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Performance Tests of 4-5 Year Old Lithium Sulphur Dioxide Batteries

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ABSTRACT

Tests of a new acoustic system in the spring of 1982, using radio frequency transmission of the data, required the Naval Ocean Research and Development Activity (NORDA) to reconsider the use of lithium battery technology. A request was made to the Navy Safety Office, Naval Sea Systems Command Code 06H, for permission to utilize lithium batteries in the R&D project and for permission to use existing lithium sulphur dioxide cells, which had been purchased in previous years. The Safety Office tentatively approved the intended useage but subject to a performance test and evaluation of a representative sample of the existing cells. In response to the NAVSEA direction, 32 cells were randomly chosen and subjected to forming and discharge tests. The cells, as a group, performed beyond expectations and provided energy in excess of the manufacturer's original specifications for these cells. All tests were performed without safety problems or any incidents. Similiar cells from the same lot were subsequently used at sea in the R&D project and performed equally as well as those tested in the laboratory. This report documents the testing procedures used to evaluate 4-5 year old Li/SO_2 cells and the test results achieved.

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PERFORMANCE TESTS OF 4-5 YEAR OLD LITHIUM SULPHUR DIOXIDE BATTERIES

1.0 INTRODUCTION

The Naval Ocean Research and Development Activity (NORDA) purchased a quantity of lithium sulphur dioxide (Li/SO_2) batteries during 1977-1978 for experimentation in advanced acoustic measurement systems. A Navy moratorium on the use of lithium battery technology in the fall of 1979 caused the collection and "bunker" storage of these batteries until the summer of 1982 when a pressing research need dictated that NORDA seek special permission for use of these batteries from the Naval Sea Systems Command Safety Office (NAVSEA Code 06H). This report outlines the research need, procedures followed in obtaining permission for use, and the detailed testing performed on a sample of the stored Li/SO_2 batteries.

1.1 INTENDED APPLICATION

During the two years prior to the 1979 moratorium, the Ocean Technology Division of NORDA had been experimenting with Li/SO_2 batteries for remote instrumentation applications. The primary interest was long-term powering of light weight, compact, Versatile Experimental Kevlar Arrays (VEKA) for acoustic measurements. While the moratorium halted further battery experimentation, efforts were continued on the other subsystem developments. In early 1982 it became clear that successful demonstration of the performance advantages of the VEKA II technology required the lithium energy system. The necessary at sea demonstration simply could not be performed in a cost effective manner using any other battery technology. In the paragraphs that follow, the VEKA II telemetry buoy tested is briefly described.

The VEKA II RF Buoy designed by NORDA is a ship-deployed floating buoy connected to an acoustic data hydrophone array. Data and control signals are transmitted to and from the buoy via an RF telemetry link.

The system consists of three major parts, which are shown in figures 1, 2, and 3. Figure 1 shows the buoy shell that is a COSRAM buoy. It is an aluminum tube 90 inches long, 8 inches in diameter, and a wall thickness of 0.185 inches. A flotation collar 39 inches long and 27 inches in diameter is welded near the top. Sufficient ballast is placed in the bottom to provide proper buoyancy. Figure 1B shows the battery and electronics assembly. As indicated, these items can be removed as a single unit by first removing the buoy cover and antenna (Fig. 2). The buoy, in operation, is a nonpressurized vessel and is vented through the buoy cover, antenna mast, and antenna.

The VEKA II acoustic telemetry buoy battery system consisted of 63 30AH lithium sulfur dioxide batteries arranged into three battery packs as shown in figure 3. The battery packs were assembled with protective diodes, current limiting fuses, and thermally sensitive fuses. 1N914B diodes were used to prevent reverse voltage on the LI/SO_2 cells while 1N4007 diodes were used to prevent charging current from one battery stack to another. Current limiting fast blow fuses were used in the ground leg of each stack to limit short circuit currents to the maximum battery rating specified by the Navy Safety Office (3.0 amps). Thermally sensitive fuses designed to open at 91°C were also installed at the center of each battery cluster (pack) and connected electrically in series with the current limiting fuses. Fusing was also provided at each supply point for the primary system voltages.

