Evaluation of Battery Packs for Liquid Microclimate Cooling Systems

DEPARTMENT OF THE NAVY
SUPPLY SYSTEMS COMMAND

NAVY CLOTHING AND TEXTILE RESEARCH FACILITY

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The Navy Clothing and Textile Research Facility conducted a literature and industry survey to determine the best commercially available battery technology for use with liquid microclimate cooling systems (MCS), and a laboratory evaluation of a battery pack utilizing that technology. Nickel/cadmium batteries were determined to be the best battery technology commercially available at the present time. However, several other battery technologies are nearing commercialization and may be available in the near future.

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INTRODUCTION

The U.S. Navy is interested in the use of microclimate cooling systems (MCS) as a means of alleviating heat stress aboard ship. The Navy Clothing and Textile Research Facility (NCTRF) has evaluated several types of MCS for possible shipboard use with the general utility uniform and chemical defense ensemble (e.g. 1-4). Based on these evaluations and the special needs of the chemical defense ensemble, liquid MCS is the most promising technology available in the near term for alleviating heat stress on board ship in a chemical warfare environment (4). A prototype liquid MCS for use with the chemical defense ensemble has been developed and tested (3, 5). Although further development is required, it appears promising for future use.

To improve the prototype liquid MCS, each component must be optimized for maximum performance with minimum weight. The purpose of this study was to optimize the power supply (i.e., battery) used with the prototype liquid MCS. This was accomplished by surveying the literature, and making industry and government contacts to identify the best battery technology commercially available, followed by testing the identified battery with the prototype MCS. The best commercially available battery technology, incorporated into a battery pack sized to operate the MCS for slightly more than two hours, will ensure that the minimum possible battery weight is used with the MCS.

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(1) Pimental, N. A., B. A. Avellini, and C. R. Janik. Microclimate cooling systems: a laboratory evaluation of two commercial systems. Natick, MA: Navy Clothing and Textile Research Facility, 1988; Technical Report No. 164.

(2) Pimental, N. A., and B. A. Avellini. Effectiveness of three portable cooling systems in reducing heat stress. Natick, MA: Navy Clothing and Textile Research Facility, 1989; Technical Report No. 176.

(3) Pimental, N. A., W. B. Teal, Jr. and B. A. Avellini. Effectiveness of a prototype microclimate cooling system for use with chemical protective clothing. Natick, MA: Navy Clothing and Textile Research Facility, 1990; Technical Report No. 180.

(4) Janik, C. R., Feasibility study on the use of microclimate cooling systems by the US Navy. Natick, MA: Navy Clothing and Textile Research Facility, 1985; internal report.

(5) Development of a shipboard microclimate cooling system, phase I, final report. Frederica, DE: ILC Dover, 1987; Technical report.

Literature Search and Industry Survey. Batteries may be divided into two classes (6): primary (non-rechargeable) and secondary (rechargeable) batteries. On board ship, a rechargeable battery would be needed to keep the number of batteries required to a minimum. Hence, only secondary batteries were considered during the remainder of the study.

A significant number of types of secondary batteries exist. The best one for use with a liquid MCS will be the one which has the greatest gravimetric energy density that is commercially available in a form suitable for use with the MCS. Table 1 contains the energy densities of various secondary batteries. It should be noted that the exact energy density attained in use will be dependent upon the actual battery design, discharge rate, and use conditions.

TABLE 1 ENERGY DENSITIES OF SOME BATTERY TECHNOLOGIES

Battery technology	Charge density (wh/lb) (7)
Nickel/hydrogen	19-26
Rechargeable lithium	23 (8)
Nickel/zinc	14-23
Cadmium/silver oxide	13-23
Nickel/iron	9-12
Nickel/cadmium	4-14
Lead/acid	7-12

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(6) Brodd, R. J. Advanced batteries. Chemtech. pages 612-21, October, 1985.

(7) Batteries and Fuel Cells. Published by McGraw-Hill, pages 13-10 to 13-14.

(8) Moli Energy brochure on the MoliCell.

