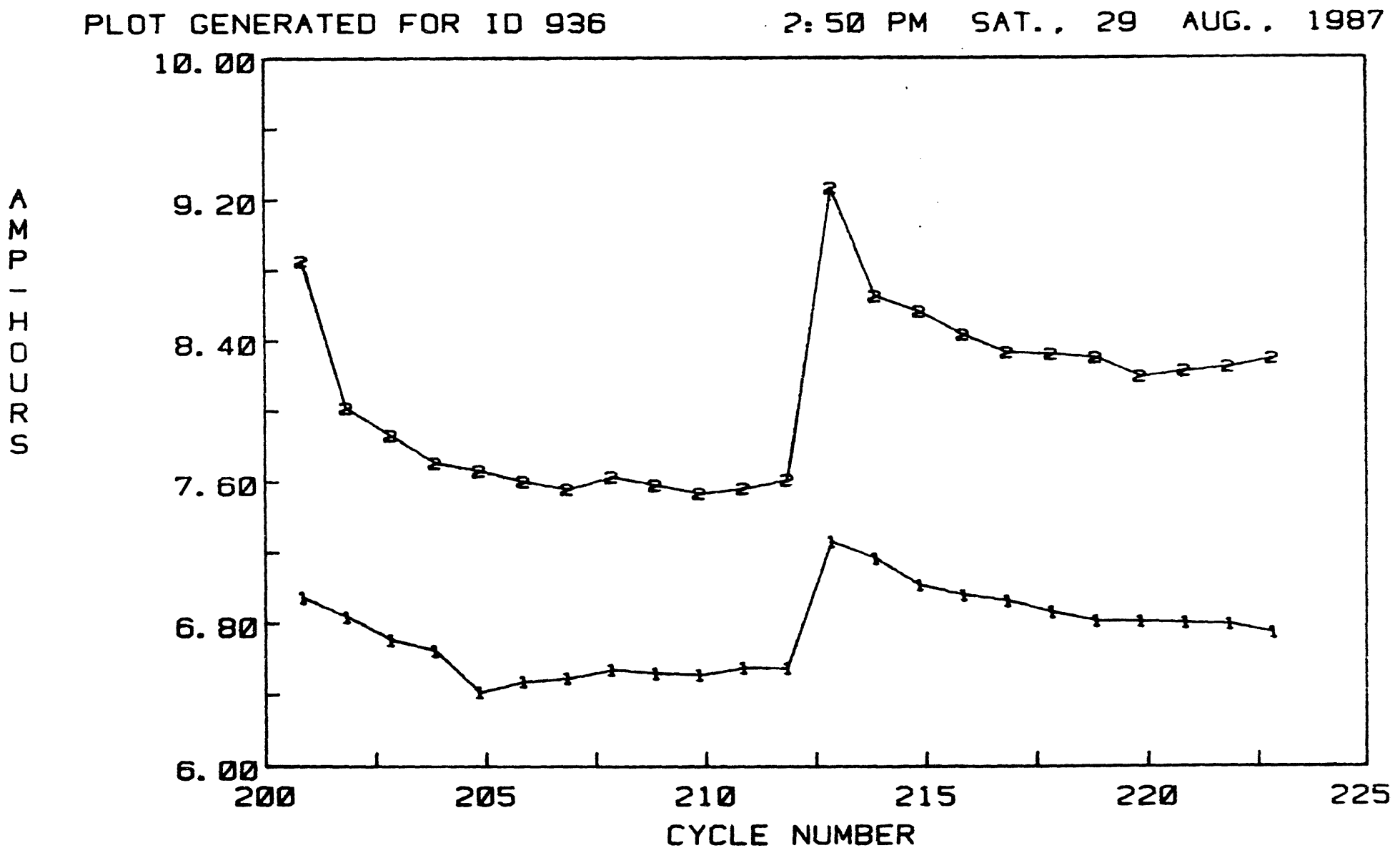

FIGURE 5. CHARGE (2) AND DISCHARGE (1) AMP HOURS VS. CYCLE NUMBER FOR PROTOTYPE T1576 # 936 USING MODIFIED CHARGE REGIME

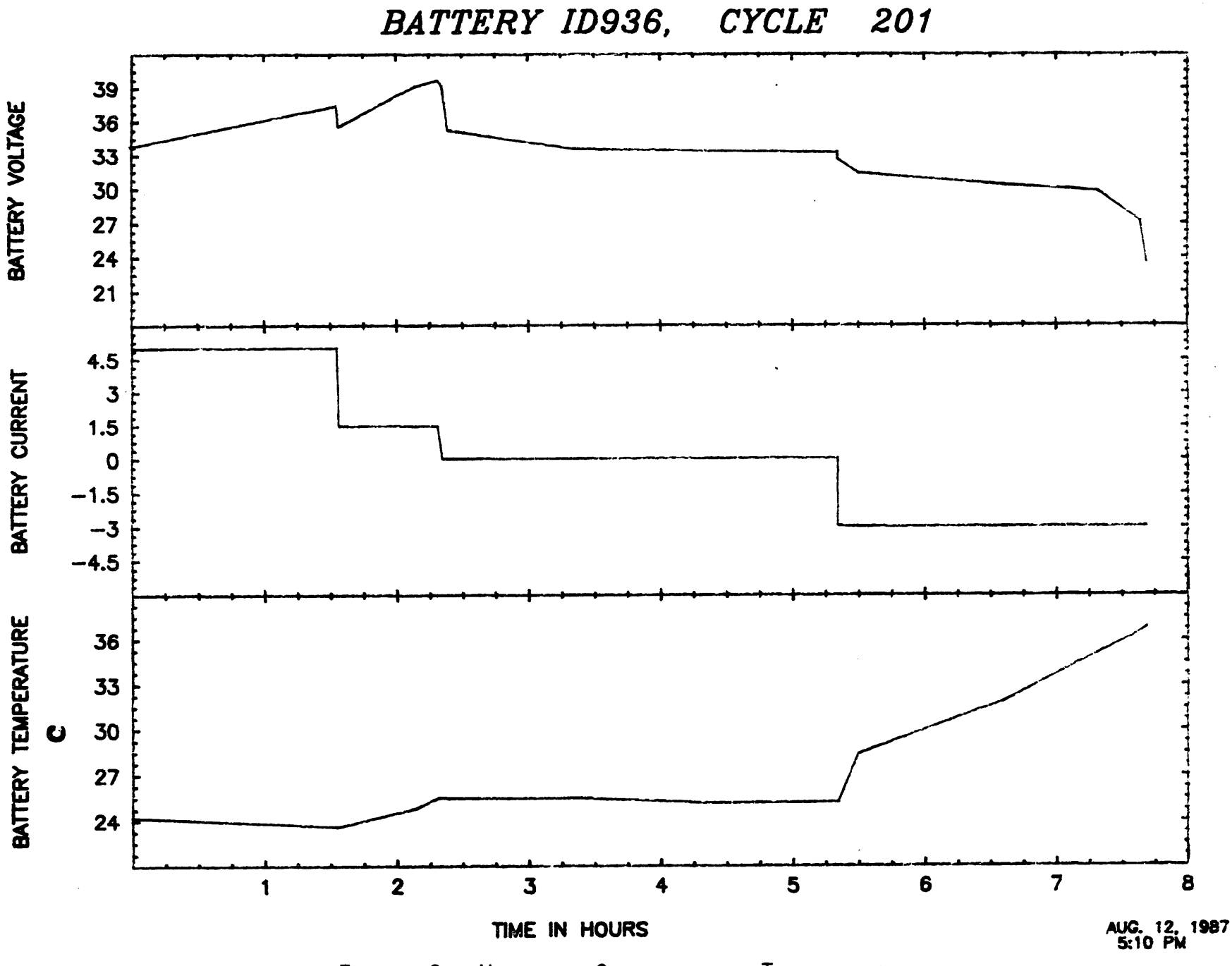

FIGURE 6. VOLTAGE, CURRENT, AND TEMPERATURE FOR CYCLE # 201 FOR T1576, # 936

TABLE 5
T1576/MC3935 Preliminary-TMS Test Results

PS PARA:	3.1.1	3.2.1	3.2.2	3.2.3	3.3.1	3.3.2	3.4.1	3.4.2	3.4.3
NAME	30-DAY STAND	ROOM TEMP. DISCH.	-35 C DISCH.	HIGH TEMP. STAND	TEMP. SHOCK	VERY HIGH TEMP.	HUMIDITY	VIBRA-TION	SHOCK
PRELIMINARY ACCEPTANCE CRITERIA									
MIN.	20	110	40	110	110	110	110	110	110
Ah	4.1	5.5	2.0	5.5	5.5	5.5	5.5	5.5	5.5
BATTERIES-SNL ID#/EP SERIAL NUMBER									
930/1	-	146 7.3	64 3.3	-	-	-	-	-	-
933/4	-	138 6.9	56 2.8	122 6.1	-	72 3.6	-	-	-
935/5	-	134 6.7	-	-	-	-	-	118 5.9	112 5.6
936/6	-	140 7.0	-	-	-	86 4.3	-	-	-

- Denotes no test.

Based on these results, the acceptance criteria of several tests were revised to provide more realistic criteria, while still satisfying the performance specified in the CD. Any test which involved elevated temperature was determined to have a significant effect on discharge capacity, and the acceptance criteria were reduced. None of the 30-day stand tests were run at this point due to the amount of time involved in this test.

TMS Testing

Following the delivery of the second group of prototypes to Sandia in April, 1987, the TMS tests were begun. This group consisted of 12 batteries; they were identical to batteries built in the first production lot. The results are summarized in Table 6. The data show the number of minutes and ampere-hours obtained during each test discharge. The acceptance requirements for the tests are listed at the top of the table. The batteries passed all of the tests. These requirements met the specifications listed in CD368509.

TABLE 6
T1576/MC3935 FINAL TMS TEST RESULTS

PS PARA:	3.1.1	3.2.1	3.2.2	3.2.3	3.3.1	3.3.2	3.4.1	3.4.2	3.4.3
NAME	30-DAY STAND	ROOM TEMP. DISCH.	-35 C DISCH.	HIGH TEMP. STAND	TEMP. SHOCK	VERY HIGH TEMP.	HUMIDITY	VIBRA-TION	SHOCK
FINAL ACCEPTANCE CRITERIA*									
MINUTES	20	110	40	80	90	30	80	110	110
Ah	4.1	5.5	2.0	4	4.5	1.5	4	5.5	5.5
BATTERIES-SNL ID NUMBER/EP SERIAL NUMBER									
938/7	25	156	90	-	111	-	96	142	-
	4.8	7.8	4.5		5.5		4.8	7.1	
939/8	22	158	-	-	113	36	90	-	139
	4.7	7.9			5.7	1.8	4.5		6.9
940/9	25	156	-	120	108	-	94	138	-
	4.8	7.8		6.0	5.4		4.7	6.9	
941/10	25	158	50	-	113	32	96	-	126
	4.8	7.9	2.5		5.7	1.6	4.8		6.3
942/11	29	166	-	-	136	-	116	134	142
	5.6	8.3			6.8		5.8	6.7	7.1
943/12	30	166	-	122	122	60	97	140	-
	5.9	8.3		6.1	6.1	3.0	4.8	7.0	
944/13	31	166	-	-	138	-	110	-	160
	6.0	8.3			7.0		5.5		8.0
945/14	30	160	70	118	126	40	102	140	-
	5.8	8.0	3.5	5.9	6.3	2.0	5.1	7.0	
946/15	28	154	76	-	112	-	93	-	136
	5.5	7.7	3.8		5.6		4.7		6.8
947/16	29	158	-	-	118	46	90	132	-
	5.6	7.9			5.9	2.3	4.5	6.6	
948/17	29	156	-	118	121	38	86	-	130
	5.7	7.8		5.9	6.1	1.9	4.3		6.5
949/18	27	154	-	-	-	-	-	-	-
	5.3	7.7							

* Discharge cutoff voltage was 26.8 V for all tests except: 30-day stand test for 938 and 940-949, cutoff was 26.0 V.

Battery performance was lower than expected for the 30-day stand, high-temperature stand, very-high-temperature stand, and humidity tests. All batteries experienced an apparent increase in resistance during the 30-day stand period. Higher resistance resulted in lower battery voltage during discharge and reduced capacity. Figure 7 illustrates the reduced voltage during discharge after a 30-day stand compared to discharge without a stand. The discharge cutoff voltage was reached prematurely due to the reduced voltage. The data show that battery voltage declined very gradually around 27 V, and slight variations in test conditions or battery capacity could cause a large variability in test results.

Initially, a discharge cutoff value of 26.8 V was selected for all tests because certain PAL controllers will not operate below this voltage. This cutoff voltage is relatively high for a 24-cell battery. Normally, nickel/cadmium batteries are discharged to 1 volt per cell. The lower value reduces the impact of increased battery resistance.

The high discharge rate used in the 30-day stand test (12-14 A) increased the severity of the voltage drop compared to the nominal PAL controller rate of 3 A. Typically, the discharge cutoff voltage is lowered as discharge rate is increased. The discharge cutoff voltage was therefore lowered to 26.0 V from 26.8 V for this test. The lower cutoff voltage reduced the variability in the results and provided a meaningful measure of battery capacity.

The cutoff voltage was not changed for the discharge test used in the field. In that case, discharge is run soon after charging, when battery resistance is relatively low.

Problems with the other tests were a manifestation of the higher resistance noticed on the 30-day stand test. Charged, open-circuit stand, at elevated temperature, also caused increased resistance. Since all of these tests were run at a 3-A discharge rate, it was not appropriate to reduce the discharge cutoff voltage. Instead, the discharge time requirement was reduced. The new times (and ampere-hours) are listed in Table 6.

The mechanism which explains the observed increase in resistance is related to the "voltage depression effect" (5). When nickel/cadmium batteries are allowed to stand in the charged condition for a prolonged time period, recrystalization of the active materials occurs. The crystals tend to grow in size, effectively decreasing the contact area of the active material with the electrolyte. This phenomena leads to an increase in cell resistance. The effect is more pronounced at elevated temperature.

Another issue for consideration when interpreting these results was the sequence of the tests. Originally, the order of the TMS tests was thought to be unimportant, as long as the batteries were completely discharged between tests. Thus, these tests were run in random order, with a minimum 16-hour complete discharge between cycles. The TMS results, and subsequent test data, indicated it might be necessary to run conditioning cycles between certain tests or

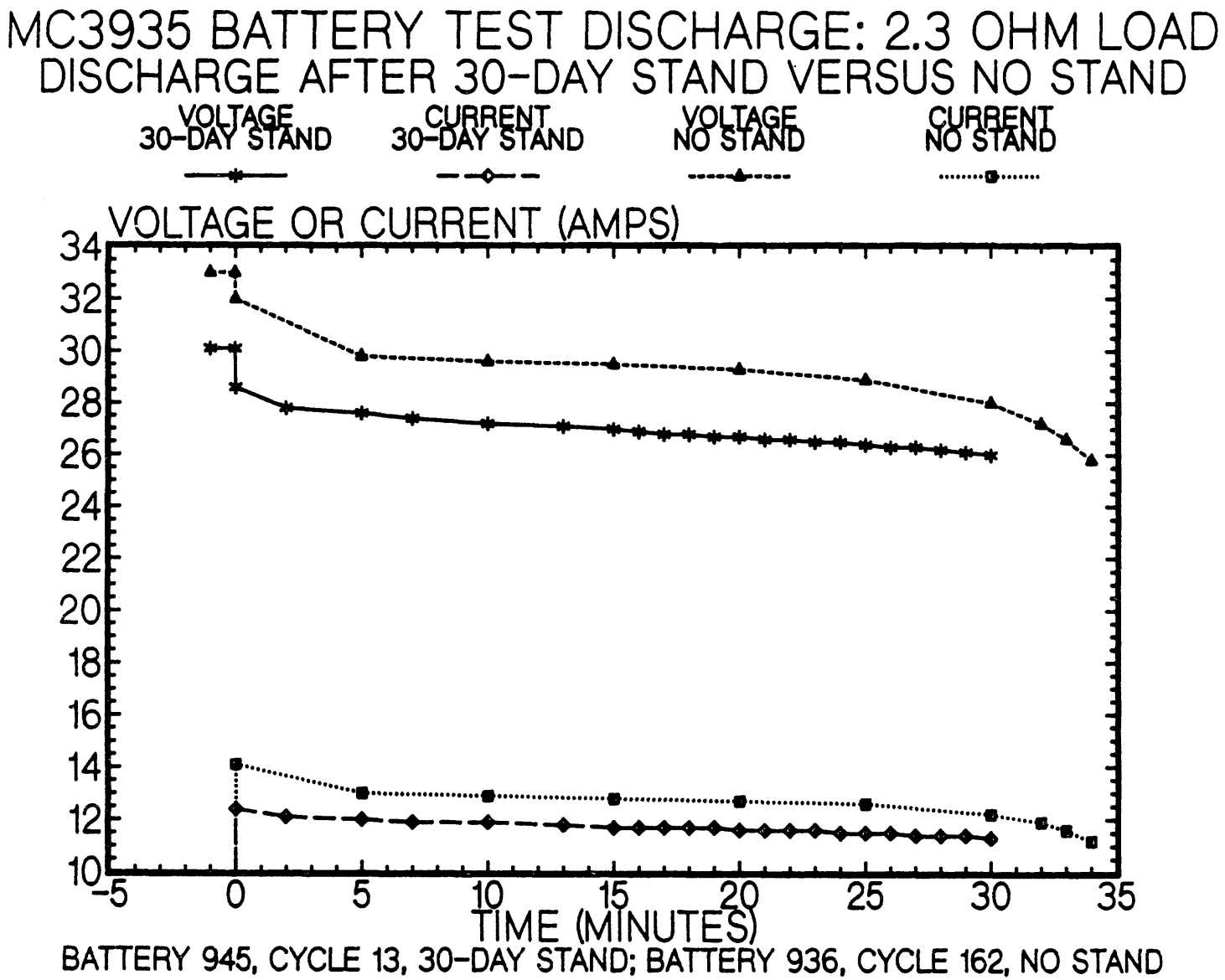

FIGURE 7. CONSTANT RESISTANCE DISCHARGE OF A MC3935 BATTERY ILLUSTRATING THE VOLTAGE LOSS FOLLOWING A 30-DAY CHARGED STAND

specify a sequence for the tests. A lowered discharge capacity was observed on room temperature discharge tests which followed elevated temperature stand tests. The capacities recovered to expected levels after two or three conditioning cycles. A conditioning cycle is one, room temperature discharge test, followed by a complete discharge for at least 16 hours.

Product Acceptance Tests

Power supplies and batteries built by EP for use by the Armed Forces are extensively tested at the factory before being accepted by Allied Signal Aerospace or the DOE. The tests specified in the PS (Appendix 2) are the product acceptance tests. The testing regime was developed in conjunction with the Components and Systems Reliability Division (7222).

The acceptance tests consist of both 100% tests and sample tests. The 100% tests are performed to insure that no defective batteries are shipped to the end users. Sample tests are used to spot check battery performance under extreme conditions. The two types of sample tests are environmental (E) tests and degrading (also called destructive, D) tests. The sampling rates are high during the first few months of production. Assuming no failures are detected, the rate of sampling ultimately decreases to two E-test and one D-test sample per month. The sample regime was selected to insure that there would be a very low probability of any inferior batteries being sent to the military.

The PT3515 battery tester was designed and built by Allied Signal Aerospace. It was delivered to EP in early 1988, and was installed in a room dedicated to testing these products. The tester is capable of independently charging and discharging 10 batteries at once. A microprocessor controls all tests and also acquires, stores, displays, and prints data. The tester room is air conditioned to remove excess heat generated during charge and discharge.

Representative data for each PS test are presented in Appendix 5 for reference purposes. Table 6 identifies the tests and lists the PS paragraph which specifies each test. These data were selected from batteries manufactured during 1988 by EP in production lots 5, 6, and 7 (lot date codes E88, F88, and G88, respectively). The data plots were taken directly from the PT3515 tester printouts.