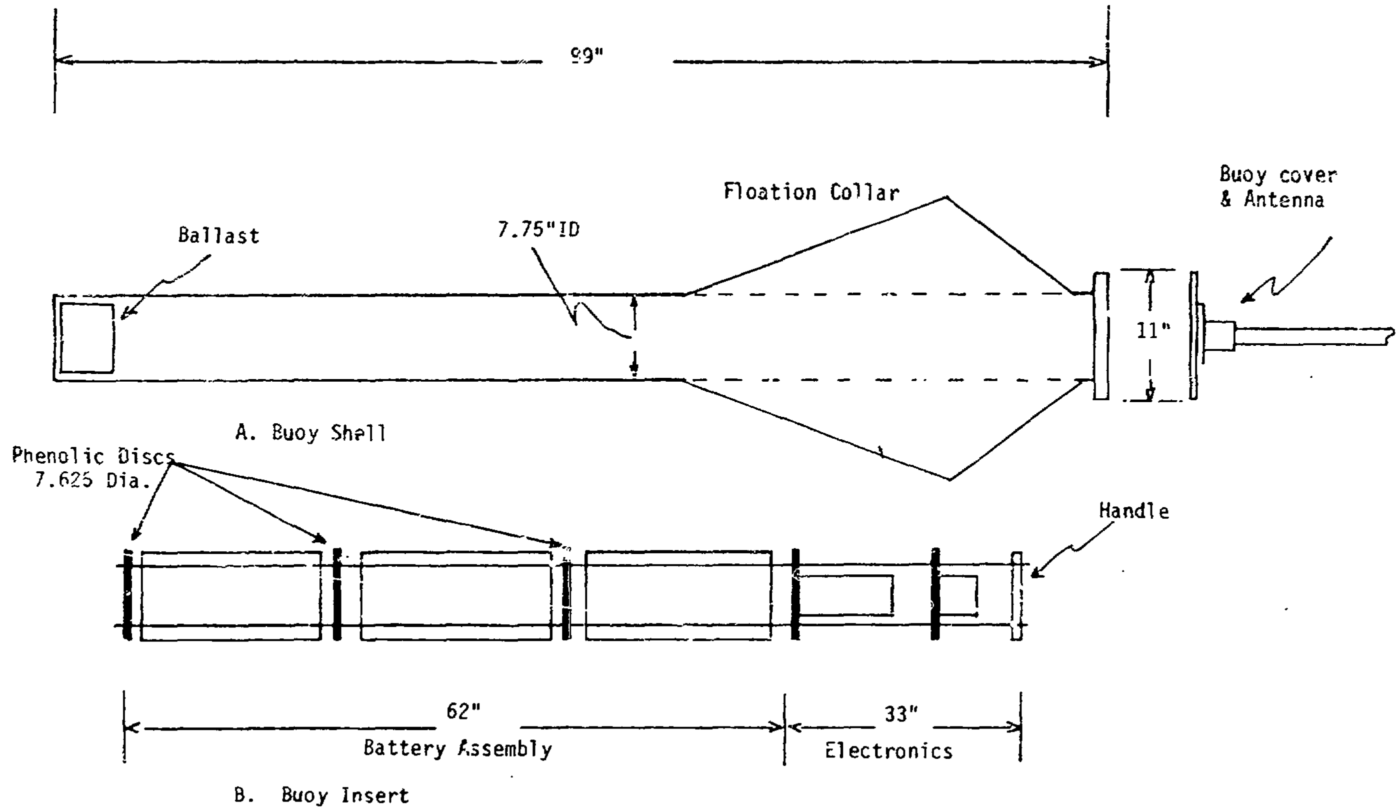

Figure 1. Buoy Shell and Insert

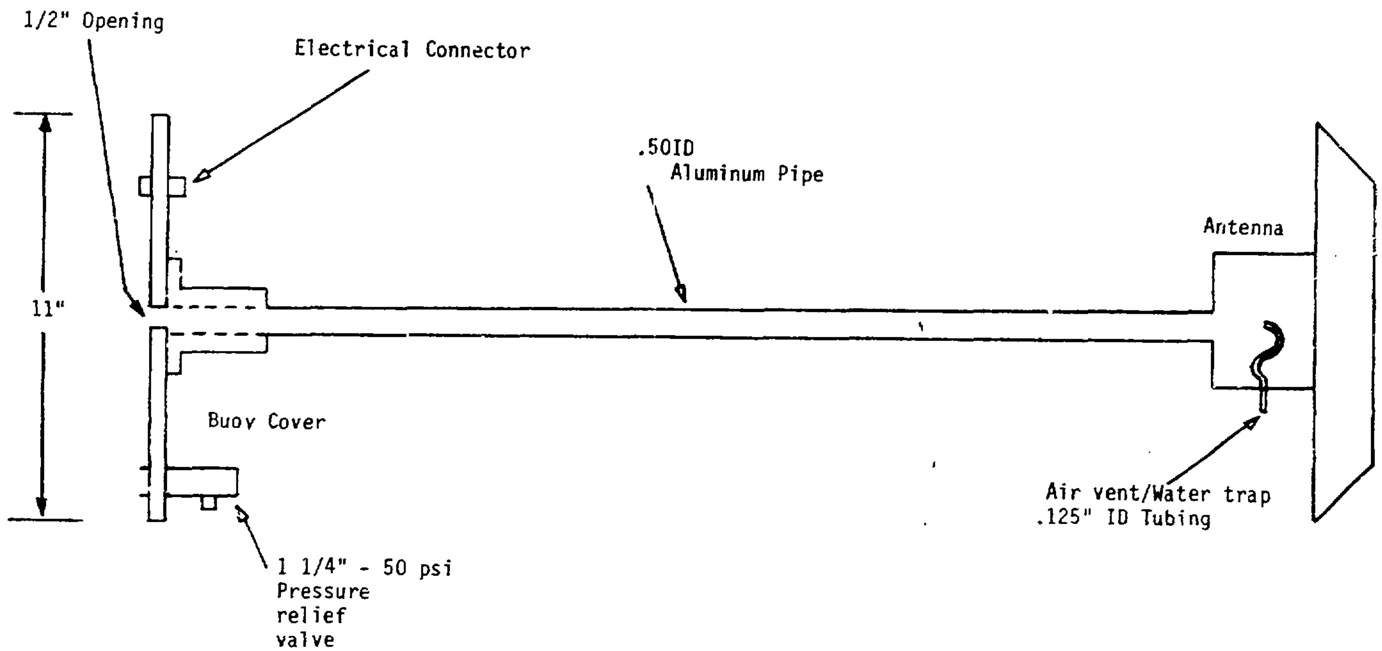

Figure 2. Buoy Cover and Antenna

NOTES:
All remaining diodes are type 1N914

F_1 - system supply voltage fuses

F_2 - battery safety fuses

T - thermal fuses (located at approx. center of each cell cluster)

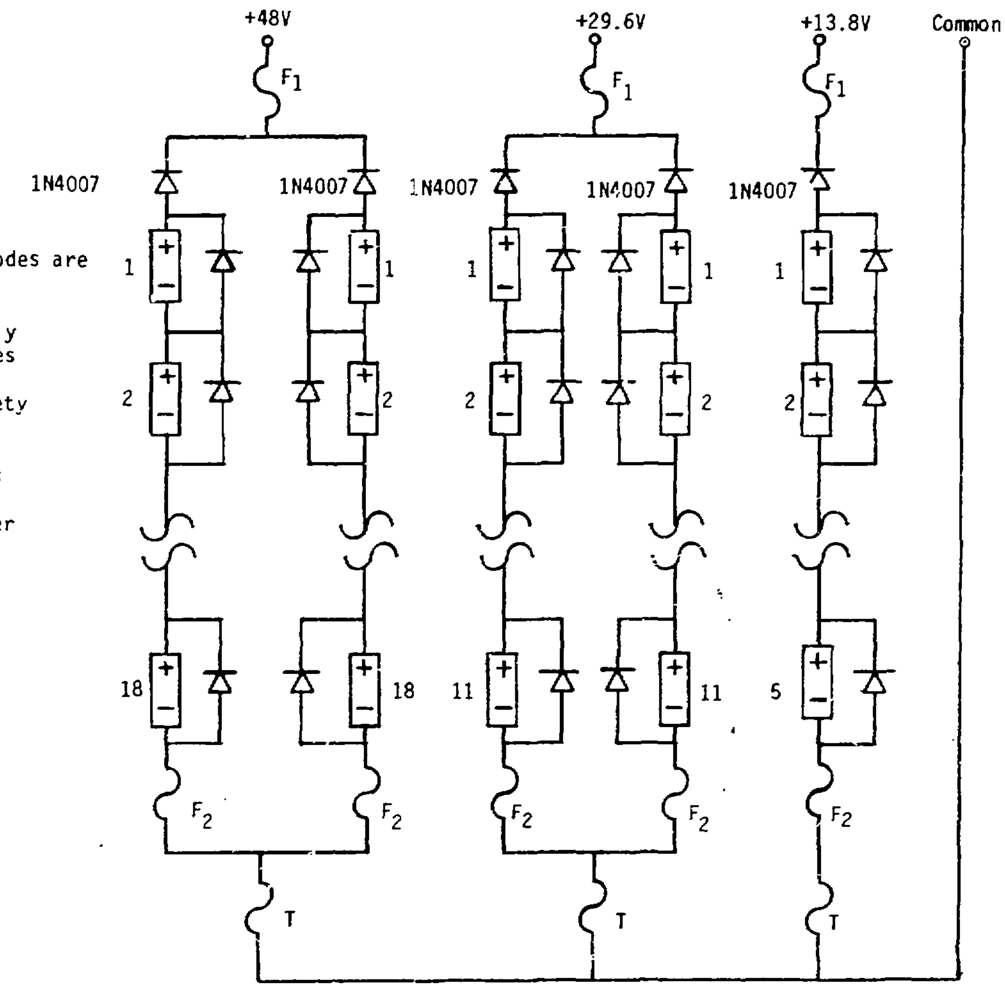

Figure 3. VEKA II Battery Pack Arrangement

The lithium batteries being considered for the prototype feasibility demonstration were Power Conversion, Inc., Model 660-5AS. The cells were on hand, but were rather old having been manufactured by PCI during 1977-1978.