Comparison of Battery Technologies. From Table 1 it is clear that the greatest energy densities may be obtained from batteries based on nickel/hydrogen, rechargeable lithium, nickel/zinc, or cadmium/silver oxide technology. However, none of these technologies is available in a form suitable for use with the current prototype MCS. Ovionic manufactures a nickel/hydride "C" cell (a variation of the nickel/hydrogen technology). However, the cell is only available in limited quantities for test and evaluation purposes. NASA is pursuing nickel/hydrogen technology as a replacement for the nickel/cadmium batteries now in wide use. A rechargeable lithium battery known as the MoliCell is available from Moli Energy. Currently, only "AA" cells are available in limited quantities. Nickel/zinc and cadmium/silver oxide battery technologies are still under development.

The remaining technologies, nickel/iron, nickel/cadmium, and lead/acid, have somewhat lower energy densities than the other systems. The nickel/iron technology is not yet commercially available. This leaves only two battery technologies to choose from for liquid MCS: nickel/cadmium and lead/acid. Batteries utilizing one or the other of these two technologies are available from a number of manufacturers.

Table 1 indicates that there is a significant overlap in the energy density ranges of nickel/cadmium and lead/acid batteries. After discussions with Navy Department battery experts (9, 10), the nickel/cadmium technology was chosen due to its slightly higher energy density, flat voltage profile (important for maintaining constant liquid flow rate), and excellent cycle life (the number of times a battery may be used and recharged).

The prototype liquid MCS was originally developed with nickel/cadmium batteries. Therefore the best available technology has been used with the prototype. The question remains, however, whether or not the delivered batteries are sized properly for the MCS. It is important that the battery maintain a relatively constant voltage output for at least two hours when used throughout the temperature range of interest. If the battery voltage begins to drop off too early, i.e., before the two hour interval between battery changes expires, then the rate of flow of the cooling fluid would decrease, and the cooling power of the MCS would decrease. On the other hand, the battery should not maintain constant voltage too far beyond two hours since this would indicate that the user is carrying excess battery capacity, and hence, more weight than necessary.

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(9) V. Alminaskas and B. Dantin, Naval Weapons Support Center, Crane, IN, 25 Jan 89 (Personal communication).

(10) T. Griffey, Naval Weapons Support Center, Crane, IN, 23 Oct 89 (Personal communication).

METHODS

Description of the Battery Packs. The nickel/cadmium battery packs developed for use with the prototype liquid MCS are 2-1/8 by 2-1/8 by 5-1/4 inches and weigh 1.7 pounds (769 grams). The outer battery pack case is made from Noryl^{R} plastic which has excellent chemical resistant properties. Internally, the battery pack consists of 18 nickel/cadmium cells, manufactured by Marathon, Inc., connected in series. This results in a nominal 24 volt battery pack with 0.80 ampere-hour capacity. Four battery packs were available for testing.

Test Design. The test was conducted to determine the voltage versus time profile for the nickel/cadmium battery packs at several operating temperatures. It is anticipated that the battery packs will be used primarily in the 70 to 125^{o}F (21 to 52^{o}C) temperature range (4). The temperatures selected for the present tests were 70, 95, and 125^{o}F (21, 35, and 52^{o}C), which represent the low, approximate mid-point, and high temperatures of interest. Four identical battery packs were tested. Prior to use, each battery was fully charged in accordance with the manufacturer's instructions. The prototype liquid MCS was used to provide a current load on the battery during the test, thereby reproducing actual battery use conditions. A test was terminated when the battery could no longer provide enough power to maintain fluid flow in the MCS. The time and voltage at which fluid flow ceased were termed the cutoff time and cutoff voltage, respectively. The voltage at the battery terminals was monitored at 5 minute intervals with a computerized data acquisition system.

Data Analysis. At each temperature, the voltage versus time data for the four batteries was plotted to assess the uniformity of the discharge characteristics of each battery. At each temperature, the voltages of the batteries at 5 minute intervals were averaged, and the average was plotted along with the individual voltage versus time plots mentioned above. Next, a plot of the average voltage versus time curves at each of the three temperatures was generated. To compare the data at the three different temperatures, the cutoff time and cutoff voltage data were analyzed by repeated measures one way analysis of variance. Tukey's test was used to locate significant differences. Significance was accepted at the 0.05 level.