Cycle Life Testing

After the TMS tests were concluded, several batteries were placed on life cycle tests at Sandia to validate the 500 cycle life goal stated in the PS. The twelve cycle test regime described above was used to age these batteries. Constant current, room temperature discharge data for the first cycle of each set of 12 is presented in Figure 8. To date, two batteries have surpassed the life cycle requirement. During the first 400 cycles of testing, several different discharge regimes described in the PS were applied to these batteries. Most of these regimes were more demanding or degrading to the battery than the life test. The scatter in the capacity life test data was a result of the more severe test conditions influencing subsequent discharge performance. Generally, after several life cycles, with intervening complete discharges, capacity returned to expected levels.

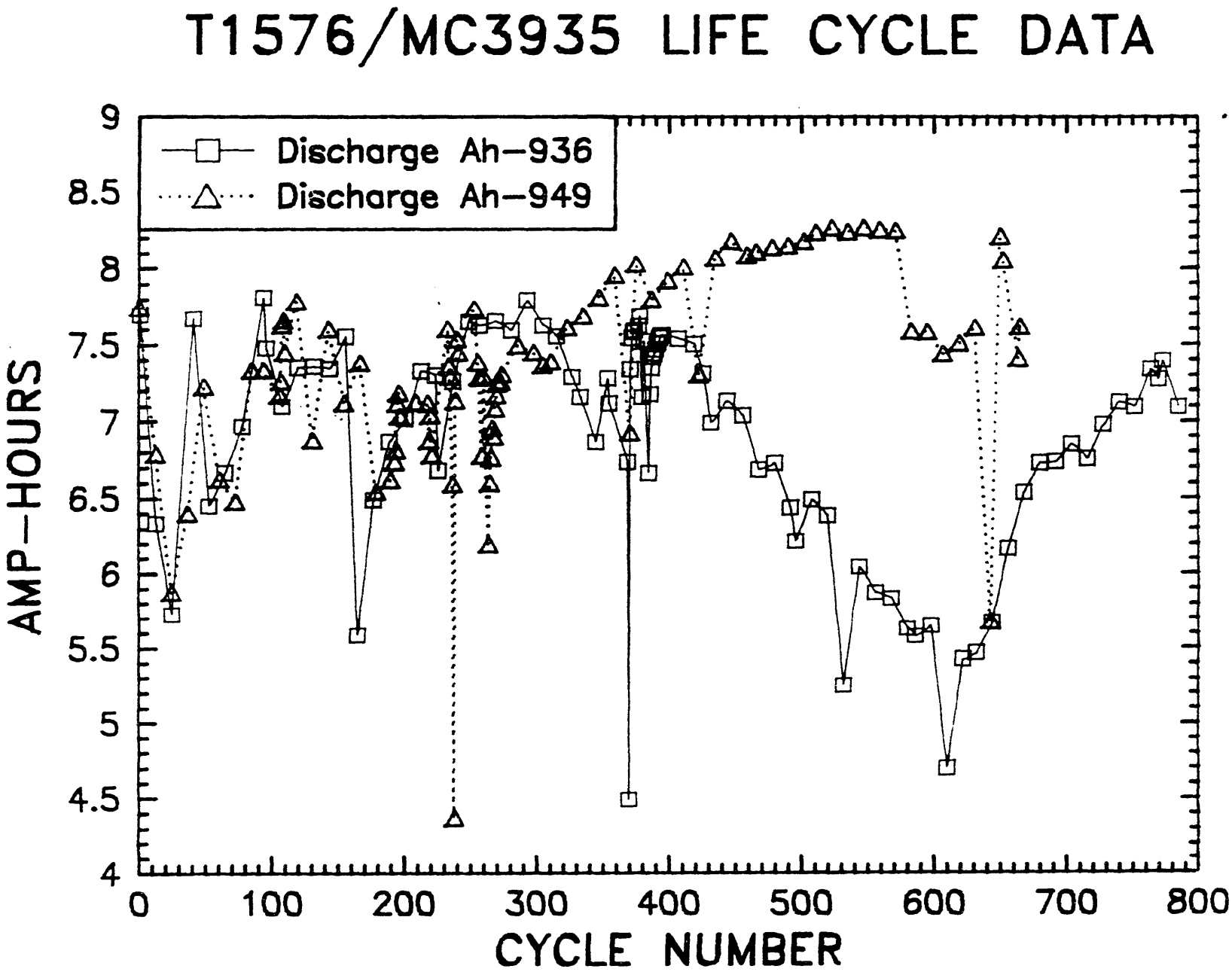

FIGURE 8. LIFE CYCLE DATA FOR TWO MC3935 BATTERIES

Later in the data plotted in Figure 8, only life tests were run, and battery performance was more consistent. Battery 949 retained a high capacity until it was removed from test after 677 cycles; its performance was still well above the 5.5-Ah requirement. Battery 936 demonstrated gradually declining capacity. The temporary decreases in capacity at cycles 530 and 610 were correlated with a lack of water in the cells; capacity increased substantially after distilled water was added to the cells. Both batteries required water addition after every 12-20 cycles of the life test regime. Approximately 5 milliliters of distilled water was added to each cell every time a battery was watered.

After 600 cycles, battery 936 began to approach the failure point; discharge capacity began to drop below 5.5 Ah. Representative samples of electrolyte were taken and hydroxide concentration was analyzed. It averaged about 10 wt% in several cells, compared to the nominal 30 wt%. Concentrated potassium hydroxide solution was added to each cell instead of water several times over the next 100 cycles. Discharge capacity markedly increased, and was approximately 7 Ah after 750 cycles. The hydroxide concentration was 24 wt% after the additions of caustic. These data strongly suggest that the declining battery capacity was caused by gradual loss of hydroxide in the electrolyte and decreased conductivity. Hydroxide is lost from the cell when electrolyte is forced past the cell vent seal during overcharge. When distilled water is subsequently added to replace lost volume, the hydroxide is not replaced. It can also be lost by chemical reaction through exposure of the electrolyte to carbon dioxide in the air. This battery was removed from test after 796 cycles.

Parametric Testing

A series of special tests were conducted on four batteries to quantify the loss of capacity during open circuit stand periods at elevated temperature. Unexpectedly large capacity losses were observed during the PS preliminary TMS involving high temperature exposure. The batteries were fully charged and stored on open circuit at 50 C for four different time periods. The percent of capacity lost compared to no stand was plotted against time in Figure 9. After 200 hours at 50 C, about 50% of the available capacity was lost. This loss can be attributed to the self-discharge reactions which occur in nickel/cadmium cells.

In a related test, the batteries were boost charged following a 48-hour stand at 50 C. The boost amounted to about one hour on charge at 1.5 A. During the subsequent discharge, the capacity loss was only about 11%, compared to a loss of about 20% without a boost charge.

Other characterization experiments were performed in order to better understand battery operation. The effect of the duration of complete discharge on subsequent discharge capacity was studied. The minimum duration was 16 hours, as specified by EP. For these experiments, the duration of complete discharge was varied from 16 to 130 hours. No definite impact was observed on battery discharge capacity over this range. Therefore, there appears to be no benefit to prolonging the complete discharge for greater than 16 hours.

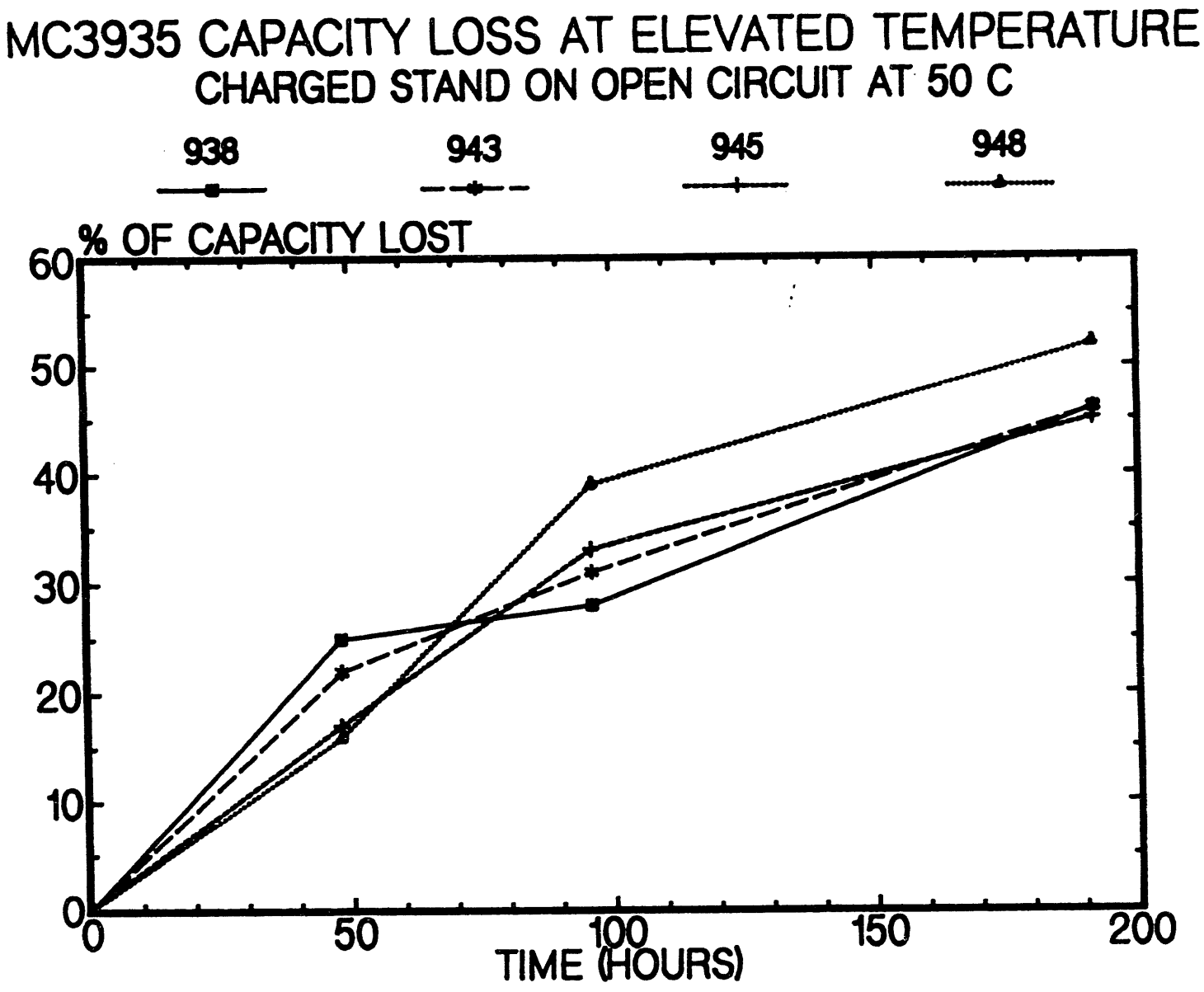

FIGURE 9. MC3935 CAPACITY LOSS AFTER EXPOSURE TO ELEVATED TEMPERATURE FOR A RANGE OF TIME PERIODS. FOUR BATTERIES WERE USED IN THESE TESTS; THE IDENTIFICATION NUMBERS (I.E. 938) ARE DESCRIBED IN TABLE 6.

Polarization studies were conducted to determine the internal battery resistance. Both MC1605 and MC3935 batteries were tested over a range of depths-of-discharge. Voltage versus current data were obtained under both charge and discharge conditions. Battery resistance was calculated from the slope of the line based on a linear regression of these data. Resistances from the discharge data are given in Figure 10. The values ranged from 200 to 700 milliohms. The two MC3935 batteries demonstrated comparable resistances, while the two MC1605 batteries had significantly higher resistances. The resistance values obtained from charge data were similar to the discharge values, except at full charge. Battery resistance at full charge was approximately four times higher than the comparable resistance based on discharge data.

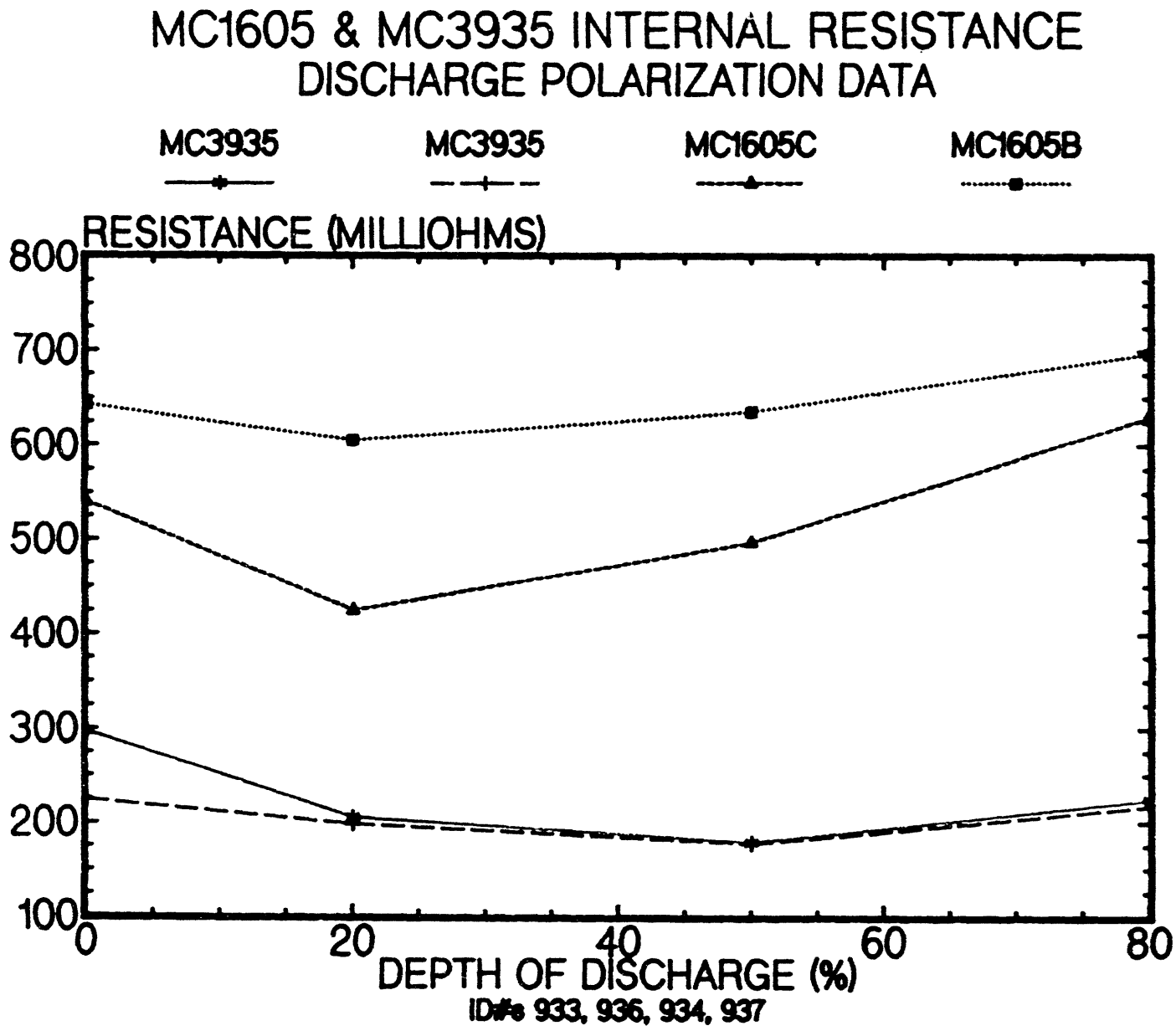

FIGURE 10. INTERNAL RESISTANCE VS. DEPTH-OF-DISCHARGE FOR TWO MC1605 AND TWO MC3935 BATTERIES

CONCLUSIONS

The T1576 was developed to provide a simple, low cost, and minimum maintenance power supply for PAL ground controllers. Development was a joint effort between Sandia, EP, and Allied-Signal Aerospace. The final designs for the T1576 and the MC3935 battery satisfied all requirements. Prototypes were extensively tested at Sandia and appropriate acceptance specifications were established. An optimized charge regime also resulted from these tests. The first production units were accepted and shipped on schedule, in March 1988.

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REFERENCES

1. "Characteristics and Development Report for the MC1605 and MC1605A Storage Battery", B. G. Neeld, 1323-1, Sandia National Labs, Albuquerque, NM, SC-DR 405-62, May, 1964.

2. "The MC1605B Nickel/Cadmium Battery", T. A. Reinhart, 1912, Sandia National Labs, Albuquerque, NM, SC-DR-71 0865, May, 1972.

3. "Alkaline Storage Batteries", S. U. Falk and A. J. Salkind, John Wiley and Sons, 1969.

4. "Handbook of Batteries and Fuel Cells", D. Linden, editor, Chapter 17, McGraw-Hill, 1984.

5. "Nickel/Cadmium Battery Application Engineering Handbook", Second Edition, J. C. Grant, editor, General Electric Company, Gainesville, FL, GET-3148A, 1975.

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APPENDIX 1

FSCM NO. 14213

CD368509
-000

EVANS 5127 RRE 5/12/87
MARSH 2833
SUPVR 5127 5/11/87
SUPVR 2525 RRE 5/12/87
DISK.81/MAR-PC NO. 13

COMPATIBILITY, T1576

INTERFACE CONTROL DRAWING

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1. GENERAL

1.1 Scope. This document defines those characteristics of the T1576 Power Supply that are subject to special controls to assure interface compatibility with next-assembly usage.

1.2 Description. The T1576 is a portable 28-volt power supply which provides electrical input power for the following Permissive Action Link (PAL) ground controllers.

T1533
T1534
T1535
T1536
T1539
T1554
T1555
T1563

The T1576 will consist of a single replaceable battery protected by an external housing. The power supply will be connected to controllers by a CT1478 (or equivalent) power cable.

This power supply requires periodic maintenance and recharging.

1.3 Change Control. The approval of the following is required for any technical changes to this document:

a. Supervisor, Command and Control Division 5127, and

b. Supervisor, Storage Batteries Division 2525 (if the change affects battery performance and reliability).

1.4 Definitions. The following definition applies throughout this document.

Ampere-Hour Capacity - The battery capacity is the quantity of electricity that the battery can deliver until the loaded voltage drops to the minimum operate level. It is measured in ampere-hours where the current for the 28-volt system described herein is calculated as 28 volts divided by its fixed resistive test load.

2. DOCUMENTS

2.1 Required. The following documents form a part of this specification to the extent stated herein.

DG10001	Design Guide, Special Design Equipment for Use in Critical Assembly Areas
SB343825	Physical Environments, Portable PAL Controllers
MD25-51	General Instructions Applicable to Nuclear Weapons

2.2 References. The following documents are listed for the convenience of the user.

AY209467	CT1478
CD338781	Compatibility, T1533
CD338782	Compatibility, T1534
CD338783	Compatibility, T1535
CD338784	Compatibility, T1536
CD338966	Compatibility, T1539
CD339085	Compatibility, T1554
CD339086	Compatibility, T1555
CD339125	Compatibility, T1563
CD367193	Compatibility, Power Sources, PAL Controllers
MIL-STD-810	Environmental Test Methods

3. PHYSICAL CHARACTERISTICS

The T1576 will be designed within the following physical constraints.

3.1 External Configuration. The T1576 will be externally configured as shown in Figure 1. The cover will be easily opened with luggage latches.

3.2 Composition. The T1576 will consist of one MC3935 battery, a steel electromagnetic shielded case and cover as illustrated in Figure 1.

3.3 Internal Configuration. The T1576 will be internally configured as shown in Figure 1. Easy access to the battery within the T1576 will be provided for charging and cleaning maintenance. The case shall be designed to adapt and hold two MC1605 batteries if desired. Additional brackets and spacers for MC1605 adaption are acceptable.

3.4 Markings. The T1576 base will be externally labeled with the appropriate identification markings per Figure 1 and TP35-51, Section 5.

3.5 Weight. The maximum weight will be 20 pounds for portability.

3.6 Size. The T1576 will occupy a volume of approximately 0.5 ft^3 so that it can easily be handled and stored with a high degree of portability.

3.7 Handles. The T1576 will have a foldable carrying handle on the top surface that facilitates handling with heavy gloves.

3.8 Corrosion Protection. The T1576 will be protected within itself from the corrosive effects of the electrolyte within the MC3935 battery.

3.9 Connectors. The T1576 output connector will be compatible with the CT1478 (or equivalent) power cable.

4. FUNCTIONAL CHARACTERISTICS

The T1576 will have the following power functions.