Based on measured power consumption for the acoustic telemetry buoy, the battery arrangement of figure 3 had been calculated to provide for 120 hours of operation before the first battery pack (29.6 volts) faltered. One hundred and twenty hours corresponded to 5 days of continuous buoy operation. Because of the time series nature of the engineering evaluation coupled with the necessity to collect a variety of data sets, it was not feasible to use alkaline or lead-acid battery types due to size constraints. Considering the available volume in the buoy, alkaline, or lead-acid batteries would provide, at best, one to two days of operation. The reduced operating time would not permit an adequate technical evaluation. In fact, the 5 days provided by lithium batteries was less than ideal.

It was desirable that the VEKA II acoustic telemetry buoy be evaluated in September and October of 1982; so plans were made to request, from the Navy Safety Office, permission to use the lithium batteries on hand and for safety certification of the system design.

1.2 REQUIREMENT FOR SAFETY CERTIFICATION

The development of lithium based battery systems seems to have been haunted, from the beginning, by occassional spectacular "accidents"; some that resulted in serious injury or death to the user. A particularly tragic accident in Bermuda in mid-1979 resulted in a Navy moratorium on lithium battery use, establishment of a Lithium Battery Safey Program, and issuance of an upgraded lithium battery safety instruction, NAVSEA INST 9310.1A. This instruction is available from the Commander, Naval Sea Systems Command, Attention SEA 06H, Washington, DC 20362.

Instruction 9310.1A has as its purpose: To establish and promulgate policy, responsibilities and guide lines for the design, acquisition, testing, evaluation, use, packaging transportation, storage and disposal of lithium batteries and equipment powered by such batteries.

The applicability of 3910.1A is broad as stated in its paragraph 3. Scope: This instruction is applicable to all Navy activities and to Marine Corps activities to the extent specified by the Commandant. Material to which this instruction applies includes lithium batteries and all equipment powered by lithium electrochemical power source(s) through all phases of the life cycle of such systems.

In accordance with 9310.1A, a detailed description of the research need, proposed battery/hardware configuration, safety considerations, and operating procedures was submitted to SEA 06H for review. SEA 06H, in turn, submitted the technical description to the Naval Surface Weapons Center, Code R33, which performs as technical review agents for the Navy Safety Office (06H). This technical review resulted in safety improvements to the proposed system configuration and permission to use the existing lithium sulphur dioxide batteries provided a randomly chosen sample of these batteries demonstrated performance consistent with the manufacturer's original specifications.

1.3 SUMMARY OF RESULTS

A sample size consisting of 32 batteries was subjected to forming and discharge testing. The batteries were randomly chosen from a lot of 273 "good" batteries. All units tested performed within expected limits with regard to ampere hour (AH) capacity. There were no ruptures, venting, or other undesirable effects during testing or subsequent at sea use. During discharge tests a few of the batteries developed some bulging of end caps but all casings maintained integrity.

Forming tests revealed a very slow rate of return to full cell voltage at the relatively low current (0.9 to 1.3 amperes) used for discharge.

At sea use of approximately 130 batteries arranged into two identical battery packs further verified the laboratory test results. The research project was safely and successfully completed in the fall of 1982.

In the following sections a detailed description is given of the testing procedures and test results on the 4-5 year old lithium sulphur dioxide batteries used in our research project.

2.0 TEST PROCEDURES AND RESULTS

The primary purpose in performing a series of forming and discharge tests on a random, statistically significant, sample of the existing battery inventory was to determine their suitability for use in the research experiment. The advantage to be gained was economic since several thousand dollars would be required to obtain new batteries. The testing concentrated, then, on normal performance and safe utilization. No attempt was made to abuse, stress, or strain these batteries in any way.

2.1 BACKGROUND OF BATTERIES TESTED

The batteries were originally purchased from Power Conversions Inc. (PCI) during 1977 and 1978 for various research experiments. Six different sizes of LI/SO_2 batteries were purchased including 281 Model 660-5AS units, 32 of which were used in these tests. The Model 660-5AS is rated by PCI as a 30 AH cell (to 2.0 volts) having a nominal open circuit voltage of 2.8 volts and a rated load current of 1000 ma (1.0A). Each cell measures 4.56 cm (dia.) by 13.97 cm (long), often referred to as triple D size, and contains 11.95 grams of lithium. Each cell weighs about 290 grams (10+ oz).

After initial receipt, the cells were stored in cabinets in air-conditioned laboratory spaces until November 1979 when the Navy moratorium caused them to be stored, for safety reasons, in a concrete block 'bunker'. In August of 1982, 32 of the 660-5AS units were removed for testing. On the average, then, each cell had been in an air-conditioned environment for the first 1-2 years of its "life" and an uncontrolled environment for the next three years. In Southern Mississippi, where the cells were stored, this means a temperature range of upper teens to upper 90s fahrenheit and relatively high humidity year round. The cells had been hastily stored in cardboard boxes, some of which were the original shipping containers from PCI. Black plastic electrical tape had been used to electrically insulate the conductive tabs to prevent short circuits during movement and storage. Of the 281 cells inspected visually and by open circuit voltmeter measurements, 273 appeared good; the 8 rejects consisted of 3 dead (zero volts open circuit) and 5 rusty (outer casing only; no leakage evident). From the 273 "good" cells, 32 were selected at random for detailed testing.

2.2 DESCRIPTION OF TEST PROCEDURES

Two basic tests were performed on each cell; time to form using the highest in service current drain and time to discharge using the same in service current. Each of these tests is described in detail in the following subsections.

2.2.1 Forming Tests

It is well-known that Li/SO_2 batteries form a passivating layer on the anode during periods of non-use. This layer is created by the self discharge current internal to the cell and acts as a high resistance impediment to further self discharge. It is this characteristic of lithium cell electrochemistry that gives these batteries their extremely long shelf life. It is also this characteristic that causes a stored cell not to give full rated voltage and current until sometime after the load has been applied. The result of a load applied to a lithium cell that has been in storage for some time is an immediate drop in cell voltage (from open circuit conditions) followed by an increase in cell potential toward, but never quite reaching, the starting open circuit value. The length of time taken and the amount of initial cell potential drop (or droop) depends on the load current demanded. The purpose of this test, was to determine the recovery characteristics for a current approximately equal to the manufacturer's specified rated load for the 660-5AS cell (1.0 ampere); which was very close to our maximum required load of 1.1 ampere.

2.2.1.1 Forming Test Set-Up

Figure 4 shows the circuit used to perform the cell forming tests. The protective diode was installed to prevent any possibility of reverse polarity being felt by the cell under test. The load resistor used in the first forming operation was 3.10 ohms.

Each of 32 cells were "formed" in the following manner: A cell was placed in the circuit, the strip-chart recorder was started, and a "no-load" voltage recorded. Next the on/off switch was closed, establishing a load current of approximately 0.9 amperes through the resistor. Continuous voltage recordings were taken until the cell voltage reached a maximum loaded value. This usually took some number of minutes. At this point, the recorder was stopped, the on/off switch was opened and the cell replaced with the next to be formed.