RESULTS

Figures 1, 2, and 3 display the voltage versus time plots for each of four identical batteries at three temperatures. The average of batteries 1, 2, and 3 is also plotted. The data points for battery 4 differ substantially from the data points for the other batteries. The test of battery 4 was repeated at 70°F to verify that the abnormal data was a true representation of battery 4's performance. There was reasonably good agreement between the repeat and original tests. It is important to note that the shape of the voltage versus time profile for battery 4 is not normal. It is well known that the discharge profile of nickel/cadmium batteries (indeed for most batteries) consists of an initial rapid drop in voltage from the open circuit voltage, followed by a relatively long discharge period during which the voltage remains nearly constant (6, 7). Near the end of the discharge profile, there is a rapid drop in voltage. Batteries 1, 2, and 3 follow this classic pattern at all three temperatures tested. The discharge profile for Battery 4, however, does not follow the normal pattern. This indicates that there may have been a problem with one or more of the cells in battery pack 4, perhaps an internal short, or some other abnormality. These four battery packs had been used numerous times during testing of the prototype liquid MCS. Therefore, it is possible that battery 4 was damaged in some way during the earlier testing. Since the discharge profile for battery 4 indicates that it was likely damaged in some way, the data from tests of battery 4 were not used during the analysis.

Figure 4 contains the average voltage versus time curves for each temperature. These are the same curves displayed individually in Figures 1, 2, and 3. They are displayed together in Figure 4 for ease of comparison.

Table 2 contains the average cutoff voltage and cutoff time data for each of the three temperatures. The differences between the cutoff voltage data at the three temperatures were not statistically significant ($p<0.05$). The cutoff time for the 125°F test was significantly longer ($p>0.05$) than the cutoff time at the other two temperatures. The difference between the 70 and 95°F cutoff times was not statistically significant ($p<0.05$).

DISCUSSION AND CONCLUSIONS

The literature search, industry contacts, and advice of battery experts revealed that nickel/cadmium batteries are the best commercially available technology for liquid MCS use. However, several promising battery technologies are near commercialization. Therefore, it will be important to continue to monitor advances in commercially available batteries so that they may be applied to liquid MCS, thereby decreasing the overall weight of the system.

The nickel/cadmium batteries delivered with the prototype liquid MCS maintained a relatively constant voltage output for more than 2 hours over the temperature range of interest. This is important since constant voltage output means that the liquid flow rate, and hence the cooling power of the liquid MCS, will be relatively constant during the two hours of use between battery (and ice pack) changes. It is also important to note that the voltage begins to drop rapidly soon after two hours of operating time. This is especially true at 70°F. This indicates that the battery is properly sized for the prototype MCS, and that the user is not carrying the additional weight of unused battery capacity.

The capacity of most batteries is dependent upon several factors including ambient temperature (capacity generally increases with temperature) (7). However, tests of these nickel/cadmium batteries showed that only the cutoff time at 125°F was significantly longer than the other two cutoff times ($p>0.05$), and that there was no significant difference between the three cutoff voltages ($p<0.05$). It is possible that if a wider temperature range were investigated, significant differences in cutoff voltage and cutoff time would be apparent, but a wider temperature range is not of concern here.

The discharge profile of battery 4 indicates that it may have been damaged in some way. This equates to a failure rate of 25% (one in four). However, nickel/cadmium batteries have seen wide use and are considered to be a very reliable battery system (6, 7). The failure rate of 25% experienced in this testing is probably an artifact of the small number of batteries tested. It is expected that if a larger sample of nickel/cadmium batteries were tested, the actual failure rate would be much lower.