4.1 Usage Configuration. The T1576 will provide power to the PAL controller in the configurations of Figure 2.

4.2 Discharged Configuration. The T1576 will be maintained in the discharged condition by the application of shorting plugs (see Figure 3) connected to the output connector.

4.3 Storage Configuration. The T1576 will be stored and ready for usage with the application of a protective dust cap connected to the output connector.

5. ELECTRICAL CHARACTERISTICS

The T1576 will have the following electrical characteristics.

5.1 Schematic. The T1576 will be wired per the simplified schematic shown in Figure 4. Separate wires in Pins A and C shall be terminated at the positive terminal of the MC3935 battery.

5.2 Operating Voltage. The T1576 will deliver a nominal 28 volts under load (ref 5.4) and temperature (-40 to +160°F). The maximum voltage will be 37.2 volts and the minimum will be 26.8 volts.

5.3 Current. The T1576 will be capable of delivering 2.50 amperes average. The peak current capability will be 12 amperes for a duration of 200 milliseconds.

5.4 Initial Capacity. The initial capacity of the T1576, immediately after charging, will be determined by discharging the T1576 into a 15 ±2 ohm load until the minimum operate voltage of 26.8 volts is reached. The initial capacity at ambient room temperature will be 2.6 ampere-hours (Ah) minimum. The minimum initial capacity at -40°F will be 0.8 Ah.

5.5 Storage Charge Retention. The initially available capacity after 30 days continuous storage at 110°F will be determined by discharging the battery into a 15 ±2 ohm load at ambient room temperature until the minimum operate voltage of 26.8 volts is reached. The minimum available capacity will be 1.0 Ah.

5.6 Charging. The T1576 will be capable of being recharged by the T431A and by a new charger, the T1577.

5.7 TEMPEST Shielding. The case and cover of the T1576 will provide shielding to reduce TEMPEST emanations during controller operations. The shielding effectiveness will be 55 dB for frequencies from 100 kHz to 300 MHz.

6. NUCLEAR SAFETY

The T1576 will be used as a PAL tester power source designed for operational support of weapons in critical assembly areas. DG10001 will be followed as a design guide wherever appropriate.

7. PERSONNEL SAFETY

In the event of plugged battery vents, the T1576 will be capable of containing a battery explosion.

8. ENVIRONMENTAL REQUIREMENTS

8.1 Operating Environments. The T1576 shall be operational during and following exposure to the following environments.

8.1.1 Temperature.

a. High: +160°F - deliver 0.8 Ah capacity.

b. Low: -40°F - deliver 0.8 Ah capacity.

8.1.2 Humidity. The T1576 shall provide power to PAL controllers during any part of the 24-hour humidity cycle in Figure 5.

8.1.3 Electromagnetic Radiation (EMR). The T1576, while in an operational configuration, may be exposed to the following EMR fields:

Transmission	Frequency	RMS Field Intensity (V/m)	Peak Field Intensity (V/m)	Polarity
CW	200 kHz to 10 MHz	100	200	Vertical
CW	200 kHz to 10 MHz	10	20	Horizontal
CW	10 kHz to 100 MHz	100	200	All
Pulse	100 MHz to 16 GHz	200	4000	All

8.1.3 continued

NOTES:

1. For pulse environments, duty cycles are assumed to be 5%.

2. The following definitions apply to pulse environments:

   a. RMS field intensity is the effective value obtained by averaging over many modulation cycles.

   b. Peak field intensity is the effective value obtained by averaging over the entire pulse.

3. Average power density is determined by averaging over the pulse repetition period and is equal to the duty cycle multiplied by the peak power density level.

8.2 Nonoperating Environments. The T1576 is not required to operate during exposure to the following environments; however, following exposure the T1576 shall be capable of meeting all functional and electrical requirements.

8.2.1 Temperature Shock.

Change from ambient room temperature (RT) to +160°F within 5 minutes,
Hold at +160°F for 3 hours,

Change from +160°F to ambient RT within 5 minutes,
Hold at ambient RT for 3 hours,

Change from ambient RT to -40°F within 5 minutes,
Hold at -40°F for 3 hours, then

Change from -40°F to ambient RT within 5 minutes.

8.2.2 Rain. The T1576 shall survive heavy rainfall of 16 inches total in 2 to 4 hours with the case lid closed.

8.2.3 Salt Spray. With the lid closed, the T1576 shall operate after exposure to a continuous spray of 5 ±1% salt solution for 48 hours.

8.2.4 Sand and Dust. The T1576 shall operate after exposure to blowing sand and dust with the lid closed. MIL-STD-810, Method 510.2 may be used as a testing guideline.

8.2.5 Pressure. The T1576 may be exposed to altitudes varying from sea level to 60,000 feet (31 to 2.13 in. Hg) within 30 minutes and from 60,000 feet to sea level within 30 minutes, both while at -30°F.

8.2.6 Vibration. The T1576, with the case lid closed, shall meet the following vibration specifications:

Composite Random Vibration	Figure 6	1 hr/axis
Sine Vibration	.25 inch double amplitude 5-15 Hz	1/2 oct/min
	3 g 15-2000 Hz	(approx. 36 min/axis) Sweep up and down

8.2.7 Mechanical Shock. The T1576, with the case lid closed, shall survive a drop onto a flat concrete surface from a height of 36 inches with the base down. Additionally, three shocks of 150 g, 1.7 ms shall be applied through the three main axes.

8.2.8 Nuclear Radiation. The T1576 shall survive the following levels of radiation.

Total dose: 1600 rad (tissue)

Maximum gamma, continuous: 450 rad (tissue)

Maximum neutron, continuous: 1300 rad (tissue)

Peak neutron exposure: 7.1×10^{11} neutrons/cm^2 (1.8 MeV Si equiv)

Peak gamma dose rate: 10^9 rad/sec (Si)

9. LIFE

The T1576 will meet the following life requirements. Each battery will be capable of completing a minimum of 500 full charge/discharge cycles or a 5-year life, whichever occurs first.

10. HUMAN FACTORS ENGINEERING

The T1576 will be designed to minimize the probability of human error which could result in improper operation and maintenance; could cause loss of battery performance; and/or could affect personnel safety.

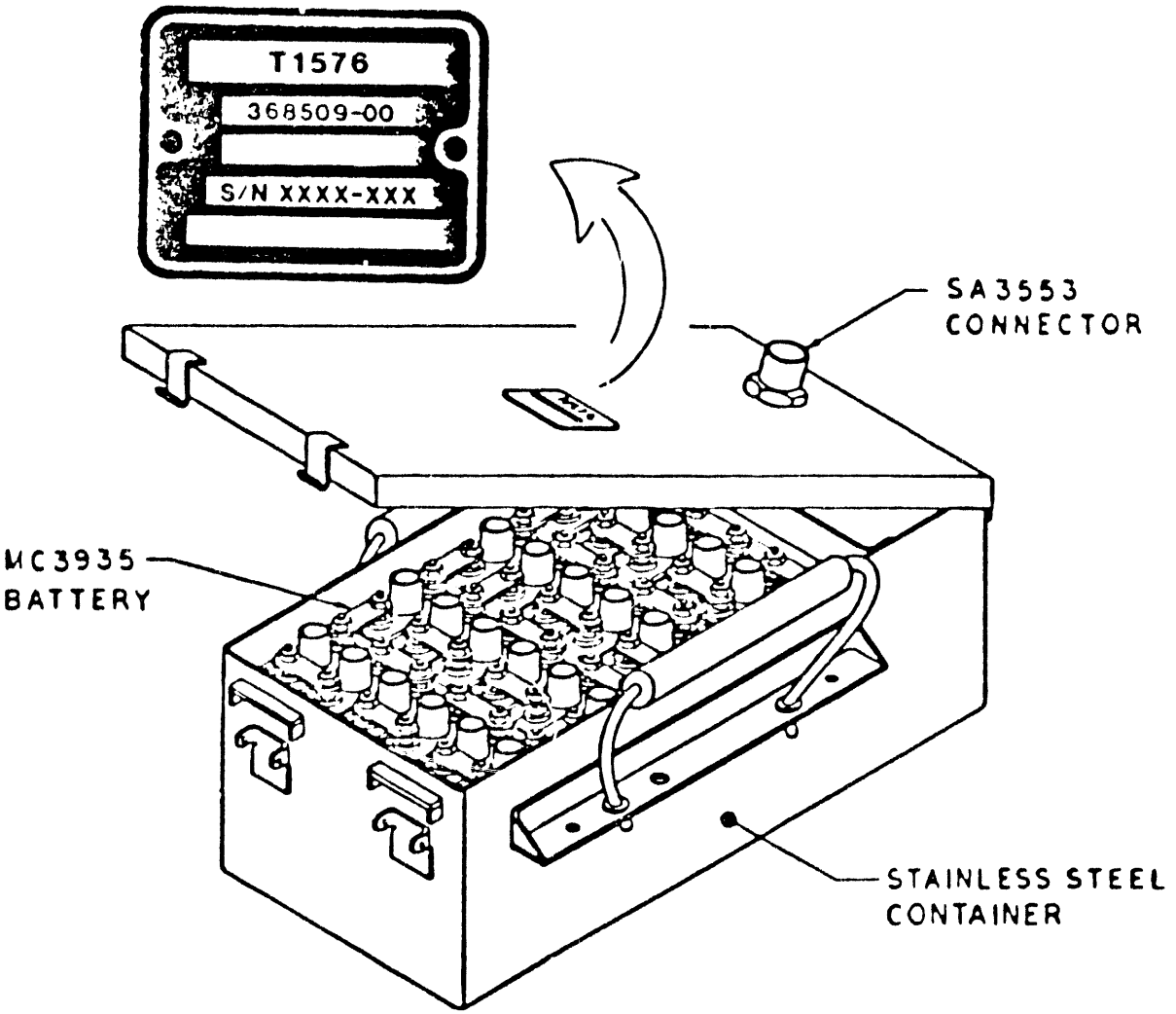
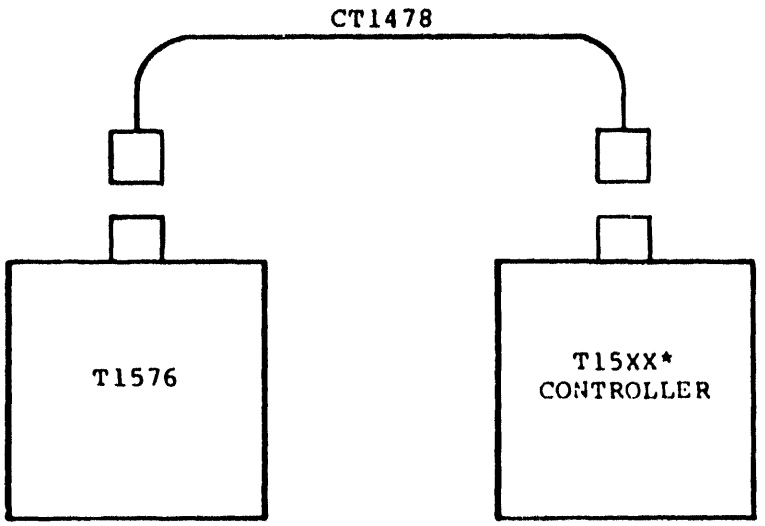


