

WL-TR-96-2069

NICKEL-METAL HYDRIDE BATTERY
TECHNOLOGY EVALUATION



John K. Erbacher

GRC International, Inc.
Systems Engineering Group
2940 Presidential Dr., Suite 390
Fairborn, OH 45324-6223

APRIL 1996

FINAL REPORT FOR 06/14/94-03/15/96

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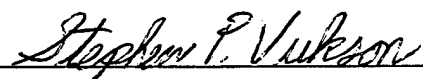
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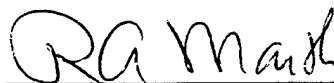
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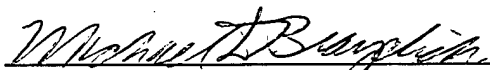


STEPHEN P. VUKSON
Project Engineer



RICHARD A. MARSH, Chief
Battery Branch

FOR THE COMMANDER



MICHAEL D. BRAYDICH, LT COL, USAF
Chief, Aerospace Power Division
Aero Propulsion and Power Directorate

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REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE April 1996	3. REPORT TYPE AND DATES COVERED Final Report: From 6/14/94 to 3/15/96	
4. TITLE AND SUBTITLE Nickel-Metal Hydride Battery Technology Evaluation			5. FUNDING NUMBERS C F33615-93-D-5302, DO 0010 PE 63716D PR 3145 TA 22 WU 3	
6. AUTHOR(S) John K. Erbacher				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) GRC International, Inc. Systems Engineering Group 2940 Presidential Dr., Suite 390 Fairborn, OH 45324-6223			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Aeropropulsion and Power Directorate Wright Laboratory (WL/POOB) Air Force Material Command Wright-Patterson AFB, OH 45433-7251			10. SPONSORING / MONITORING AGENCY REPORT NUMBER WL-TR-96-2069	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for Public Release; Distribution is Unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Available cylindrical and prismatic commercial Ni-MH batteries using AB ₅ and AB ₂ cathodes were evaluated for application to military aircraft batteries. Self discharge, capacity, and constant discharge and charge current tests were conducted along with some equipment limited internal resistance tests. Commercial AB ₅ technology is further advanced than AB ₂ technology and would require less development for near term (3-5 years) applications. Cylindrical and prismatic AB ₅ cells will require alloy, electrolyte and single cell/battery development to increase discharge and charge current capability to 10C and 5C respectively; and extend the low temperature limit to at least -20 °C. Tested AB ₂ technology appears inadequate to meet the near term military requirements and would require a major advance in the alloy to overcome the irreversible capacity loss incurred at temperatures above 49 °C. In addition, alloy, electrolyte and single cell/battery development would be needed to extend the low temperature limit by 30 degrees to at least -20 °C, and to double the charge and quadruple the discharge current capabilities of this technology.				
14. SUBJECT TERMS Aircraft Battery, Nickel-Metal Hydride, AB ₅ Alloy, AB ₂ Alloy, Rechargeable Battery			15. NUMBER OF PAGES 145	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASS. OF THIS PAGE Unclassified	19. SECURITY CLASS. OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT SAR	



TABLE OF CONTENTS

SECTION	TITLE	PAGE
1.0	INTRODUCTION.....	1
1.1	BACKGROUND.....	1
1.2	OBJECTIVE.....	2
1.3	APPROACH	2
	1.3.1 Baseline Commercial Ni-MH Battery Technology	2
	1.3.2 Hazardous Materials and Chemical Identification	3
	1.3.3. Development Program Definition	3
	1.3.4 Industrial Base Assessment.....	3
1.4	SCHEDULE	4
2.0	BATTERY ACQUISITIONS.....	5
3.0	DATA ACQUISITION	7
3.1	WL/POOB BATTERY TEST FACILITY (BTF).....	7
3.2	BATTERY TEST PLAN.....	8
4.0	RESULTS AND DISCUSSION	10
4.1	LITERATURE REVIEW	10
	4.1.1 Technology Development	10
	4.1.2 Environmental Issues	13
	4.1.3 Industrial Base.....	15
4.2	TECHNICAL MEETINGS	17
4.3	CAPACITY TESTS (CTs).....	18
	4.3.1 Manufacturer's Rating Verification (MRV).....	18
	4.3.2 C/10 Capacity Test	19
	4.3.3 2C/5 Capacity Test	19
	4.3.4 Capacity and Cycle No. Effects.....	22
	4.3.5 CT Observations and Summary	35
4.4	SELF DISCHARGE (SD) TEST	36
	4.4.1 AB ₅ Batteries and Single Cell SD Tests.....	37
	4.4.2 AB ₂ Single Cells SD Tests	57
	4.4.3 Temperature Effects on Self Discharge.....	60
	4.4.4 SD Observations and Summary	63
4.5	CONSTANT DISCHARGE CURRENT (CDC) TESTS	65
	4.5.1 AB ₅ Battery and Single Cell CDC Tests	66
	4.5.1.1 Company A (AB ₅ Cylindrical Cells).....	66
	4.5.1.2 Company C (AB ₅ Prismatic Cells).....	66

TABLE OF CONTENTS

SECTION	TITLE	PAGE
	4.5.1.3 Company E (AB ₅ Prismatic Cells)	74
	4.5.1.4 Company F (AB ₅ Prismatic Cells)	79
	4.5.1.5 Company G (AB ₅ Cylindrical Cells).....	83
	4.5.2 AB ₂ Single Cell CDC Tests	88
	4.5.2.1 Company D (AB ₂ Cylindrical Cells).....	88
	4.5.2.2 Company H (AB ₂ Cylindrical Cells).....	92
	4.5.3 CDC Observations and Summary	94
4.6	CONSTANT CHARGE CURRENT(CCC) TESTS	99
	4.6.1 AB ₅ Single Cell CCC Tests.....	100
	4.6.1.1 Company A (AB ₅ Cylindrical Cells).....	100
	4.6.1.2 Company E (AB ₅ Prismatic Cells)	102
	4.6.1.3 Company F (AB ₅ Prismatic Cells)	109
	4.6.1.4 Company G (AB ₅ Cylindrical Cells).....	110
	4.6.2 AB ₂ Single Cell CCC Tests.....	117
	4.6.2.1 Company D (AB ₂ Cylindrical Cells).....	117
	4.6.2.2 Company H (AB ₂ Cylindrical Cells).....	119
	4.6.3 CCC Observations and Summary.....	125
4.7	INTERNAL RESISTANCE (IR) TESTS	128
5.0	CONCLUSIONS	130
5.1	AB ₅ METAL HYDRIDE BATTERIES	131
5.2	AB ₂ METAL HYDRIDE	131
6.0	RECOMMENDATION.....	133
6.1	NICKEL-METAL HYDRIDE (NI-MH) AIRCRAFT BATTERY DEVELOPMENT PROGRAM.....	133
	REFERENCES.....	135

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1-1	Schedule	4
3-1	WL/POOB Battery Test Facility	8
3-2	Test Matrix	9
4.3.4-1	Company A Cell Capacity vs. Cycle No.	23
4.3.4-2	Company B Cell Capacity vs. Cycle No.	24
4.3.4-3	Company C Battery Pack/Single Cell Capacity vs. Cycle No.	25
4.6.4-4	Company D Cell Capacity vs. Cycle No.	26
4.3.4-5	Company E Cell Capacity vs. Cycle No.	27
4.3.4-6	Company F Cell Capacity vs. Cycle No.	28
4.3.4-7	Company G Cell Capacity vs. Cycle No.	29
4.3.4-8	Company H Cell Capacity vs. Cycle No.	30
4.4-1	Company A Self Discharge Capacity vs. Time	39
4.4-2	Company B MRV Self Discharge vs. Time	41
4.4-3	Company C Self Discharge Capacity vs. Time	43
4.4-4	Company D Self Discharge Capacity vs. Time	45
4.4-5	Company E Self Discharge Capacity vs. Time	47
4.4-6	Company F Self Discharge Capacity vs. Time	49
4.4-7	Company H Self Discharge Capacity vs. Time	50
4.4-8	Company G Self Discharge Capacity vs. Time	52
4.4.1-1	Self Discharge AB ₅ Cells at Room Temperature	53
4.4.2-1	Self Discharge of AB ₂ Cylindrical Cells t Room Temperature	58
4.4.3-1	Self Discharge Capacity vs. Temperature	62
4.4.4-1	Self Discharge of Ni-MH Cylindrical Cells at Room Temperature	64
4.5.1.1-1	Company A CDC Capacity vs. Current	70
4.5.1.1-2	Company A CDC Capacity vs. Temperature	71
4.5.1.2-1	Company C Group 2 CDC Capacity vs. Current	73
4.5.1.3-1	Company E CDC Capacity vs. Current	77
4.5.1.3-2	Company E CDC Capacity vs. Temperature	78
4.5.1.4-1	Company F CDC Capacity vs. Current	81
4.5.1.4-2	Company F CDC Capacity vs. Temperature	82
4.5.1.5-1	Company G CDC Capacity vs. Current	86

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
4.5.1.5-2	Company G CDC Capacity vs. Temperature	87
4.5.2.1-1	Company D CDC Capacity vs. Current	90
4.5.2.1-2	Company D CDC Capacity vs. Temperature	91
4.5.2.2-1	Company H CDC Capacity vs. Current	95
4.5.2.2-2	Company H CDC Capacity vs. Temperature	96
4.5.3-1	CDC Capacity vs. Discharge Rate at Room Temperature ...	97
4.5.3-2	CDC Capacity vs. Temperature at the 1C Discharge Rate...	98
4.6.1.1-1	Company A CCC Capacity vs. Current.....	103
4.6.1.1-2	Company A CCC Capacity vs. Temperature	104
4.6.1.2-1	Company E CCC Capacity vs. Current.....	107
4.6.1.2-2	Company E CCC Capacity vs. Temperature.....	108
4.6.1.3-1	Company F CCC Capacity vs. Current	111
4.6.1.3-2	Company F CCC Capacity vs. Temperature	112
4.6.1.4-1	Company G CCC Capacity vs. Current.....	115
4.6.1.4-2	Company G CCC Capacity vs. Temperature	116
4.6.2.1-1	Company D CCC Capacity vs. Current.....	120
4.6.2.1-2	Company D CCC Capacity vs. Temperature	121
4.6.2.2-1	Company H CCC Capacity vs. Current.....	123
4.6.2.2-2	Company H CCC Capacity vs. Temperature	124
4.6.3-1	CCC Capacity vs. Charge Rate at Room Temperature	126
4.6.3-2	CCC Capacity vs. Temperature at the 1C Charge Rate.....	127

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2-1	Nickel-Metal Hydride Battery Suppliers.....	6
4.1.1-1	AB ₅ Battery Development.....	13
4.1.1-2	AB ₂ Battery Development.....	14
4.1.3-1	US Metal Hydride Battery Development and Production Companies.....	16
4.3.3-1	Cell Capacity Comparisons at 23 °C	21
4.3.4-1	Company A (AB ₅ Cylindrical Cells): Discharge Capacity vs. Cycle No.	22
4.3.4-2	Company B (AB ₅ Bipolar Vented Cells): Discharge Capacity vs. Cycle No.	31
4.3.4-3	Company D (AB ₂ Cylindrical Cells): Discharge Capacity vs. Cycle No.	31
4.3.4-4	Company C (AB ₅ Prismatic Cells): Discharge Capacity vs. Cycle No.	32
4.3.4-5	Company E (AB ₅ Prismatic Cells): Discharge Capacity vs. Cycle No.	33
4.3.4-6	Company G (AB ₅ Cylindrical Cells): Discharge Capacity vs. Cycle No	33
4.3.4-7	Company F (AB ₅ Prismatic Cells): Discharge Capacity vs. Cycle No. ¹	34
4.3.4-8	Company H (AB ₂ Cylindrical Cell): Discharge Capacity vs. Cycle No.	35
4.4-1	Company A (AB ₅ Cylindrical Cells) Self Discharge at 23.4 °C	38
4.4-2	Company B (AB ₅ Bipolar Vented Cells) Self Discharge at 23.0 °C	40
4.4-3	Company C (AB ₅ Prismatic Cells) Self Discharge at 23.7 °C	42
4.4-4	Company D (AB ₂ Cylindrical Cells) Self Discharge at 22.7 °C	44
4.4-5	Company E (AB ₅ Prismatic Cells) Self Discharge at 23.1 °C	46
4.4-6	Company F (AB ₅ Prismatic Cells) Self Discharge at 21.5 °C	48

LIST OF TABLES

TABLE NO.	TITLE	PAGE
4.4-7	Company H (AB ₂ Cylindrical Cells) Self Discharge at 23.3 °C	48
4.4-8	Company G (AB ₅ Cylindrical Cells) Self Discharge at 22.5 °C	51
4.4.3-1	Self Discharge at Various Temperatures after 2 Days Storage.....	61
4.5.1.1-1	Company A CDC Results at 71 and 49 °C	67
4.5.1.1-2	Company A CDC Results at 24 and 0 °C	68
4.5.1.1-3	Company A CDC Results at -18 and -40 °C.....	69
4.5.1.2-1	Company C Group 2 CDC Results at 24 °C.....	72
4.5.1.3-1	Company E CDC Results at 71 and 49 °C.....	74
4.5.1.3-2	Company E CDC Results at 24 and 0 °C.....	75
4.5.1.3-3	Company E CDC Results at -18 and -40 °C.....	76
4.5.1.4-1	Company F ¹ CDC Results from 71 to -18 °C.....	80
4.5.1.5-1	Company G CDC Results at 71 °C.....	83
4.5.1.5-2	Company G CDC Results at 49 °C.....	84
4.5.1.5-3	Company G CDC Results at 24, 0 and -18 °C.....	85
4.5.2.1-1	Company D CDC Results from 71 to 0 °C.....	89
4.5.2.2-1	Company H CDC Results at 71 to 0 °C.....	93
4.5.2.2-2	Company H CDC Results at -18 and -40 °C.....	94
4.6.1.1-1	Company A CCC Results at 2.4 A (1C) and at 4.8 A (2C)	101
4.6.1.1-2	Company A CCC Results at 49 and 24 °C	102
4.6.1.2-1	Company E CCC Results at 71 and 49 °C.....	105
4.6.1.2-2	Company E CCC Results from 24 to -40 °C ^a	106
4.6.1.3-1	Company F CCC Results at 71 and 49 °C.....	109
4.6.1.3-2	Company F CCC Results at 24 and 0 °C.....	110
4.6.1.4-1	Company G CCC Results at 71 and 49 °C	113
4.6.1.4-2	Company G CCC Results at 49 and 24 °C	114
4.6.2.1-1	Company D CCC Results at 71 °C.....	117
4.6.2.1-2	Company D CCC Results at 49 and 24 °C	118
4.6.2.1-3.	Company D CCC Results at 0 and -18 °C.....	119
4.6.2.2-1	Company H CCC Results from 71 to -40 °C.....	122
6.0-1	6.2 Development Program Fund Allocation.....	133

ACKNOWLEDGMENTS

The work performed under Contract F33615-93-D-5302 Delivery Order 0010 was financially supported by the USAF Strategic Environmental Research and Development Program (SERDP).

WL/POOB provided use of the Battery Test Facility, its equipment, and personnel for testing under this contract. Technical support for battery testing was furnished by Mr. Gary Loeber, Mr. J. Malone, and Mr. M. French of the USAF Wright Laboratory and Mr. C. Riepenhoff of SelecTech Services Corp.

Some commercial batteries and single cells for testing under this contract were supplied at no cost by Energizer Power Systems, Inc. SAFT America, Inc. and Eagle-Picher Industries, Inc.

FINAL REPORT
ON
NICKEL-METAL HYDRIDE BATTERY TECHNOLOGY EVALUATION

1.0 INTRODUCTION

1.1 BACKGROUND

For military airborne and ground applications, the mainstay in rechargeable batteries has been nickel-cadmium (Ni-Cd) and, more recently, sealed Lead-Acid. The government has been very supportive of these technologies for both commercial and military applications; specifically, WL/POO has funded efforts in the Ni-Cd battery. The recent growth in commercial applications for small rechargeable batteries (laptop and notebook computers, as well as other portable electronic devices) has been fueled by developments in the government sector that improved the overall lifetime, current and power densities, and charging cycles. The increased demand also fostered commercial development of other battery technologies, such as the nickel-metal hydride (Ni-MH), rechargeable lithium, and new polymer batteries that may offer more improvements in technical capability. Yet the commercial developments have not considered military rechargeable battery requirements.

These newer battery technologies use environmentally safe materials, a shortcoming of the Ni-Cd battery. Cadmium is currently on the EPA proposed list for reduced exposure limits and may be banned from use in the US. Exposure to cadmium powder, residues, and products (batteries), particularly with respect to disposal of the end product, creates a significant health hazard. If the proposed ban goes into effect, the entire domestic Ni-Cd battery industry will move to offshore production. This could result in increased costs associated with battery products and their disposal, and possibly high import taxes for use in domestic products. These hazardous material aspects expedited development of alternatives (Ni-MH technology) for portable commercial applications.

Therefore, a need now exists to evaluate and assess the technical performance of the new Ni-MH batteries with respect to military applications, identify and plan military specific developments and assess the industrial base for this technology.

1.2 OBJECTIVE

The objectives of this task were to make a baseline assessment of commercial Ni-MH batteries and their associated materials, processes and components for applicability to USAF air and ground applications; identify existing and potential environmentally hazardous materials and chemicals used in Ni-MH batteries and non hazardous alternatives; define a development program for materials, product and processes and the timeline needed to develop a military, environmentally safe Ni-MH battery; and evaluate the Ni-MH industrial base capability to support military battery requirements.

1.3 APPROACH

1.3.1 BASELINE COMMERCIAL Ni-MH BATTERY TECHNOLOGY

This task evaluated the capabilities of current commercial production Ni-MH battery technology with reference to military operational parameters for rechargeable batteries. In the analysis and testing of commercial products for military applications it was necessary to obtain a firm basic assessment of the limitations and capabilities of the candidate technology. Use of commercial Ni-MH batteries for the military is no exception. To obtain that basic assessment GRC International (GRCI), Inc. reviewed commercial literature and conducted technical discussions with providers and developers as needed to fully understand the literature and determine if there were unpublished data available which may be pertinent to the existing analysis. GRCI then conducted experiments to gather test data under the new conditions on candidate batteries identified through the data gathering process.

To accomplish the Ni-MH battery evaluation a detailed research plan was needed. GRCI experience suggested the research plan should contain the following steps:

- Technical Literature Review.
- On-Site Visits.
- Acquisition of Commercial Ni-MH Batteries.
- Battery Test.
- Analysis of Data.
- Conclusions and Recommendations.

1.3.2 HAZARDOUS MATERIAL AND CHEMICAL IDENTIFICATION

The most recent EPA hazardous materials list and proposed new hazardous materials were cross referenced to the bill of materials for existing and planned commercial Ni-MH batteries. The purpose of the cross reference was to identify potential material and process problems in future developments directed to a military qualified Ni-MH battery. An example of a process to be avoided would be the use of heavy metal additives in the negative and positive battery electrodes. Depending on concentrations and the actual additive, these materials could generate hazardous exposure conditions for workers either in manufacturing/assembly or in the disposal of spent batteries where the cases may be broken open or damaged in handling.

1.3.3 DEVELOPMENT PROGRAM DEFINITION

Using the baseline Ni-MH battery technology and associated environmental hazards, risks and limitations, GRCI planned to define an engineering development program to upgrade commercial Ni-MH batteries to meet military specifications as a replacement for USAF Ni-Cd and Lead-Acid rechargeable batteries. The proposed program would include:

- Identified limitations of the existing commercial battery.
- Existing and potential environmental hazards, costs and alternatives.
- Potential new component, electrode, electrolyte and casing materials.
- Manufacturing process, material, and equipment developments needed.
- Cost and schedule estimates.
- Potential military and commercial test vehicles, experiments and windows of opportunity that offer synergistic opportunities to advance Ni-MH technology
- Anode, cathode and electrolyte developments needed to improve cycle life, discharge characteristics and increase power.

1.3.4 INDUSTRIAL BASE ASSESSMENT

GRCI planned to develop an assessment of the domestic Ni-MH battery industrial base. The assessment was to include not only the current status of the technology (the commercial baseline analysis) but also status of vendors, component suppliers, component availability, foreign sources and dependencies, manufacturing processes and equipment and

test capabilities and the available business base for a domestic Ni-MH battery dual use industry. GRCI has had marked success developing an industrial base taxonomy for complex military systems. A similar taxonomy for the Ni-MH battery, although less complex, would provide insight into potential applications and guide government development of materials, components, and processes for a viable industrial base infrastructure and product.