TABLE 2 VOLTAGE AND TIME WHEN FLUID FLOW CEASED

Temperature (°F)	Cutoff Voltage (volts) (Mean ± S.D.)	Cutoff Time (minutes) (Mean ± S.D.)
70	19.2 ± 0.08	158 ± 7.6
95	18.6 ± 0.09	172 ± 12.6
125	18.1 ± 0.71	198 ± 7.6

Appendix A. Illustrations

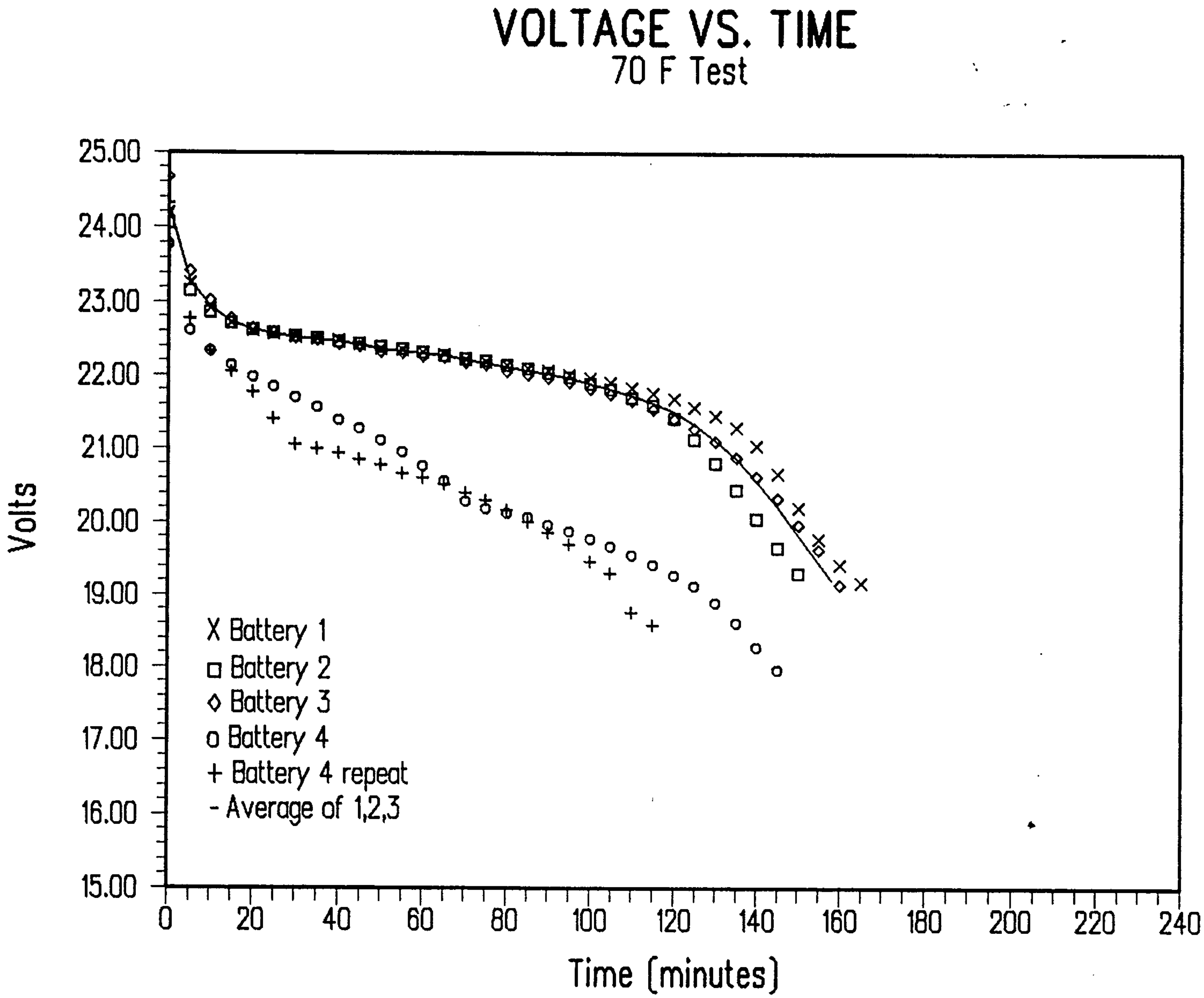

Figure 1. Voltage vs. time 70 F test