FIGURE 1 - T1576 POWER SUPPLY



*T15XX
T1533
T1534
T1535
T1536
T1539
T1554
T1555
T1563

FIGURE 2 - USAGE CONFIGURATION

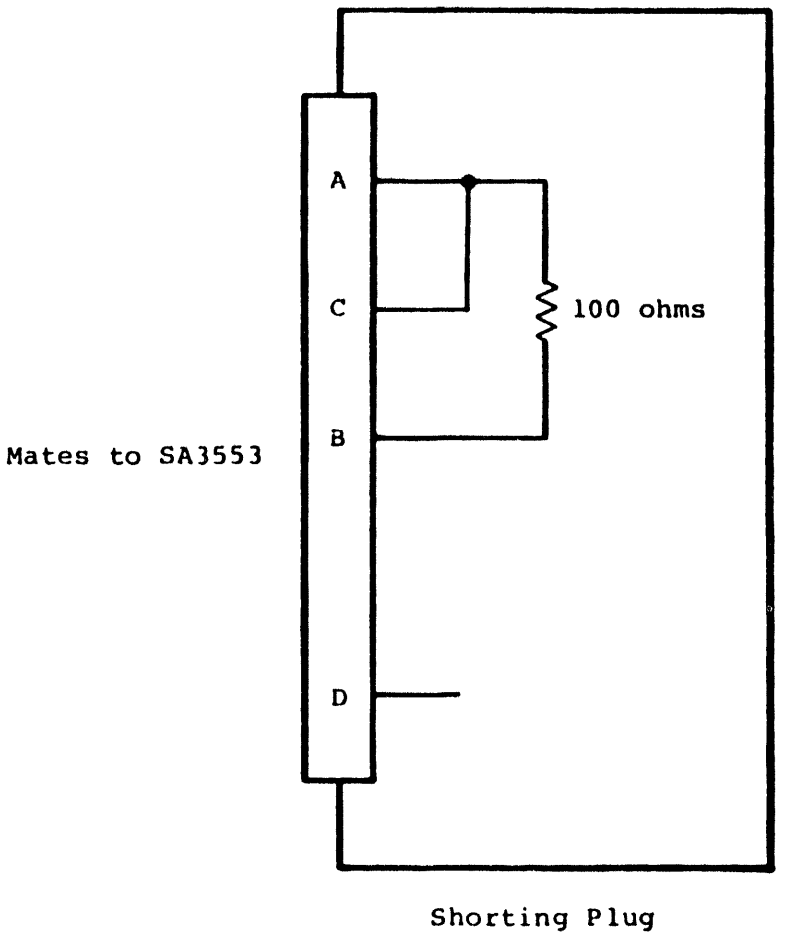


FIGURE 3 - SCHEMATIC OF SHORTING PLUG

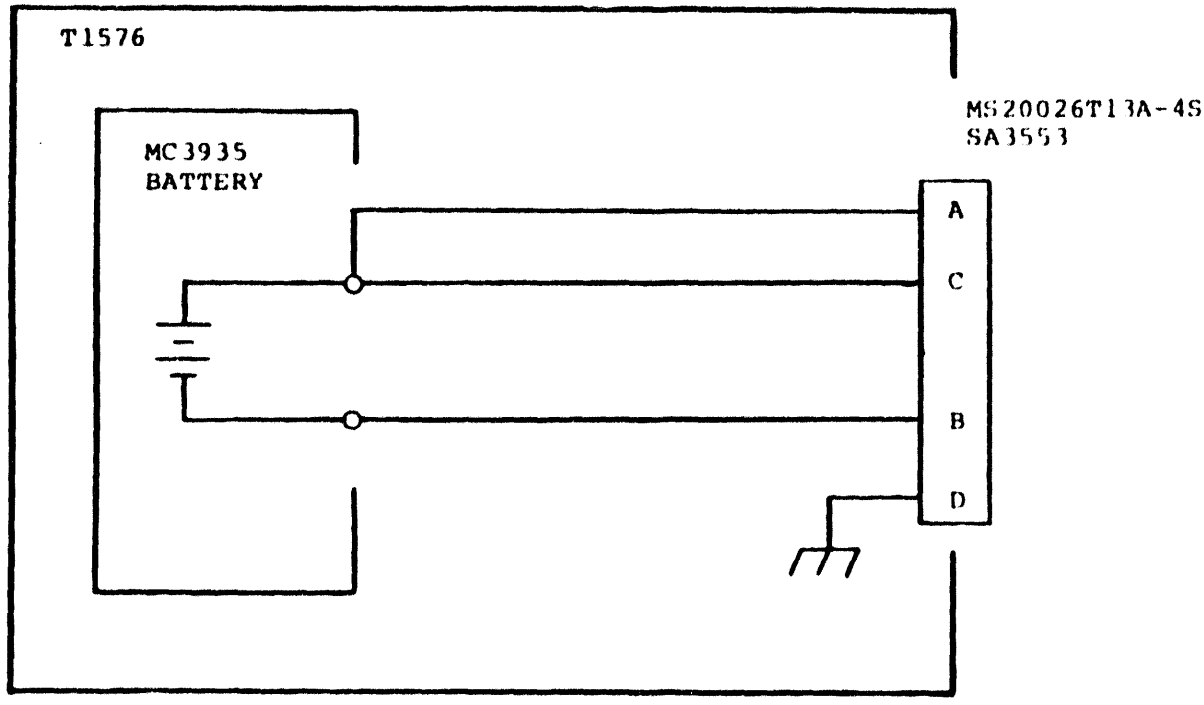


FIGURE 4 - T1576 SCHEMATIC

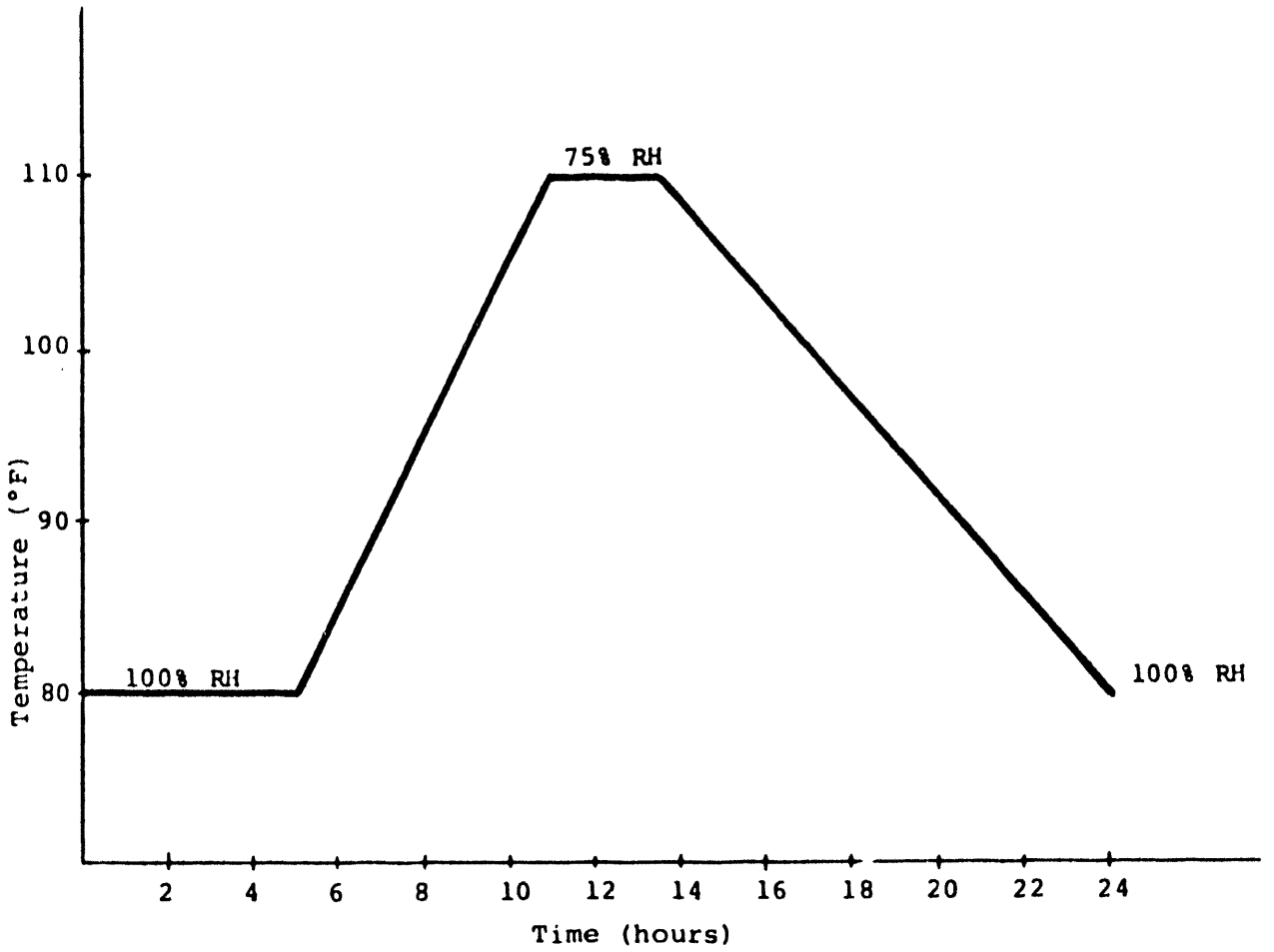


FIGURE 5 - 24-HOUR HUMIDITY CYCLE

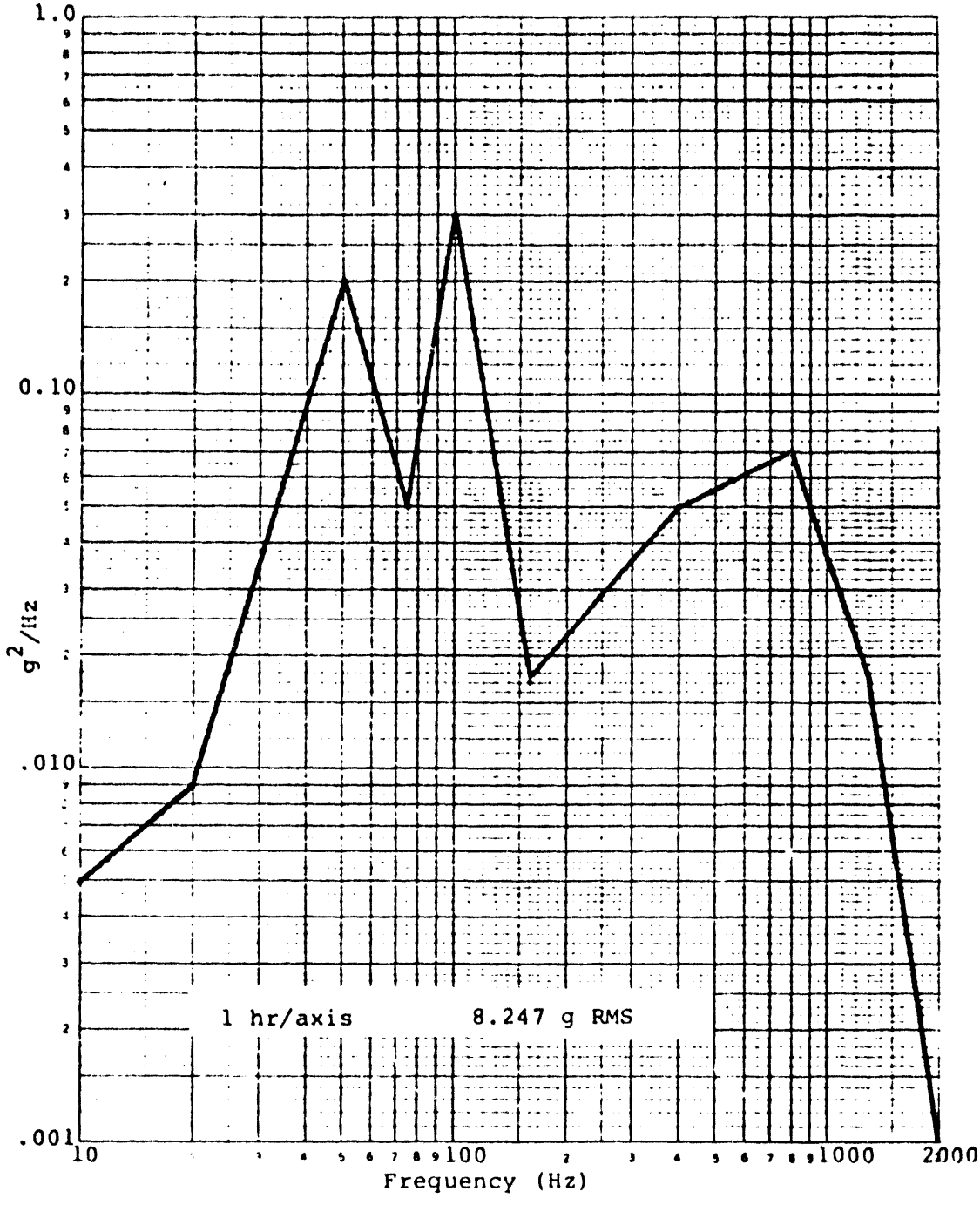


FIGURE 6 - COMPOSITE RANDOM VIBRATION

G. Neal, 557BX
P. Butler, 2525
M. Finch, 834BX MF
BKC(g)-WPC II (P4eu)
TIE SC/BX/B DRC 2

Released 4-10-89 Jr

PRODUCT SPECIFICATION, T1576

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Issue	H	D	D

DESIGN AGENCY CONTROL NUMBER	ISSUE	RELEASE/CHANGE NO.	DATE
PS368509-000	D	881925BX C	3/88
	E	883382BX C	5/88
	F	884277BX C	6/88
	G	885340BX C	8/88
	H	887158BX C	10/88
	J	891540BX C	4/89

1. GENERAL.

This specification defines the requirements for the T1576 Power Supply. The T1576 is a power supply for Permissive Action Link (PAL) ground controllers. It consists of a container assembly, part number 382196, and an MC3935 battery. The T1576 configuration is shown in Figure 1.

2. DEFINITIONS, RECORDS, AND GENERAL REQUIREMENTS.

2.1 Definitions. The following definitions are in addition to those contained in 9900000, General Requirements, and DOE/AL Quality Control Policy, QC-1.

a. Conditioning Cycle. A conditioning cycle consists of a charge per 2.1.f and discharges in accordance with 2.1.b or c, and 2.1.i. These operations are for battery conditioning and need not be performed with PT equipment.

b. Constant Current Discharge. The discharge conducted at 3 ±0.1A constant current to a cutoff voltage of 26.8 ±0.3 volts per battery.

c. Constant Resistance Discharge. The discharge that takes place at a constant resistance of 2.3 +0.2, -0 ohms to a cutoff voltage of 26.0 ±0.3 volts per battery.

d. Cycle. A cycle consists of a charge followed by a discharge. There may be open circuit wait periods between charge and discharge.

e. Electrolyte Level Check. Electrolyte level checks are performed only on fully charged batteries within one to three hours after removal from charge. The electrolyte level of each cell is checked with a calibrated syringe. The syringe is placed into the opening at the top of the cell as far as possible. If a small volume (less than 1.0 milliliter) of liquid can be withdrawn from the cell into the syringe, no adjustment is required. Otherwise, if no liquid can be withdrawn, distilled water must be added to the cell with the syringe, in small increments, until liquid just can be withdrawn. If excess liquid (greater than 1.0 mL) is present, it should be withdrawn.

2.1 Continued.

f. Full Charge. Each MC3935 is charged at a constant current of 5 ±0.2A, until the battery voltage rises to 37.4 ±0.5 volts, or for a maximum of two and a half hours. The charge current is then reduced to 1.5 ±.1A and held constant. The maximum time allowed for the second charge level is one hour. The 1.5A charge shall be terminated if the voltage exceeds 41V.

g. Life Cycle. A life cycle is a complete charge/discharge operation which consists of a charge period and a discharge period. A rest of 1 hour, minimum, to 5 hours, maximum, shall follow both charge and discharge. The charge is carried out per 2.1.f and the discharge per 2.1.b. Periodically, a shorting discharge per 2.1.i is performed following discharge per 2.1.b.

h. Rated Capacity. The MC3935 has a rated capacity of 5.5 Ah when discharged in accordance with 3.2.1.b at 25°C.

i. Shorting Discharge. This procedure follows either a constant current or constant resistance discharge. The battery voltage is reduced to less than 5.0 volts using either discharge method, or a combination of both. The battery is then shorted using a shorting plug or clip leads and a 100 ohm or less, 1 watt minimum resistor. It must remain shorted for a minimum of 16 hours.

2.2 Test Records. Test results associated with the MC3935 battery shall be reported in accordance with DR410083. These records shall be signed by the Supplier's inspector, or authorized representative, and shall be distributed in accordance with instructions on the forms.

2.3 Test Conditions.

a. Unless otherwise specified, tests shall be performed at room atmospheric conditions and the T1576 shall be at room temperature when each test is started.

b. At the Buyer's discretion, each power supply may complete one or more conditioning cycles per 2.1.a prior to start of test program.

2.4 Tolerances. 9900000 applies. Unless otherwise specified, test tolerances shall be:

Temperature:	±6°C
Time:	±10 percent
Vibration:	
Acceleration or Amplitude:	±5 percent (approximate sine wave)
Frequency:	±2 percent or 3 Hz, whichever is greater
Shock:	
Duration:	
a. 2 msec or more:	±0.6 msec or ±15 percent, whichever is greater
b. less than 2 msec:	±0.1 msec or ±30 percent, whichever is greater
Voltage:	±2 percent
Resistance:	±2 percent
Current:	±1 percent

2.5 Lot. A lot shall consist of 30 to 50 T1576 units. These units shall be the deliverable units from a manufacturer's lot of 31 to 56 batteries that have passed the 100 percent of 3.1. Specified quantities of D-test batteries per 2.6.3 shall be selected from the manufacturer's lot. Units in a lot shall have been manufactured and assembled without significant changes in materials, tools, processing, design essentials or other factors which substantially affect the homogeneity of the units. Unless otherwise approved by the Design Agency, all tests shall be completed before the lot is shipped.

2.6 Lot Acceptance Requirements.

2.6.1 100% Tests. All units in a lot must have passed the tests specified in 3.1. Units which fail any of the 100% tests may be reworked and retested once. Any reworked units which pass the tests in 3.1 must be included in the next lot. The reworked units may not be used if the next lot is assembled more than two months following the test failure.

2.6.2 Environmental Test (E-Test) Lot Sampling. Each lot shall be sampled at random; that is, each unit in a lot, including units which have been reworked or resubmitted for any reason, shall have an equal chance of being drawn as part of the lot sample. Selected units shall be tested per 3.2. The sequence of testing is up to the discretion of the Supplier, except where noted. Exceptions to this sampling method must be approved by the Design Agency. Any failures shall result in the lot being held. See paragraph 2.7.

2.6.2.1 Initial Sampling. Fifteen units from the initial lot shall be submitted to the E-Tests per 3.2 with no failures. The Design Agency may authorize previous E-Tests of record for the T1576 or MC3935 as all or part of this initial sampling requirement.

2.6.2.2 Secondary Sampling. After successful completion of sampling per 2.6.2.1, the E-Test sample shall be six per lot until two consecutive lots have been accepted at this sample rate with no failures in E- or D-testing. The Design Agency may authorize previous E-Tests of record for the T1576 or MC3935 as all or part of this secondary sampling requirement.

2.6.2.3 Nominal Sampling. After initial and secondary sampling, the E-Test sample shall be 2 units per lot until such time that a failure occurs. If an E-test or D-test failure occurs, sampling shall revert to the secondary rate per 2.6.2.2.

2.6.3 Destructive Test (D-Test) Lot Sampling Requirements. D-Test sample units shall be selected randomly from the lot E-Test units that have passed the requirements of 3.2. The sequence of testing is up to the discretion of the Supplier, except where noted. The sampling stages noted below refer to and are determined by the E-Test sampling in 2.6.2. The Design Agency shall be notified immediately of any D-Test failures, and it will decide the effect on current lot shipment and future sampling rates.

2.6.3.1 Initial Sampling. Six of the 15 E-Test units shall be tested per 3.3 and 3.4. The Design Agency may authorize previous D-Test of record for the T1576 or MC3935 as all or part of this initial sampling requirement.

2.6.3.2 Secondary Sampling. Two of six E-test sample units shall be tested in accordance with 3.3 and 3.4. The Design Agency may authorize previous D-Tests of record for the T1576 or MC3935 as all or part of this secondary sampling requirement.

2.6.3.3 Nominal Sampling. The D-Test sample shall be one unit out of the two E-Test units per lot. It shall be tested per 3.3 and 3.4.

2.7 Lots Held on Sample Tests. In the case of lot sample failure, the Production Agency shall be notified immediately and the lot shall be held pending review of the failure. After review of the failure and the circumstances leading to it, a lot acceptance proposal will be considered.

2.8 Disposition of Lot Samples. E-Test samples not selected for D-Testing may be returned to the lot. Units subjected to tests designated as destructive or degrading shall be marked "D-Tested" in a contrasting color, preferably red, and these units shall not be returned to the lot. D-Tested units shall be shipped to the Buyer in clearly-marked separate containers.

3. PERFORMANCE TESTING.

Table 1 summarizes the T1576 performance tests. Table 2 lists the acceptance criteria for each test.

3.1 100% Testing.

3.1.1 Retention of Charge at Room Temperature. All test activities shall be performed at 25 ±6°C. The T1576 shall begin this test in the discharged condition, per 2.1.b, or 2.1.c, and 2.1.i. The T1576, after being fully charged per 2.1.f, shall be stored for 30 +5, -0 days. After this storage, the unit shall be discharged at constant resistance per 2.1.c. Time to complete the discharge shall be 20 minutes, minimum. Following this test, the unit must satisfy the continuity requirement of 3.1.2.

3.1.2 Continuity. Begin this test with the T1576 in the discharged condition per 2.1.b or 2.1.c, and 2.1.i. The resistance between SA3553 connector Pin D and the power supply case shall be measured with a standard ohmmeter, or by the volt-ampere method. The resistance shall not exceed 100 milliohms. The resistance between Pin A and the "A" lead end (or positive battery terminal), and between Pin B and the "B" lead (or negative battery terminal), shall meet the same requirement. The resistance between Pin C and the "C" lead end (or positive battery terminal) shall meet the same requirement. The resistance between Pins A, B, and C individually to Pin D (ground) shall be 10k ohms, minimum.

3.1.3 External Visual and Mechanical Inspection. The T1576 may be either charged or discharged. After visual inspection, only T1576s meeting the requirements of 9900000 shall be used for further testing or returned to the lot.

3.2 Lot/Block Sample Testing (E-Tests).

3.2.1 Discharge Test at Room Temperature. Begin this test with the T1576 in the discharged condition per 2.1.b or 2.1.c, and 2.1.i. This test shall be conducted at ambient temperature conditions (25 ±6°C).

a. The unit shall be charged per 2.1.f. It then shall be placed on an open-circuit wait of 1 hour, minimum, to 24 hours, maximum.

b. Open-circuit voltage shall be measured immediately prior to discharge. The unit shall be discharged at constant current in accordance with 2.1.b. The battery voltage under load must remain at or above 26.8 ±0.3 volts for 110 minutes, minimum. After this test, the unit must meet the continuity requirement of 3.1.2.

3.2.2 Discharge Test at -35°C. The provisions of 9958000, Temperature Test Instrumentation and Equipment, shall apply. The T1576 shall begin this test in the discharged condition per 2.1.b or 2.1.c, and 2.1.i. The unit shall be charged at room temperature per 2.1.f. Within 5 hours after the end of charge, the unit shall be exposed to a temperature of -35 +6°C for 16 hours, minimum. It then shall be discharged at constant current per 2.1.b while at this low temperature. The battery voltage under load must remain at or above 26.8 ±0.3 volts for 40 minutes, minimum. After this test, and while at room temperature, the unit shall meet the continuity requirement of 3.1.2.

3.2.3 Retention of Charge at High Temperature. The provisions of 9958000 shall apply. Begin this test with the T1576 in the discharged condition per 2.1.b or 2.1.c, and 2.1.i. The unit shall be charged at room temperature conditions per 2.1.f. After a 1-hour minimum wait on open circuit, and within 5 hours, the unit shall be exposed to a temperature of 50 ±6°C and maintained at this temperature for 48 hours, minimum. After this period, the unit shall be allowed to cool to room temperature for 3 hours, minimum, to 24 hours, maximum. It then shall be discharged at constant current per 2.1.b. The battery voltage under load must remain at or above 26.8 ±0.3 volts for 80 minutes, minimum. After discharge, the T1576 must meet the continuity requirement of 3.1.2.

3.3 Group 1 D-Test. Each D-Test sample unit shall be subjected to the tests described in this paragraph.

3.3.1 Temperature Shock. The provisions of 9958000 shall apply. Begin this test with the unit in the discharged condition per 2.1.b or 2.1.c, and 2.1.i. The unit shall be charged per 2.1.f. It then shall be subjected to three cycles of the following conditions:

Change from ambient room temperature (RT) to +71°C within 5 minutes,

Hold at +71°C for 3 hours,

Change from +71°C to ambient RT within 5 minutes,

Hold at ambient RT for 3 hours,

Change from ambient RT to -40°C within 5 minutes,

Hold at -40°C for 3 hours, then

Change from -40°C to ambient RT within 5 minutes and hold for 3 hours.

After completing the third cycle, the unit shall be allowed to stabilize at room temperature for at least 3 hours. The unit shall be discharged at constant current in accordance with 2.1.b. The battery voltage under load must remain at or above 26.8 ±0.3 volts for 90 minutes, minimum. This test is considered to be a destructive test (D-Test).

3.3.2 Retention of Charge at Very High Temperature. The provisions of 9958000 shall apply. Begin this test with the T1576 in the discharged condition per 2.1.b or 2.1.c, and 2.1.i. The unit shall be charged at room temperature conditions per 2.1.f. Within 5 hours, the unit shall be exposed to a temperature environment of +71 ±6°C for 48 hours, minimum. After this period, the unit shall be allowed to cool to room temperature for 3 hours, minimum, to 24 hours, maximum. The unit shall be discharged at constant current in accordance with 2.1.b. The battery voltage under load must remain at or above 26.8 ±0.3 volts for 30 minutes, minimum. This test is considered to be a destructive test (D-Test).

3.4 Group 2 D-Tests. Each Group 1 D-Test unit shall be subjected to one of the tests described below (3.4.1 through 3.4.3). The Group 1 units shall be assigned to the Group 2 tests such that approximately equal numbers of units will be subjected to each of the tests. At the rate of one D-test unit per lot, three lots will be required for each test to be run once.

3.4.1 Humidity. The provisions of 9958006, Relative Humidity Test Instrumentation and Equipment, shall apply. The T1576 shall be installed in a container assembly, P/N 382196, for this test. Begin this test with the T1576 in the discharged condition per 2.1.b or 2.1.c, and 2.1.i. The unit shall be fully charged per 2.1.f. With a potted mating connector installed, the unit shall be placed in a relative humidity chamber and subjected to 10 cycles of the 24-hour sequence shown in Figure 2. The temperature changes shall be linear and the humidity shall not drop below 75 percent during testing. A maximum of two interruptions during testing is permissible. Upon completion of the tenth cycle, the unit shall be removed from the chamber and, within 48 hours, the unit shall be discharged at constant current in accordance with 2.1.b. The battery voltage under load must remain at or above 26.8 ±0.3 volts for 80 minutes, minimum. Visual inspection shall reveal no damage that might ultimately result in malfunction.

3.4.2 Vibration. The provisions of 9958002, Sinusoidal Vibration Test Instrumentation and Equipment, and 9958004, Complex-Wave Vibration Test Instrumentation and Equipment, shall apply. The T1576 shall be installed in a container assembly, P/N 382196, for this test. Begin this test with the T1576 in the discharged condition per 2.1.b or 2.1.c, and 2.1.i. The unit shall be charged per 2.1.f. The battery terminal voltage shall be monitored and recorded throughout this testing. There shall be no "shorts" or "opens" as evidenced by voltage drops of more than 1.0 volts.

The unit shall be installed on a test fixture and oriented in accordance with the three axes shown in Figure 1. It shall be subjected to the following vibration environments.

a. Complex-Wave Vibration. One hour along each of the three mutually perpendicular axes shown in Figure 1, per the vibration spectrum of Figure 3.

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3.4.2 Continued.

b. Sinusoidal Vibration. Approx. 36 minutes along each of the three mutually perpendicular axes shown in Figure 1, at the accelerations and frequencies shown below. Sweep up and down at approx. 1/2 octave/minute.

Frequency	Acceleration or Double Amplitude
5 - 15 Hz	0.25 inch
15 - 2000 Hz	3g

Upon completion of vibration testing, the unit shall meet the requirements of the constant current discharge test per 3.2.1.b. Vibration testing is considered to be destructive (D-Test).

3.4.3 Mechanical Shock. The provisions of 9958003, Mechanical Shock Test Instrumentation and Equipment, shall apply. The T1576 shall be installed in a container assembly, P/N 382196, for this test. Begin this test with the T1576 in the discharged condition per 2.1.b or 2.1.c, and 2.1.i. The unit shall be charged per 2.1.f, and subjected to the following shock environments.