1.4 SCHEDULE

The project started on 13 June 1994 and was originally scheduled to be complete by 12 June 1995. Delays in acquiring test batteries due to manufacturer availability, test equipment modifications and unscheduled power outages as well as problems with data analysis resulted in several schedule slips. The project was completed 15 March 1996. A detailed schedule of events is shown in Figure 1-1.

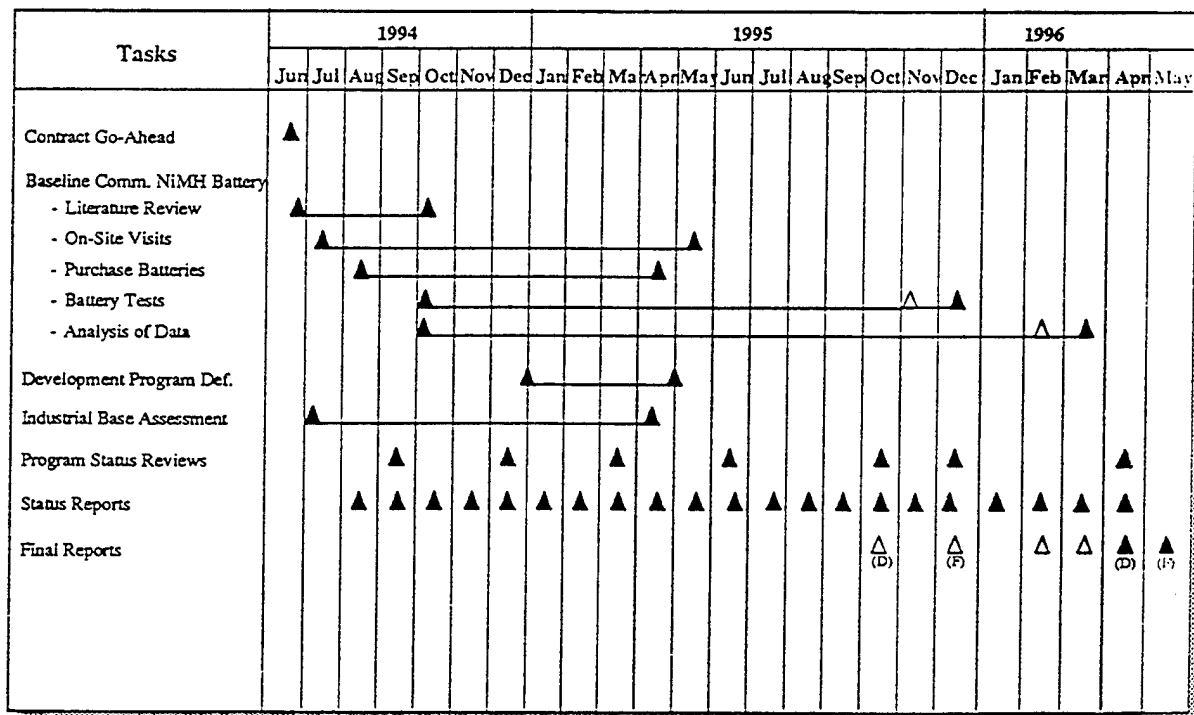


Figure 1-1. Schedule

2.0 BATTERY ACQUISITIONS

Products potentially suitable for military aircraft applications were identified through technical discussions with researchers, contractors and manufacturers and review of available commercial literature. Acquisition costs and delivery availability were obtained from appropriate suppliers. WL/POOB reviewed the list of candidate test batteries. The plan was to purchase only US manufactured batteries for the test program which also would have established the domestic industrial base capability. The list of possible sources included development batteries from Electro Energy, Inc. (EEI), Ovonic Battery Co., Inc. and Hughes Electron Dynamics Division (EDD). Production batteries were available from Energizer Power Systems (EPS) Inc., Eagle-Picher Industries (EPI), Inc., Harding Energy, Inc. and potentially Duracell Inc.

Development batteries were purchased in order to test several different metal hydride alloys in both bipolar and prismatic designs. Two development manufacturers could not be included for the following reasons. A corporate business decision eliminated the Hughes batteries from consideration. Ovonic cells were tied up in the DOE electric vehicle program and were not available as test articles nor was the manufacturer-generated test data available due to proprietary considerations between Ovonic, DOE, and the US Advanced Battery Consortium (USABC) which includes Chrysler Corp., GM Corp. and Ford Motor Co.

Duracell production batteries were potentially available late in the test program due to Duracell plans to build a US manufacturing facility with batteries available in the first quarter of 1995. These cells were based on the technology developed by Toshiba Corp. and licensed to Duracell Inc. and Varta Corp. for US and European manufacture and sales, respectively. Production plans slipped and in order to evaluate these potentially US manufactured cells, Toshiba production cells were purchased through Duracell Inc.

Subsequent to the initial battery purchases, WL/POOB, in consultation with GRCI, decided to expand the test program to include foreign manufactured cells for comparison purposes. This allowed the inclusion of Sanyo Inc., Gold Peak Industries (GPI), Inc., Maxell Inc., SAFT Inc. and Yuasa/Exide, Inc. batteries. Sanyo and Maxell batteries were in short supply and deliveries were designated for computer OEMs with large volume requirements

and hence, were not available for small batch purchase. US battery importers did have access to Yuasa/Exide and GPI batteries which were purchased for the test program. In addition, through WL/POOS and SAFT America, Inc., a sample of French SAFT manufactured cells were made available in Summer 1995. These SAFT cells were based on the same technology used in the SAFT-DOE electric vehicle battery program, but of smaller size.

At the conclusion of the test program sample batteries, both R&D and production, had been acquired and tested from eight manufacturing sources worldwide. Six of the samples were AB₅ cells in bipolar, cylindrical and prismatic construction in both single cell and battery/cell pack configurations. The other two samples were AB₂ cells in cylindrical configurations only. The suppliers of purchased and donated cells are listed in Table 2-1.

Table 2-1: Nickel-Metal Hydride Battery Suppliers

AB ₅ Cells and Batteries	AB ₂ Cells
• Eagle-Picher Industries (EPI), Inc. Joplin, MO (417) 623-8333 • Electro Energy Inc. (EEI) Danbury, CT 1-800-BIPOLAR • Energizer Power Systems (EPS), Inc. Gainesville, FL 1-800-67-POWER • SAFT Inc. (SAFT America, Inc.) Cockeysville, MD (410) 770-3200 • Toshiba, Inc. (Duracell, Inc.) Bethel, CT (203) 791-3274 • Yuasa/Exide, Inc. (Engineered Assemblies & Components (EAC) Corp.) Teterboro, NJ (412) 775-3610	• Gold Peak Industries (GPI), Inc. (House of Batteries) Huntington Beach, CA (714) 375-0222 • Harding Energy, Inc. Norton Shores, MI (616) 798-7033

3.0 DATA ACQUISITION

Due to the extensive battery and single cell test facilities of WL/POOB, GRCI personnel used those facilities and government technicians to conduct current, voltage, power, lifetime and cycle studies of the commercial Ni-MH batteries. GRCI developed the detailed tests to be done, their duration and subsequent data analysis, and modified tests, as needed, in consultation with the government delivery order manager (GDOM). GRCI monitored the tests as they were performed by WL/POOB personnel.

During the test program, WL/POOB personnel identified a shortage of low current electronic loads needed to test the capacity of some of the batteries which limited the number of units under test and created a backlog as batteries arrived from the suppliers. Subsequent technical literature review by government and GRCI personnel identified programmable, rack mount electronic loads compatible with the existing hardware, cabinetry and computer systems used in the battery test facility (BTF). GRCI purchased the necessary electronic loads which were installed by WL/POOB technicians in the test racks. This increased the number of units under test from 33 to a maximum of 49 with individual manual and computer control of temperature, voltage, current and limit switches.

3.1 WL/POOB BATTERY TEST FACILITY (BTF)

A schematic diagram of the WL/POOB Battery Test Facility (BTF) is shown in Figure 3-1. Each test rack in the BTF is equipped with removable test loads, voltage, current and temperature monitors and limit switches and individual circuit strip chart recorders. All of the racks are electronically connected to the computer control room adjacent to the test rack area where individual test programs can be coded and monitored in real time during the test. The entire system is capable of 24 hour operation and many of the routine reconditioning cycles between tests were run unattended. Although the diagram shows four cells to a circuit, more than one cell could be placed in either series or parallel in each circuit. Doing so, however does not allow control of the individual cell or battery. Racks 1-6 are wired to control currents from 200 milliamps to 100 amps without damage simply by changing the electronic load. Rack 7 is wired for currents from 1-1000 amps.

The four environmental chambers have the full military range of cold and hot temperature controls from -85 to 175 °C. Chambers 1 and 3 are semipermanently located with a 5.35 ft.³ internal capacity (22-in. H x 21-in. W x 20-in. D). Chamber 2 is portable with a 1.82 ft.³ internal capacity (16-in. H x 14-in. W x 14-in. D). Chamber 4 is permanently located with a 9 ft.³ internal capacity (36-in. H x 36-in. W x 36-in. D). Electrical wiring can be installed from any rack to any of the environmental chambers. A typical configuration used in the Ni-MH battery tests with up to 12 cells or batteries in environmental chambers 1-3 is shown in Figure 3-1. Chamber 4 was used to test the two cell packs from Company C.

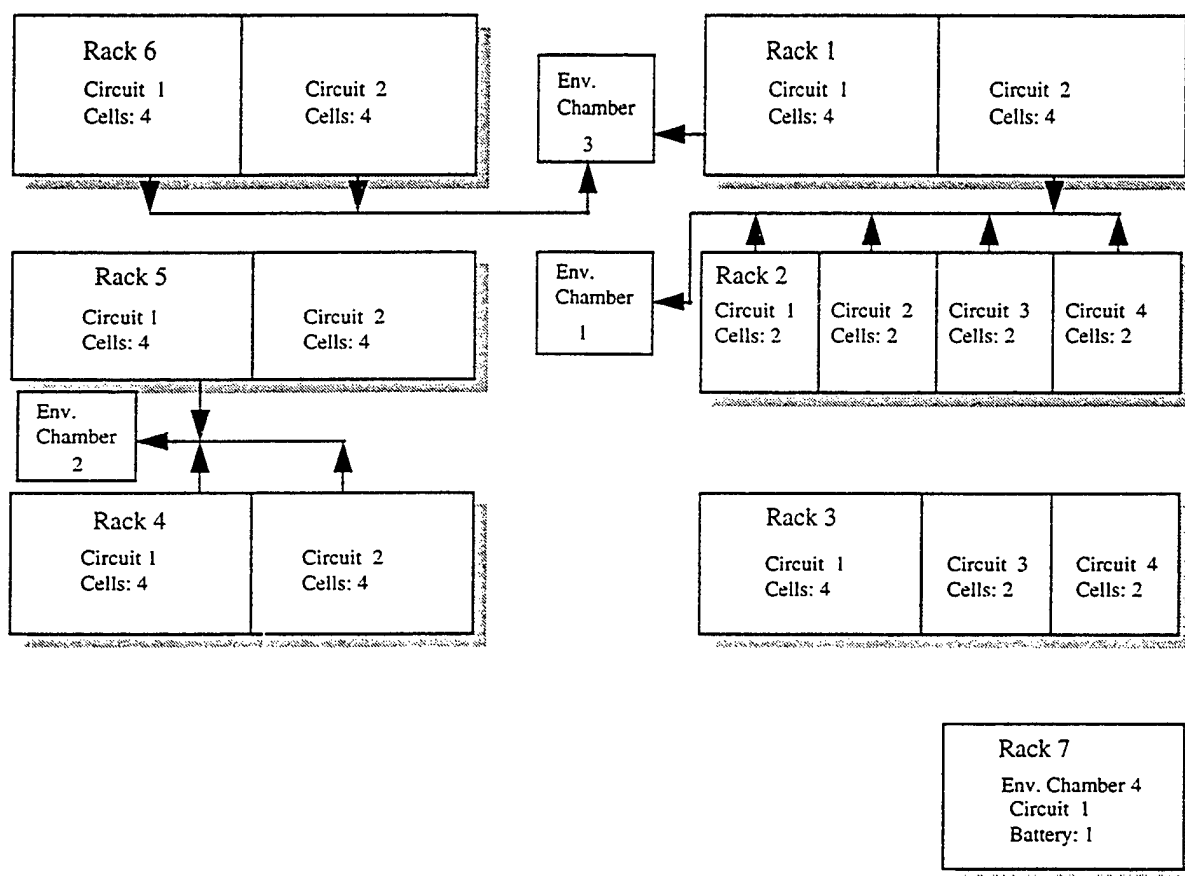


Fig. 3-1. WL/POOB Battery Test Facility

3.2 BATTERY TEST PLAN

To accomplish battery tests required a detailed test plan. Based on reviews of current Air Force acceptance test procedures, discussions with WL/POOB, NSWC Crane Division

and NASA Johnson Space Center personnel, GRCI developed a test plan to establish the baseline cell characterization of commercial Ni-MH batteries. These characterization tests included a manufacturer rating verification (MRV) and various discharge/charge tests at temperatures from -40 to 71 °C. The discharge/charge tests included:

- Capacity tests (CTs),
- Self discharge (SD) tests,
- Constant discharge current (CDC) tests,
- Constant charge current (CCC) tests, and
- Internal resistance (IR) tests.

Individual items in this test plan are discussed in Section 4.0. The test matrix for all the tests is presented in Figure 3-2.

COMPANY	BATTERY TESTS					
	MRV	IC	SD	CDC	CCC	IR
A	●	●	●	●	●	●
B	●	●	●	X	X	X
C	●	●	●	●	⊗	X
D	●	●	●	●	●	⊗
E	●	●	●	●	●	●
F	●	●	●	●	●	●
G	●	●	●	●	●	●
H	●	●	●	●	●	●

○ - Planned ● - Complete ⊗ - Cancelled X - Not Scheduled

Fig. 3-2. Test Matrix

4.0 RESULTS AND DISCUSSION

4.1 LITERATURE REVIEW

Literature was obtained from a variety of sources including the Defense Technical Information Center (DTIC), libraries, symposia and conference proceedings, journal publications, unpublished results of workers in the development of Ni-MH batteries and existing and proposed pertinent EPA hazardous materials. Examples of the technical data needed include electrode and chemical kinetics, high and low temperature behavior, effects of additives, cell and component configurations, toxicity of materials, worker exposure limits, environmentally safe alternatives, environmental risk reduction techniques and alternative electrode and electrolyte materials. Much of this information was obtained through personal contacts and technical discussions at conferences, workshops, symposia, and facility visits.

One of the primary sources of information was the DTIC. With the assistance of WL/POOB, a technical search of the DTIC system dating back to 1991 yielded almost 300 references to articles, abstracts and patents in eight databases. These references were reviewed to remove duplicates and combined with other literature references from journals and conference/symposia/workshop proceedings to yield a total of 166 literature references and 50 patents. The conferences and symposia proceedings dating back to 1990 reviewed pertinent to this task included:

- Power Sources Conferences (PSCs)
- The Fall and Spring meetings of the Electrochemical Society (EcS), Inc.
- NASA Aerospace Battery Workshops
- Intersociety Energy Conversion Engineering Conferences (IECECs)
- The Annual Battery Conference on Applications and Advances.

Subsequent to the basic literature review, additional articles and publications were reviewed and added to the data base as they became available. The results of the literature review are discussed in the following sections.

4.1.1 Technology Development

Metal hydride batteries are based on two types of compounds that derive their names from the physical structures of the metal alloys. These are AB_5 and AB_2 compounds. AB_5

alloys are made from the lanthanide series and the AB_2 alloys from the transition metal series in the periodic table. Their usefulness as battery cathode materials is due to their ability to absorb into and then subsequently desorb hydrogen out of the intermetallic structure of the alloy like a sponge absorbs water. This process is called decrepitation and causes the alloy structure to expand as the hydrogen is absorbed and to shrink as it is desorbed. The expansion and contraction also causes the alloy material to break up into smaller and smaller pieces. The ability of the alloys to absorb hydrogen is not only temperature and structure dependent but also particle size dependent. Hence, as the alloy breaks up with each cycle the hydrogen absorption and the cell capacity increase to a maximum and then decrease gradually with the number of cycles.

Much of the current work in Ni-MH batteries is driven by three factors which also apply to aircraft batteries. These are the need to replace cadmium in Ni-Cd batteries for environmental reasons, the desire for a higher energy battery, and an almost identical charge and discharge behavior as the Ni-Cd battery. Metal hydride cathodes are an environmentally (green) suitable substitute because the cathode material is not hazardous and therefore is safe to use for commercial purposes without having to take precautions in disposal and shipment of the batteries. Metal hydride batteries also have approximately 50 percent higher energy density per unit volume than Ni-Cd batteries. This translates to three hours of operating time on a portable computer vs. two hours with a Ni-Cd battery pack. The third factor of nearly identical charge and discharge characteristics means the same chargers built into portable computers and other electronic devices can be used with either battery. This last factor lowers manufacturing costs and allows the user to use more than one type of battery.

AB_5 Batteries Battery developments based on the AB_5 type alloys use mischmetal (Mm) ores as a starting point for the battery alloy. These ores occur naturally in nature and are rich in lanthanide series metals. The Mm composition can vary but typically contains lanthanum, cerium, praseodymium, and neodymium in varying weight percents depending on the mining location of the ore. The Mm is alloyed with nickel which has several transition elements added to it to impart desirable properties to the alloy. These transition elements can be manganese, aluminum, chromium, cobalt, silicon or zirconium or various combinations.

Theoretical capacity of AB_5 alloy batteries is 450 milliamp-hours/gram (mA-h/g) of material but the best reported capacities are 250-350 mA-h/g so there is much room to improve alloy performance. The US Advanced Battery Consortium (USABC) in conjunction with the DOE have funded SAFT, Inc. of France to develop these batteries for electric vehicle applications but details of the program and results are proprietary at this time.

The AB_5 alloys are manufactured using different processes such as arc/induction melting followed by either mechanical grinding and sieving or hydrogen decrepitation, rapid solidification, or ion atomization. There is a growing body of evidence that suggests the manufacturing process, to make the alloy as well as post alloy treatment of the powder, has a marked effect on battery performance. This is in addition to the well documented effects of trace elements substitution for the nickel in the alloy. Development of better alloys through manufacturing process and treatment changes is receiving serious attention by many commercial developers but little has been published due to the proprietary nature of the results and the fiercely competitive market for these batteries. However, it appears that an induction process with rapid solidification of the alloy powder followed by nickel coating the alloy powder may be a best choice for retention of alloy capacity and long cycle life. Information on AB_5 battery developments is summarized in Table 4.1.1-1.

AB_2 Batteries These batteries are based on alloys containing vanadium, titanium, chromium and nickel as the primary transition metal elements with other metals added in trace quantities in a multiphase disordered structure. Known research on these alloys is primarily done by Ovonic Battery Co., Inc. in Troy, MI who have licensed Harding Systems, Inc. of Michigan and Gold Peak Industries, Inc. of Hong Kong to manufacture AB_2 batteries using Ovonic technology. Recent trade journals also indicate several Japanese companies have agreed to pay license rights to Ovonic but are not selling any AB_2 batteries commercially. Theoretical energy density of these batteries is 700 mA-h/g using an AB_2H_6 alloy which gives them a higher and hence more desirable capacity than the AB_5 alloy batteries. Reported data has only shown 393 mA-h/g capacity. The USABC and the DOE have funded Ovonic Battery Co., Inc. to develop these batteries for electric vehicles but the details and results are proprietary.

Table 4.1.1-1. AB₅ Battery Development

Alloy Formula	$MmNi_{5-x}M_x$ • $Mm = La (25-30 \text{ wt.}\%) + Ce (45-55 \text{ wt.}\%) + Pr (3-7 \text{ wt.}\%) + Nd (10-20 \text{ wt.}\%)$ • $M = Mn, Al, Cr, Co, Si \text{ or } Zr.$
Manufacturing Processes	• ARC/Induction Melt Components with Mechanical Grinding and Sieving • ARC/Induction Melt Components with Hydrogen Decrepitation • Rapid Powder Solidification • Ion Atomization • Post Powder Manufacturing Treatments
Activation Process	3-5 Decrepitation Cycles
Energy Capacity	450 mA-h/g (Theoretical); 250-350 mA-h/g (Reported)
Additive Effects	Worldwide Proprietary Research
Manufacturing Process Development	Worldwide Proprietary Research
R & D Development Countries (Companies)	Japan (8), USA (5), France (1), Germany (2), China (2), Sweden (1) and Korea (2)

The manufacturing process for AB₂ alloys consists of ARC melting the components followed by mechanical grinding, but presumably other methods are in research and development. Alloy additive effects have been reported with mixed results. For instance, substituting trace quantities of iron for one of the main ingredients can have opposite effects depending on which constituent of the basic alloy it replaces. One report mixed the AB₂ and AB₅ alloys which reduced the activation cycles. Ovonic has reported some work in the patent literature on alloys that give increased capacity retention and indicated in 1990 that modifications to the electrolyte (no details given) also improved capacity retention. Information on AB₂ batteries is summarized in Figure 4.1.1-2.