Sixteen of the original 32 cells were also subjected to a second/ forming test approximately one week later to determine the change, if any, on the time required to reach the same maximum load voltage. The procedure used was identical; however, the value of the load resistors was changed. Cells numbered 9-16 (half of the 16 batteries) were reformed with a 3.18 ohm resistor and number 17-24 (the other half) were reformed with a 2.06 ohm resistor. The load current produced by the 3.18 ohm resistor was essentially the same as that produced by the 3.10 ohm resistor used in the first forming operation. The 2.06 ohm resistor was selected so that a higher (approximately 50%) forming current could be evaluated since recovery times at a load of 3.10 ohm to 3.18 ohm seemed quite long, although not critical to the intended use.

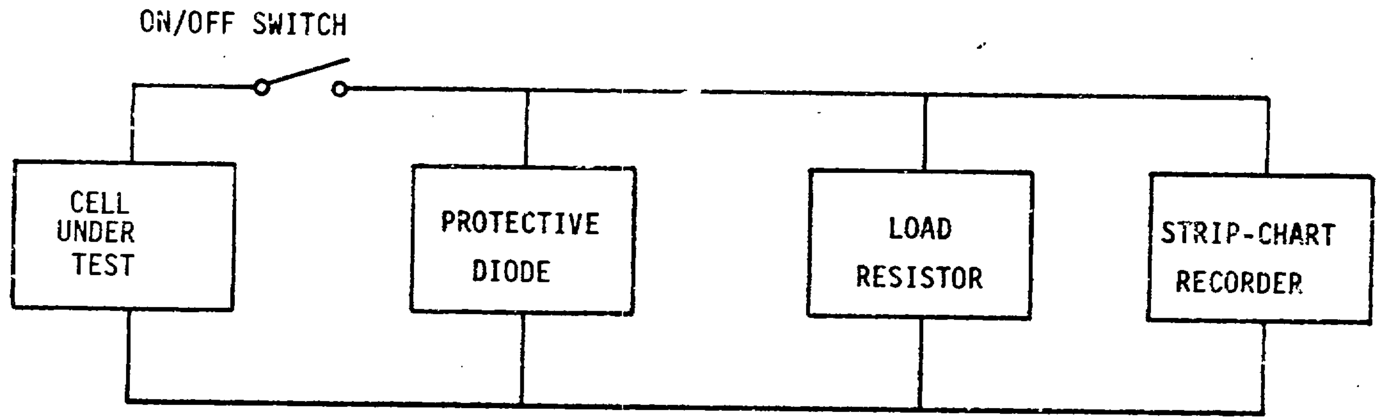

Figure 4. Test Set-up for Forming Tests

TABLE 1 - FORMING TEST RESULTS
(Initial Forming, 3.10 ohms)

Cell Number	No load Voltage	TØ Min Voltage	T1 20%	T2 40%	T3 60%	T4 80%	T5 Max Voltage
B1	2.60v	2.48v	2.54v 4.8 sec	2.61v 24 sec	2.67v 38 sec	2.73v 182 sec	2.8v 626 sec
B2	2.44v	2.36v	2.44v 9.6 sec	2.52v 28.8 sec	2.60v 81.6 sec	2.68v 297.6 sec	2.76v 792 sec
B3	2.58v	2.48v	2.51v 6.8 sec	2.58v 7.2 sec	2.63v 34 sec	2.68v 310 sec	2.74v 720 sec
B4	2.68v	2.60v	2.64v 12 sec	2.68v 36 sec	2.72v 108 sec	2.74v 228 sec	2.76v 948 sec
B5	2.74v	2.64v	2.66v 19.2 sec	2.68v 52.8sec	2.70v 115.2 sec	2.72v 276 sec	2.74v 523.2 sec
B6	2.82v	2.65v	- did not recover under load -				2.67v
B7	2.60v	2.50v	2.55v 4.8 sec	2.59v 14.4 sec	2.64v 48 sec	2.68v 120 sec	2.73v 537.6 sec
B8	2.5v	1.95v	2.06v 2.4 sec	2.17v 9.6 sec	2.28v 28.8 sec	2.39v 151.2 sec	2.50v 576 sec
B9	2.6v	2.48v	2.53v 7.2 sec	2.58v 24.0 sec	2.63v 67.2 sec	2.68v 213.6 sec	2.73v 573.6 sec
B10	2.5v	2.33v	2.38v 4.8 sec	2.44v 14.4 sec	2.49v 40.6 sec	2.55v 81.6 sec	2.60v 384 sec
B11	2.38v	2.34v	2.42v 2.4 sec	2.50v 12.0 sec	2.57v 21.6 sec	2.65v 88.8 sec	2.73v 700.8 sec
B12	2.55v	2.43v	2.48v 7.2 sec	2.54v 19.2 sec	2.59v 52.8 sec	2.65v 168 sec	2.70v 480 sec
B13	2.80v	2.73v	- showed little droop under load -				2.73v
B14	2.56v	2.45v	2.50v 7.2 sec	2.55v 26.4 sec	2.59v 72 sec	2.64v 180 sec	2.69v 612 sec
B15	2.56v	2.46v	2.51v 7.2 sec	2.57v 19.2 sec	2.62v 48 sec	2.68v 180 sec	2.73v 600 sec
B16	2.58v	2.48v	2.52v 7.2 sec	2.57v 24 sec	2.61v 48 sec	2.66v 204 sec	2.70v 456 sec

TABLE 1 - FORMING TEST RESULTS
(Initial Forming, 3.10 ohms)
(continued)

Cell Number	No load Voltage	TØ Min Voltage	T1 20%	T2 40%	T3 60%	T4 80%	T5 Max Voltage
B17	2.54v	2.34v	2.39v 9.6 sec	2.44v 21.6 sec	2.50v 86.4 sec	2.55v 216 sec	2.60v 480 sec
B18	2.46v	2.35v	2.40v 4.8 sec	2.45v 21.6 sec	2.49v 36 sec	2.54v 242.2 sec	2.59v 564 sec
B19	2.54v	2.43v	2.49v 4.8 sec	2.55v 14.4 sec	2.61v 40.8 sec	2.67v 168 sec	2.73v 576 sec
B20	2.52v	2.40v	2.46v 7.2 sec	2.52v 19.2 sec	2.57v 40.8 sec	2.63v 132 sec	2.69v 492 sec
B21	2.56v	2.45v	2.51v 7.2 sec	2.56v 16.8 sec	2.62v 48 sec	2.67v 153.6 sec	2.73v 552 sec
B22	2.48v	2.42v	2.48v 4.8 sec	2.54v 14.4 sec	2.60v 43.2 sec	2.67v 156 sec	2.73v 576 sec
B23	2.52v	2.40v	2.45v 7.2 sec	2.50v 16.8 sec	2.56v 52.8 sec	2.61v 96 sec	2.66v 480 sec
B24	2.28v	2.20v	2.30v 2.4 sec	2.41v 7.2 sec	2.51v 24 sec	2.62v 69.6 sec	2.72v 600 sec
B25	2.52v	2.45v	2.50v 7.2 sec	2.55v 14.4 sec	2.61v 48 sec	2.66v 156 sec	2.71v 552 sec
B26	2.48v	2.39v	2.46v 9.6 sec	2.52v 21.6 sec	2.59v 52.8 sec	2.65v 156 sec	2.71v 588 sec
B27	2.57v	2.50v	2.54v 4.8 sec	2.59v 26.4 sec	2.63v 52.8 sec	2.68v 168 sec	2.72v 624 sec
B28	2.40v	2.35v	2.41v 4.8 sec	2.47v 12 sec	2.53v 31.2 sec	2.59v 103.2 sec	2.65v 590.4 sec
B29	2.55v	2.47v	2.52v 7.2 sec	2.57v 19.2 sec	2.63v 55.2 sec	2.68v 192 sec	2.73v 612 sec
B30	2.54v	2.45v	2.50v 4.8 sec	2.55v 16.8 sec	2.61v 48 sec	2.66v 144 sec	2.71v 564 sec
B31	2.50v	2.42v	2.47v 7.2 sec	2.53v 19.2 sec	2.58v 40.8 sec	2.64v 134.4 sec	2.69v 600 sec
B32	2.42v	2.37v	2.43v 7.2 sec	2.49v 16.8 sec	2.55v 40.8 sec	2.61v 112.8 sec	2.67v 640.8 sec