Test Number	Description
1	Three 150g, 1.7 msec shocks, one each in the direction of the three positive axes of Figure 1.
2	One 36-inch drop onto concrete, on the container bottom.

During each shock, the battery voltage shall be monitored and recorded, there shall be no "shorts" or "opens", as evidenced by a voltage drop of more than 1.0 volts. Upon completion of this shock testing, the unit shall meet the requirements of the constant current discharge test per 3.2.1.b. This shock testing is considered to be destructive (D-Test).

TABLE 1 - T1576 TEST REQUIREMENTS SUMMARY

Test Title	Test Para.	100%	Test Type E[1]	Test Type D[2]	Notes
Retention of Charge at Room Temp.	3.1.1	X			
Continuity	3.1.2	X			
External Visual and Mech. Inspection	3.1.3	X			
Discharge Test at Room Temp.	3.2.1		X		
Discharge Test at -35°C	3.2.2		X		
Retention of Charge at High Temp.	3.2.3		X		
Group 1					
Temp. Shock	3.3.1			X	
Retention of Charge at Very High Temp.	3.3.2			X	
Group 2[3]					
Humidity	3.4.1			X	4
Vibration	3.4.2			X	4
Mech. Shock	3.4.3			X	4

NOTES:

1. See 2.6.2 for sampling requirements of the E-tests.
2. See 2.6.3 for sampling requirements of the D-tests.
3. Sample units will rotate through the three tests in sequence.
4. Charge for these tests prior to testing will be in accordance with 2.1.f but does not need to be done on UA4176 or UA4177.

TABLE 2 - T1576 ACCEPTANCE CRITERIA

Test Para.	Test Condition	Discharge Rate	Minimum Discharge Time(min)	Temperature °C	Discharge Cut-Off Voltage(V)
3.1.1	30-Day Stand	2.3 Ω	20	25	26.0
3.1.2	Continuity				
3.1.3	Inspection				
3.2.1	Immediate Charge/Discharge	3.0 A	110	25	26.8
3.2.2	Stand and Discharge at -35°C	3.0 A	40	-35	26.8
3.2.3	48 Hours Stand at 50°C	3.0 A	80	25	26.8
3.3.1	Temperature Shock	3.0 A	90	25	26.8
3.3.2	48 Hours Stand at 71°C	3.0 A	30	25	26.8
3.4.1	Humidity	3.0 A	80	25	26.8
3.4.2	Vibration	3.0 A	110	25	26.8
3.4.3	Mechanical Shock	3.0 A	110	25	26.8

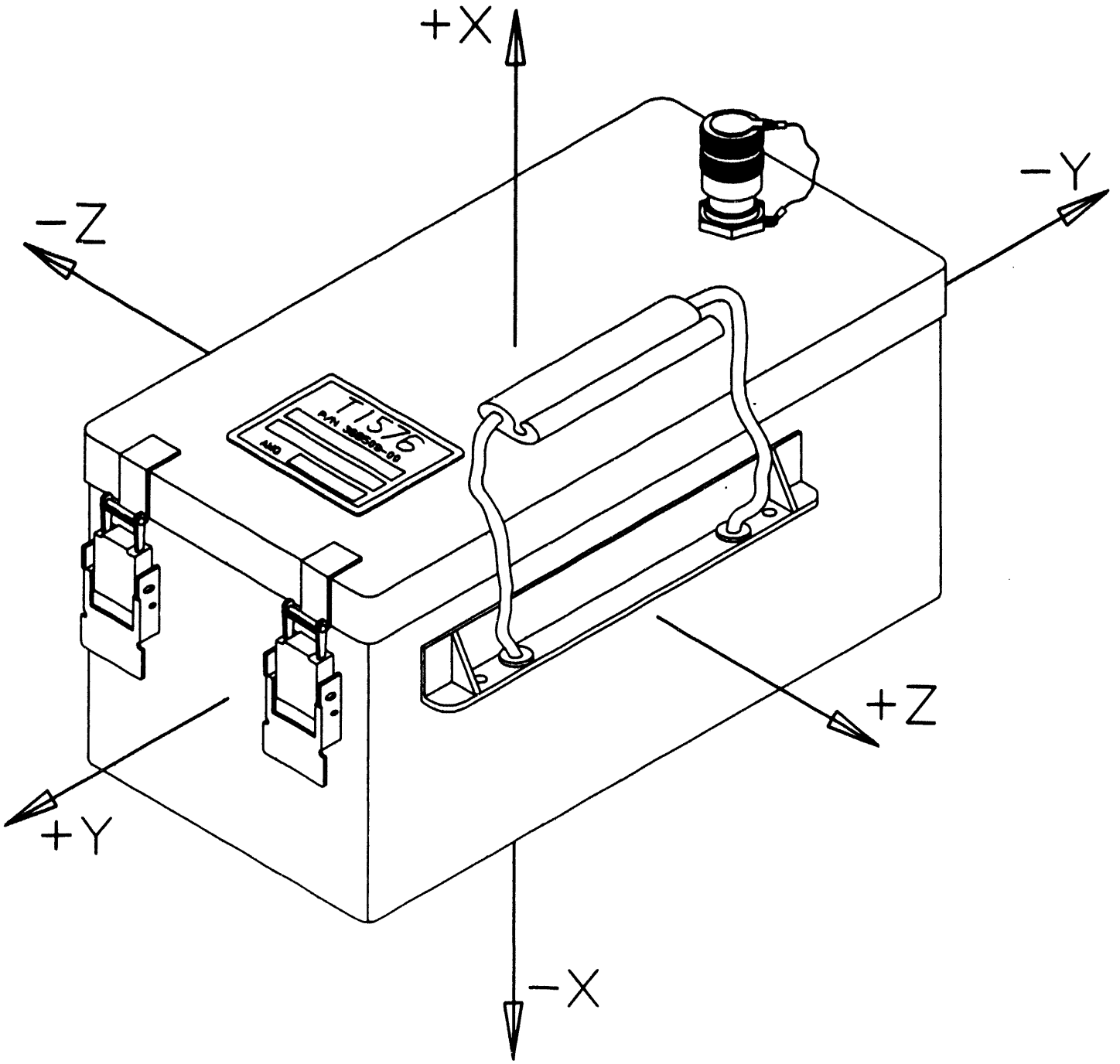

FIGURE 1 - T1576 POWER SUPPLY

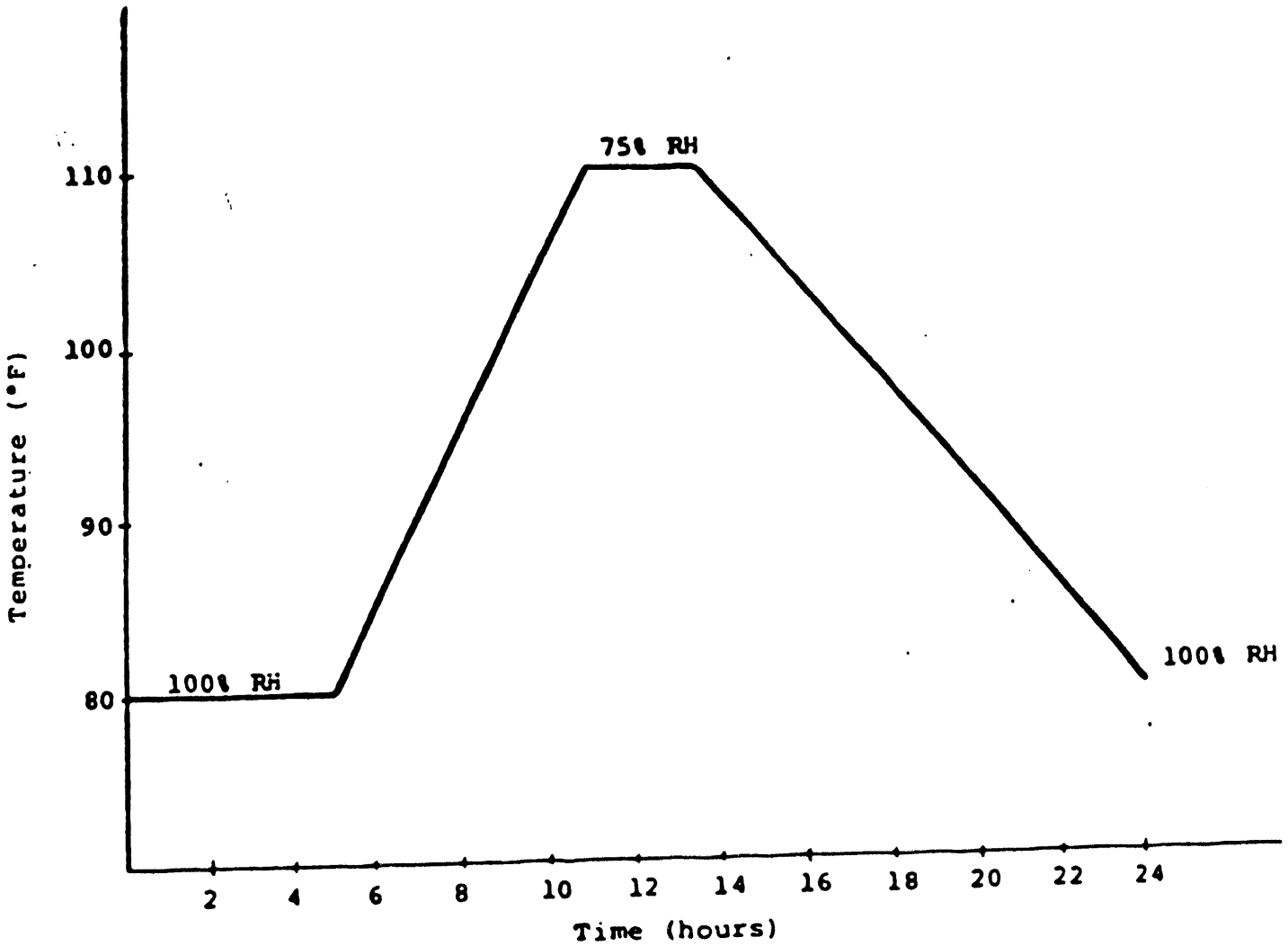

FIGURE 2 - 24-HOUR HUMIDITY CYCLE

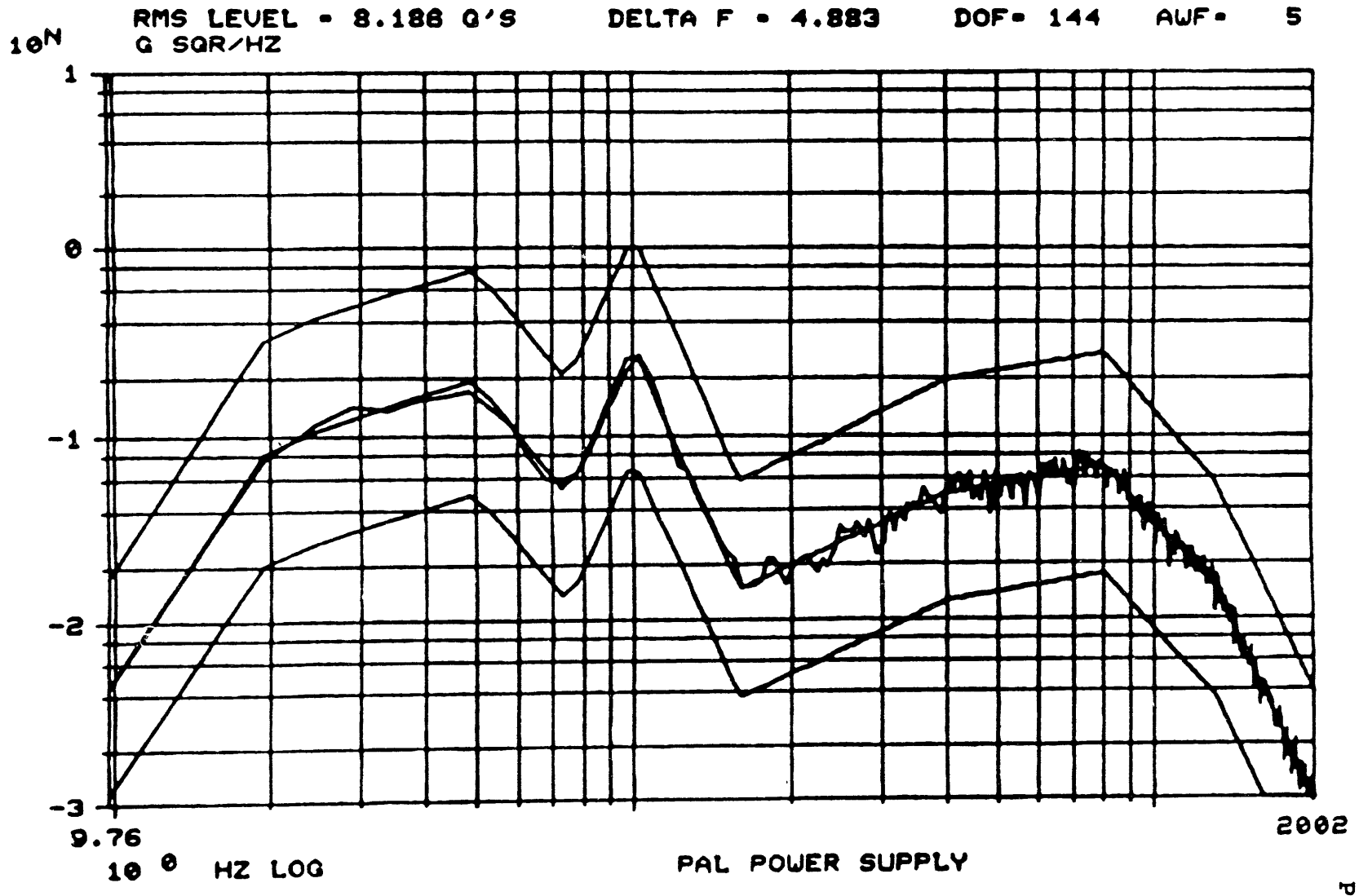

FIGURE 3 - COMPLEX-WAVE VIBRATION SPECTRUM

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APPENDIX 3

Sandia National Laboratories
Albuquerque, New Mexico 87185

date: May 29, 1986

to: R. R. Evans, 5127

P. C. Butler

from: P. C. Butler, 2525

subject: PAL Battery (MC 3935) Technology Selection

Prior to the selection of a battery technology and a development contractor for the MC3935, a thorough review of available electrochemical systems was conducted. The characteristics of these systems were compared with the application requirements described in the Compatibility Document (CD368509), dated 2/26/85. Some systems were eliminated from further consideration because of a failure to meet the requirements. Other systems were evaluated in detail to determine the degree to which they satisfied the requirements.

To compile a list of candidate battery development and manufacturing contractors, an advertisement was placed in the Commerce Business Daily (CBD). This advertisement described the application requirements and invited qualified companies to submit letters expressing their interest. Approximately 20 responses were received. A formal Request for Proposal (RFP) was sent by Sandia to each of these companies. The RFP described the battery requirements in detail and outlined a Statement of Work (SOW) for prototype battery development and evaluation.

In parallel with this contractual process, the initial technology screening was conducted. Table 1 identifies the rechargeable systems considered while Table 2 lists the primary systems evaluated. A rating of "Good" indicates that the technology will probably satisfy the PAL application requirements while a "Poor" rating indicates the requirements will probably not be met. Vented technologies require maintenance such as watering and cleaning.

From this initial screening, four technologies were selected for further consideration. These were the rechargeable vented and sealed nickel/cadmium batteries, and the primary lithium/sulfur dioxide and lithium/thionyl chloride batteries.

The vented nickel/cadmium system is used in the MC1605 battery and thus is proven to satisfy the application requirements. Its chief drawback is the necessity of routine maintenance such as watering and cleaning. This is a burden in terms of cost, personnel, and training once the batteries reach the field. The design of the MC3935 using this technology will decrease but not eliminate the required maintenance. The MC3935 will have approximately three times the capacity of the MC1605. Thus it can complete more duty operations (recode, decode discharges) per charge and consequently require less frequent watering than the MC1605. Also, only one MC3935 will be used in place of two MC1605 batteries. Therefore, instead of 48 cells requiring maintenance, only 24 cells will be maintained.

A vented nickel/cadmium battery will have a 5.5 Ah capacity and a nominal life of 500 cycles. A single PAL controller duty operation (discharge) consumes approximately 1 A-min. Therefore, a vented nickel/cadmium battery could complete a maximum of 165,000 duty operations in its life.

K. D. Murphy, Division 2525, was consulted regarding the relative cost comparison between the four technologies. The cost of a single vented nickel/cadmium battery without connector or container can be estimated at $750. The cost of a new T1577 battery charger can be estimated at $5,000, but this cost would be distributed over many batteries and only a fraction of this cost could be applied to one battery. A conservative estimate of 0.25 of $5,000, or $1,250 can be assumed. The cost of maintenance per battery can be estimated by assuming each MC3935 would require 15 minutes of maintenance (watering, cleaning, charger operation) per quarter. A labor cost of $32/hour is assumed. These costs are plotted (Ni/Cd(v)) versus the number of duty operations per year in Figure 1.

The sealed nickel/cadmium technology offers the advantage of no maintenance. However, its performance is inferior to that of the vented nickel/cadmium, particularly at low temperature. Tests have been initiated in the Division 2525 evaluation labs to characterize this behavior. Initial results using commercial Saft "F" size cells indicate three possible problems that might prevent this technology from satisfying the requirements. Under load, the battery voltage is less than the minimum required operating voltage when the ambient temperature is below -15 C. At -15 C, the battery delivers approximately half of its room temperature capacity. Another problem identified with the sealed nickel/cadmium battery was long recharge time.

Manufacturer specifications require 14 hours for recharge. This exceeds the PAL requirement by at least six hours. Finally, near the end of charge, the closely packed cells generated a large quantity of heat. Battery temperatures exceeded 60 C under room temperature conditions. Either charge control or active cooling would be required to prevent early cell failure for this cell design. Other sealed designs such as fast charge and low temperature types are also being evaluated.

The cost of a sealed nickel/cadmium battery, without connector or container, is approximately $750. The charger costs would be the same as for the vented nickel/cadmium case. The total cost of the sealed battery differs from the vented by the cost of maintenance. This cost is also plotted in Figure 1 (Ni/Cd(s)). With the assumptions of this analysis, the cost advantage of the sealed battery is relatively minor.

For the lithium primary systems, S. Levy and N. Godshall, Division 2523, were consulted regarding the requirements. For the sulfur dioxide type, five parallel strings of 11 D-cells in series were recommended in order to meet the high current and low temperature requirements. This configuration results in a battery of 55 cells having 37.5 Ah of capacity, a weight of 11.5 lbs, and a volume of 0.12 cu.ft. With PAL controller duty operations consisting of a 1 A-min discharge, one lithium/sulfur dioxide battery could complete a maximum of 2250 duty operations during its life. These cells are estimated to cost $7 each. For 55 cells, the cost per battery would be $385. The cost of maintaining a supply system for the primary batteries is unknown.

The cost of the primary battery types is highly dependent on the number of duty operations required per year by the using organization. This is illustrated in Figure 1. The more operations required, the more frequently the primary batteries must be replaced and the higher the cost. The cost of the rechargeable batteries become less than the primary lithium/sulfur dioxide at about 1,400 duty operations per year. From the Brideau service questionnaire, the range of PAL controller duty operations required per 24 hours is 3-700, with the majority requiring about 60. Therefore, it would require only 23 days in one year of 60 duty operations per day for the cost advantage to shift to the rechargeable batteries. At 700 operations per day, only 2 such days per year are necessary to shift the cost advantage to the rechargeables.

The lithium/thionyl chloride system, with its higher current capability compared to the sulfur dioxide type, would allow the use of just two parallel strings of 11 cells each. This battery would have a capacity of about 15 Ah, and it would complete a maximum of about 900 duty operations in a life-time. These cells cost about $20 each. Again refering to Figure 1, this technology is less attractive than the sulfur dioxide type from a cost perspective.