4.1.2 ENVIRONMENTAL ISSUES

Discussions with EPA personnel indicate there are no new regulations pending that would effect Ni-MH batteries. In addition, the latest newspaper and trade journal information indicates that the EPA is shifting its emphasis from specific chemical control to a more systems oriented approach which would cover all areas related to a particular industry, such

as batteries. If this shift in focus is real then a more functional control of batteries, their manufacturing and disposal processes should result with a corresponding decrease in specific chemical control and lower costs for managing and controlling hazardous battery materials.

Table 4.1.1-2. AB₂ Battery Development

Alloy Formula	V-Ti-Cr-Ni-X where X can be any other metal in a Multiphase Disordered Structure
Manufacturing Process	ARC Melt Components Followed by Mechanical Grinding
Activation Process	Up to 40 Decrepitation Cycles
Energy Capacity	700 mA-h/g (Theoretical); 393 mA-h/g (Reported)
Additive Effects	Limited and Variable Information
Manufacturing Process Development	Proprietary Research Predominantly at Ovonic Battery Co., Inc., USA
R & D Development Countries (Companies)	Japan (3), USA (2), and Hong Kong (1)

In 1992, as a result of the joint DOE and USABC development efforts for Ni-MH batteries for electric vehicles, the DOE funded the National Renewable Energy Laboratory (NREL) to evaluate the "Current Status of Environmental, Health, and Safety Issues of Nickel Metal-Hydride Batteries for Electric Vehicles." The resulting report, NREL/TP-463-5475, August 1193, summarized the findings of this study and concluded:

- "...Ni-MH EV cells and batteries present few health and safety risks. ... In addition, the design of the Ni-MH EV cells minimizes the chance of hydrogen gas venting;...."
- "Nickel and nickel compounds ...are of primary concern for workplace exposure ..., since the National Toxicology Program considers nickel and nickel compounds probable carcinogens. However, workplace exposure....should be within acceptable limits as long as OSHA standards for workplace exposure are met."
- "... Ni-MH EV batteries would probably be classified as 'nonspillable' batteries and, therefore, be exempt from many of the Department of Transportation (DOT) regulations for hazardous waste transport." In addition, "...if the batteries meet the 'dry' criteria, (i.e., not capable of leaking or spilling any free liquid if the battery is

ruptured),” and “...providing they pose no other transport hazard, ..., they would not be subject to DOT regulation at all.”

- “The environmental concerns associated with Ni-MH EV batteries, like the safety and health risks, were also considered small. The main environmental issue discussed was the recycling.... Test results showed that Ni-MH AB₂-type EV batteries would not be considered a hazardous waste under existing EPA regulations, although they would be considered hazardous under California state and European Community environmental regulations.”

The NREL study did not address the AB₅-type EV battery. Such a study would be a logical part of the DOE and USABC development program with SAFT Inc. of France for AB₅-type EV batteries and presumably should have similar results. A possible area of difference would be heavy metal poisoning since AB₅ batteries use lanthanide series heavy metals as part of the cathode vs. the use of lighter transition metals in the AB₂ batteries.

Based on the above study of MH EV batteries, any USAF sponsored development of Ni-MH batteries should have the same relatively benign environmental, health and safety impact and be an environmentally acceptable substitute for current Ni-Cd and Lead-Acid batteries used in military aircraft applications.

4.1.3 INDUSTRIAL BASE

GRCI evaluated the US industrial base capability to support manufacture and production of Ni-MH batteries for military aircraft applications. Currently there are seven companies in the US involved in R&D and production of MH batteries. Two of the seven work with AB₂ batteries and five with AB₅ batteries. These companies, their locations and telephone numbers are listed in Table 4.1.3-1.

For AB₅ batteries, two of the five companies (Duracell and EPS) mass produce batteries for commercial customers for portable electronic applications and have major production facilities. Hughes EDD is developing batteries for military and commercial space applications and have had experience producing small batch production batteries for space applications for the DoD. EPI manufactures larger commercial Ni-Cd batteries for automotive, boat and aircraft applications and are a primary supplier of a variety of batteries

to the DoD. EPI has also produced larger prismatic AB₅ batteries for R&D and experimental electric vehicles so their production facilities could easily be adapted to produce a military aircraft MH battery. EEI is a relatively new small business developing a bipolar AB₅ battery concept for a variety of commercial and military applications. Presuming success with their concept EEI should have prototype production batteries in the near future (2-3 years) and mass production capability in 3-5 years. In addition to the five companies listed, presumably SAFT France, if they are successful with their EV battery development program, will mass produce automotive type batteries in the US, probably through SAFT America, Inc., Cockeysville, MD. SAFT America, Inc. also has experience producing a variety of batteries for DoD applications.

Table 4.1.3-1. US Metal Hydride Battery Development and Production Companies

AB ₅ Batteries	AB ₂ Batteries
Duracell, Inc., Bethel, CT Tel.: (203) 791-3274 Fax: (203) 791-3273	Harding Energy Inc., Norton Shores, MI Tel: (616) 798-7033 Fax: (616) 798-7044
Eagle-Picher Industries (EPI), Inc. Joplin, MO Tel: (417) 623-8333 Fax: (417) 623-0233	Ovonic Battery Co., Inc., Troy, MI Tel: (810) 362-1750 Fax: (810) 362-0332
Electro Energy, Inc. (EEI), Danbury, CT Tel: 1-800-BIPOLAR Fax: (203) 797-2697	
Energizer Power Systems (EPS) Gainesville, FL Tel: 1-800-67-POWER Fax: (904) 462-4726	
Hughes EDD, Los Angeles, CA (Space only) Tel: (310) 517-7620	

The component and material industrial base to support production of either AB₅ or AB₂-type MH batteries is available from many sources in the US that already supply the battery industry. The only known metal hydride alloy production capability in the US is at Rhone-Poulenc Basic Chemicals Co. which has small batch and research facilities at Cranbury, NJ and production facilities at Phoenix, AZ. There is another small company developing production capabilities for AB₅ alloys but the name and location of the company

is considered proprietary at this time. The basic ores to make AB₅ alloys are distributed worldwide including California, Ontario, Canada and Brazil in the Western hemisphere, but the largest sources are in the Far East in China, Australia, India, and Malaysia. In the event of a regional armed conflict, supplies of metal hydride ores should be available to support any military battery production.

For AB₂ batteries the only US production source is Harding Energy, Inc. which is associated with Ovonic Battery Co., Inc. and has access to their technology for commercial purposes. Currently, Harding produces cylindrical cells for portable commercial applications while Ovonic is developing prismatic EV batteries in conjunction with the USABC and the DOE. Little information is available on Ovonic production facilities but presuming success with their EV battery development program production batteries should be available by 1998. Neither Harding or Ovonic has experience manufacturing products for the military.

In summary, the US industrial base for AB₅ batteries has research, development and production experience with both military and commercial batteries and has a large mass production capability in existence. For AB₂ batteries the research capability is more limited and production facilities are being developed for commercial EV battery production with no known consideration given to a military aircraft application. Whether AB₂ or AB₅-type MH EV battery technology can be adapted to a military aircraft application has not been proven, but the infrastructure and experience for success with an AB₅ aircraft battery development and production is available.

4.2 TECHNICAL MEETINGS Based on known development efforts in Ni-MH batteries and environmental concerns with Ni-MH batteries GRCI held technical discussions with numerous companies and government agencies and attended several professional society meetings. The list of meetings and visits made included:

- The Department of Energy (DOE), Wash., DC
- The Environmental Protection Agency (EPA) Resource Conservation and Recovery Act (RCRA) Information Center, Wash., DC
- Texas A&M University, College Station, TX.
- Electro Energy Inc.(EEI), Danbury, CT

- Eagle-Picher Industries (EPI), Joplin, MO and Colo. Spgs., CO
- The Naval Surface Warfare Center (NSWC), Crane Division, Crane, IN
- Sacramento Air Logistic Center, SM-ALC/LIEO, Sacramento, CA
- Hughes Aircraft Co., Electron Dynamics Division, Los Angeles, CA
- The Fall 1994 186th Meeting of the EcS, Inc., Miami Beach, FL
- NASA Johnson Space Center, Houston, TX
- The 1994 NASA Aerospace Battery Workshop, Huntsville, AL
- Rutgers University, Piscataway, NJ
- Rhone-Poulenc Basic Chemicals Co., Cranbury, NJ.
- The Central Intelligence Agency, Roslyn, VA.
- The 1995 30th IECEC, Orlando, FL

Attempts to arrange meetings with technical representatives of commercial US manufacturers, such as Ovonic Battery Co., Duracell, Inc., Energizer Power Systems (EPS), Inc., SAFT America, Inc. and Harding Systems, Inc. were unsuccessful. However, discussions did occur by telephone and some additional information was obtained.

4.3 CAPACITY TESTS (CTs)

Three capacity tests were used during this study the Manufacturer Rating Verification (MRV), the C/10 and the 2C/5 tests. The conditions described for all three tests were subsequently used to recondition cells between discharge, charge and internal resistance tests. However, due to the length of time required between tests for both MRV and C/10 reconditioning cycles, 2C/5 discharge/charge cycles became the standard cell reconditioning process. In addition, manufacturer recommendations for upper voltage and temperature limits during charging cycles were strictly adhered to unless the test being conducted required an exception, such as a temperature limit when the test was a charge experiment at 71 °C. The upper temperature and voltage limits became very important during charging tests above room temperature and are discussed in section 4.6. Descriptions of the procedures for all three tests and reconditioning cycles are described in the following sections.

4.3.1 Manufacturer's Rating Verification (MRV) This was the most complex test and reconditioning process used during this study since it changed for each manufacturer's

recommended procedure. Basically the test relied on the manufacturer supplied data on charge and discharge currents, charge termination method and test temperature to verify the capacity of the cells. A minimum of three and preferably five cycles were used to verify the manufacturer's capacity rating. These data provided a baseline to compare capacity results determined using a C/10 and 2C/5 standard test procedure for all the different cells whether large or small capacity and whether cylindrical, bipolar or prismatic construction. These data are reported in Table 4.3-1.

4.3.2 C/10 Capacity Test In the absence of manufacturer recommendations, a test procedure developed by the Naval Surface Weapons Center, Crane Div. for cylindrical AA size cells was used as a zero baseline for comparison with the manufacturer literature and to compare test results between different manufacturer's cells. The cut-off voltage was lowered from 1.00V to 0.90V to obtain additional data and to duplicate the typical depth of discharge experienced by a military aircraft battery. This C/10 CT procedure included:

- Charging the cells at C/10 amps (based on the MRV results) for 15 hr. with a temperature limit of 75°C.
- Resting the cells on open circuit for 5 minutes.
- Discharging the cells at 2C/5 amps to a 0.90V cut-off for each cell.
- Resting the cells for 2 hours.
- Repeat the charge, rest, discharge, and rest sequence for five complete cycles.

This C/10 CT procedure was also used for two cycles to recondition the cells between tests, whenever there was an unscheduled interruption in the test sequence, or if changes to the cells were needed, such as adding electrolyte or water. The results of the C/10 CT are also contained in Table 4.3-1.

4.3.3 2C/5 Capacity Test The C/10 CT procedure initially used was found to lengthen test time for other tests to unacceptable lengths, so a fast charge version was developed. This 2C/5 CT and reconditioning procedure changed the charge current from C/10 to 2C/5 amps. The duration of the charge was reduced such that the cells received the same amp-hours of charge with both tests. This gave a typical charge time of 3.75 hours. The 2C/5 charge and discharge rate was adjusted based on the results of either the MRV or the C/10 tests. Because

the cell temperatures increased to higher levels using the 2C/5 rate, the rest time between charge and discharge was also increased to allow the cells to cool to the test temperature before initiating the next test or cycle. This change to a 2C/5 reconditioning or fast charge reconditioning (FCR) cycle cut the testing time in half. The results of the 2C/5 CT are also contained in Table 4.3.3-1.

Comparisons of the data for the three capacity tests in Table 4.3-1 showed no surprises. Essentially the three tests verified the manufacturer's data for all the cells with the exception of those for Company C. The deviation from the rated capacity vs. measured was easily explained after discussion with company personnel. The company's rating was based on "clamping" the cells during their internal rating test. "Clamping" is a process of actively cooling the cells or cell pack to prevent overheating and early termination of the charge. This results in a higher capacity for the cells. Since WL/POOB and GRCI personnel were unaware of the "clamping" requirement, the first tests on the 5 cell pack overheated the cells and caused premature failure of one cell and damage to the remaining four. Subsequent tests showed a residual 24.9 A-h capacity compared to the test data furnished by the manufacturer. Company C data showed an 85 A-h capacity before shipment to GRCI. Two replacement cells were furnished that were rated at 66 A-h "clamped" but yielded approximately 40 A-h without benefit of "clamping." Precautions were taken not to overheat the two replacement cells which were tested separately from the 5 cell pack and furnished much of the test data for the large prismatic AB₅ cells manufactured by Company C.

During the charging cycles for all the tests and the reconditioning cycles, the cells were set up to receive a standard 50 percent overcharge except for specific charging studies where the overcharge was set to 10 percent. Voltage and temperature rise limits were set in the control software to 1.55 V and 75 °C, respectively, unless specific limits were identified by the manufacturer. The two manufacturer exceptions to these limits that were lower were the large prismatic AB₅ cells from Company C and the AB₂ cylindrical cells from Company H. The cells for Company C were set to cut off when they reached either a 1.48 V increase or +10 °C temperature rise. Company H cells were set to terminate the charge at a 1.50 V limit.

Table 4.3.3-1. Cell Capacity Comparisons at 23 °C

Cathode Type	Manufacturer	Battery/Cell Type	Manufacturer's Rating (A-h)	Discharge Capacity (A-h)		
				MRV Charge	C/10 Charge	2C/5 Charge
AB ₅	"A"	Cylindrical	2.50	2.40	2.39	2.36 ¹
AB ₅	"G"	9 Cell Pack (Cylindrical.)	2.40	2.45	2.52	2.48
		Cylindrical	2.40	N.A.	N.A.	2.62 ²
AB ₅	"B"	Bipolar	1.66	1.66	1.63	N.A.
		Bipolar	1.84	1.76	1.90	N.A.
AB ₅	"C"	5 Cell Pack (Prismatic)	85	xxxx ³	21.5	24.9
		Prismatic	66	40	29.2	42
		5 Cell Pack (Prismatic)	40 ⁴ (25-30)	24.4	N.A.	30 ⁵
AB ₅	"E"	Prismatic	3.00	3.11	2.96	3.05 ⁶
AB ₅	"F"	Prismatic	0.85	0.96	0.92	0.93 ⁷
AB ₂	"D"	Cylindrical	1.80	1.82	1.75	1.79 ⁸
AB ₂	"H"	Cylindrical	2.50	2.3	2.2	1.9 ⁹

¹ Increased gradually with cycle no. and peaked around cycle 50-90 then gradually declined.

² Increased gradually with cycle no. and peaked around cycle 60-80 then gradually declined.

³ Cell pack passivated at high temperature

⁴ Cell pack used in electric vehicle for 2 years; originally rated at 40 A-h, manufacturer derated the pack to 25-30 A-h due to use.

⁵ Stabilized after water addition on cycle 17 and recovered when water was added after cycle 70.

⁶ Stable and repeatable after the first few cycles.

⁷ Increased gradually, peaked around cycle 80 and remained steady.

⁸ Capacity varied from cycle to cycle and cell to cell but no overall trend up or down.

⁹ Capacity varied from cell to cell but the overall trend was down as cycle no. went up.

4.3.4 Capacity and Cycle No Effects During testing of all the cells, using the FCR between tests, there was a gradual rise in cell capacity which was not noticeable over a 5-10 cycle range. The rising baseline was discovered when plots of capacity versus cycle no. for AB₅ cylindrical cells from Company A and AB₂ cells from Company D were done. Rechecks of all the cell data for all the companies were done to determine if the rising baseline was common or due to the cylindrical cell construction. Plots of cell capacity vs. cycle no. were used to identify the baseline trend and are reported in Figures 4.3.4-1 through 4.3.4-8 for companies A through H. These plots showed a changing baseline on almost all the cells but it was not as prominent with the prismatic cells. This real but small change required cell test data to be normalized and reported as percent capacity for Self Discharge (SD), Constant Discharge Current (CDC), Constant Charge Current (CCC) and Internal Resistance (IR) tests. To localize the baseline, GRCI calculated either five or ten cycle average capacities for each group of cells from every company through the entire test regime. These average capacities determined if the drift in baseline was outside the norm expected over the entire range for each group and were used to normalize the results on all subsequent tests. The five and ten cycle averages are presented in Tables 4.3.4-1 through 4.3.4-8.

Table 4.3.4-1. Company A (AB₅ Cylindrical Cells): Discharge Capacity vs. Cycle No.

Group No.	1	2	4	5
Cycle No.	Discharge Capacity, C _d (Amp-hours)			
1-10	NA	NA	NA	NA
11-20	NA	NA	NA	NA
21-30	NA	2.398	2.356	2.377
31-40	NA	2.412	2.344	2.394
41-50	NA	2.469	2.353	2.406
51-60	2.374	2.485	2.388	2.438
61-70	2.430	2.549	2.454	2.502
71-80	2.459	2.530	2.451	2.473
81-90	2.472	2.429	2.452	2.494
91-100			2.407	2.438
Test Conditions				
Discharge Current (mA)	960			
Charge Current (mA)	956			
Temperature (°C)	23.7			

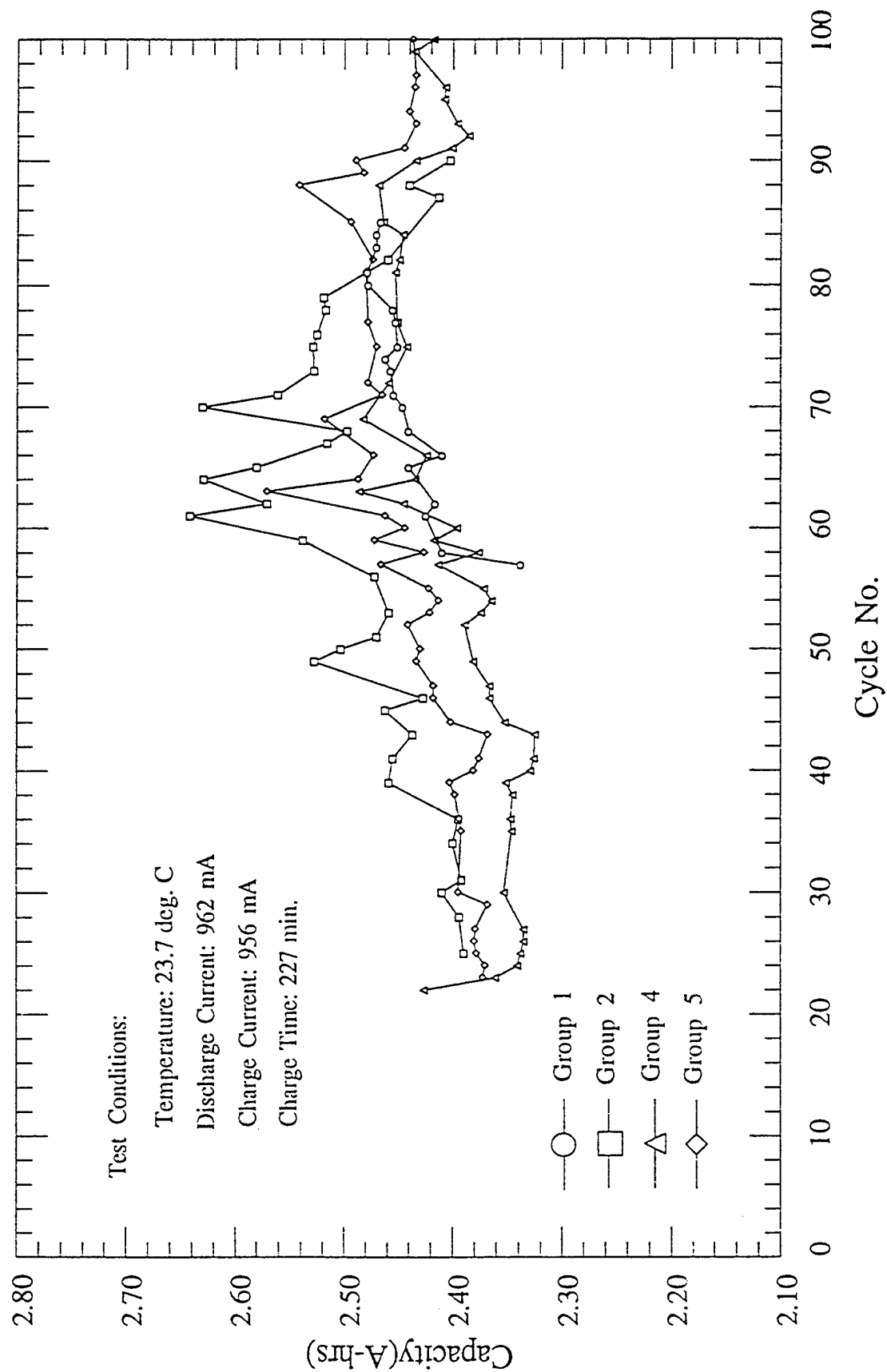


Figure 4.3.4-1. Company A Cell Capacity vs. Cycle No.