TABLE 2 - FORMING TEST RESULTS
(Second Forming, 3.18 ohms)

Cell Number	No load Voltage	TØ Min Voltage	T1 20%	T2 40%	T3 60%	T4 80%	T5 Max Voltage
B9	2.55v	2.58v	2.61v 10 sec	2.65v 36 sec	2.68v 76.4 sec	2.71 256.4 sec	2.75v 501.2 sec
B10	2.64v	2.56v	2.59v 6 sec	2.63v 18 sec	2.66v 50 sec	2.69v 198 sec	2.73v 522 sec
B11	2.52v	2.48v	2.53v 3.2 sec	2.58v 9.2 sec	2.63v 25.2 sec	2.68v 101.2 sec	2.73v 437.2 sec
B12	2.60v	2.53v	2.57v 6 sec	2.61v 19.2 sec	2.64v 37.2 sec	2.68v 177.2 sec	2.72v 453.2 sec
B13	2.85v	2.78v	- did not change after initial load -				2.77v
B14	2.54v	2.48v	2.51v 2 sec	2.54v 12 sec	2.56v 32 sec	2.59v 82 sec	2.62v 502 sec
B15	2.58v	2.51v	2.55v 6 sec	2.59v 18 sec	2.63v 42 sec	2.67v 190 sec	2.71v 442 sec
B16	2.62v	2.54v	2.57v 5.2 sec	2.60v 13.2 sec	2.64v 48 sec	2.67v 144 sesc	2.70v 384 sec

TABLE 3 - FORMING TEST RESULTS
(Second Forming, 2.06 ohms)

Cell Number	No load Voltage	TØ Min Voltage	T1 20%	T2 40%	T3 60%	T4 80%	T5 Max Voltage
B17	2.52v	2.47v	2.51v 2 sec	2.56v 10 sec	2.60v 44 sec	2.65v 182 sec	2.69v 470 sec
B18	2.58v	2.51v	2.55v 6 sec	2.59v 16 sec	2.63v 42 sec	2.67v 134 sec	2.71v 348 sec
B19	2.48v	2.36v	2.42v 4.4 sec	2.48v 12.4 sec	2.53v 40.4 sec	2.59v 204 sec	2.65v 744 sec
B20	2.45v	2.43v	2.48v 4 sec	2.53v 12 sec	2.58v 52 sec	2.63v 268 sec	2.68v 688 sec
B21	2.44v	2.43v	2.48v 4 sec	2.53v 10 sec	2.59v 48 sec	2.64v 162 sec	2.69v 548 sec
B22	2.35v	2.34v	2.38v 3.2 sec	2.43v 9.2 sec	2.47v 25.2 sec	2.52v 99.6 sec	2.56v 497 sec
B23	2.44v	2.42v	2.47v 4 sec	2.52v 11.2 sec	2.58v 59.2 sec	2.63v 201 sec	2.68v 649 sec
B24	2.25v	2.25v	2.33v 1.6 sec	2.40v 5.2 sec	2.48v 15.2 sec	2.55v 61.2 sec	2.63v 571.2 sec

2.2.1.2 Forming Test Results

Tables 1 and 2 summarize the results of the initial forming operation on all 32 cells. The tables give, by column for each cell; the open circuit (unloaded) voltage, the minimum voltage under the 3.10 ohm load, and the time to reach 20%, 40%, 60%, 80% and 100% of the maximum load voltage ultimately achieved while connected to the resistive load.

Tables 2 and 3 summarize the results of the second forming operation performed about a week later on 16 of the 32 cells. This time separation resulted from the discharge test work being performed on the first few cells. Initially, no plans had been made for a second forming test but after reviewing the data, it was decided to determine if a few days of shelf storage altered the forming charateristic. It was also decided to use a higher forming current for half of the 16 cells to determine if reasonably small changes in load (on the order of 50%) altered the characteristic.

A comparison of Tables 1 and 2 shows that there were small but relatively insignificant changes in the forming characteristics over a timespan of a few days. It does appear that the initial droop in cell load voltage was reduced by the initial forming operation indicating that the layer had not totally reformed, but the times to achieve maximum output under load do not appear to have been reduced. Figure 5 illustrates a "typical" forming curve of load voltage versus time.

A comparison of Tables 1 and 3 shows that, once again, there were small but relatively insignificant changes in the forming characteristic. In retrospect, it is surmized that the load currents used in the forming operation were far too small to successfully and completely reduce the passivating layer and that channels and paths through the layer were created during energy withdrawal which quickly "healed" after the short term (compared to total capacity) forming operation was concluded. Use of a much higher current was not of interest for the intended application and so only those characteristics pertinent to the actual operation were explored.

2.2.2 Discharge Tests

Having evaluated the initial forming characteristics and determined that the effects were completely acceptable, attention was given to determining the ampere hour capacity that could be expected from these "old" cells. Every effort had been made to reject used and physically damaged cells from the original lot prior to the random selection of the 32 test units. There was, however, no way to be absolutely sure that none of the 32 cells had been used during "clip lead" bench tests and therefore partially discharged. As will be pointed out later, two cells appear strong candidates for the "previously used" category and a few others may be suspect.

2.2.2.1 Discharge Test Set-Up

Figure 6 shows the set-up used to perform the cell discharge tests. It is similar to the one used for the forming tests, however, there are differences. Here, eight cells are tested at one time instead of just one. Also the output voltages are sent to an HP 9825 computer via two four-channel analog to digital converters (HP 59313). Photographs of the testing equipment and set-up are shown in figures 7 and 8.