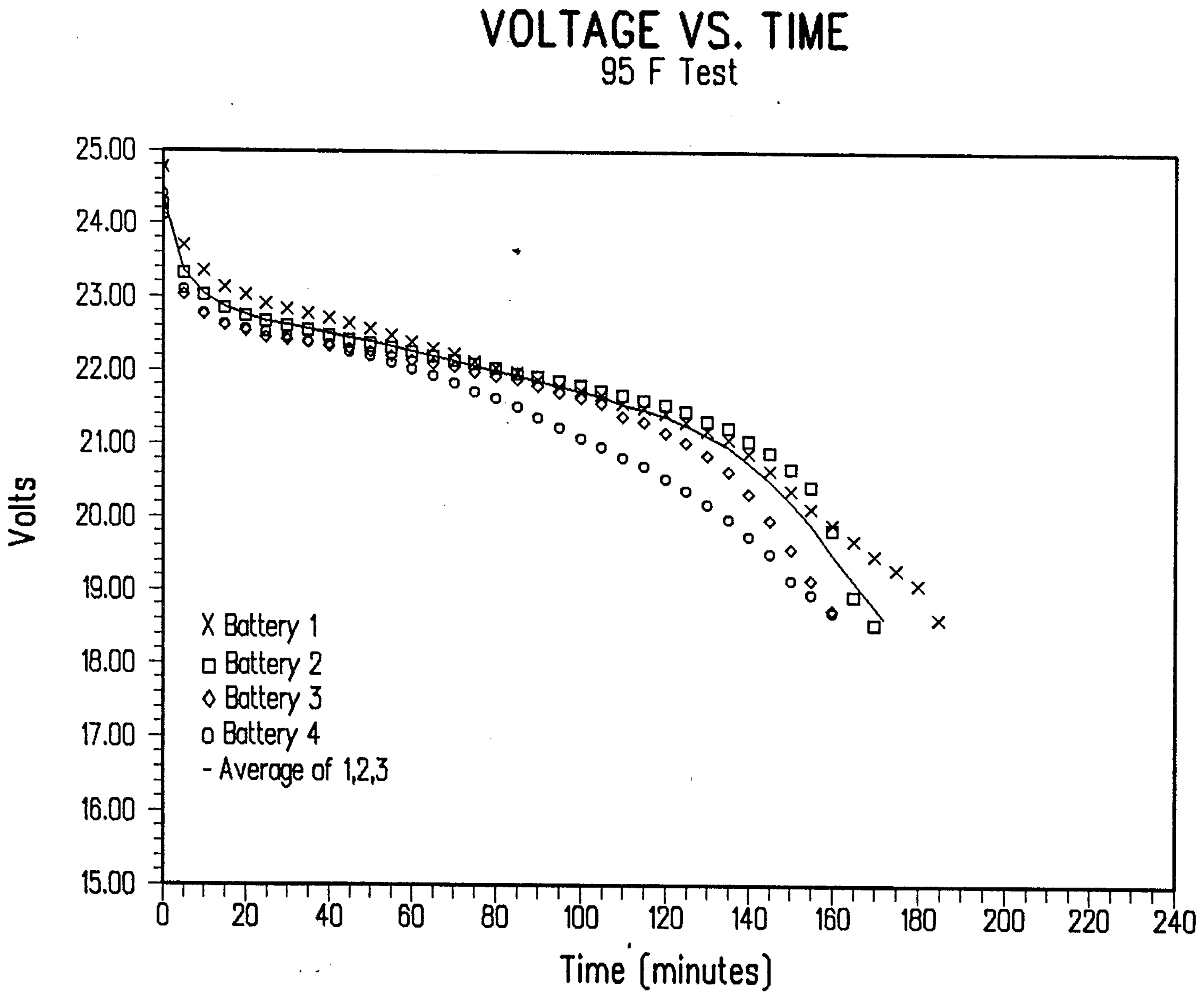

Figure 2. Voltage vs. time 95 F test

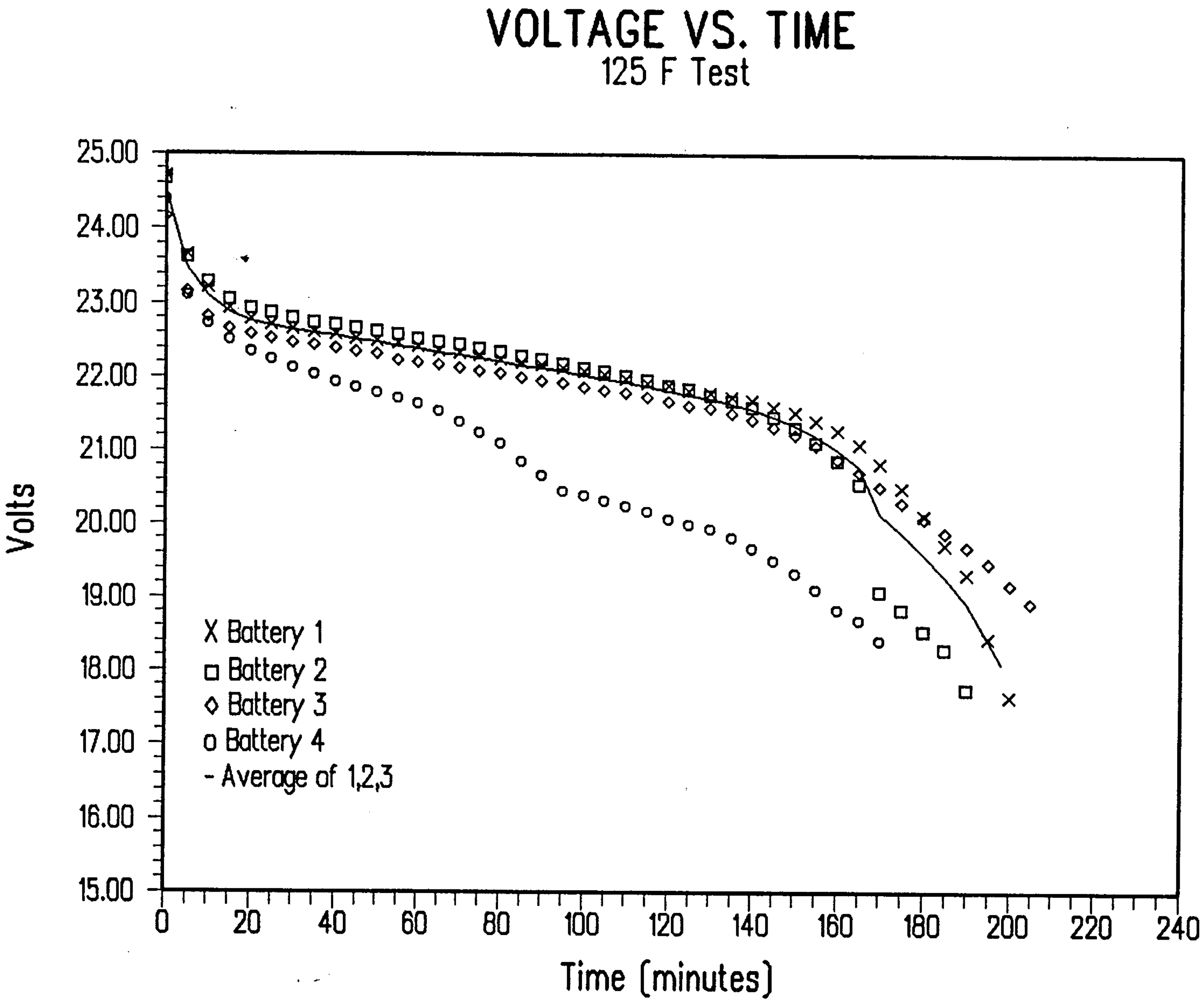

Figure 3. Voltage vs. time 125 F test