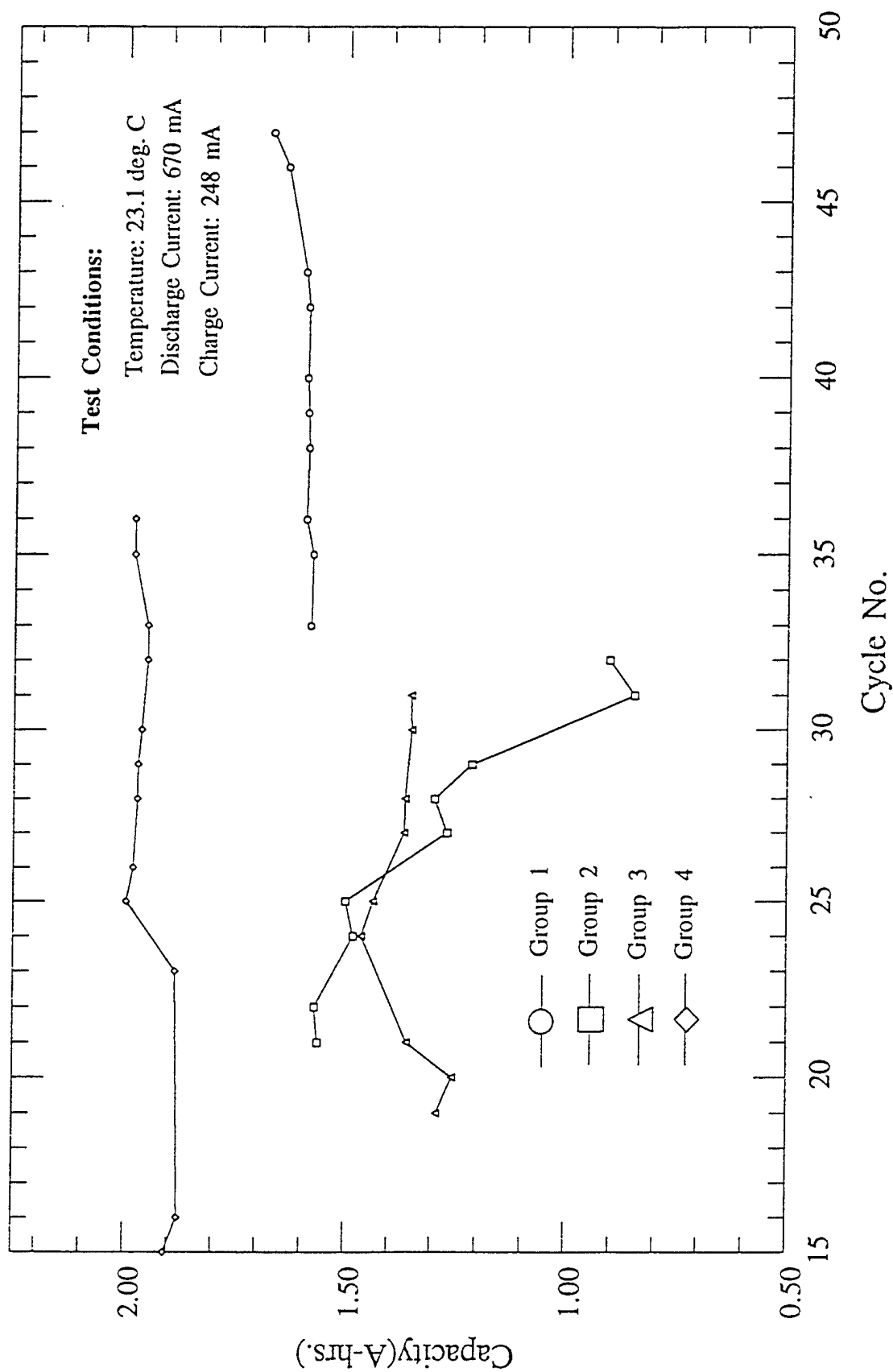


Figure 4.3.4-2. Company B Cell Capacity vs. Cycle No.

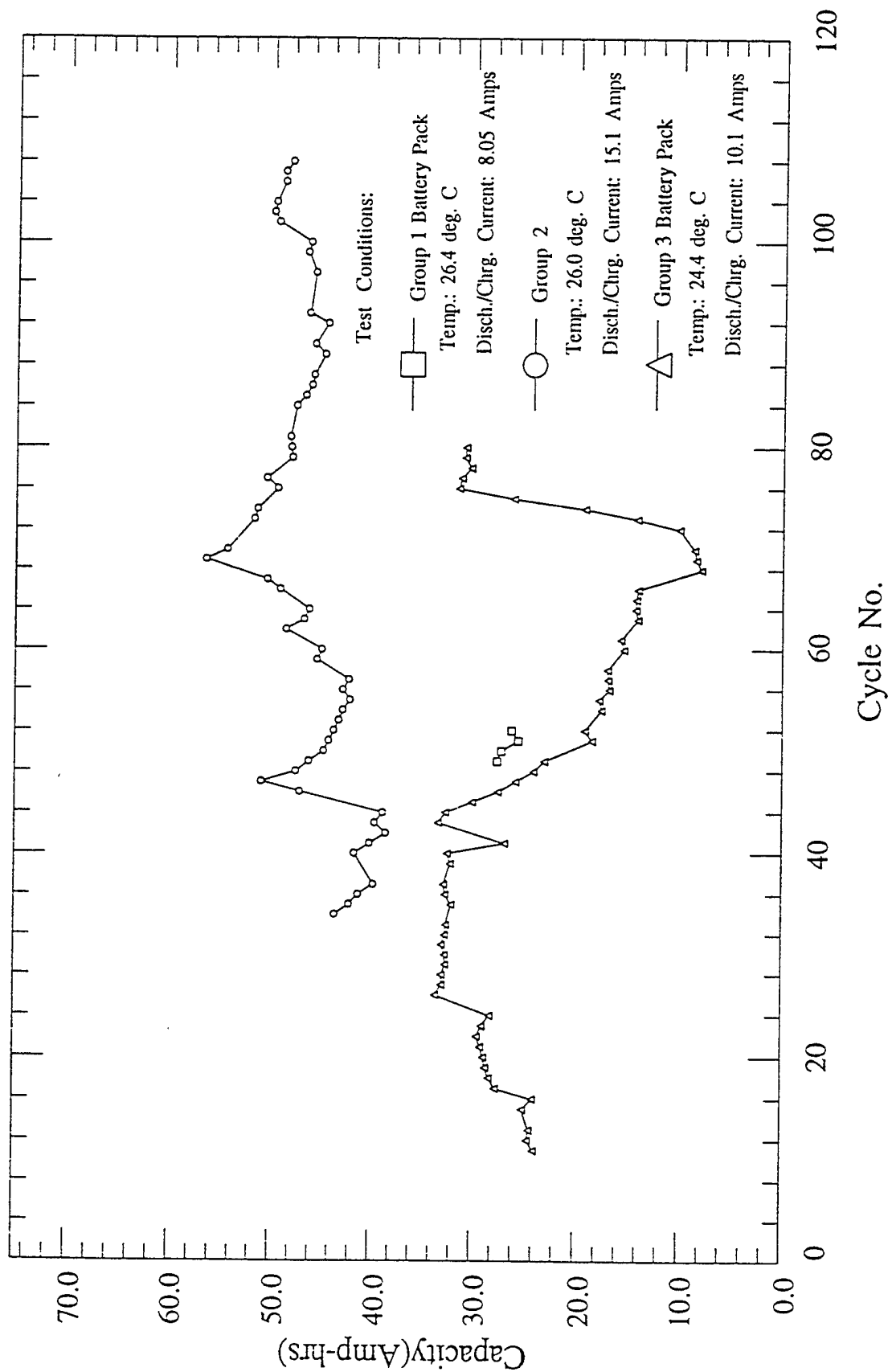


Figure 4.3.4-3. Company C Battery Pack/Single Cell Capacity vs. Cycle No.

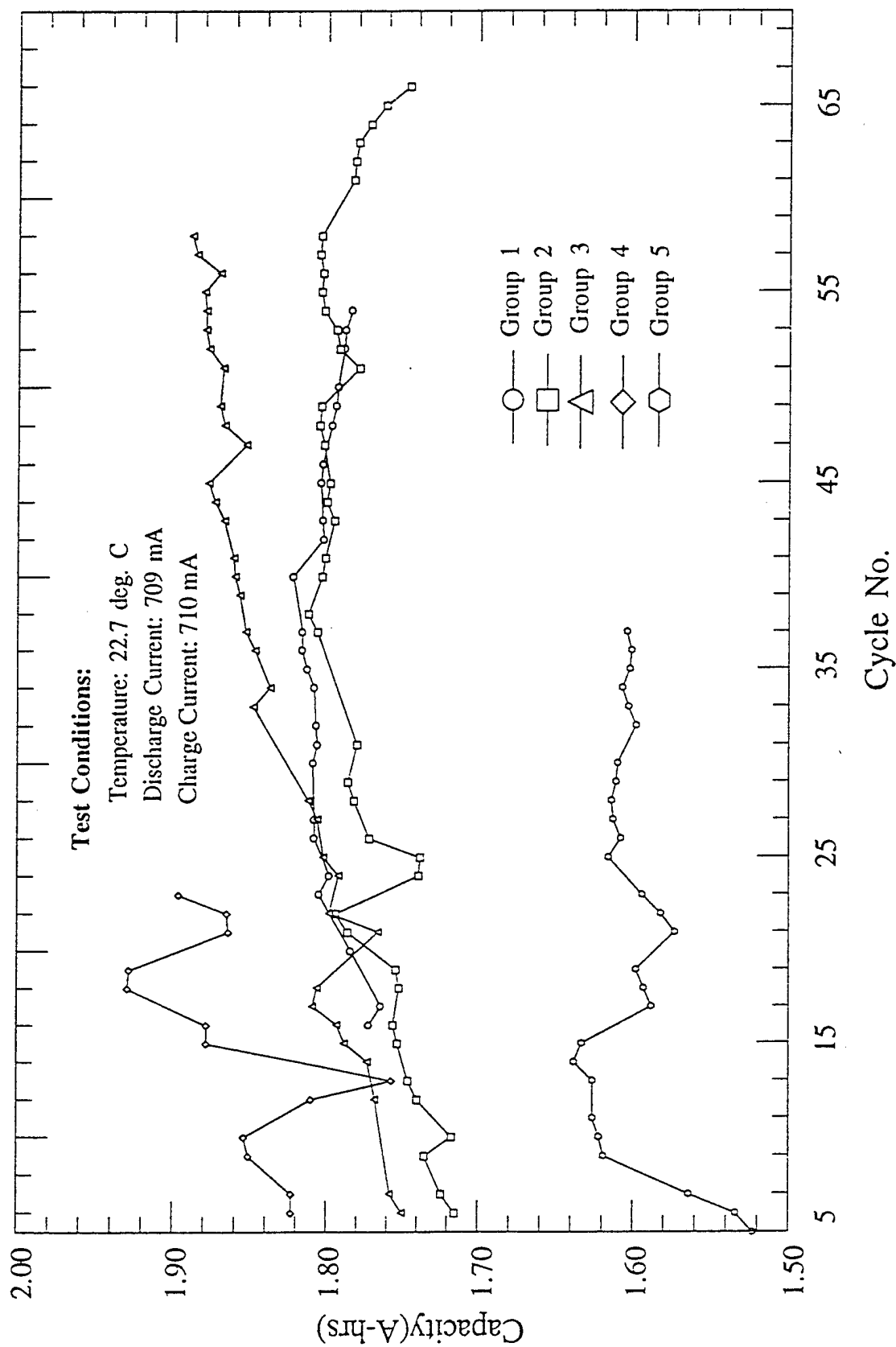


Figure 4.3.4-4. Company D Cell Capacity vs. Cycle No.

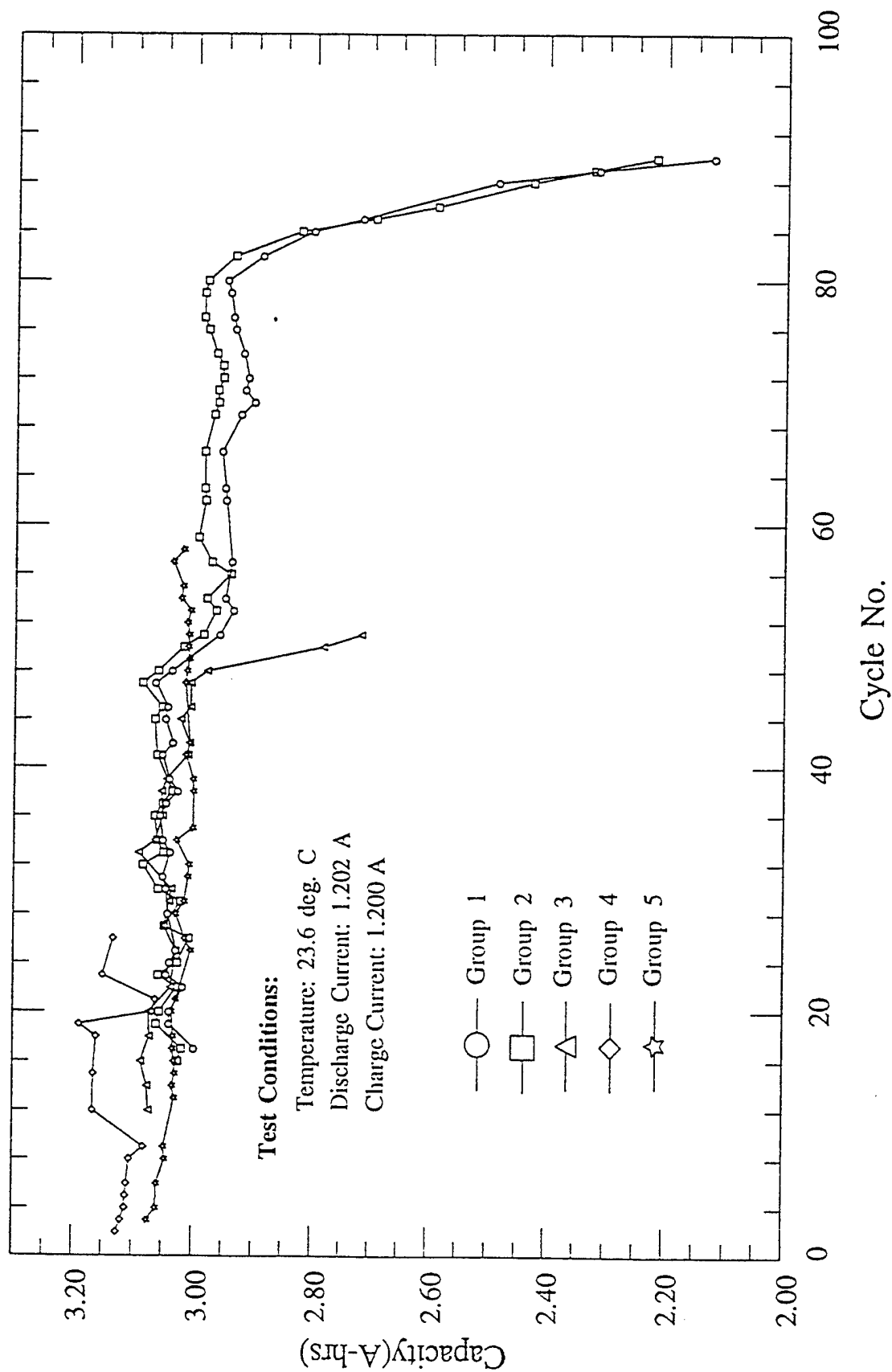


Figure 4.3.4-5. Company E Cell Capacity vs. Cycle No.

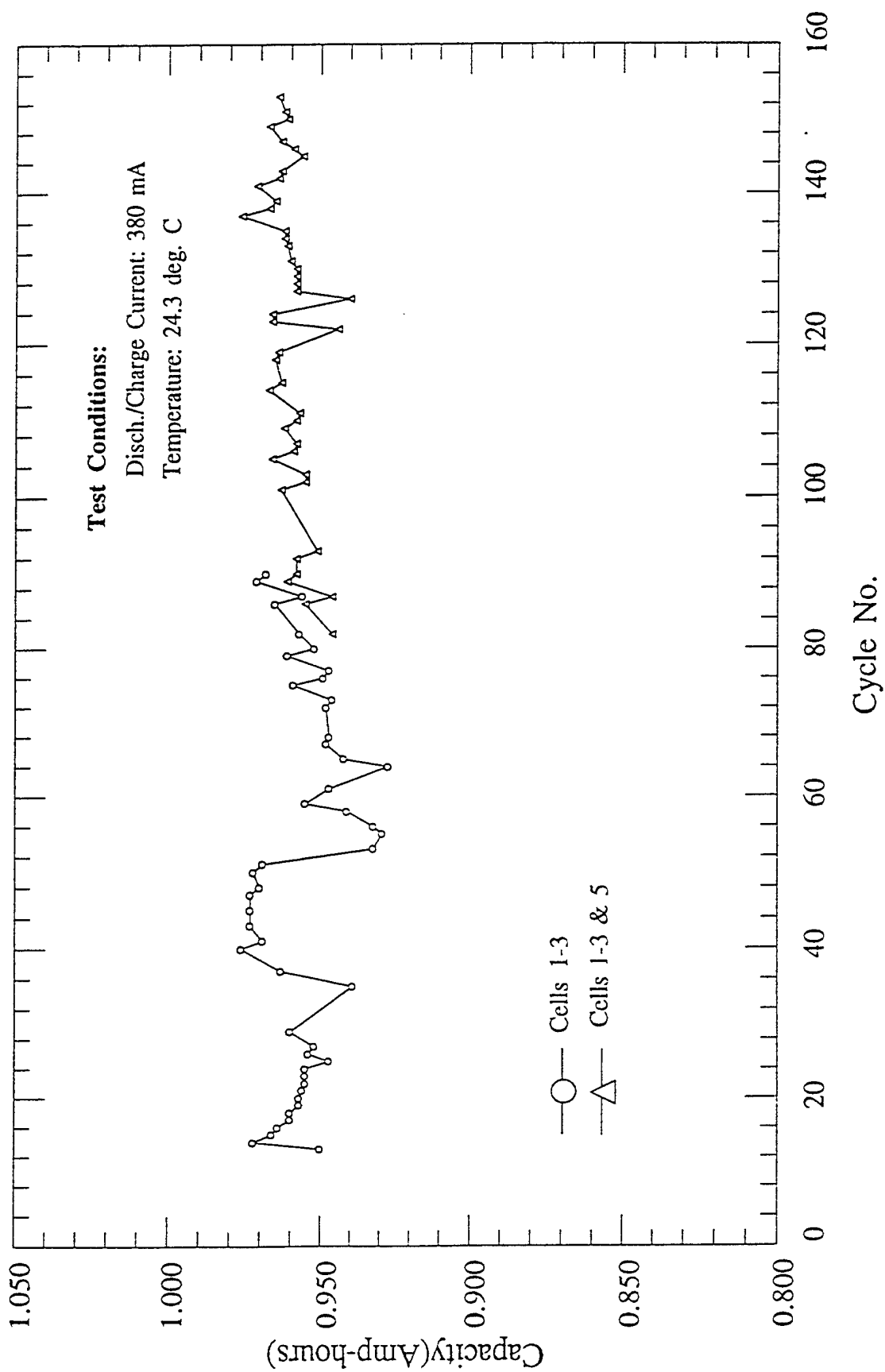


Figure 4.3.4-6. Company F Cell Capacity vs. Cycle No.