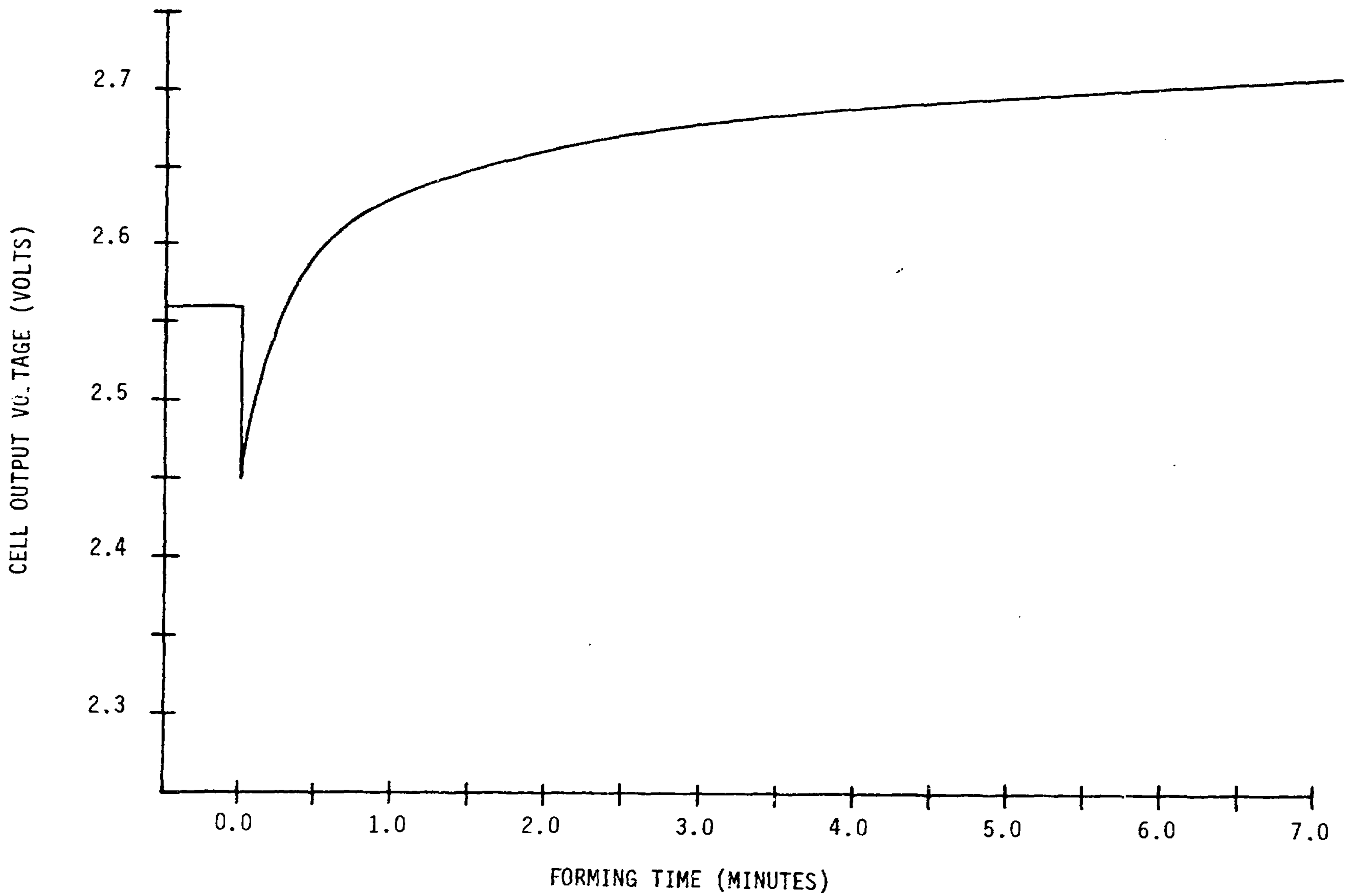

Figure 5. "Typical" cell forming characteristic (Data from cell B21)