From these simple estimates, it does not appear to be economic to use primary batteries for this application, unless very few duty operations per year are required. Some development might be necessary before the primary technologies could be used in this application. Of significance is the fact that only one company responded to the Commerce Business Daily advertisement recommending a lithium primary battery. No formal proposals were received from the RFP that considered a primary battery.

Only two serious proposals were received from the RFP for the development activity. One recommended sealed nickel/cadmium while the other proposed vented nickel/cadmium. Because of the uncertainty of satisfying the application requirements using the sealed technology (low temperature capacity and long recharge time), the vented nickel/cadmium type was selected in June, 1985, for the PAL application. This technology satisfies all the stated application requirements except the desire for no maintenance. If the requirements change, other systems could be re-evaluated based on the specific requirements.

PCB:tdp

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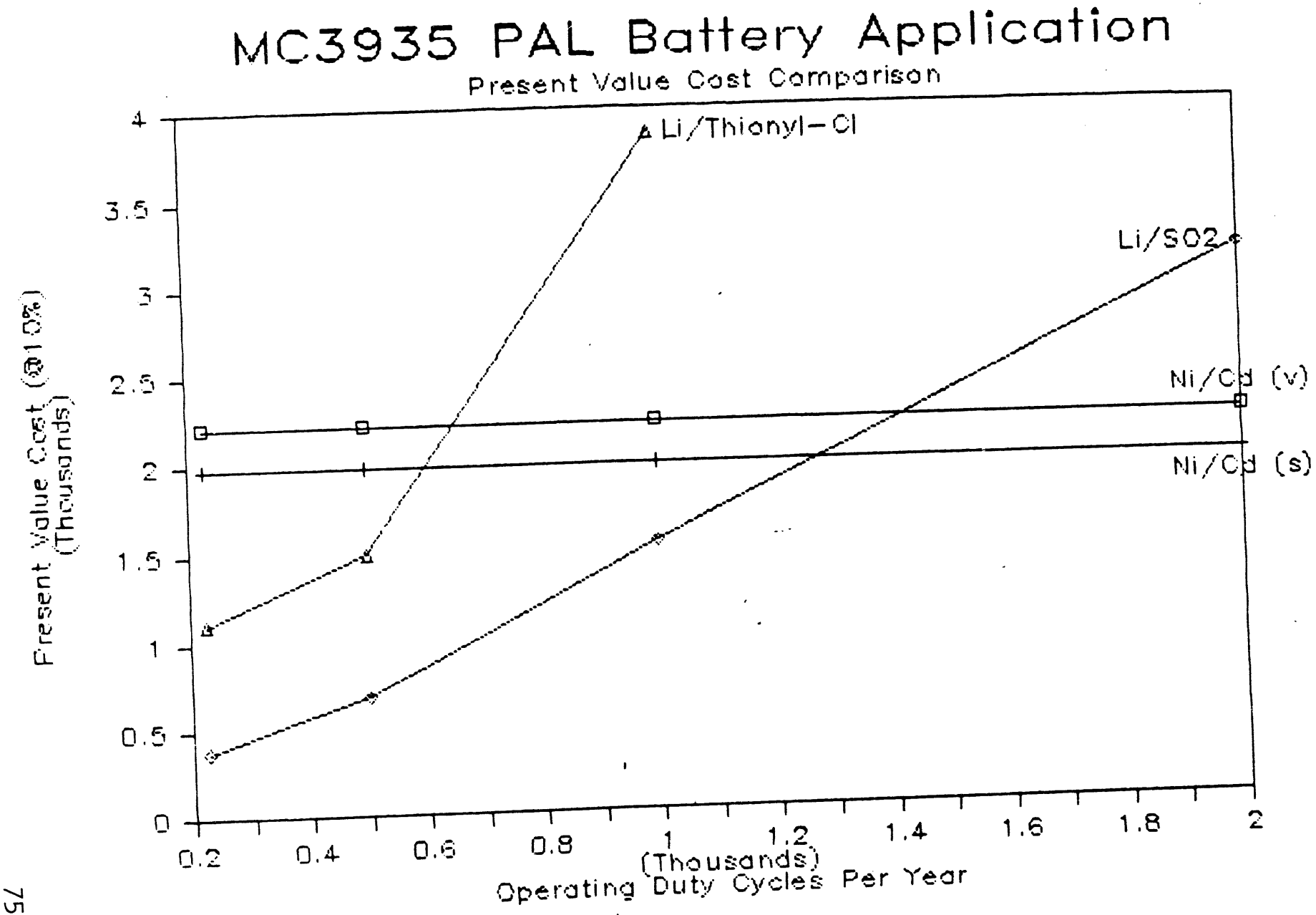
TABLE 1
BATTERY TECHNOLOGIES COMPARISON FOR PAL APPLICATION
RECHARGEABLE BATTERIES

BATTERY TECHNOLOGY	WEIGHT & VOLUME	TEMP. RANGE	MC3935 REQUIREMENT HIGH CURRENT	CHARGED STORAGE	LIFE	MISCELLANEOUS CHARACTERISTICS
Flooded lead-acid	Poor	Poor	Poor	Good	Good	Short shelf life
Sealed lead-acid	Good	Poor	Poor	Good	Good	Short shelf life
Vented nickel/ cadmium (sintered)	Good	Good	Good	Good	Good	Maintenance required
Vented nickel/ cadmium (pocket)	Poor	Good	Good	Good	Good	Commer. size > 8.5 Ah
Sealed nickel/ cadmium (sintered)	Good	Poor	Good	Good	Good	Thermal & charge time problems
Nickel/iron	Poor	Poor	Good	Poor	Good	Maint. required
Nickel/zinc	Good	Poor	Good	Poor	Poor	Maint. required
Zinc/silver oxide	Good	Poor	Good	Good	Poor	High cost
Cadmium/silver oxide	Good	Poor	Good	Good	Poor	High cost
Nickel/hydrogen	Poor	Good	Good	Poor	Good	High cost

TABLE 2
BATTERY TECHNOLOGIES COMPARISON FOR PAL APPLICATION
PRIMARY BATTERIES

BATTERY TECHNOLOGY	MC3935 REQUIREMENT					
	WEIGHT & VOLUME	TEMP. RANGE	HIGH CURRENT	CHARGED STORAGE	LIFE	MISCELLANEOUS CHARACTERISTICS
Lithium/sulfur dioxide	Good	Good	Poor	Good	Poor	Parallel strings necessary
Lithium/thionyl chloride	Good	Good	Poor	Good	Poor	Possible safety hazard
Alkaline manganese dioxide	Good	Poor	Poor	Poor	Poor	
Mercury/zinc & silver/zinc	Good	Poor	Poor	Poor	Poor	High cost

Figure 1


MC3935 PAL Battery Application
Present Value Cost Comparison
Li/Thionyl-Cl
Li/SO2
Ni/Cd (v)
Ni/Cd (s)
Present Value Cost (@10%)
(Thousands)
4
3.5
3
2.5
2
1.5
1
0.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
(Thousands)
Operating Duty Cycles Per Year

APPENDIX 4

STATEMENT OF WORK
MC 3935 (PAL) BATTERY DEVELOPMENT PROGRAM
MARCH 22, 1985

STORAGE BATTERIES DIVISION-2525
SANDIA NATIONAL LABORATORIES
P. O. BOX 5800
ALBUQUERQUE, NM 87185

I. OBJECTIVES AND INFORMATION

Sandia National Laboratories has the responsibility to provide an improved battery for use with PAL controllers, used by the U. S. Army, Air Force, and Navy. For the last twenty years, the MC 1605 has been used in this application. The MC 1605 is a conventional vented nickel/cadmium battery. Motivation for a new battery is due to a desire to obtain a battery with increased capacity and minimal maintenance requirements. The new battery has been designated the MC 3935. The power supply including case, connector, fuse, and battery are designated the T1576.

The goal of this program is to develop and produce prototype batteries which most closely satisfy the application requirements described below, and prepare for production of these batteries for purchase by the military by November, 1986. Proposals should include a recommendation of a battery type and a description of all necessary development activities to ready a specific design for production for an agency of the Department of Energy (DOE). Although Sandia considers that the sealed, sintered electrode nickel/cadmium type may most closely satisfy the application requirements, other battery types will be considered. If a suitable cell or battery design already exists, the proposal should so state and describe any necessary activities such as testing or packaging to prepare for production. The developer must be able to demonstrate battery production capability at the required rate by the end of this contract. The battery is expected to be required for a twenty year period.

In addition to battery development, one auxiliary item may be included in a response. A battery container is required that is mechanically sound and provides adequate shielding. These devices must be portable and they will be used in field environments. Consequently, the container must withstand mechanical stresses typical of those experienced in field use. Depending on expertise and interest, the container may be included in a response, in addition to the battery proposal.

Battery requirements are summarized in Table 1. Priorities have been assigned to the major technical requirements and tradeoffs

between them must be considered. The stated capacity of 2.6 Ah at the 1 hour rate represents the minimum required; it is desired to maximize the available capacity for the allowed weight and volume. A maximum recharge time of eight hours is required. The application requires a maximized amount of charge retention. Methods of maintaining balance among cells in the battery must be identified. It is also desired to minimize the product purchase cost. A battery with a minimum of required maintenance is a necessity. The program schedule requires that the first batteries be available for purchase by November, 1986.

Preparation of a quality control plan for the production activities will be required during this contract. The plan must address methods for controlling procurement, receiving, inspection, calibration and testing activties. This list is not all inclusive. Enclosed is a copy of Sandia Engineering Procedure EP401418, issue C, which provides complete information regarding applicable quality control requirements. This document applies to both battery and container development. The quality control plan will be evaluated using EP 401418.

II. STATEMENT OF WORK

Task 1-Battery Development

This task encompasses all activities required for battery development. It is anticipated that an existing cell design will be utilized and optimized as necessary. If a completely new design is required, the motivation must be carefully justified. In either case, the design should address each item on the battery requirements list (Table 1) and specify compliance or cell design activities to satisfy the requirements.

Of particular importance is battery operation at low temperature. If the -40 C requirement cannot be met, an alternative must be suggested and justified. The -40 C requirement is not absolute and may be adjusted based on tradeoffs with other requirements, such as maintenance. In addition, methods of maintaining balance among cells in a battery configuration must be described. Shelf life must be satisfied without maintenance or charging. Charge stand retention and/or frequency of recharge must be considered. Battery thermal management must be addressed. A reliability requirement may be specified early in the contract period by Sandia. It may consist of a requirement for the probability of completing a specific duty cycle at any point in life. Recommended optimum charging methods must either be specified or determined during the program.

This task may consist of preparing a preliminary design or optimization of an existing design with construction and testing

of prototypes. A final design or optimization, with prototype fabrication and testing, may be performed as necessary. In any case, the design or optimization activities should be completely described in the proposal and a time schedule provided. The proposal should provide justification such as test data or experimental evidence as necessary for the design. An estimate of the production cost to the procurement agency of the anticipated battery design should be provided in the proposal. A test regime should be proposed early in the contract to exercise the prototypes in a manner according to the application requirements to determine battery design status. Also, a duty cycle test regime may be specified by Sandia during the contract for additional testing.

At least 6 batteries will be shipped to Sandia for testing from the preliminary design stage. The preliminary design prototypes should be delivered as early as possible in order for the evaluation to impact the final design. Both electric cycle testing and post-mortem failure analysis will be performed at Sandia. Life cycle testing will be performed at Sandia on at least one of these deliverables. A minimum of 12 batteries shall be delivered to Sandia representing the final design. These units will be considered as qualification batteries and will be tested on a regime to be specified early in the contract period. This regime will be defined based on the list of battery requirements given in Table 1 and its attachments.

This task proposal should also specify a battery production plan to follow completion of the development program. A requirement of 200-400 batteries per year is estimated. Plans for acquisition of necessary equipment or tooling should be specified. Any anticipated purchases of capital or plant equipment on this contract must be clearly specified in the proposal. All such items will be considered by Sandia on an individual basis for approval. Schedules leading to the initiation of production, with detailed milestones, must be prepared. Plans and/or past experience in battery production programs should be presented in the proposal for evaluation.

Optional Task 2-Container Development

The design and development of a battery container is an optional task. A container is required that will house the battery and withstand mechanical stresses typical of field environments, within the weight and volume restrictions listed in Table 1. It must provide electromagnetic shielding of 50 dB signals at frequencies up to 300 MHz for the battery. The container will be subjected to shock, vibration, and other environmental stress tests as part of qualification.

This task will involve container design, materials selection, and prototype production. Past experience in this area should be described in the proposal. The proposal must contain estimates of production costs, preliminary specifications for materials, dimensions, and production methods. Plans for producing 200-400 containers per year must be described. The design should incorporate provisions for fuses and electric cables for connection of the battery to external devices. Final prototype containers should be shipped to Sandia with the final battery design deliverables.

Task 3-Documentation and Reporting

A final written report will be required which summarizes all contract activities. Test data on prototype and final design batteries will be completely described. Monthly, informal, letter written reports describing activities and test data for each contract month will be required. A maximum of two review meetings will be held. One will review the preliminary design and another, if necessary, to review the final design. Plans should be made for at least one trip to Sandia and one trip to the procurement agency.

A complete set of engineering drawings and blueprints of all final component designs will be required.

III. PERIOD OF PERFORMANCE AND DELIVERABLES

It is anticipated that no more than one year will be required for the technical effort of this program. A shorter contract period would be desirable. If additional time is required, it must be thoroughly justified. All engineering drawings and blueprints are due at Sandia within one month after completion of the technical effort. Two copies of the draft final report are also due at this time. One copy suitable for reproduction and two copies of the final report will be due at Sandia one month after approval of the draft report by Sandia. Monthly letter reports must be delivered by the 15th of the month following the reporting period. The final quality control plan must be delivered no later than half way through the contract period. Six preliminary design batteries should be delivered to Sandia no later than the fourth contract month. The qualification batteries and cases should be delivered during the final month of the technical contract.

IV. PROPOSAL CONTENT

To be acceptable, a technical proposal must contain the following information.

1. A detailed technical description of the cell type and design proposed, which addresses each item in the requirements list (Table 1).

2. An estimate of the final cost to the procurement agency of the cell, battery, container, if quoted, and complete power supply assembly (T1576).

3. A description of all anticipated contract activities for development, preparation for production, and quality control measures for the proposed cell, battery, and container, if quoted.

4. A tabular time schedule for number 3 above which lists activities, milestones, deliverables and other measures of contract progress.

5. A description of personnel qualifications and facilities that will be assigned to the contract.

Proposals that are concise and which address the above issues are desired.

V. CONTRACT AWARD CRITERIA

All proposals will be evaluated by Sandia battery engineers and a contractor or contractors will be selected. Sandia reserves the right to reject all proposals or accept only parts of a proposal. The following criteria will be considered.

1. Technical Approach-25 points. The quality of the technical proposal will be judged. Rationale for selection of the proposed battery system will be considered. Completeness of the proposed technical work will be evaluated. The degree of satisfaction of the application requirements by the proposed battery design will be judged.

2. Development Capabilities-20 points. Overall research and development capabilities will be considered. Personnel qualifications and experience will be evaluated. Facilities will be considered.

3. Production Capabilities-15 points. The capability to produce the battery and auxiliary components will be judged based on the proposal. Past experience and existing facilities will be considered.

4. Quality Control Issues-15 points. The responsiveness of the quality control aspects of the proposal will be considered. A preliminary outline of the Quality Control Plan will be evaluated.

Past experience in battery quality control programs will be part of the consideration.

5. Schedule-15 points. The timeliness and appropriateness of the proposed development program will be judged. The schedule for initiating production will also be considered.

6. Container Development-10 points(if quoted.) Consideration will be given to the plan to provide a battery container. It will be judged from technical and engineering perspectives in satisfying the application requirements.

Although the cost quotation (proposal) is not included with a numerical value in the evaluation criteria for award selection, the cost quotation will be evaluated as to reasonableness for the work to be performed as set forth in the RFQ and in the submitted technical proposal, and as such will be a factor in the consideration for final determination of contract award.

Table 1
MC3935 Rechargeable Battery Requirements
March 22, 1985

Notes: T 1576 Power supply includes MC3935 battery, battery container, fuse, and connector.
Priority 1 is highest; 10 lowest.

Parameter	Priority	Requirement
Voltage Range	1	26.8 - 33, nominal 28 V
Battery Weight (maximum)	5	12 lb (5.4 kg)
T 1576 Weight (maximum)	5	20 lb (9.1 kg)
Battery Volume (maximum)	5	0.3 ft^3 (8.5ℓ)
T 1576 Volume (maximum)	5	0.5 ft^3 (14.2ℓ)
Temperature Range	6	-40 to 160°F (-40 to 71°C)
Capacity (minimums) initial @ 25°C	2	2.6 Ah @ ~1 hr rate, load = 15 + 2Ω
initial @ -40°C		0.8 Ah @ ~1 hr rate, load = 15 ± 2Ω
Peak Current	1	12 A for 200 msec
Charged Storage Capacity (minimum)	3	1.0 Ah @ ~1 hr rate @ 25°C load = 15 ± 2Ω, after 30 days @ 43°C (110°F) OC
Operating Life (minimum)	7	500 100% DOD cycles or 5 years
Shelf Life	4	10 years - no trickle charging
Reliability		~95% per cycle (TBD)
Environmental	1	Requirements for temperature and mechanical shock, vibration, electromagnetic radiation, and nuclear radiation. Refer to attached specification.
Shielding (container)	1	50 dB at frequencies up to 300MHz
Maintenance	4	None, except recharge and periodic complete discharge, if necessary
Duty Cycle		Each operation: 1 A min at various rates - 60 operations required per charge (1 Ah)
Recharge Time	4	Max. 8 hours @ 25°C - goal: 4 hours
Availability		11/86
Production Rate		200 - 400 per year
Cost to Procurement Agency (T 1576) (maximum)	8	$1000 each

APPENDIX 5

PT3515/UA5208 CHARGE REPORT

PRODUCT CHARGED: T1576 TCP #: AM-386002-005/F

Serial Number of Battery: SN/177

LOT NUMBER: 006____ 3.1.1

INSPECTOR: R. ROMAN

CHARGE BEGAN: 25 Jun 1988 15:02:20

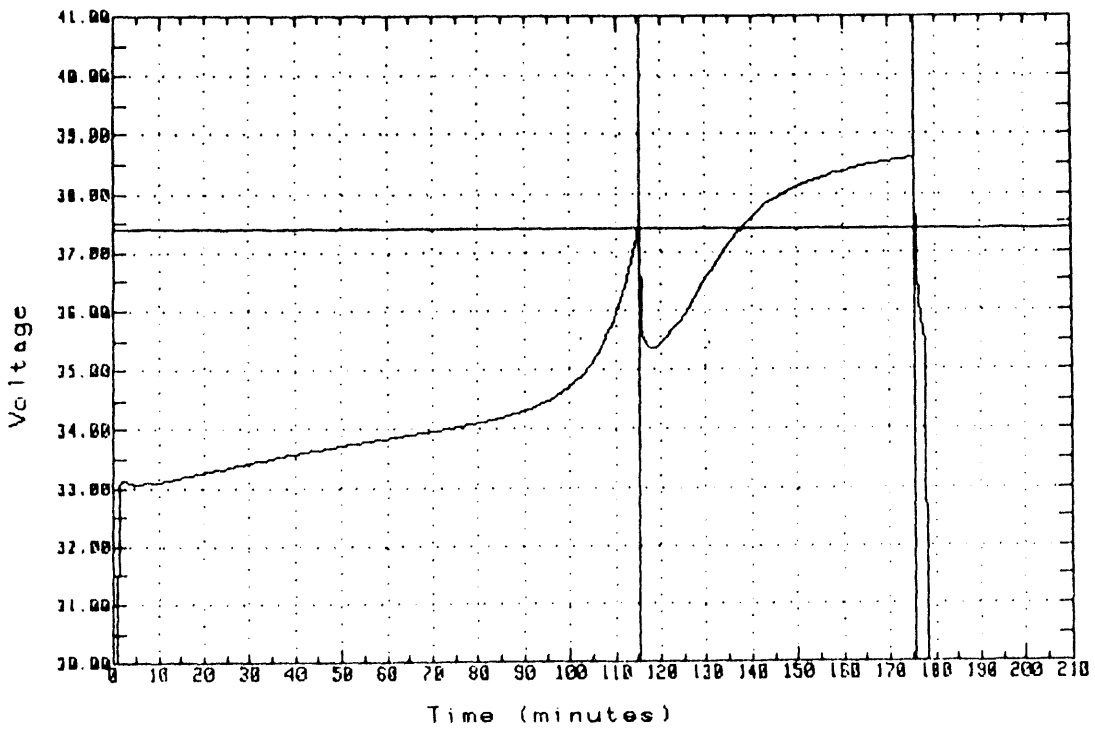
Equipment Charging Battery: UA4177 SN101

The current switched from 5 to 1.5 after 115.5 minutes.