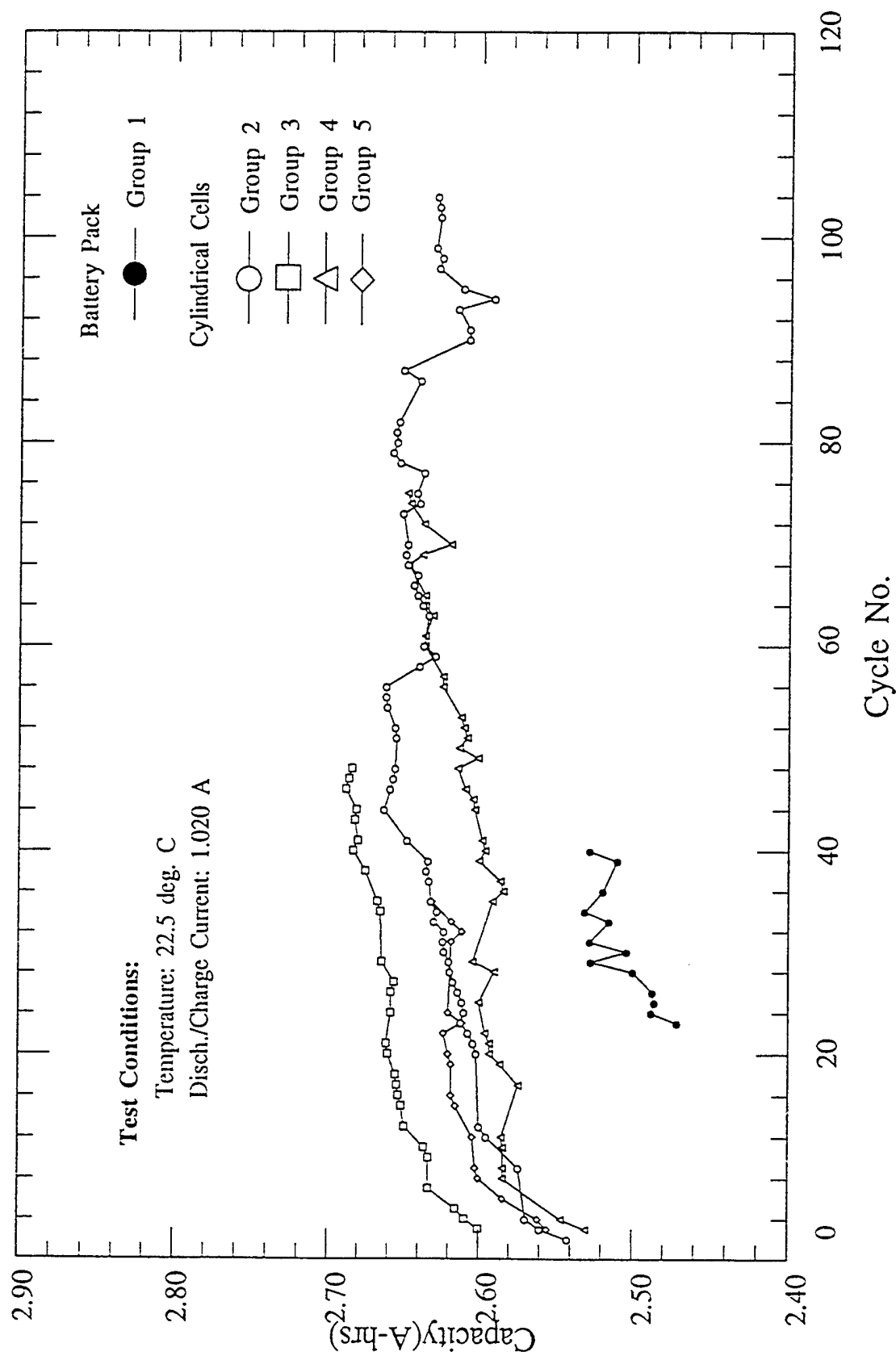


Figure 4.3.4-7. Company G Cell Capacity vs. Cycle No.

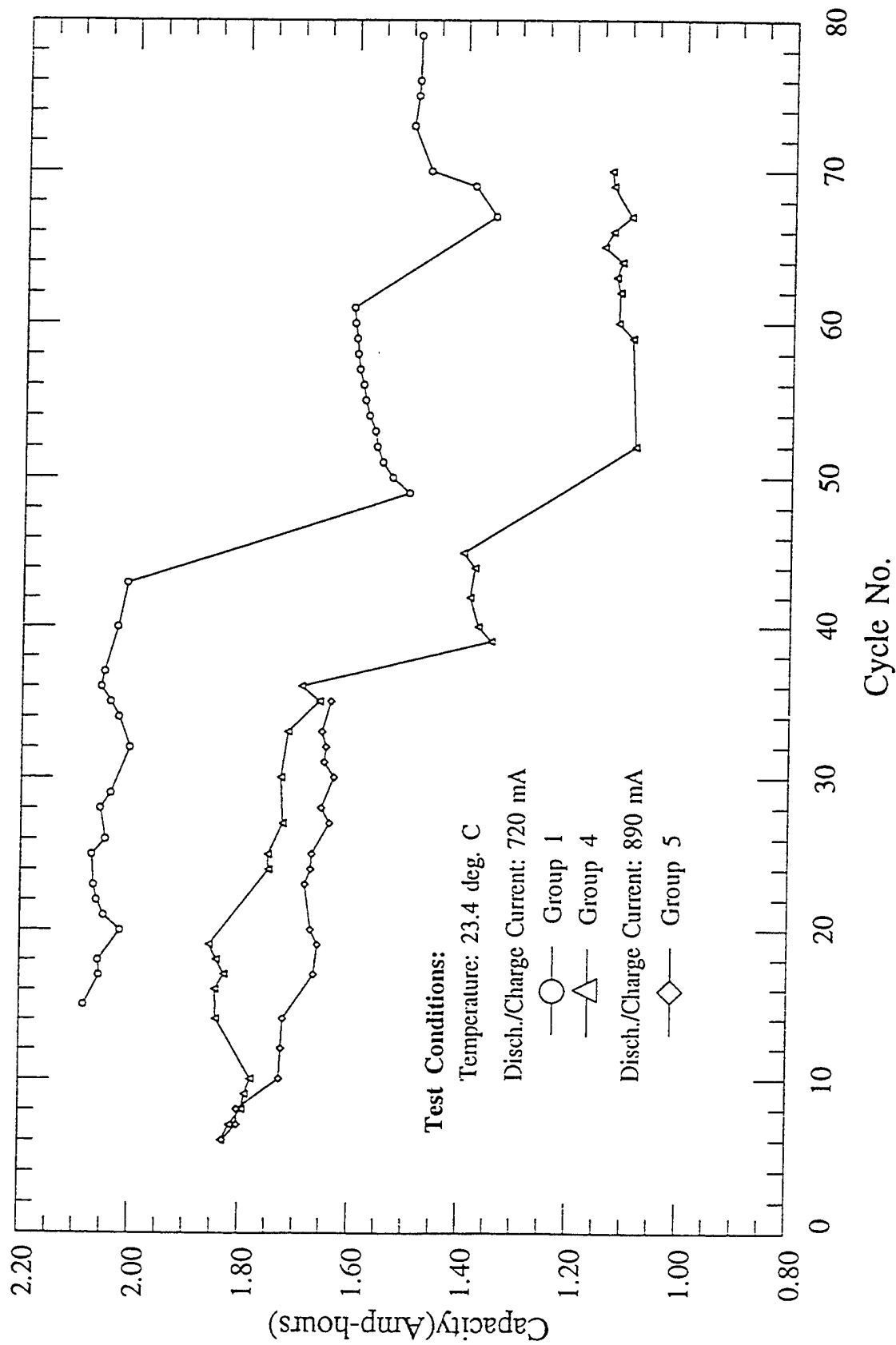


Figure 4.3.4-8. Company II Cell Capacity vs. Cycle No.

Table 4.3.4-2. Company B (AB₅ Bipolar Vented Cells): Discharge Capacity vs Cycle No.

Group No.	1	2	3	4
Cycle No.	Discharge Capacity, C _d (Amp-hours)			
1-10	NA	NA	NA	NA
11-20	NA	NA	1.270	1.892
21-30	NA	1.526 ^a	1.387	1.961
31-40	1.586	X	X	1.965
41-50	1.619	X	X	X
Test Conditions				
Discharge Current (mA)	670			746
Charge Current (mA)	248			301
Temperature (°C)	23.1			22.4

^a Cycle 21-25 only; capacity degraded with each cycle from cycle 27-32.

Table 4.3.4-3. Company D (AB₂ Cylindrical Cells): Discharge Capacity vs. Cycle No.

Group No.	1	2	3	4	5
Cycle No.	Discharge Capacity, C _d (A-h) ¹				
1-10	N.A.	1.723	1.754	1.838(3)	1.525
11-20	1.773	1.750	1.790	1.784(3) ^b 1.900(1)	1.627(3) ^a 1.637(2)
21-30	1.804	1.771	1.796	1.875(1)	1.602(2)
31-40	1.813	1.800	1.850(3)	X	1.602(2)
41-50	1.799	1.801(3)	1.867(3)	X	X
51-60	1.787	1.798(2)	1.878(3)	X	X
Test Conditions					
Discharge Current (mA)	709				
Charge Current (mA)	710				
Temperature (°C)	22.7				

¹ Four cells unless designated otherwise as (x)

^a Cycles 11-15

^b Cycles 11-13

Table 4.3.4-4. Company C (AB₅ Prismatic Cells): Discharge Capacity vs Cycle No.

Group No.	1			2			3		
Cycle No.	Discharge Capacity, C _d (A-h)								
6-10				42				24.4	
11-15				37.4	29.3				22.8
16-20	22.2				29.2	34.2			26.4
21-25	21.8						38.7		27.0
26-30	20.2	21.0					36.9		30.7
31-35		21.8					39.3	39.9	30.3
36-40								38.1	30.3
41-45								36.6	28.6
46-50			25.6					44.1	23.4
51-55			24.2					40.3	17.0
56-60								40.9	15.4
61-65								44.0	13.4
65-70								49.1	7.8
71-75								48.1	16.2
76-80								45.7	28.9
81-90								43.3	
91-100								42.8	
101-110								45.9	
Test Conditions									
Discharge Current (A)	12.07	7.95	8.16	6.51	16.13	11.88	14.10	15.10	4.08
Charge Current (A)	2.97	1.98	7.94	6.47	4.02	11.67	13.96	15.06	3.98
Temperature (°C)	26.6	26.2	26.4	25.6	24.8	26.0	26.0	26.0	26.1
									24.4

Table 4.3.4-5. Company E (AB₅ Prismatic Cells): Discharge Capacity vs Cycle No.

Group No.	1	2	3	4	5
Cycle No.	Discharge Capacity, C _d (A-h)				
1-10	NA	2.985	NA	3.107	3.056
11-20	3.025	3.040	3.075	3.149	3.031
21-30	3.036	3.035	3.037	3.114	3.017
31-40	3.044	3.058	3.060	X	3.007
41-50	3.047	3.058	3.004	X	3.010
51-60	2.945	2.973	X	X	3.017
61-70	2.936	2.977	X	X	X
71-80	2.931	2.972	X	X	X
Test Conditions					
Discharge Current (A)	1.202				
Charge Current (A)	1.200				
Temperature (°C)	23.6				

Table 4.3.4-6. Company G (AB₅ Cylindrical Cells): Discharge Capacity vs Cycle No.

Group No. ^a	1	2	3	4	5
Cycle No.	Discharge Capacity, C _d (A-h)				
1-10	NA	2.561	2.614	2.560	2.580
11-20	NA	2.599	2.651	2.584	2.615
21-30	2.495	2.614	2.659	2.597	2.618
31-40	2.522	2.630	2.683	2.591	2.620
41-50	X	2.657	2.684	2.606	
51-60	X	2.637	X	2.619	
61-70	X	2.643	X	2.635	
71-80	X	2.648	X	2.644	
81-90	X	2.642	X		
91-100	X	2.618	X		
Test Conditions					
Discharge Current (A)	1.020				
Charge Current (A)	1.020				
Temperature (°C)	22.5				

^a Group 1 was a 9 cell battery pack; groups 2-5 were single cells from battery packs.

Table 4.3.4-7. Company F (AB₅ Prismatic Cells): Discharge Capacity vs Cycle No.¹

Cell No.	1-3	4	5	1-3 & 5
Cycle No.	Discharge Capacity, (A-h)			
1-10	NA	NA	NA	NA
11-20	0.961	0.861	NA	NA
21-30	0.953	0.855	NA	NA
31-40	0.959	0.840	NA	NA
41-50	0.972	0.837	NA	NA
51-60	0.941	0.797	NA	NA
61-70	0.942	0.791	NA	NA
71-80	0.952	X	0.885	0.935
81-90	0.964	X	0.922	0.953
91-100	0.974	X	0.934	0.964
101-110	0.969	X	0.930	0.960
111-120	0.970	X	0.943	0.963
121-130	0.963	X	0.936	0.956
131-140	X	X	0.948	0.964
141-150	X	X	0.947	0.963
Discharge Current (mA)	380			
Charge Current (mA)	380			
Temperature (°C)	24.3			

¹ During initial tests of Company F cells, the capacity for cells 1-3 were extremely close together with cell 4 markedly lower as can be seen in Table 4.3.4-6. Cell 4 eventually failed at cycle 68 and was replaced with cell 5 which initially gave lower capacity values as expected. Cell 5 required 22 FCR cycles to provide consistent data with cells 1-3. In subsequent data analysis only the data for cells 1-3 was used up to cycle 90. After cycle 90 data for cell 5 was included in the analysis of CDC, CCC, and IR test data. For comparison purposes, the table shows the actual capacities of cells 4 and 5, the grouped cells 1-3 and the 1-3 & 5 versus the original cycle nos. for cells 1-3.

Table 4.3.4-8. Company H (AB₂ Cylindrical Cell): Discharge Capacity vs. Cycle No.

Group No.	1 ^a	4 ^c	5
Cycle No.	Discharge Capacity, C _d (A-h)		
1-10	N.A.	1.801	1.790
11-20	2.053	1.843	1.664
21-30	2.054	1.750	1.628 ^b
31-40	2.032	1.689 ^d	1.646
41-50	1.513	1.386	X
51-60	1.579	1.098	X
61-70	1.397	1.124	X
71-80	1.490	X	X
Test Conditions			
Discharge Current (A)	0.73		0.89
Charge Current (A)	0.73		0.89
Temperature (°C)	23.4		

^a Cells damaged at -40 °C on cycles 40 and 43 and 2C/5 IR test on cycle 62.

^b Cells damaged after 9.01 amp discharge at room temperature on cycle 21.

^c Cells damaged on cycles 20, 36 and 45 after each exposure to 71 °C. ^d Cycles 31-35.

4.3.5 CT Observations and Summary Comparisons of initial capacity tests using MRV, C/10 and 2C/5 test procedures and capacity versus cycle no. confirmed:

- The manufacturer's ratings were reasonably accurate.
- Both the C/10 and 2C/5 tests showed reasonable agreement with the manufacturer supplied data and the MRV test.
- The 2C/5 CT and FCR produced higher end of charge temperatures than either the MRV or the C/10 CT, as expected.
- A gradual rise in the end of charge cell voltage with increasing cycles.
- A climbing baseline capacity for all the cylindrical cells except Company H. Company H AB₂ cylindrical cells had been damaged due to exposure to high temperature and high discharge and charge currents during testing so no conclusion on a baseline change was possible.
- The AB₅ bipolar vented cells from Company B did not acquire enough cycles to warrant any baseline conclusions but appear stable through cycle 40.

- Prismatic AB₅ cells exhibited mixed behavior. The smaller prismatic cells from Company E and F showed a stable baseline through the entire cycling regime tested. The two large prismatic cells from Company C that were undamaged exhibited a climbing baseline through cycle 108, but the rate of increase appears much lower than for cylindrical cells. The differences between the large and small prismatic cells may be due to size or it may be a function of differences in the metal hydride alloys used in manufacturing the three cells.

Summary Capacities of AB₂ and AB₅ cylindrical and some AB₅ prismatic cells show an increasing baseline that may be a function of cell construction and/or the formulation of the hydride alloy used in the battery. Data in the literature confirms the hydride alloy effect on cylindrical cells, but over a larger cycle regime. There were insufficient data to confirm or deny a similar problem with AB₅ bipolar cell construction.

A development program to build a Ni-MH aircraft battery would have to minimize or eliminate the capacity effect because replacement of a failed cell in a battery would require cells with similar cycles or replacement of the entire battery at one time. The logistics cost impact of maintaining matched cells and a data base to track cell cycles would be enormous and not in the best interests of the USAF.

4.4 SELF DISCHARGE (SD) TEST Ni-MH cells and batteries have a higher self discharge rate than Ni-Cd cells so evaluation of this factor is critical to determine suitability for use in a military aircraft battery. Cell storage temperatures were selected to match flight line aircraft battery conditions as nearly as possible and ranged from -40 °C (winter in Alaska) to 71 °C (summer in Saudi Arabia). The time requirements for SD tests, the limited availability of batteries, and the requirement to test the batteries at various charge and discharge rates limited most of the data collection to room temperature. However, some data was collected at higher temperatures for one set of AB₅ cylindrical and prismatic cells and one set of AB₂ cylindrical cells.

The following procedure was established to perform the SD tests using the charging limit restrictions discussed in Section 4.3:

- Perform a minimum of two reconditioning cycles at room temperature using either the C/10 CT or FCR reconditioning procedure then discharge the cells at the C/10 or 2C/5 rate, as appropriate.
- Charge the cells at the test temperature for 15 hours at the C/10 rate or 3.75 hours at the 2C/5 rate. Total charge capacity using the 2C/5 rate should equal the charge received using the C/10 rate for 15 hours.
- Store the cells at the test temperature for the specified period.
- Return the cells to room temperature; allow 1-2 hours or longer if needed. Record the voltage and temperature for each cell at 10 min. intervals. When at least two of the cells have reached room temperature begin the discharge.
- Discharge the cells at the 2C/5 rate to a 0.90 V cut-off.
- Record cell voltage, current, A-h, time and temperature during the discharge.
- From the measured capacity at each temperature and comparison with baseline measurements from the reconditioning cycles, calculate the percent remaining capacity at each temperature and cell configuration.
- Plot percent capacity vs. time and temperature for each group of cells by manufacturer and battery configuration.

The results of the SD tests by individual company are presented in Tables 4.4-1 to 4.4-8 with a corresponding graph of the data in Figures 4.4-1 to 4.4-8. Discussion of the data is presented by types of cells, either AB₅ or AB₂, and temperature in the following sections.

4.4.1 AB₅ BATTERIES AND SINGLE CELL SD TESTS

Six samples of AB₅ batteries from manufacturers A, B, C, E, F, and G were evaluated for their SD characteristics. One sample was a bipolar vented R&D cell, two were production cylindrical cells, two were production prismatic cells and the largest cells tested were vented and sealed configuration large prototype production prismatic cell packs and single cells manufactured on special order. The bipolar R&D cell was used in this study to evaluate different MH alloys, which was not possible with the other manufacturers due to special ordering and higher cost requirements for a non-production commercial battery. Attempts to obtain AB₅ electric vehicle (EV) cells through the USABC and the DOE were unsuccessful,

but the smallest prismatic cells that were tested were based on the technology in the EV development cells according to the manufacturer. The SD data for each sample were presented individually in Section 4.4. Based on the best fit curve to the actual data (See Figures 4.4-1, 2, 3, 5, 6, and 8) for the individual cells, a comparison graph of all six cells is presented in Figure 4.4.1-1. Each of the different cells are discussed below.