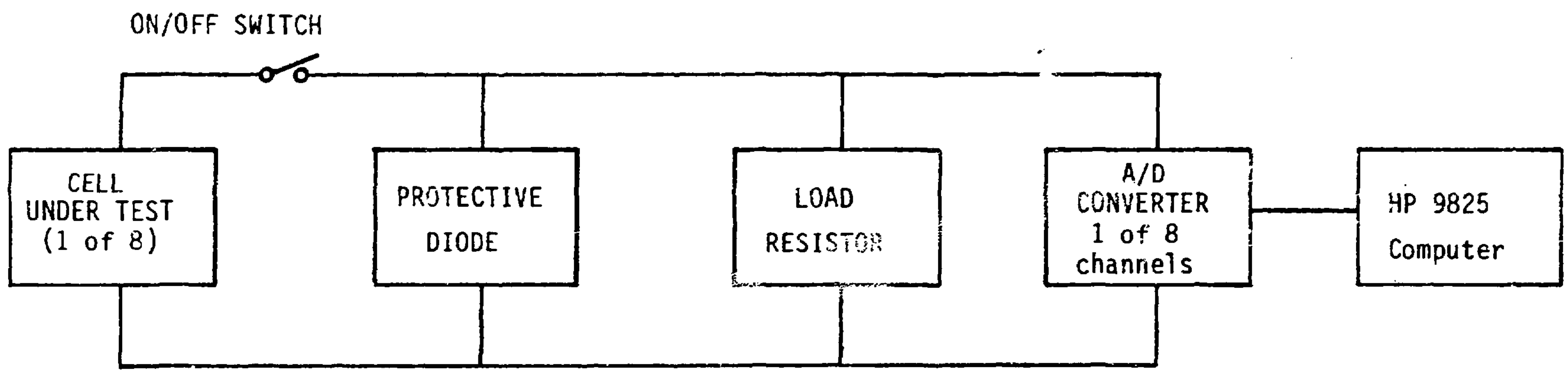

Figure 6. Test Set-up for Discharge Tests

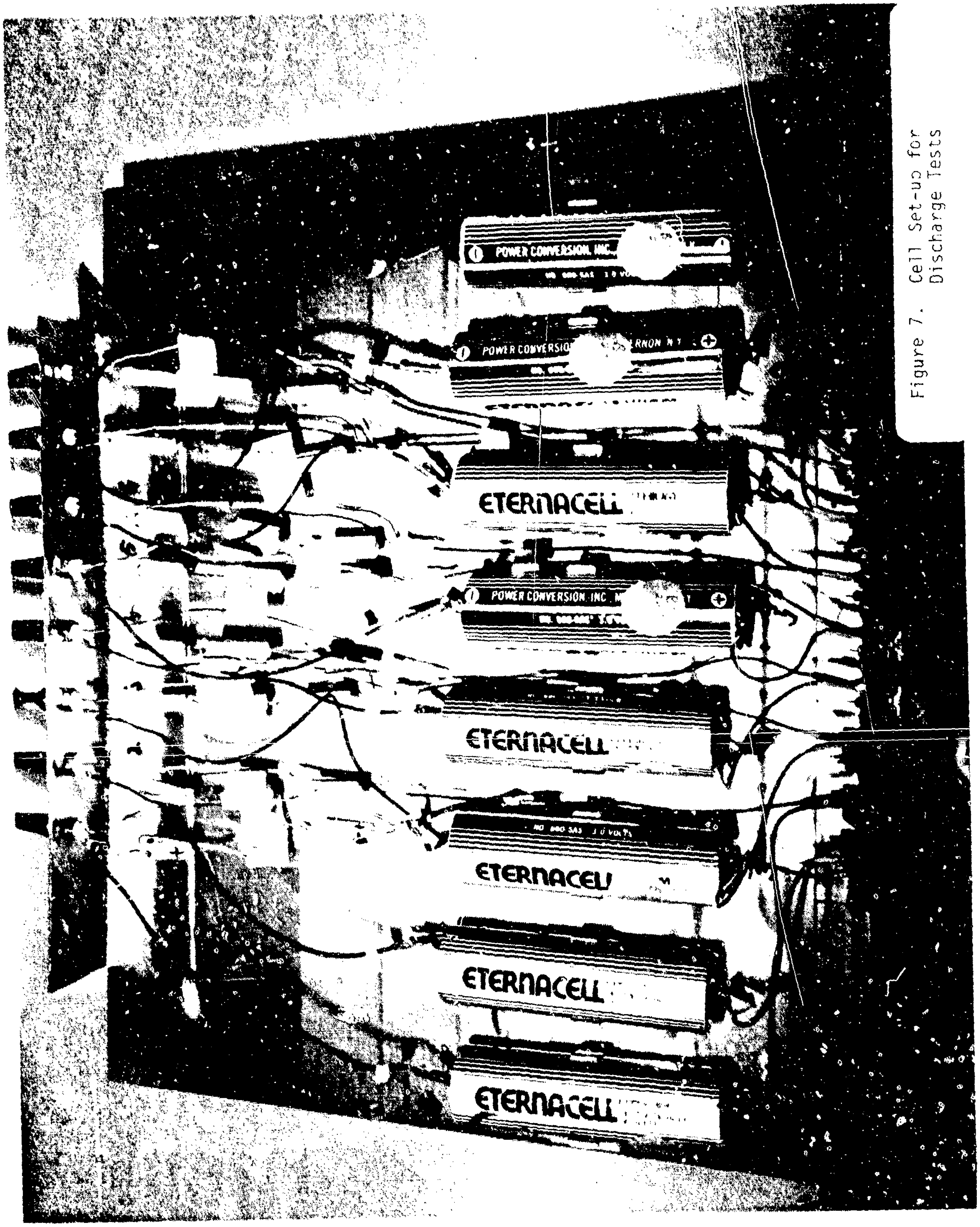

Figure 7. Cell Set-up for Discharge Tests

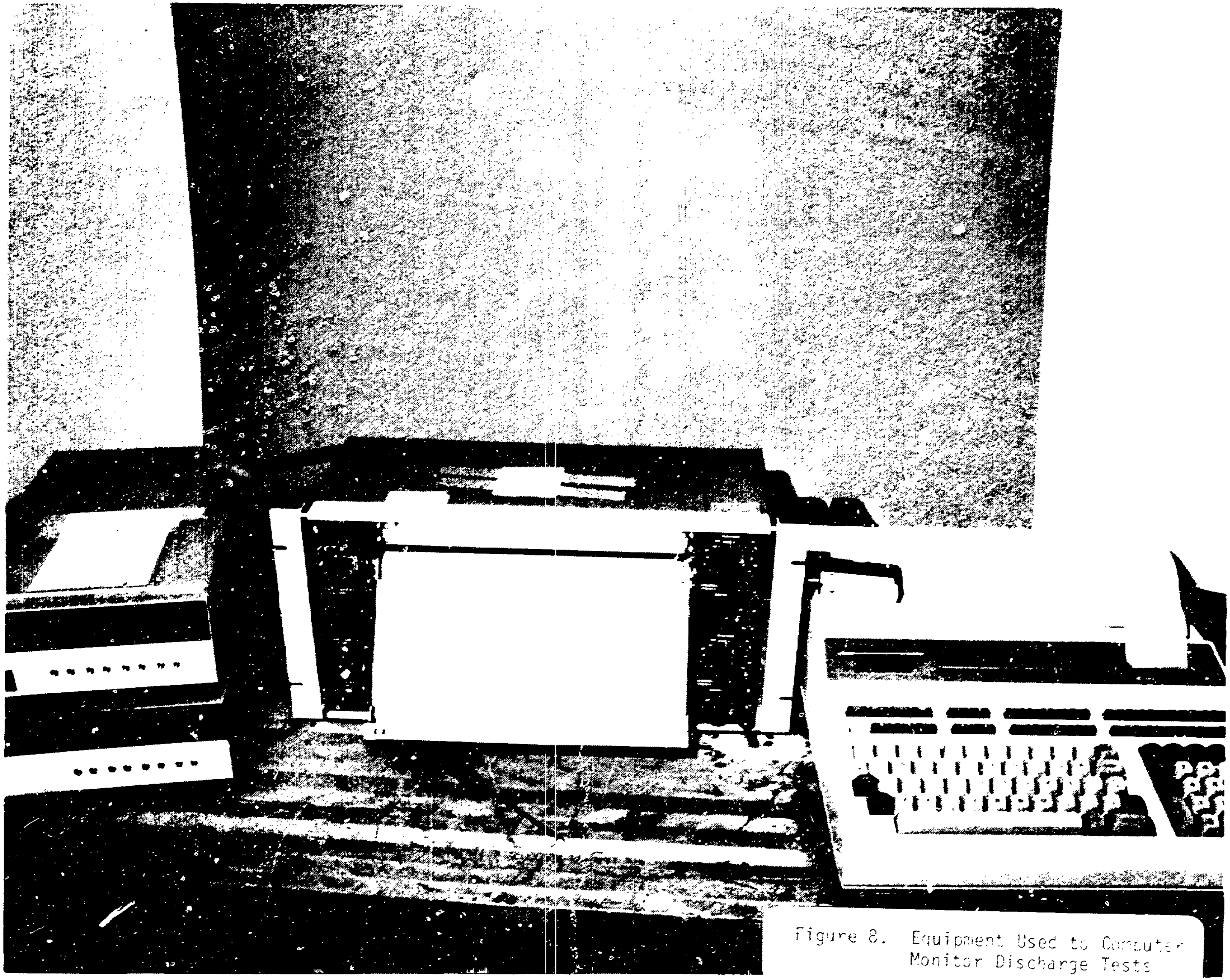

Figure 8. Equipment Used to Comsutcr Monitor Discharge Tests

The discharge tests were performed using the following procedures: Eight cells were installed in the test circuit (Fig. 7). Next, the test program was loaded into the computer (Fig. 8). The battery identifications were typed into the computer, the on/off switches were closed and the test program started. At that instant, the computer stored the calendar date, time, eight cell identifications, and voltage reading for each cell on cassette magnetic tape. As the program continued, it stored the time and voltage for each cell at fifteen minute intervals. The program ran continuously, until stopped manually. The test continued until each cell voltage had reached zero or near zero. At that time, the program was stopped, the on/off switch opened and the data cassette removed. Then, a new cassette and the next eight cells were installed and the procedure repeated.

2.2.2.2 Discharge Test Results

Table 4 summarizes the results of the discharge tests on all 32 cells. The table columns give in order: the load resistance, ampere hours to a cell load voltage of 2.0 volts, the time for the cell load voltage to decrease from 2.0 to 1.0 volts, the maximum cell load voltage during the discharge test, and the corresponding maximum load current during discharge.

A visual scan down column 3, ampere hours to 2.0 volts, indicates that most of the cells provided more than the 30 ampere hours specified by the manufacturer. Cells B6 at 20.19 AH and B13 at 18.08 AH are thus suspect since their outputs are significantly less than the majority and they may have been used cells. Even if these cells are considered to be new, the average ampere hour capacity for all 32 test units is 33.27, or 10% more than the manufacturer's specification.