The testing stopped after 175.5 minutes.

CHARGE COMPLETED: 25 Jun 1988 17:57:50

T1576 CHARGE



END OF DATA FOR THIS BATTERY.

PT3515/T1576 TEST REPORT

PRODUCT TESTED: T1576 SER#: 177

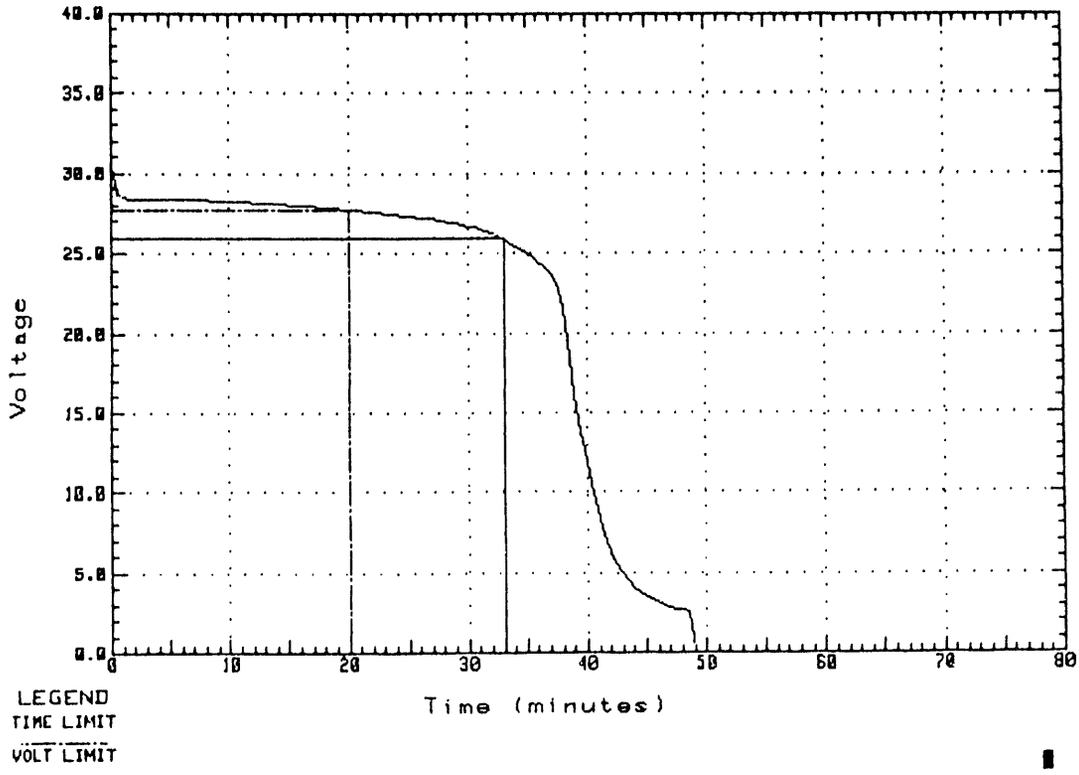
TEST PARAGRAPH: 3.1.1 TEST LOAD: 2.3 OHM

TESTER CONTROL PROGRAM NUMBER: AM-382686-002/C

DATE: 27 Jul 1988 - TIME ORIGINATED: 11:30:08

Equipment Testing Battery: UA4168-P1 SN106
DISCHARGE CURVE:

2.3 OHM TEST



ANALYSIS: 3.1.1 - 2.3 OHM TEST

TEST TITLE 30 Day Stand
LOT #: 006 INSPECTOR: RE

BATTERY SERIAL NUMBER: 177

TIME (MINUTES)	VOLTAGE
0.00	30.5431
20.00*	27.7058
33.00	26.0000*

PASS/FAIL CONTIDITION: PASS

* - Indicates a control limit, not a measured value.

END OF DATA FOR THIS BATTERY.

PT3515/T1576 TEST REPORT

PRODUCT TESTED: T1576 SER#: 177

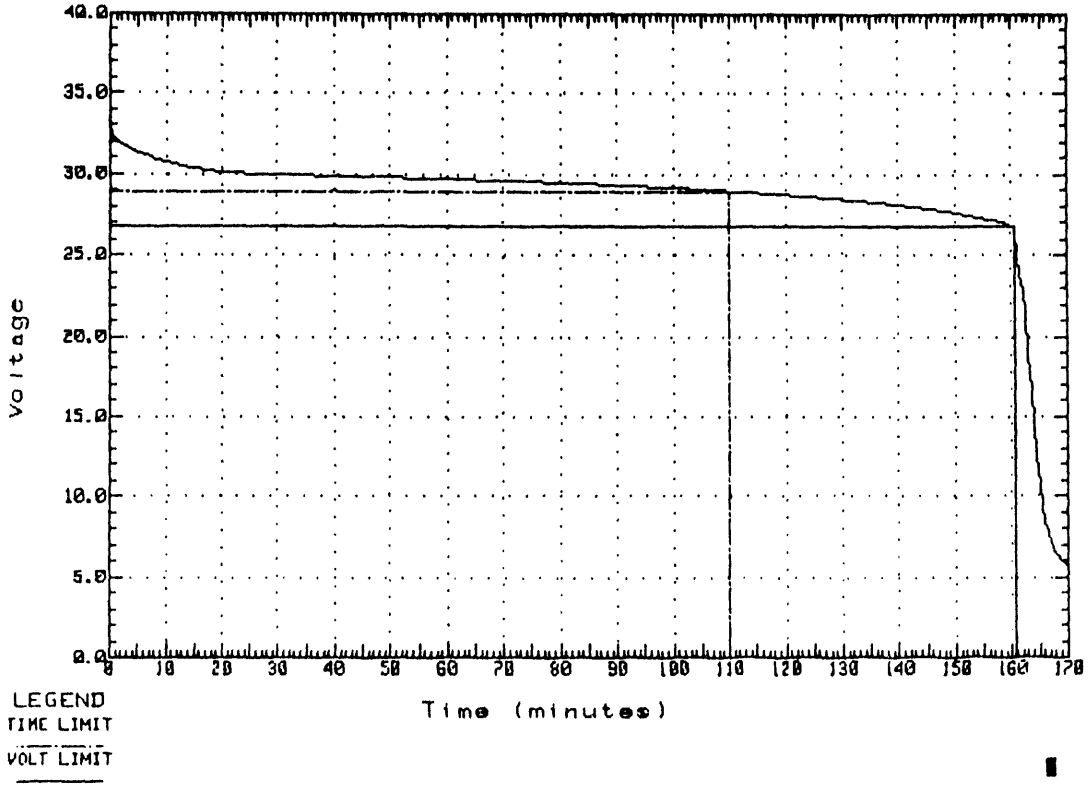
TEST PARAGRAPH: 3.2.1 TEST LOAD: 3 AMP

TESTER CONTROL PROGRAM NUMBER: AM-382686-002/C

DATE: 28 Jul 1988 - TIME ORIGINATED: 17:42:05

Equipment Testing Battery: UA4168-P1 SN107
DISCHARGE CURVE:

3 AMP TEST



ANALYSIS: 3.2.1 - 3 AMP TEST

TEST TITLE Discharge at Room Temperature 8th
LOT #: 6 INSPECTOR: [illegible]

BATTERY SERIAL NUMBER: 177

TIME (MINUTES)	VOLTAGE
0.00	33.3081
110.00*	28.9468
160.50	26.8000*

PASS/FAIL CONTIDITION: PASS

* - Indicates a control limit, not a measured value.

END OF DATA FOR THIS BATTERY.

PT3515/T1576 TEST REPORT

PRODUCT TESTED: T1576 SER#: 177

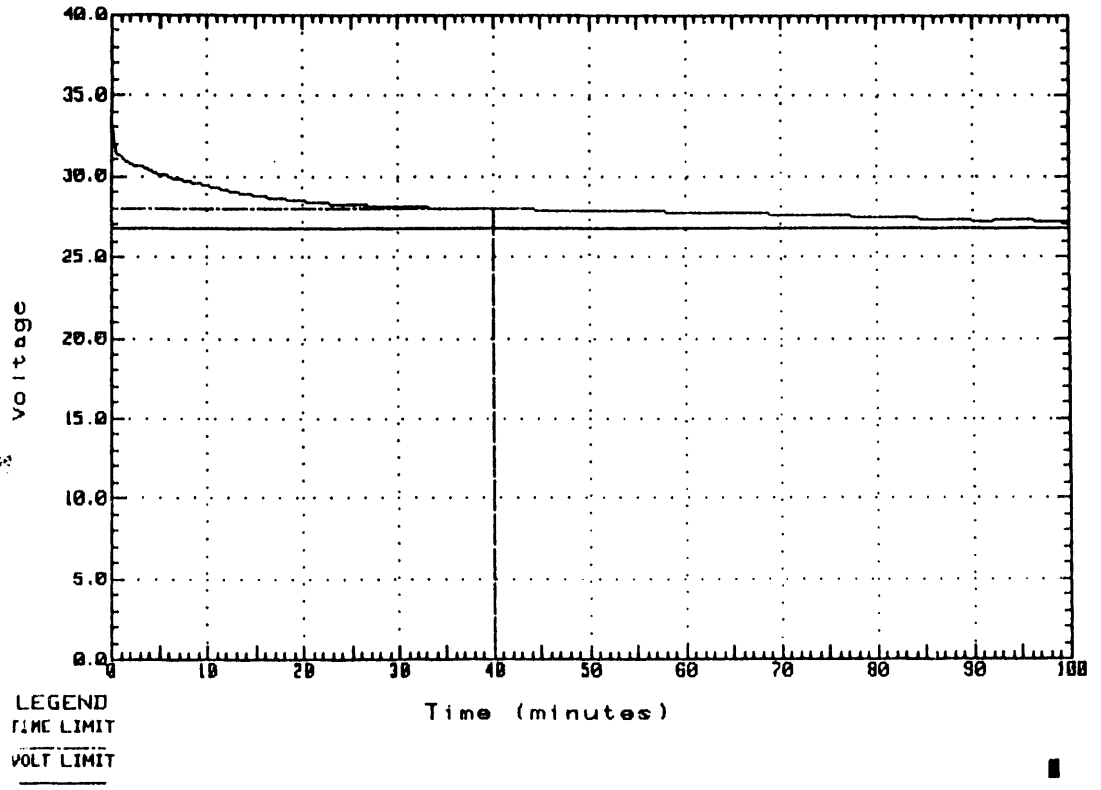
TEST PARAGRAPH: 3.2.2 TEST LOAD: 3 AMP

TESTER CONTROL PROGRAM NUMBER: AM-382686-002/C

DATE: 30 Jul 1988 - TIME ORIGINATED: 10:03:48

Equipment Testing Battery: UA4168-P1 SN107
DISCHARGE CURVE:

3 AMP TEST



ANALYSIS: 3.2.2 - 3 AMP TEST

TEST TITLE Cold Test
LOT #: 7 INSPECTOR: Ja

BATTERY SERIAL NUMBER: 177

TIME (MINUTES)	VOLTAGE
0.00	33.3221
40.00*	27.9343
106.00	26.8000*

PASS/FAIL CONTIDITION: PASS

* - Indicates a control limit, not a measured value.

END OF DATA FOR THIS BATTERY.

PT3515/T1576 TEST REPORT

PRODUCT TESTED: T1576 SER#: 177

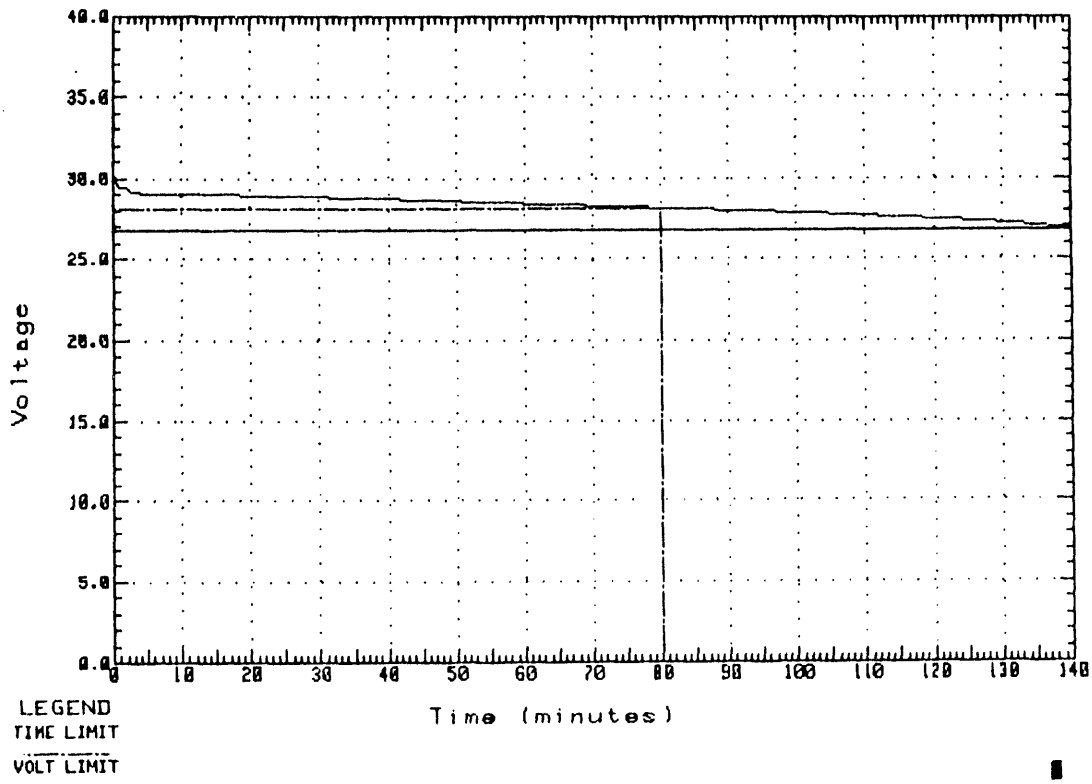
TEST PARAGRAPH: 3.2.3 TEST LOAD: 3 AMP

TESTER CONTROL PROGRAM NUMBER: AM-382686-002/C

DATE: 2 Aug 1988 - TIME ORIGINATED: 16:47:26

Equipment Testing Battery: UA4168-P1 SN106
DISCHARGE CURVE:

3 AMP TEST



ANALYSIS: 3.2.3 - 3 AMP TEST

TEST TITLE Retention at High Temperature
LOT #: 006 INSPECTOR: PE

BATTERY SERIAL NUMBER: 177

TIME (MINUTES)	VOLTAGE
0.00	30.3967
80.00*	28.1346
140.50	26.8000*

PASS/FAIL CONTIDITION: PASS

* - Indicates a control limit, not a measured value.

END OF DATA FOR THIS BATTERY.

PT3515/T1576 TEST REPORT

PRODUCT TESTED: T1576 SER#: 177

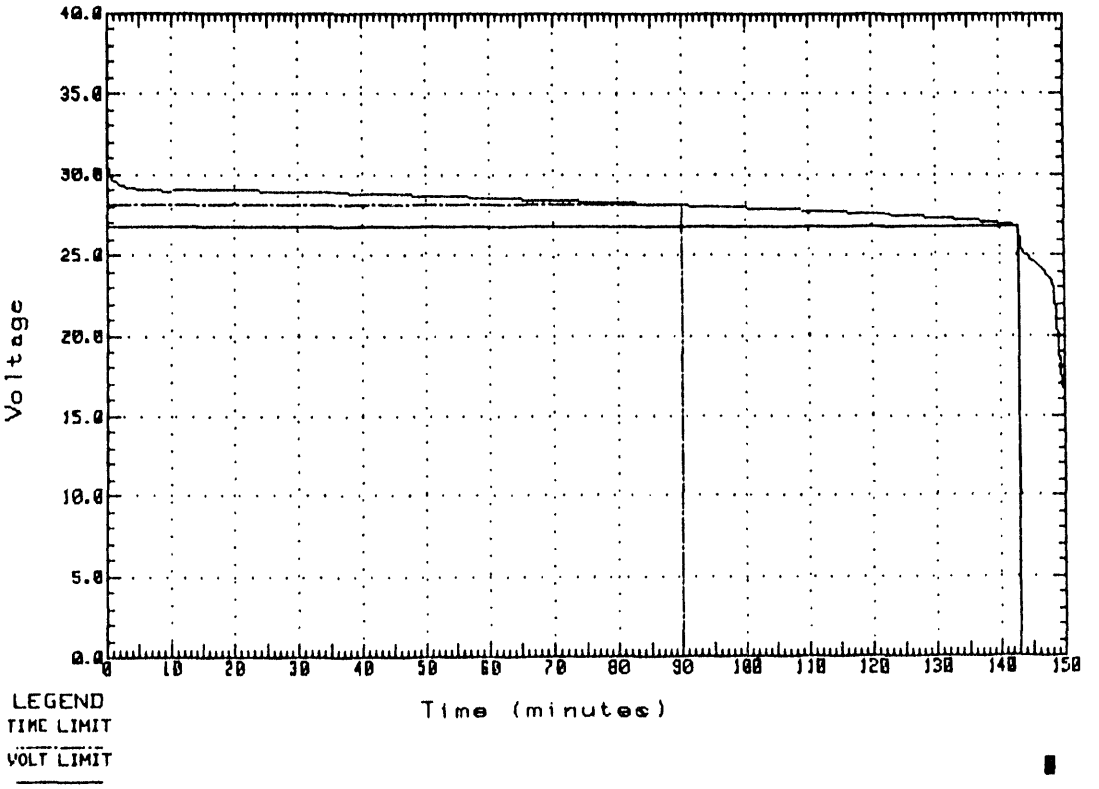
TEST PARAGRAPH: 3.3.1 TEST LOAD: 3 AMP

TESTER CONTROL PROGRAM NUMBER: AM-382686-002/C

DATE: 5 Aug 1988 - TIME ORIGINATED: 08:14:01

Equipment Testing Battery: UA4168-P1 SN101
DISCHARGE CURVE:

3 AMP TEST



ANALYSIS: 3.3.1 - 3 AMP TEST

TEST TITLE Temperature Shock.
LOT #: 6 INSPECTOR: Ja

BATTERY SERIAL NUMBER: 177

TIME (MINUTES)	VOLTAGE
0.00	30.5809
90.00*	28.0448
143.00	26.8000*

PASS/FAIL CONTIDITION: PASS

* - Indicates a control limit, not a measured value.

END OF DATA FOR THIS BATTERY.