Table 4.4-1. Company A (AB₅ Cylindrical Cells) Self Discharge at 23.4 °C

		Nominal Storage Time (Days)						
		0.0	0.50	1	2	5	10	>10
Group 1								
Cycle No.	Tbl. 4.3.4-1				69			
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-1				2.216			
Capacity (%)	100.00				91.19			
Storage Time (Days)	0.000				2.90			
Group 2								
Cycle No.	Tbl. 4.3.4-1	27 35	42	26	52	89	60	
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-1	2.330 2.358	2.319	2.156	2.131	1.782	1.365	
Capacity (%)	100.00	97.16 97.76	93.92	89.91	85.75	73.36	55.99	
Storage Time (Days)	0.000	0.438 0.210	1.152	2.61	6.19	9.85	30.00	
Group 4								
Cycle No.	Tbl. 4.3.4-1	33	76	28 31	78			
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-1	2.290	2.348	2.177 2.138	2.213			
Capacity (%)	100.00	97.70	95.80	92.40 91.21	90.29			
Storage Time (Days)	0.000	0.413	0.990	1.88 2.53	4.15			
Group 5								
Cycle No.	Tbl. 4.3.4-1	33 65	76	28 31	78			
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-1	2.322 2.434	2.376	2.209 2.168	2.234			
Capacity (%)	100.00	96.99 97.28	96.08	92.93 91.21	90.33			
Storage Time (Days)	0.000	0.412 0.267	0.938	1.96 2.52	3.99			

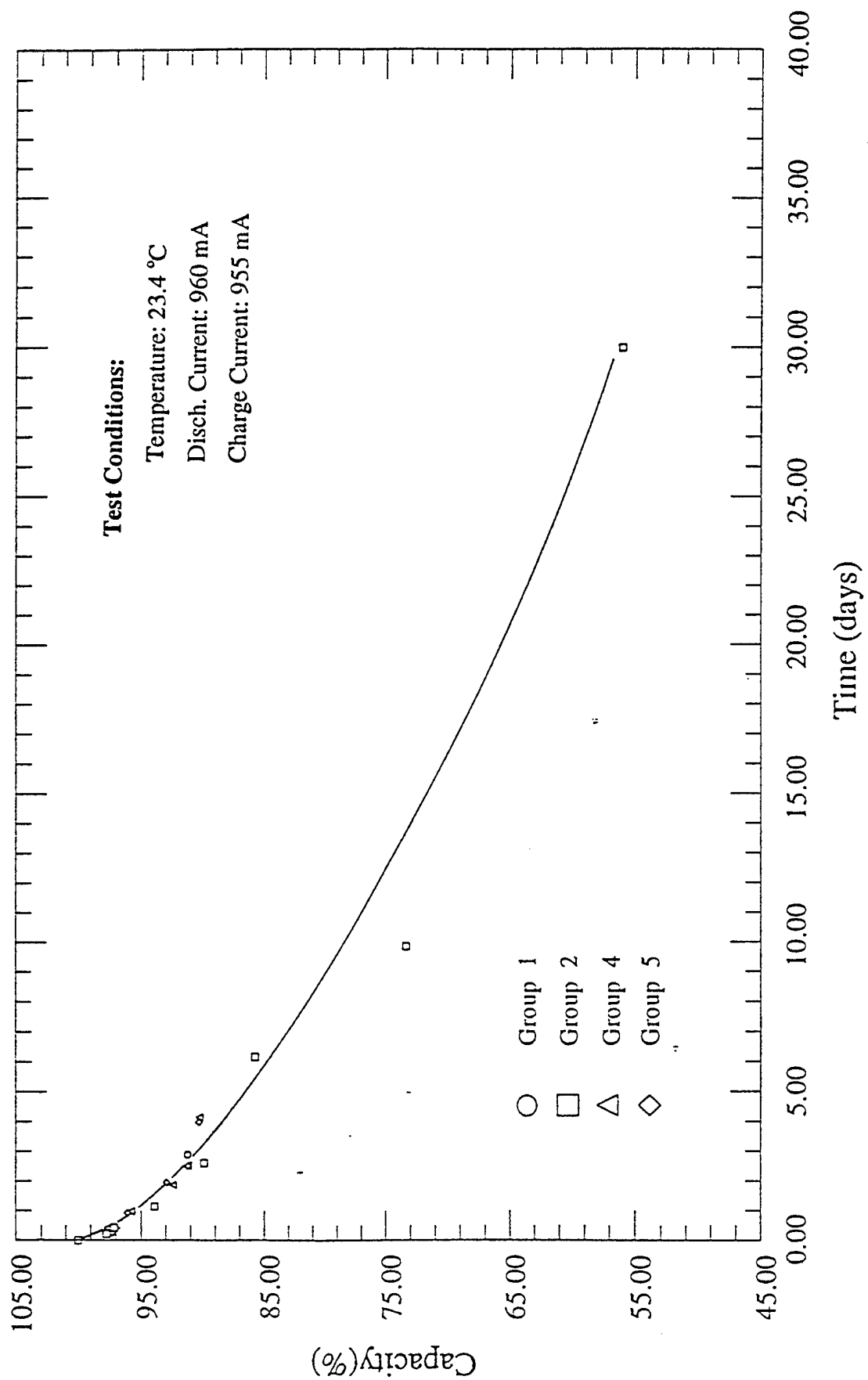


Figure 4.4-1. Company A Self Discharge Capacity vs. Time

Table 4.4-2. Company B (AB₅ Bipolar Vented Cells) Self Discharge at 23.0 °C

	Nominal Storage Time (Days)						
	0.0	0.50	1	2	5	10	>10
Group 1 (Alloy 415)							
Cycle No.	Tbl. 4.3.4-2	X	37	41	34		45
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-2	X	1.012	0.538	0.057		0.000
Capacity (%)	100.00	X	63.81	33.92	3.59		00.00
Storage Time (Days)	0.00	X	1.00	2.12	4.18		11.27
Group 2 (Alloy 414)							
Cycle No.	Tbl. 4.3.4-2	X			23	26	
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-2	X			1.160	0.833	
Capacity (%)	100.00	X			76.02	54.59	
Storage Time (Days)	0.00	X			4.58	8.98	
Group 3 (Alloy 413)							
Cycle No.	Tbl. 4.3.4-2	X		29	26		
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-2	X		0.805	0.067		
Capacity (%)	100.00	X		58.04	4.83		
Storage Time (Days)	0.00	X		2.10	3.43		
Group 4 (Alloy 414)							
Cycle No.	Tbl. 4.3.4-2	X	27		34		
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-2	X	1.788		1.500		
Capacity (%)	100.00	X	91.18		76.34		
Storage Time (Days)	0.00	X	0.99		3.00		

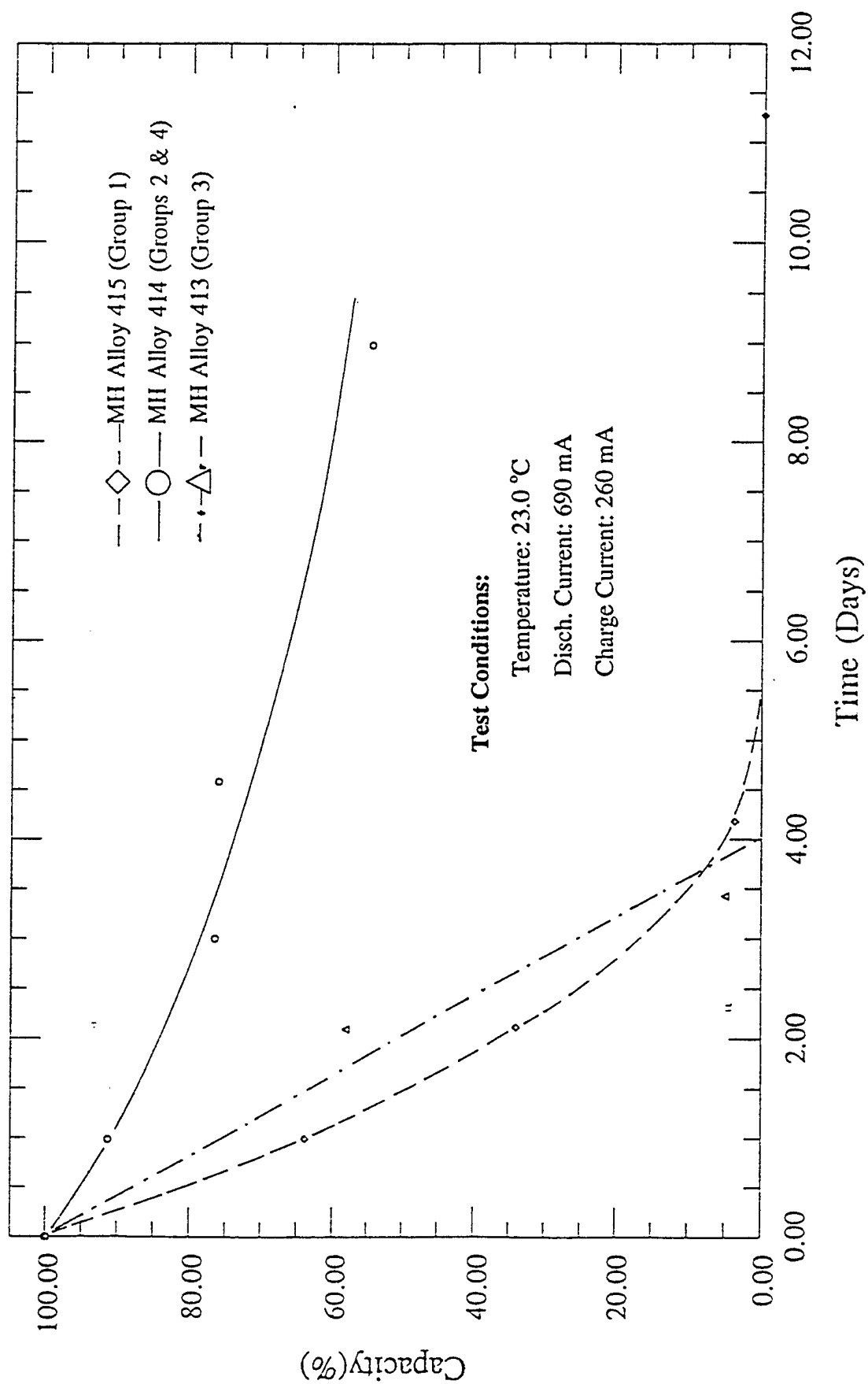


Figure 4.4-2. Company B MRV Self discharge Capacity vs. Time

Table 4.4-3. Company C (AB₅ Prismatic Cells) Self Discharge at 23.7 °C

Nominal Storage Time (Days)						
	0	0.5	1	2	5	10
Group 1 (New Cell Pack with Sealed Cells)						
Cycle No.	Tbl. 4.3.4-3	X	27		29	
Disch. Capacity, C_d (A-h)	Tbl. 4.3.4-3	X	19.73		18.45	
Capacity (%)	100.00	X	97.67		87.86	
Storage Time (Days)	0.00	X	1.042		5.101	
Group 2 (New Sealed Single Cells)						
Cycle No.	Tbl. 4.3.4-3	X	58 61	65		78
Disch. Capacity, C_d (A-h)	Tbl. 4.3.4-3	X	38.06 40.30	39.87		36.59
Capacity (%)	100.00	X	93.06 91.59	90.61		80.06
Storage Time (Days)	0.00	X	0.778 0.924	2.00		10.00
Group 3 (Used Cell Pack with Vented Cells)						
Cycle No.	Tbl. 4.3.4-3	X		34 38		
Disch. Capacity, C_d (A-h)	Tbl. 4.3.4-3	X		28.05 28.53		
Capacity (%)	100.00	X		92.57 94.16		
Storage Time (Days)	0.00	X		2.00 2.00		

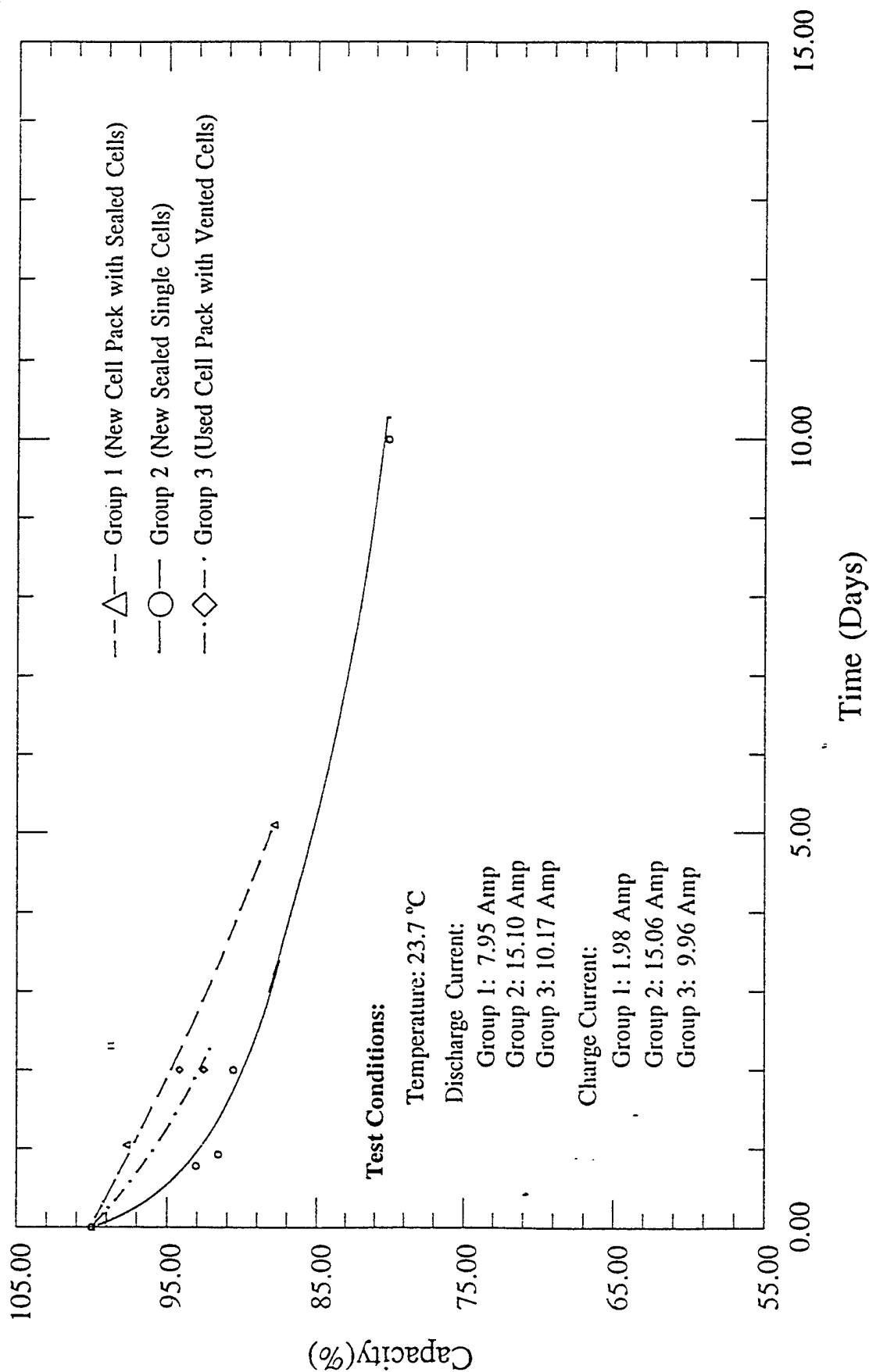


Figure 4.4-3. Company C Self Discharge Capacity vs. Time

Table 4.4-4. Company D (AB₂ Cylindrical Cells) Self Discharge at 22.7 °C

	Nominal Storage Time (Days)						
	0.0	0.50	1.00	2.00	5.00	10.00	>10.00
Group 1							
Cycle No.	Tbl. 4.3.4-4	21 39		29 55	18 25	33	
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-4	1.696 1.736		1.620 1.636	1.336 1.473	1.256	
Capacity (%)	100.00	94.01 95.75		89.80 91.55	75.35 81.65	69.28	
Storage Time (Days)	0.00	0.604 0.551		2.22 1.66	6.99 5.05	9.96	
Group 2							
Cycle No.	Tbl. 4.3.4-4	X X	11 30	8	14	17 60	
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-4	X X	1.604 1.690	1.435	1.395	1.290 1.392	
Capacity (%)	100.00	X X	91.66 95.43	83.28	79.71	73.71 77.42	
Storage Time (Days)	0.00	X X	1.00 1.00	3.07	5.08	9.16 9.02	
Group 3							
Cycle No.	Tbl. 4.3.4-4	X	26	8			13
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-4	X	1.708	1.516			1.212
Capacity (%)	100.00	X	95.10	86.43			67.71
Storage Time (Days)	0.00	X	1.00	3.04			15.0
Group 4							
Cycle No.	Tbl. 4.3.4-4	X X		8 11		14 ^a	
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-4	X X		1.616 1.591		1.536	
Capacity (%)	100.00	X X		87.92 89.18		80.84	
Storage Time (Days)	0.00	X X		3.11 2.00		7.08	

^a Three cells failed

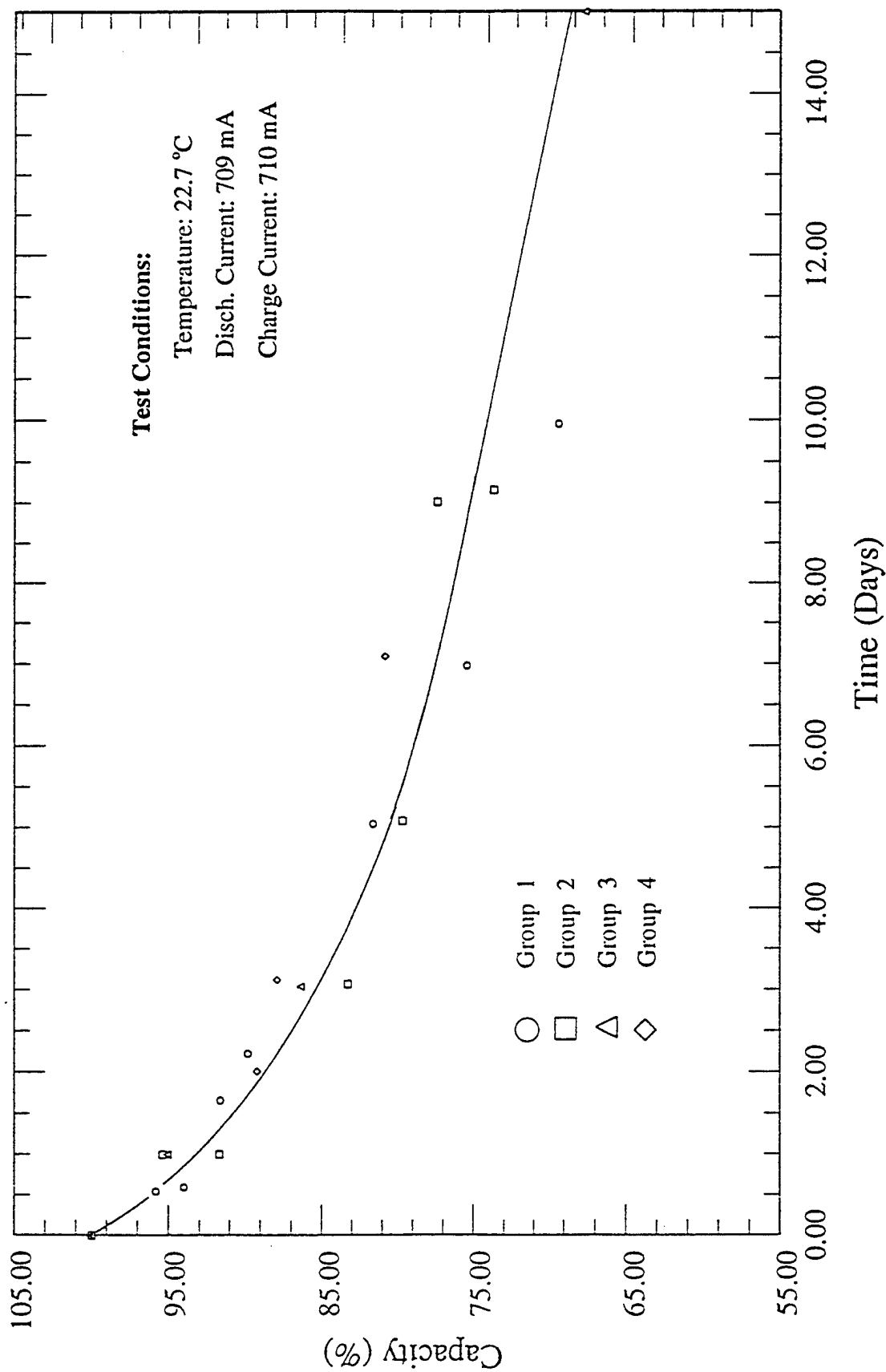


Figure 4.4-4. Company D Self Discharge Capacity vs. Time

Table 4.4-5. Company E (AB₅ Prismatic Cells) Self Discharge at 23.1 °C.