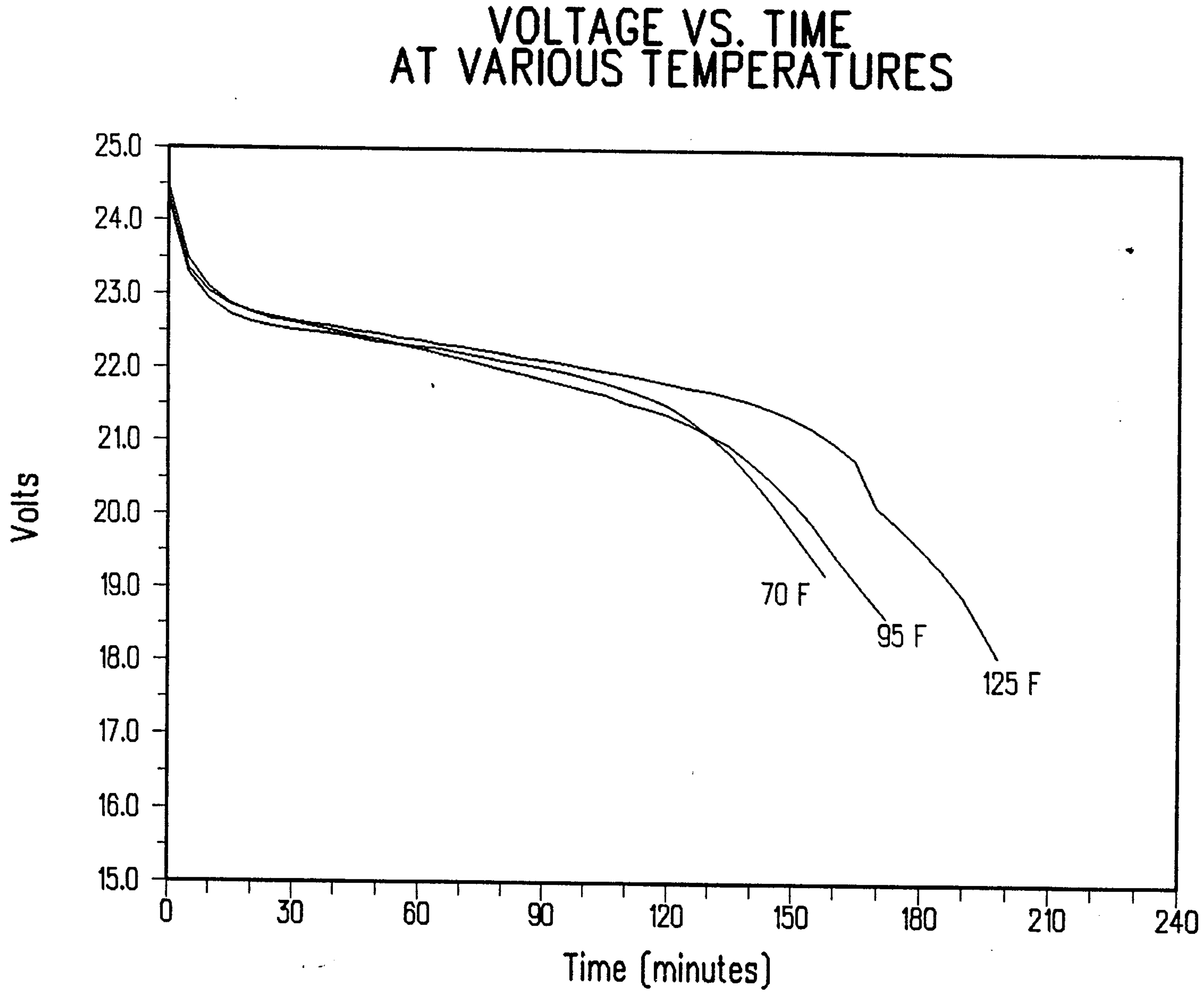

Figure 4. Voltage vs. time at various temperatures

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