PT3515/T1576 TEST REPORT

PRODUCT TESTED: T1576 SER#: 177

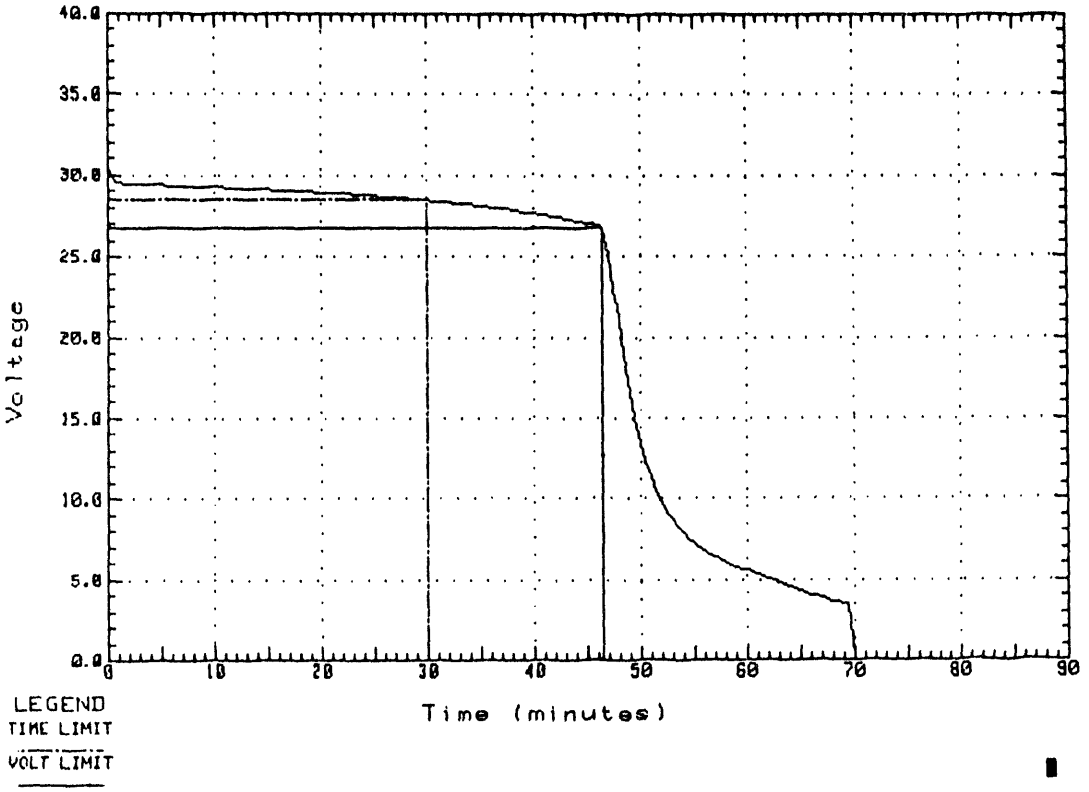
TEST PARAGRAPH: 3.3.2 TEST LOAD: 3 AMP

TESTER CONTROL PROGRAM NUMBER: AM-382686-002/C

DATE: 31 Aug 1988 - TIME ORIGINATED: 14:02:06

Equipment Testing Battery: UA4168-P1 SN102
DISCHARGE CURVE:

3 AMP TEST



ANALYSIS: 3.3.2 - 3 AMP TEST

TEST TITLE Keep High Temp
LOT #: 006 INSPECTOR: PE

BATTERY SERIAL NUMBER: 177

TIME (MINUTES)	VOLTAGE
0.00	30.5620
30.00*	28.4407
46.50	26.8000*

PASS/FAIL CONTIDITION: PASS

* - Indicates a control limit, not a measured value.

END OF DATA FOR THIS BATTERY.

PT3515/T1576 TEST REPORT

PRODUCT TESTED: T1576 SER#: 177

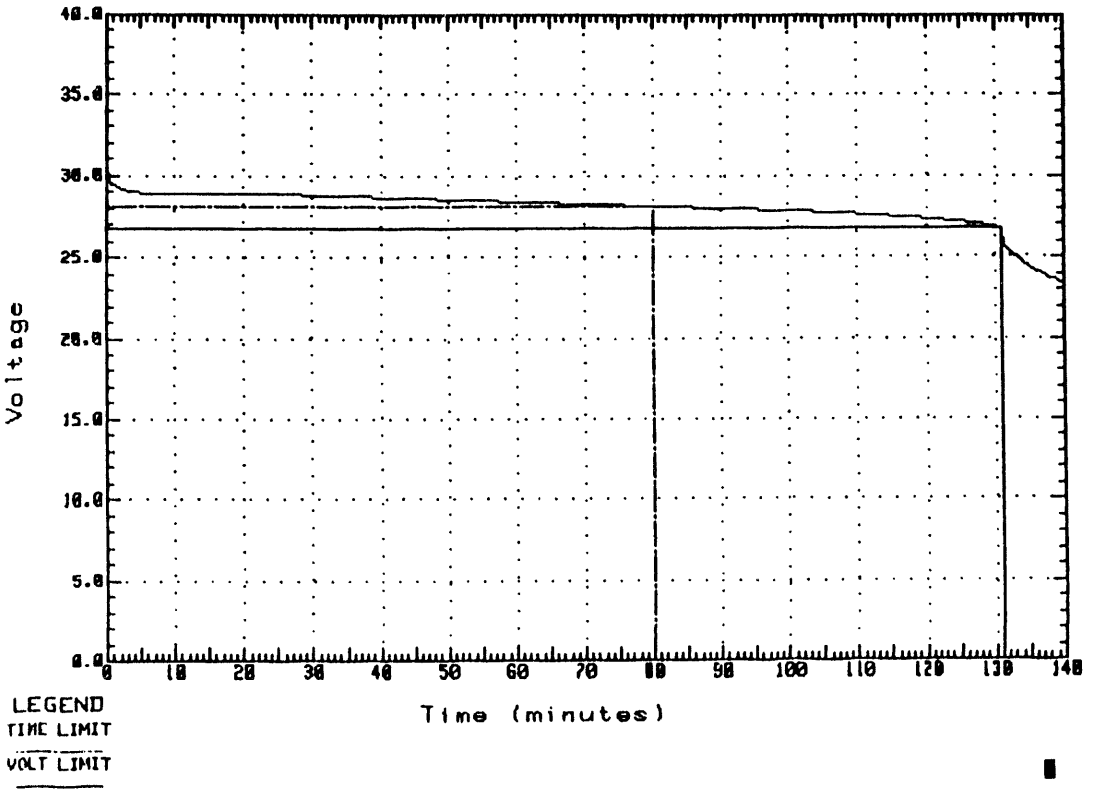
TEST PARAGRAPH: 3.4.1 TEST LOAD: 3 AMP

TESTER CONTROL PROGRAM NUMBER: AM-382686-002/C

DATE: 24 Aug 1988 - TIME ORIGINATED: 09:07:21

Equipment Testing Battery: UA416A-P1 SN101
DISCHARGE CURVE:

3 AMP TEST



ANALYSIS: 3.4.1 - 3 AMP TEST

TEST TITLE Humidity
LOT #: 006 INSPECTOR: RE

BATTERY SERIAL NUMBER: 177

TIME (MINUTES)	VOLTAGE
0.00	30.3873
80.00*	28.1020
131.00	26.8000*

PASS/FAIL CONTIDITION: PASS

* - Indicates a control limit, not a measured value.

END OF DATA FOR THIS BATTERY.

PT3515/T1576 TEST REPORT

PRODUCT TESTED: T1576 SER#: 154

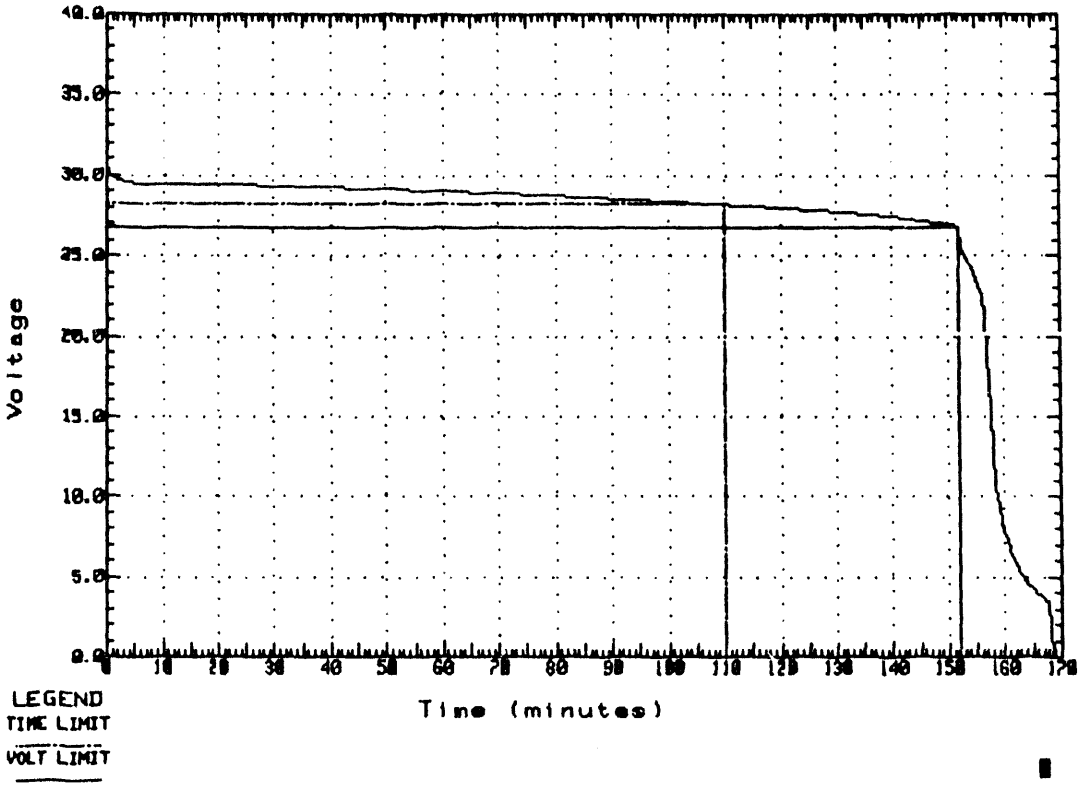
TEST PARAGRAPH: 3.4.2 TEST LOAD: 3 AMP

TESTER CONTROL PROGRAM NUMBER: AM-382686-002/C

DATE: 25 Jul 1988 - TIME ORIGINATED: 09:32:43

Equipment Testing Battery: UA4168-P1 SN101
DISCHARGE CURVE:

3 AMP TEST



ANALYSIS: 3.4.2 - 3 AMP TEST

TEST TITLE Vibration
LOT #: 5 INSPECTOR: Jg

BATTERY SERIAL NUMBER: 154

TIME (MINUTES)	VOLTAGE
0.00	30.8206
110.00*	28.1701
152.00	26.8000*

PASS/FAIL CONTIDITION: PASS

* - Indicates a control limit, not a measured value.

END OF DATA FOR THIS BATTERY.

PT3515/T1576 TEST REPORT

PRODUCT TESTED: T1576 SER#: 221

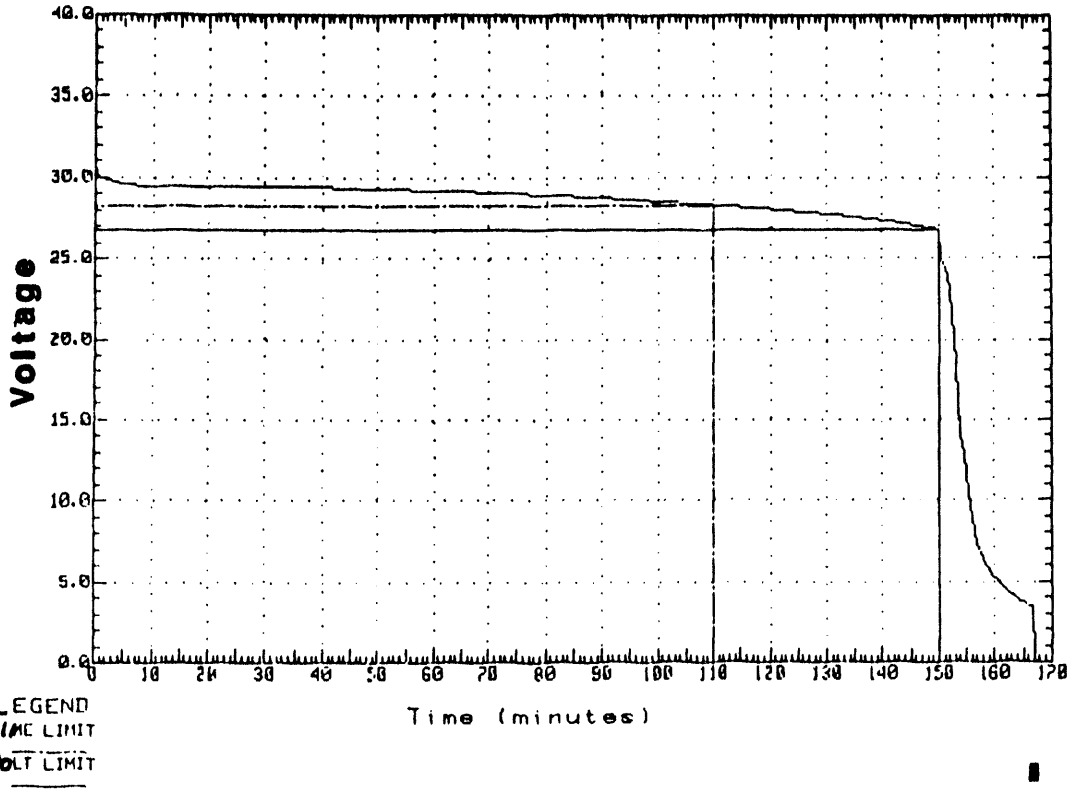
TEST PARAGRAPH: 3.4.3 TEST LOAD: 3 AMP

TESTER CONTROL PROGRAM NUMBER: AM-382686-002/C

DATE: 15 Sep 1988 - TIME ORIGINATED: 11:03:42

Equipment Testing Battery: UA4168-P1 SN102
DISCHARGE CURVE:

3 AMP TEST



ANALYSIS: 3.4.3 - 3 AMP TEST

TEST TITLE Mechanical Shock
LOT #: 007 INSPECTOR: RE

BATTERY SERIAL NUMBER: 221

TIME (MINUTES)	VOLTAGE
0.00	30.9819
110.00*	28.2788
150.00	26.8000*

PASS/FAIL CONTIDITION: PASS

92 * - Indicates a control limit, not a measured value.

END OF DATA FOR THIS BATTERY.

APPENDIX 6

T436C Design and Development

At the conclusion of the T1576 development program, an effort was initiated at the request of the Command and Control Division to develop the T436C (P/N 368521). The objective of this activity was to design the necessary hardware to enable MC1605B or MC1605C batteries to be installed in the T1576 container assembly (P/N 382196). The motivation for this was to continue using good MC1605B/C batteries while enclosing them in a simple, easy to maintain, EMI-shielded container. The assembly of batteries and container was identified as the T436C (see Figure 11).

A development contract (P.O. 63-6412) was placed in May, 1988, with EP for this work. The necessary brackets, screws, and electrical parts were designed, fabricated, and installed in the stainless steel containers at EP and at Sandia. See Figure 11 for a diagram of the T436C power supply. MC1605B/C batteries were installed in the containers at Sandia and the assembly was exposed to mechanical shock and vibration testing. Following the mechanical shock tests, a limited number of support brackets and battery flanges were observed to have failed. A molded neoprene support was designed to distribute the load of the batteries over the bottom of the container. There were no failures on subsequent shock tests with the neoprene support installed in the container.

Figure 11 caption: Illustration of the T436C power supply.

Another design issue was the attachment of the connector wiring harness to the battery terminals. The stud on MC1605B/C batteries is a size 8, while the terminal lug is a size 10, to match the stud on the MC3935 battery. To insure a reliable electrical contact on the MC1605B/C batteries, a shouldered washer (P/N 387929) was designed and fabricated. This washer permitted the larger terminal lug to firmly attach to the smaller battery stud.

The T436C was intended to be assembled in the field by Armed Forces personnel. Therefore, the parts developed in this project were incorporated into the T436B/T436C Retrofit Kit (P/N 411620), for field installation. A complete set of assembly instructions were prepared, tested and approved for the installation process.

Allied Signal Aerospace ordered retrofit kits from EP in late 1988. The first kits were shipped in early 1989.

T436C POWER SUPPLY

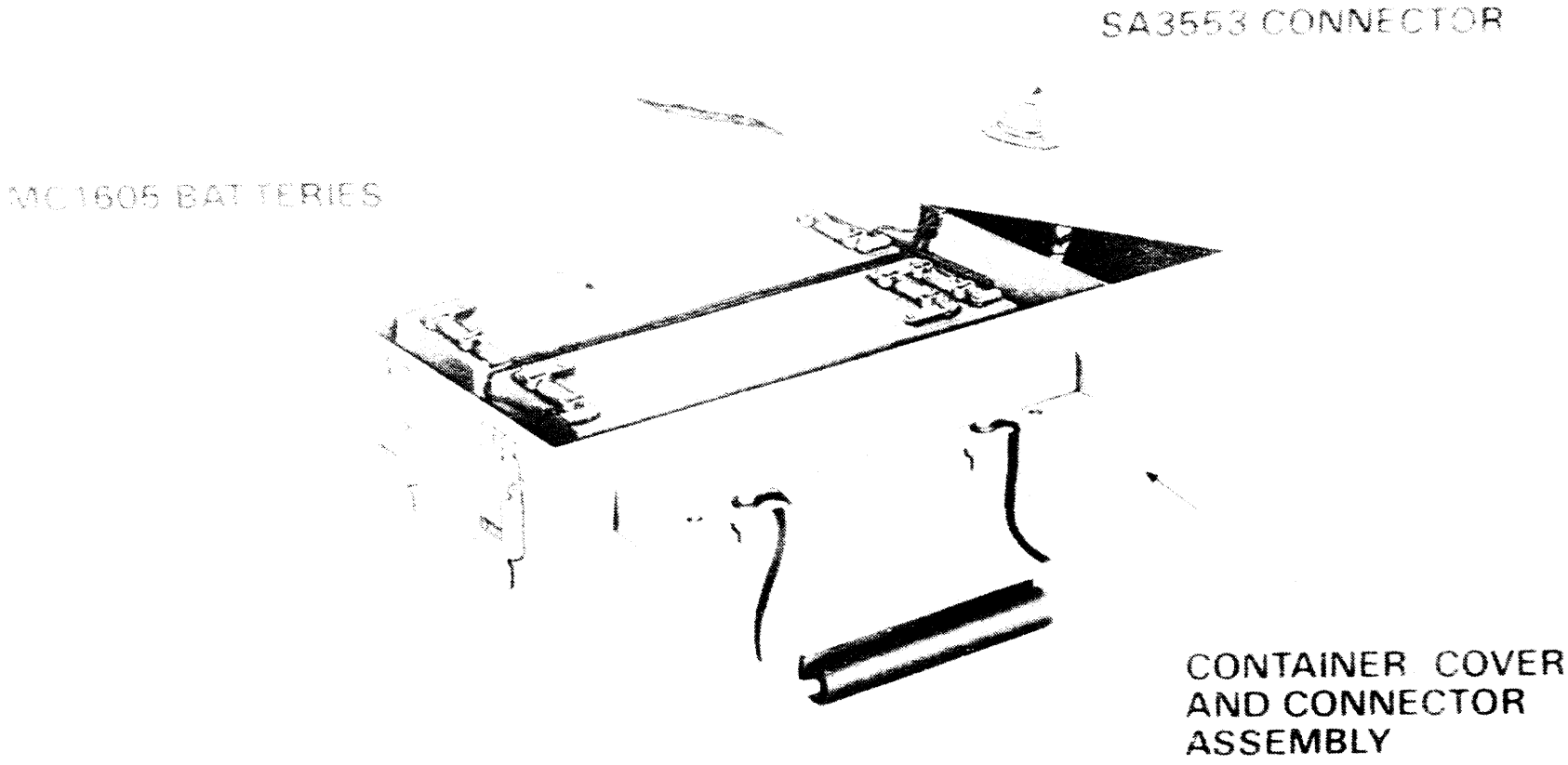


FIGURE 11. T436C POWER SUPPLY

Distribution:

Eagle-Picher Industries (4)
Attn. R. Farmer
T. A. Edgar
G. R. Burns
Z. Johnson
3820 S. Hancock Expy.
Colorado Springs, CO 80911

Allied-Signal Company (5)
Kansas City Division
Attn: M. D. Finch (3), D/834-4
R. E. Myers, D/137-4
2000 East 95th St.
Kansas City, MO 64131

335	D. L. Wright
336	R. A. Hanson
2472	C. E. Robinson
2500	G. N. Beeler
2504	R. P. Clark
2522	K. R. Grothaus
2522	F. P. R. Lasky
2523	D. H. Doughty
2525	P. C. Butler (10)
5713	J. W. Bonahoom
5512	C. L. Christensen
5514	M. A. Stringer
8523-2	Central Technical Files
7141	Technical Library (5)
7151	Technical Publications
7613-2	Document Processing for DOE/OSTI (10)

END DATE
1-12-94