	Nominal Storage Time (Days)						
	0.0	0.50	1.00	2.00	5.00	10.00	>10.00
Group 1							
Cycle No.	Tbl. 4.3.4-5	68	58	16	61		
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-5	2.876	2.792	2.680	2.405		
Capacity (%)	100.00	97.96	94.80	88.60	81.91		
Storage Time (Days)	0.00	0.417	1.04	3.01	5.36		
Group 2							
Cycle No.	Tbl. 4.3.4-5	X X	58	15	60 61		
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-5	X X	2.834	2.720	2.529 2.427		
Capacity (%)	100.00	X X	95.29	89.24	85.04 81.61		
Storage Time (Days)	0.00	X X	0.99	2.68	5.10 6.72		
Group 3							
Cycle No.	Tbl. 4.3.4-5	X X	26		13 35		43
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-5	X X	2.844		2.496 2.468		0.750
Capacity (%)	100.00	X X	93.64		81.17 80.65		24.97
Storage Time (Days)	0.00	X X	1.28		6.41 6.30		30.00
Group 4							
Cycle No.	Tbl. 4.3.4-5	X	7	22			
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-5	X	2.872	2.837 ¹			
Capacity (%)	100.00	X	92.44	91.10			
Storage Time (Days)	0.00	X	1.00	2.86			
Group 5							
Cycle No.	Tbl. 4.3.4-5	X X X	46 59	37 40	5 7 43	33	
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-5	X X X	2.794 2.834	2.584 2.723	2.586 2.575 2.560	2.297	
Capacity (%)	100.00	X X X	92.82 93.93	85.93 90.46	84.62 84.26 85.05	76.39	
Storage Time (Days)	0.00	X X X	1.51 0.985	3.53 2.16	4.04 5.09 4.43	9.99	

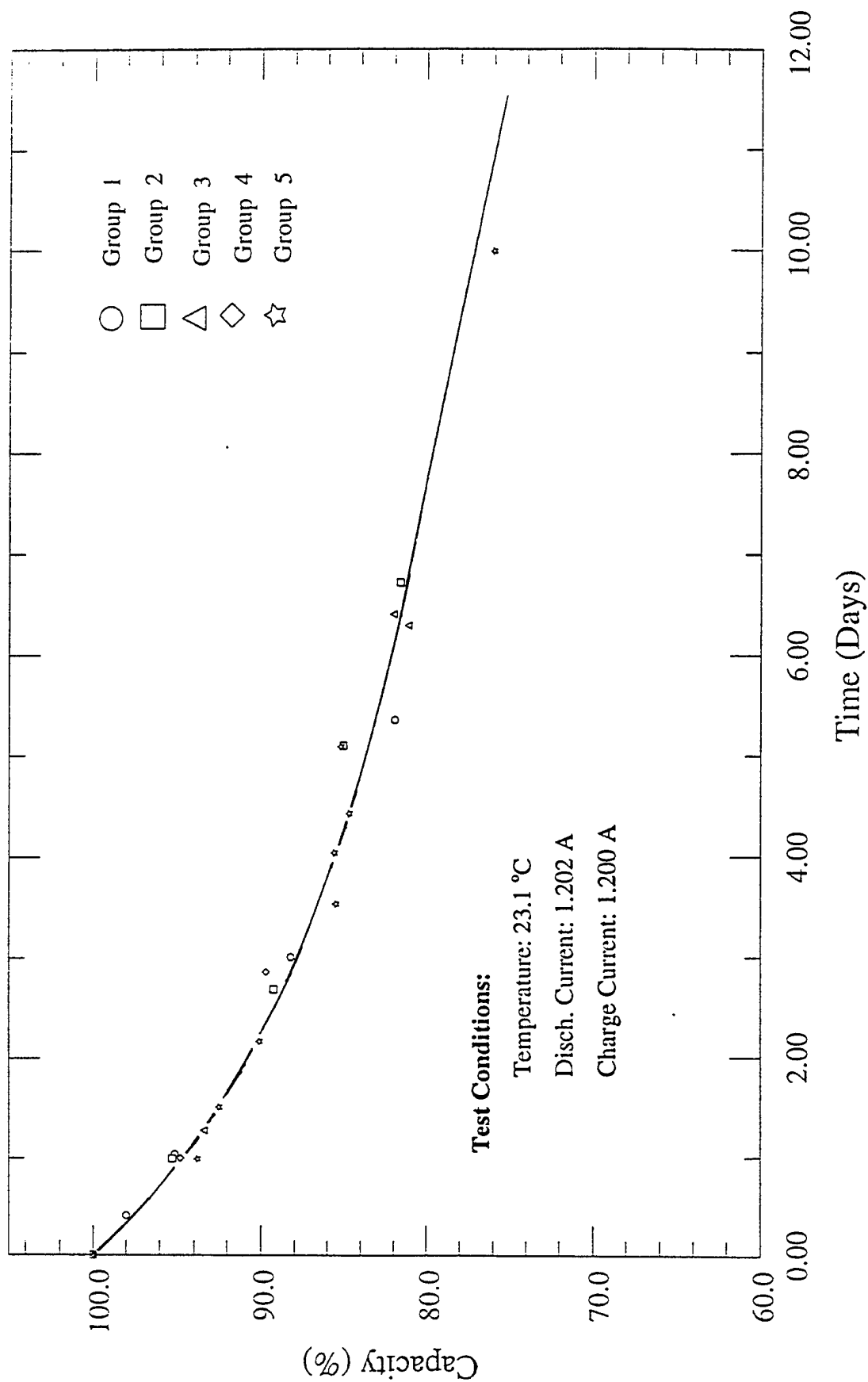


Figure 4.4-5. Company E Self Discharge Capacity vs. Time

Table 4.4-6. Company F (AB₅ Prismatic Cells) Self Discharge at 21.5 °C.

Test Parameters	Nominal Storage Time (Days)					
	0.0	0.5	1	2	5	10
Cycle No.	Tbl. 4.3.4-6	52 60	46	44 49	33	28 42
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-6	0.880 0.922	0.878	0.864 0.852	0.819	0.769 0.775
Capacity (%)	100.00	93.52 97.98	90.33	88.89 87.65	85.40	80.69 79.73
Storage Time (Days)	0.00	0.71 0.34	1.08	1.57 2.00	5.00	7.72 10.00

Table 4.4-7. Company H (AB₂ Cylindrical Cells) Self Discharge at 23.3 °C.

	Nominal Storage Time (Days)						
	0.0	0.5	1	2	5	10	>10
Group 1							
Cycle No.	Tbl. 4.3.4-8	X			14		
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-8	X			1.149		
Capacity (%)	100.00	X			55.97		
Storage Time (Days)	0.00	X			3.66		
Group 4							
Cycle No.	Tbl. 4.3.4-8	X	23 32	26	13 41		49
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-8	X	1.497 1.436	1.310	0.514 0.423		0.000
Capacity (%)	100.00	X	87.54 83.98	75.37	27.89 30.52		00.00
Storage Time (Days)	0.00	X	0.901 1.14	1.83	6.34 6.50		30.00
Group 5							
Cycle No.	Tbl. 4.3.4-8	13	11			9	
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-8	1.514	1.432			0.379	
Capacity (%)	100.00	89.74	84.88			21.17	
Storage Time (Days)	0.00	0.671	0.964			7.08	

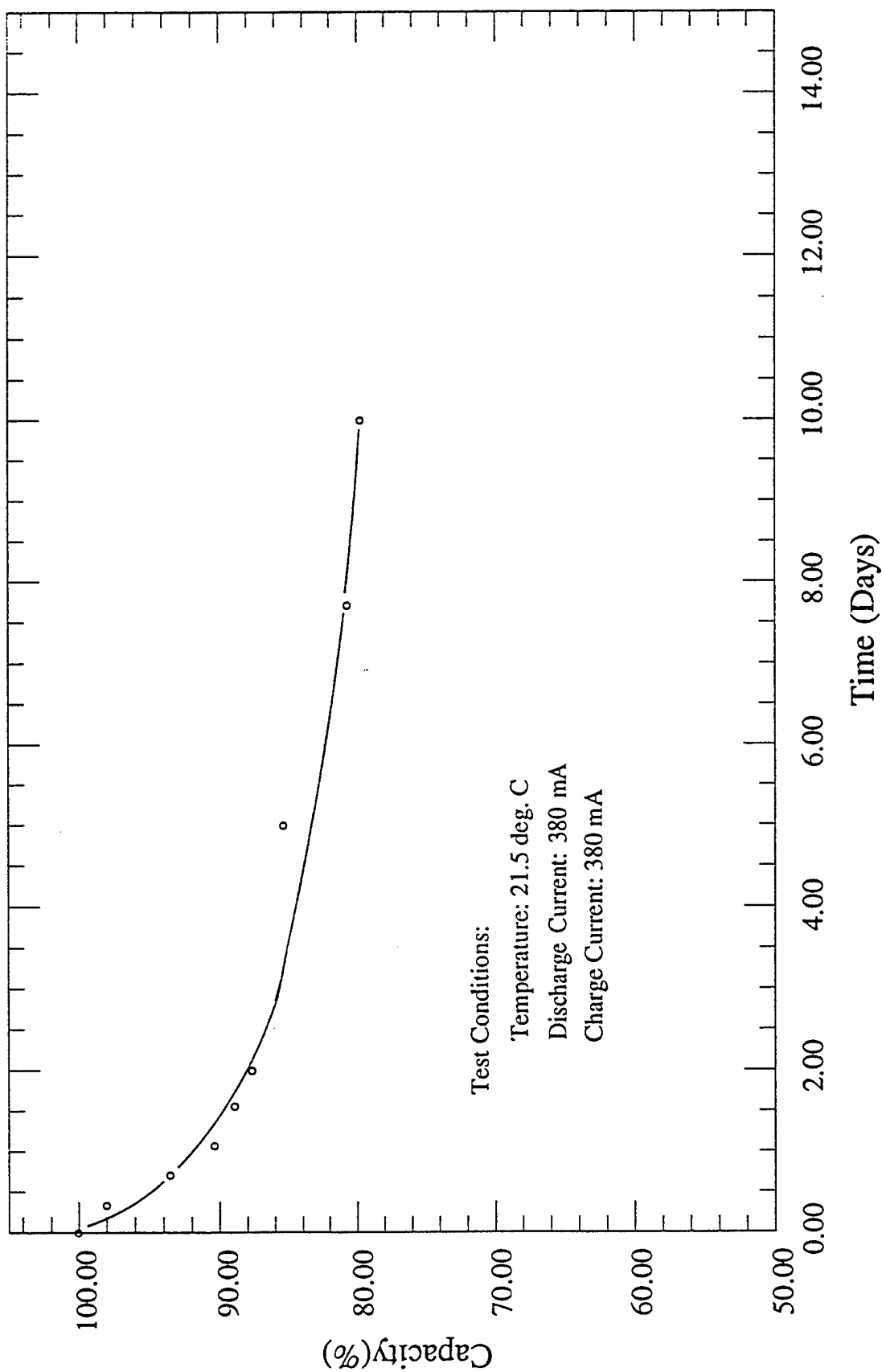


Figure 4.4-6. Company F Self Discharge Capacity vs. Time

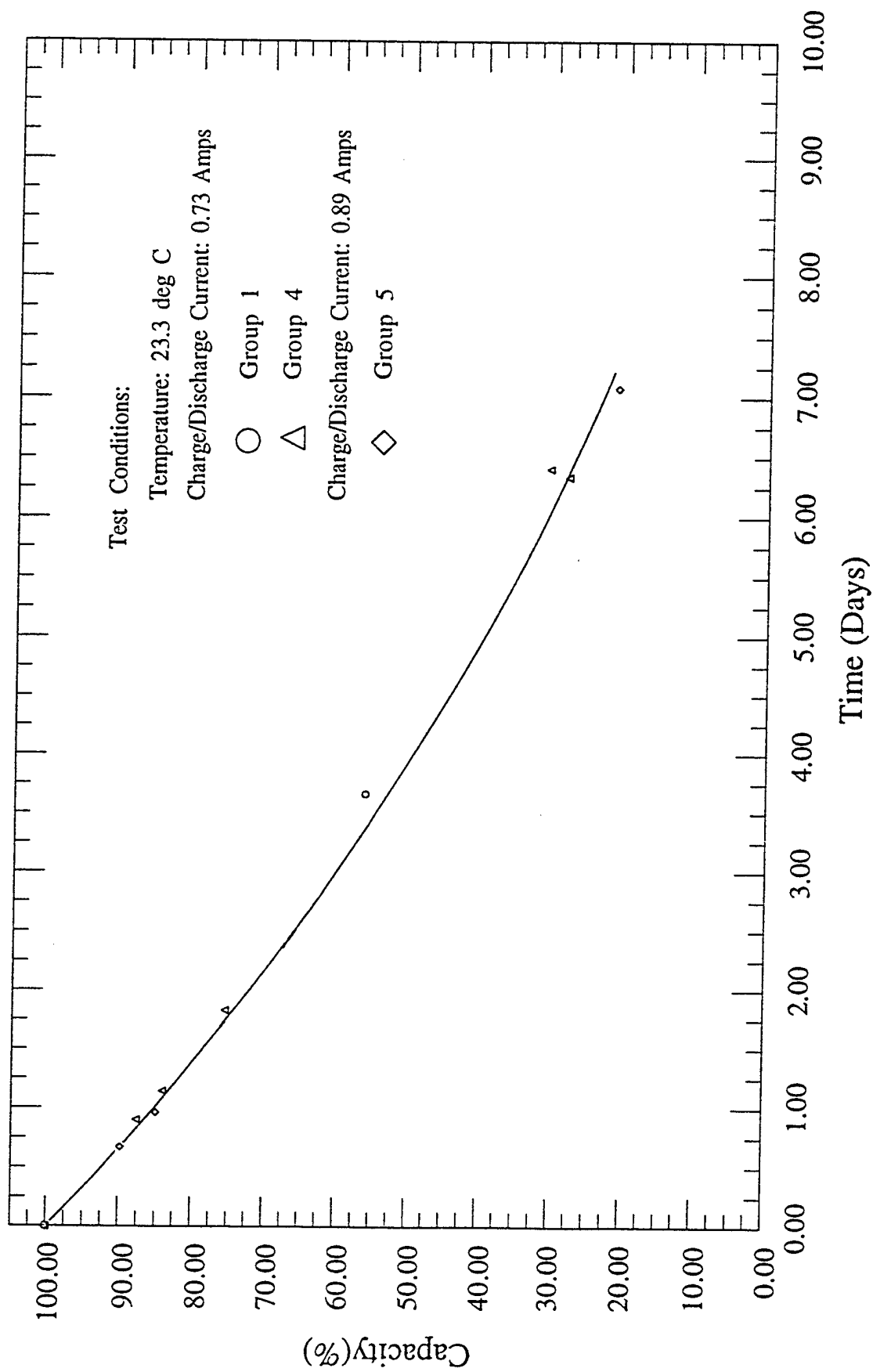


Figure 4.4-7. Company II Self Discharge Capacity vs. Time

Table 4.4-8. Company G (AB₅ Cylindrical Cells) Self Discharge at 22.5 °C.

	Nominal Storage Time (Days)					
	0.0	0.5	1	2	5	10
Group 1 ^a						
Cycle No.	Tbl. 4.3.4-7	X	32	35 41	27	38
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-7	X	2.446	2.426 2.424	2.334	2.170
Capacity (%)	100.00	X	96.99	96.19 96.11	93.55	86.04
Storage Time (Days)	0.00	X	1.00	2.00 2.00	5.17	10.00
Group 2						
Cycle No.	Tbl. 4.3.4-7	X	40		36	
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-7	X	2.535		2.402	
Capacity (%)	100.00	X	96.39		91.33	
Storage Time (Days)	0.00	X	1.22		5.20	
Group 3						
Cycle No.	Tbl. 4.3.4-7	12	6 28	9 ^b	14	
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-7	2.570	2.530 2.565	2.513 ^b	2.431	
Capacity (%)	100.00	96.94	96.79 96.46	96.14 ^b	91.70	
Storage Time (Days)	0.00	0.54	1.02 0.99	2.00 ^b	5.00	
Group 4						
Cycle No.	Tbl. 4.3.4-7	X	6	5	43	
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-7	X	2.438	2.402	2.313	
Capacity (%)	100.00	X	95.23	93.83	88.76	
Storage Time (Days)	0.00	X	0.83	2.98	5.03	
Group 5						
Cycle No.	Tbl. 4.3.4-7	X	5			
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-7	X	2.474			
Capacity (%)	100.00	X	95.89			
Storage Time (Days)	0.00	X	1.27			

^a Group 1 was a battery pack; groups 2-5 were single cells from disassembled battery packs.

^b Single cell data point.