Calculation of the ampere hour capacity is not a simple task because a constant resistance discharge produces a non-linear decreasing current with time. For the calculations used to produce column 3 of Table 4, each discharge curve was divided into three sections, a start up or forming section, a steady state discharge section, and a terminal discharge section. Linear approximations of cell load voltage were fitted to each defined section of the discharge curve and used in making current-time calculations that were then summed to produce the final ampere hour values. The calculations were made easier in that the Li/SO_2 cells demonstrate a very flat cell load voltage characteristic during discharge as illustrated by column 4 of Table 4. The calculations are believed to be 98% accurate.

The time required for a loaded cell to transition from 2.0 volts to 1.0 volts has been included in the tables to illustrate the steepness of the terminal portion of the discharge curve. Interpolation between data points was the technique used to calculate the values given in column 4 of the table. The average transition time is 31.33 minutes for a 30 AH cell discharged at approximately one ampere to change its output voltage from 2.0 to 1.0 volts. This means that if cell life were considered to be over at 1.0 volts instead of 2.0 volts it would add less than 2% to the total life of the cell. The sharp cutoff characteristic of the Li/SO_2 cell was thus verified.

Note that a maximum discharge current of approximately 0.9 amperes was used for the first 16 cells while a maximum current of approximately 1.3 amperes was used for the second 16 cells. The maximum anticipated current in the application was 1.0 to 1.2 amperes and was not as easy to produce as the currents shown in the table. The test currents created using combinations of nominal 1 ohm resistors bracketed the anticipated range and yielded the data desired in an easier to produce manner.

TABLE 4 - DISCHARGE TEST RESULTS

Cell ID	Resistance ohm	AHrs to 2v	Time 2v to 1v	Max E	Max I
B1	2.96	33.55	8.15 min	2.79v	943 ma
B2	3.10	45.10	14.22 min	2.79v	900 ma
B3	2.95	31.61	39.26 min	2.78v	941 ma
B4	2.95	26.88	118.42 min	2.78v	942 ma
B5	2.99	30.32	85.71 min	2.79v	933 ma
B6	3.18	20.19	131.87 min	2.77v	871 ma
B7	2.96	32.92	25.00 min	2.69v	909 ma
B8	2.90	37.64	7.14 min	2.79v	962 ma
B9	2.96	27.51	9.61 min	2.78v	939 ma
B10	3.10	29.56	39.13 min	2.78v	897 ma
B11	2.95	32.78	7.18 min	2.78v	942 ma
B12	2.95	33.77	10.63 min	2.80v	949 ma
B13	2.99	18.08	9.20 min	2.78v	930 ma
B14	3.18	33.18	2.84 min	2.78v	874 ma
B15	2.96	34.80	2.81 min	2.78v	939 ma
B16	2.90	33.51	5.69 min	2.78v	959 ma

TABLE 4 - DISCHARGE TEST RESULTS (continued)

Cell IO	Resistance ohm	AHrs to 2v	Time 2v to 1v	Max E	Max I
B17	1.95	25.68	8.62 min	2.73v	1400 ma
B18	2.10	25.96	113.20 min	2.75v	1310 ma
B19	2.04	36.65	42.86 min	2.74v	1340 ma
B20	1.96	39.50	8.29 min	2.80v	1430 ma
B21	2.06	35.29	4.19 min	2.74v	1330 ma
B22	2.12	36.19	46.15 min	2.73v	1290 ma
B23	2.06	36.26	63.04 min	2.71v	1320 ma
B24	1.95	36.24	20.27 min	2.71v	1390 ma
B25	1.95	38.96	65.68 min	2.74v	1410 ma
B26	2.10	37.27	8.62 min	2.75v	1310 ma
B27	2.04	37.09	9.26 min	2.74v	1340 ma
B28	1.96	36.25	10.71 min	2.82v	1440 ma
B29	2.06	35.95	11.45 min	2.67v	1300 ma
B30	2.12	36.49	42.84 min	2.75v	1300 ma
B31	2.14	34.07	21.13 min	2.74v	1330 ma
B32	1.95	35.32	9.32 min	2.69v	1380 ma
		Avg AHrs 33.27	Avg time 31.33 min		

3.0 CONCLUSIONS OF TESTS

The original purpose of the tests just described was to determine the suitability of the rather old PCI 660 5AS cells for use in an R&D project. Suitability was defined as providing reasonable amounts (in terms of percentage) of the original (new) power capacity and being safe to handle. The tests certainly proved the suitability of these old cells and, in fact, the R&D project was carried out at sea with the predicted and anticipated lithium battery performance.

3.1 COMPARISON TO ORIGINAL SPECIFICATIONS

Because of the statistically significant size of the sample tested, it has also been possible to satisfy a second and perhaps even more important (to the Navy) purpose; that of determining the actual performance degradation of years old Li/SO_2 cells. Table 5 gives the physical and electrical characteristics of the cells tested. Comparing the test data of Table 4 to these characteristics indicates that the claimed 30 AH capacity and shelf life of 5 years to 75% of initial capacity are both conservative ratings. The open circuit voltage of 2.96 and load voltage (assumed to be at 1.0 ampere load) of 2.8 were not achieved being on the average about 10% lower than stated for a new cell. All factors considered, including the rather harsh environment suffered by these cells during more than two and one half years, the results are most impressive.

3.1.1 Cell Predictability

It would appear from the data presented that these lithium cells provide very predictable performance without requiring any special precautions with regard to storage temperature or humidity control. It is sincerely hoped that with the new safety procedures and certification requirements that this marvelous battery technology (lithium) will finally achieve its rightful place in naval systems.

TABLE 5 - PHYSICAL AND ELECTRICAL CHARACTERISTICS, MODEL 660-5SA CELLS

POWER CONVERSION, INC.

MODEL 660-5A

Lithium Organic Electrolyte Cell

ETERNACELL (R)

PHYSICAL CHARACTERISTICS

Diameter	(inches)	1.64
Height	(inches)	5.5
Volume	(cubic inches)	11.5
Weight	(ounces)	10.1

ELECTRICAL CHARACTERISTICS

Open Circuit Voltage	2.96
Under Load Voltage (Nominal)	2.8

Capacity (Ampere-Hours)

Temperature	Current	
70°F	1 ampere	30
-20°F	1 ampere	18
-40°F	1 ampere	12

Energy Density

Watt-Hours/Cubic Inch	7.5
Watt-Hours/Pound	150
Operational Temperature	-65°F to +165°F
Shelf Life	Greater than 5 years to 75% of initial Capacity
Environmental	Mil Spec - shock, vibration, etc.

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Tests of a new acoustic system in the spring of 1982, using radio frequency transmission of the data, required the Naval Ocean Research and Development Activity (NORDA) to reconsider the use of lithium battery technology. A request was made to the Navy Safety Office, Naval Sea Systems Command Code 06H, for permission to utilize lithium batteries in the R&D project and for permission to use existing lithium sulphur dioxide cells, which had been purchased in previous years. The Safety Office

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) tentatively approved the intended usage but subject to a performance test and evaluation of a representative sample of the existing cells. In response to the NAVSEA direction, 32 cells were randomly chosen and subjected to forming and discharge tests. The cells, as a group, performed beyond expectations and provided energy in excess of the manufacturer's original specifications for these cells. All tests were performed without safety problems or any incidents. Similiar cells from the same lot were subsequently used at sea in the R&D project and performed equally as well as those tested in the laboratory. This report documents the testing procedures used to evaluate 4-5 year old Li/SO_2 cells and the test results achieved.