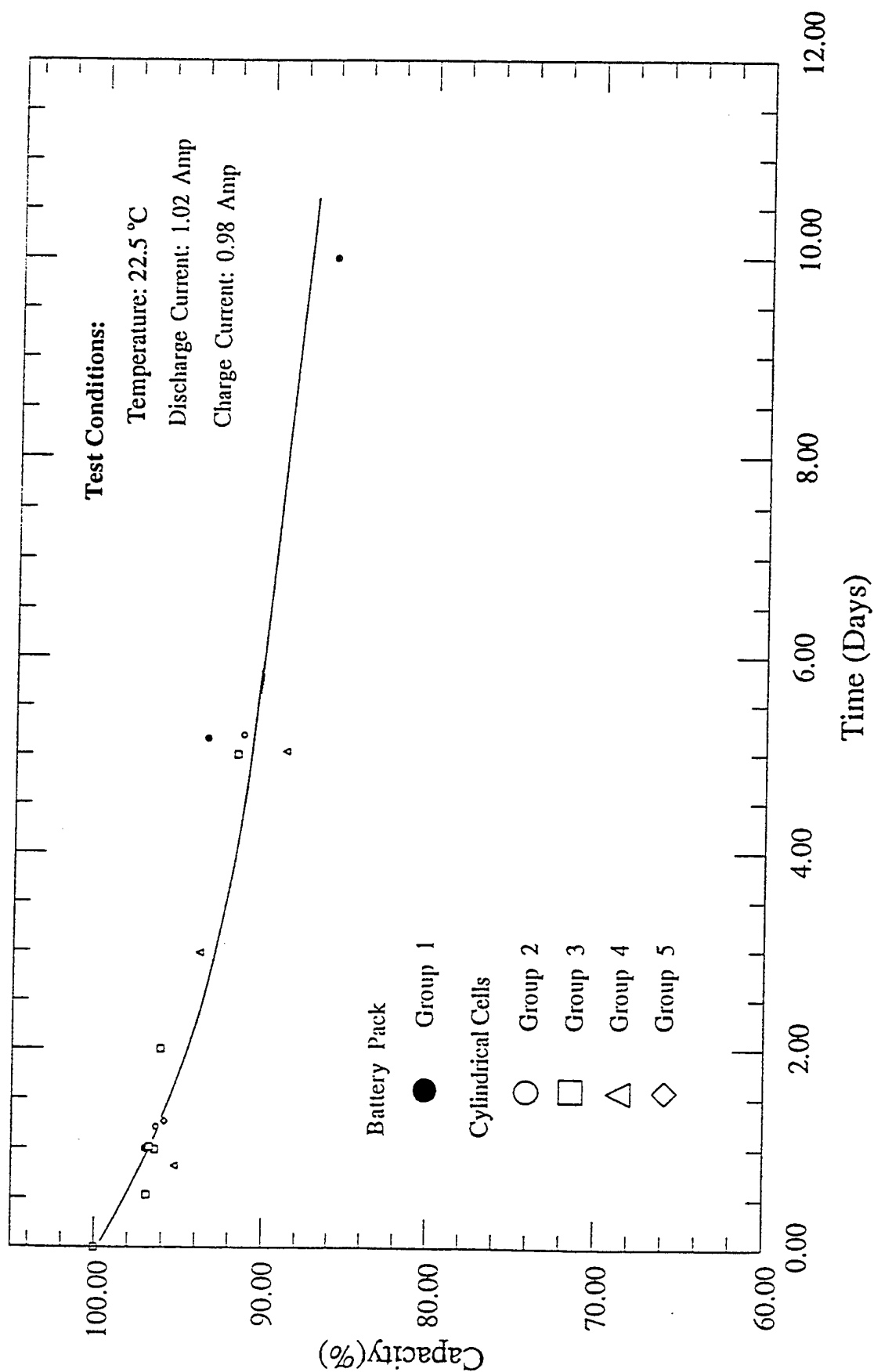


Figure 4.4-8. Company G Self Discharge Capacity vs. Time

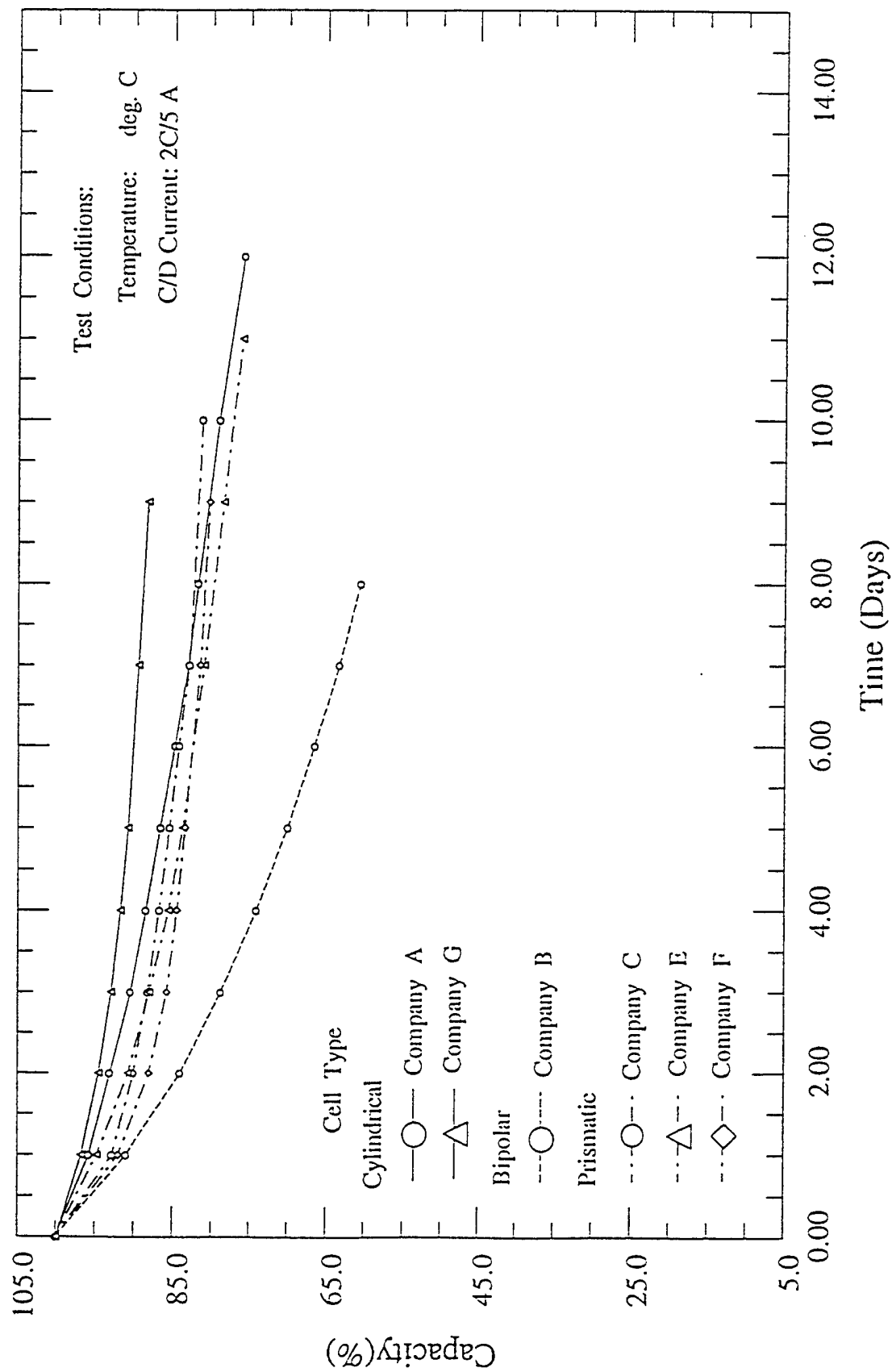


Figure 4.4.1-1. Self Discharge AB₅ Cells at Room Temperature

Company A These cells were a production 2.4 A-h rated cylindrical cell that behaved in a very predictable manner and were extremely tolerant of high and low temperatures and high currents. The data in Table/Figure 4.4-1 showed a repeatable SD with about a 2-4 percent overall variability. These cells were the only ones tested for a very long SD (30 days) due to a breakdown in the environmental chamber that occurred after the cells had been fully charged at the 2C/5 rate. The cells were left on open circuit stand while the chamber was repaired and then discharged 30 days later. The measured capacity was 56 percent and corresponds to a linear loss of about 1.5 percent capacity per day.

Company B These cells were a vented bipolar configuration obtained with three different proprietary MH alloys and rated at 1.66 A-h capacity. The objective with these developmental cells was to evaluate the effect of changing the alloy on SD characteristics of the cell. One of the cells was damaged during delivery and was replaced by the manufacturer. The replacement cell was rated at 1.84 A-h and had to be tested as a separate group, from the other two with the same alloy, due to differences in the charge and discharge currents. Cell performance drifted due to loss of electrolyte from the vented design and the shifting baseline documented in Section 4.3. However, sufficient data were obtained to verify the alloys had different SD characteristics (Table/Figure 4.4-2). In agreement with other studies on alloy additive effects, the alloy with lanthanide series trace additives for lanthanum and transition metal additives for the nickel had the lowest SD rate. The results for this alloy were included in Figure 4.4.1-1 for comparison purposes with production AB₅ alloys. Although these cells performed poorly compared to other AB₅ cells, remember the Company B cell is a vented developmental cell whereas the others are sealed production cells. Also, the alloy was not optimized (presumably the other cells were), but was selected for this test based solely on its composition. However, the bipolar R&D cell with this alloy did have better SD performance than the production AB₂ cells from Company H (Table/Figure 4.4-7).

Company C These cells were the closest in size and A-h capacity to an aircraft battery configuration. The original intent was to procure a cell pack in both vented and sealed configurations. However, the only vented cells available were a lower capacity cell that had been used for two years in an experimental EV. These cells had lost a significant amount of

their original capacity. Company C graciously donated one of these cell packs for the test and a sealed cell pack was purchased. These cells had the most restrictive voltage limits on charge (1.48 V) and temperature limits (no more than a 10 °C temperature rise from room temperature) of all cells tested.

During the initial tests, the sealed cell pack was badly overheated in a series of cycles to over 90 °C due to an error in charging. This error destroyed one of the five cells and seriously bulged the cases of the others. This was the result of not actively cooling the cells during charge. When testing was resumed the four remaining cells had lost 50 percent of their capacity which made any testing of these cells subject to question. Tests were conducted on the damaged cell pack to determine its remaining capacity and what if anything could be learned about its SD characteristics. The manufacturer supplied two additional sealed cells which were configured for single cell tests rather than substitute two full capacity cells for damaged cells in the cell pack.

The two single cells performed well but there was an almost unpredictable variation in cell capacity with each cycle. This variation was tracked down to the cells terminating the charge due to either or both the voltage or temperature limit just shortly before reaching the 50 percent overcharge limit. Typically, the cells would receive anywhere from 45-48 percent overcharge instead of the planned 50 percent overcharge. The variation was also connected to the previous experiment on the cells, as well. For instance, if the cells had been left standing for a period of time or worked hard in a high current discharge experiment the standard 50 percent charge limit would terminate the charge. Then the next reconditioning cycle would terminate on either the voltage or temperature limit without reaching a full charge. These three factors made accurate SD tests difficult but after accounting for these factors and converting the data to percent capacity the results became manageable (Table/Figure 4.4-3).

The results for the two single cells show a significant drop in capacity during the first day followed by a slower almost linear decrease with time. This result is suggestive of two mechanisms for SD or there are two electrochemically active forms of hydrogen in the cell. The latter explanation makes sense if the cell is behaving as a mixed Ni-MH and Ni-

Hydrogen cell. Excess hydrogen gas produced during charge remains in the sealed cell and is capable of an electrochemical reaction if a test is done immediately after charging as in the capacity tests. This excess hydrogen gas may diffuse into the MH alloy or leak out of the cell during the first day. This is also consistent with the bulged cells produced when the original cell pack was overheated. A pressure instrumented cell would supply data to resolve the fast initial loss of capacity. The data from the two single cells were included in the comparison in Figure 4.4.1-1 as representative of the cells produced by Company C. Note in Figure 4.4.1-1 that these cells show a flatter SD characteristic and higher retained capacity than any other prismatic design cell after the initial loss on the first day.

The vented used cell pack showed no unusual characteristics during testing. It is notable that neither the new or the used cell packs display the initial drop in capacity observed with the new single cells. Whether this lack of initial fast loss is due to a leveling effect from multiple cells in parallel, to changes in the vented pack with use and damage to the new sealed pack, or some other explanation is debatable.

Company E These production 3 A-h prismatic cells were well behaved during capacity tests and exhibited no unusual characteristics during the SD tests (Table/Figure 4.4-5). The initial capacity climbed fairly rapidly and stabilized at 3.05 A-h repeatably from cell group to group. Variation in the cells was about 2-4 percent consistent with a well controlled manufacturing process as with the cells from Company A. Capacity loss was approximately 1.5-2.0 percent per day almost matching the cells from Company A.

Company F These production prismatic cells had a measured capacity of 0.93 A-h slightly higher than the rated capacity of 0.85 A-h and were provided courtesy of Company F. These cells are based on the same technology under development for the USABC and the DOE for use in large prismatic cells for EV applications. Cell performance during SD was again well behaved (Table/Figure 4.4-6) but did exhibit a rapid loss of capacity during the first two days followed by a slower almost linear loss in capacity. Extrapolation of the linear portion of the SD curve shows an initial capacity near 0.85 A-h. It is notable that charge voltage limit recommended by the manufacturer (1.8 V) was the highest observed or used in this test. This high voltage limit is suggestive of a more stable MH alloy with a different formulation.

During testing one of the five cells consistently gave a lower value than the other three in the group and failed after 68 cycles. The remaining unused cell replaced the failed cell and after cycles to equalize its capacity was included in the test data after cycle 90. Cell to cell variability was extremely low with these cells once the failing cell was removed from consideration. All of the SD data were obtained prior to cycle 68 and data from the failing cell was not included in the test results.

Company G These production 2.5 A-h cylindrical cells were also well behaved during testing and exhibited no unusual characteristics. The cells were originally procured in 9 cell battery packs and testing was initiated using the packs. However, the packs had internal current and temperature limit switches that precluded some of the testing required by the program and were disassembled to provide single cells for later tests. Neither the cell packs or cells exhibited the rapid loss in capacity during the first day or two of storage (Table/Figure 4.4-8), but did show the steady increase in capacity with cycles exhibited by Company A cells. In addition, the cells exhibited a little more cell to cell variability (4-6 percent) compared to Company A, E or F and the highest retained capacity over time of all the cells tested. Capacity loss was close to 1 percent per day.

4.4.2 AB₂ SINGLE CELLS SELF DISCHARGE

Two samples of AB₂ batteries obtained from the only worldwide production sources Companies D and H were evaluated for their SD characteristics. Both samples were cylindrical cells. Attempts to obtain R&D prototype prismatic EV cells from Ovonic Battery Co., Inc. through the USABC and the DOE were unsuccessful. All cells were allocated and any detailed technical data could not be made available for proprietary reasons. However, both of the small commercial cells are based on licensed technology from Ovonic Battery Co., Inc. and should show similar but not the latest trends in AB₂ battery technology. The SD data was previously shown in Section 4.4. Again, as with the AB₅ cells, the best fit curve to the actual data (Figures 4.4-4 and -7) was used to generate a comparison graph and is presented in Figure 4.4.2-1.

Since both Company D and H cells are based on licensed Ovonic technology, it is obvious Ovonic has made improvements in the storage capacity of the AB₂ MH alloy. The

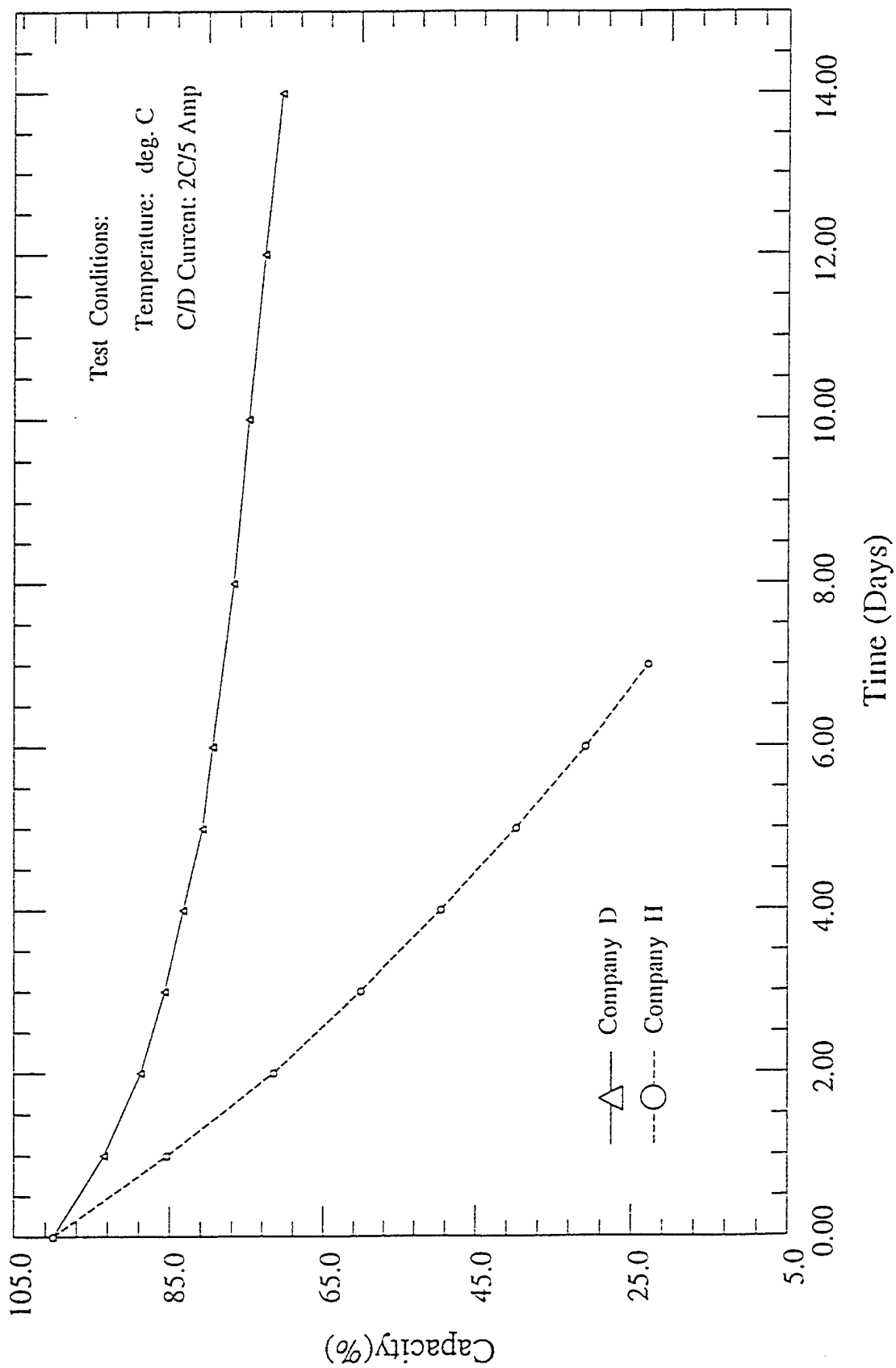


Figure 4.4.2-1. Self Discharge of AB₂ Cylindrical Cells at Room Temperature

data for Company D cells is consistent with that reported by Ovonic [Ratnakumar, et al., 1993] but that for Company H is not. This may be the difference between first and second generation technology transfer from Ovonic. Further improvements in the SD characteristics of AB₂ batteries by Ovonic are suggested in the same report by changes in the electrolyte and by a recent patent award [Fetcenko et al., 1993] for an improved electrode alloy. Future SD tests of Ovonic prismatic EV cells should substantiate any further improvements. Pertinent observations on Company D and H cells during the SD test are discussed here.

Company D These cells were rated at 1.8 A-h capacity and showed fairly erratic behavior during the capacity tests (Figure 4.3.4-4) and little tolerance for either temperature or current variations on charge or discharge. The cells exhibited a rapid rise in voltage during charge and typically the charge terminated before reaching the standard 50 percent overcharge. Since the amount of charge varied from cycle to cycle the SD data also showed a larger deviation approximately 5-10 percent. This a factor of 2-3 greater than the AB₅ cylindrical cells tested. This variance in charge acceptance and subsequent discharge capacity necessitated normalizing the SD capacity measurements as percent capacity. The normalization factor used corresponded to the 10 cycle average CT (Table 4.3.4-4) that overlapped the cycle no. for the particular SD test. Self discharge percent capacity for these cells showed large deviations from group to group with an approximate exponential loss of 25 +/- 5 percent of capacity in 10 days. There was no evidence of the fast loss of capacity during the first day or two of storage observed with several of the AB₅ cells. If the fast loss is present it was covered up by the 5-10 percent deviation in the SD data.

Company H These cells were rated at 2.5 A-h. None of the CT data (Table 4.3-1) substantiated this value. It is noticeable that the capacity test using the 2C/5 discharge rate gave a much lower capacity than either the MRV or C/10 CT. All subsequent tests on groups 1 and 4 used the 1.9 A-h capacity as a basis for reconditioning cycles whereas group 5 used the 2.2 A-h capacity obtained from the C/10 CT data. These cells were extremely sensitive to temperature and current changes. One group of cells was destroyed early in the tests when an attempt to do a 5C discharge was unsuccessful. Subsequent tests at both 71 °C and -40 °C reduced the capacity of the cells. The capacity was not recovered by reconditioning the cells

at room temperature. Presumably high and low temperature operation alters the chemical formulation of the hydride so it is unable to store hydrogen as efficiently as cells operated at room temperature and lower charge and discharge currents. Also 2 of the 25 cells obtained for tests were inoperative when the first test was done on each.

SD data obtained on Company H cells required conversion to percent capacity for comparisons from group to group and with other cell manufacturer's test data. This conversion was necessitated not by a rising baseline capacity, but by a declining capacity with increasing cycles and due to damage to the cells by high and low temperature and high current tests interspersed throughout the cycle regime for each group. Despite the variability in cell capacity, the SD data was fairly predictable since the cells did accept the standard 50 percent overcharge unlike Company D cells. Although the SD data was not as extensive as with other manufacturers the plot of SD capacity versus time (Figure 4.4-7) showed an exponential decrease in capacity at a very high rate. After 5 days storage at 23.3 °C Company H cells lost 60 percent of their initial capacity.

4.4.3 TEMPERATURE EFFECTS ON SELF DISCHARGE

Temperature effects on the SD capacity of a battery is a significant concern for an aircraft application. Aircraft typically sit on the flight line ramp overnight, for days, or even weeks if maintenance is required in temperatures that can range from -40 to 71 °C. During such maintenance and normal crew operations, repair and service personnel access the aircraft frequently to perform duties and power up various subsystems. Depending on what is to be done and how long it will take, power may be supplied by an Auxiliary Power Unit (APU) or the aircraft battery may be used to do simple equipment checks and to raise and lower the canopy. If the aircraft battery has a high SD rate at normal temperatures, does not work well at low temperatures, and/or does not retain capacity at higher temperatures the battery may have to be removed and stored creating extra work which raises the costs of flight line operations. This may also necessitate having a supply of replacement batteries available, particularly if the aircraft are deployed to a remote site.

During this study GRCI collected elevated temperature data on test cells from Company A, E and H. These were AB₅ cylindrical and prismatic and AB₂ cylindrical cells,

respectively. The data are presented in tabular form in Table 4.4.3-1 and graphically in Figure 4.4.3-1. The data indicate that after approximately two days storage the AB₅ prismatic cells retain up to 40 percent of their room temperature capacity at 71 °C. This is twice as good as the AB₅ cylindrical cells and almost 20 times better than the AB₂ cylindrical cells. At room temperature the AB₅ cylindrical cells out perform the prismatic cells by a slight margin and both are significantly better than the tested AB₂ cylindrical cell. It would be worthwhile to continue the SD temperature studies, but funds and time did not permit these extended studies. However, WL/POOB personnel are continuing to gather this data which may be the subject of a later report. Special emphasis is on the Company D AB₂ cylindrical cells which performed so much better than the Company G cells in the room temperature SD tests.

Table 4.4.3-1. Self Discharge at Various Temperatures after 2 Days Storage

Nom. Storage Temp. (°C)	71	49	24	20
Company A (AB₅ Cylindrical Cells)				
Group No.	2	2	2	2
Cycle No.	57	54	26	77
Disch. Capacity, C _d (A-h)	0.581	1.807	2.156	2.283
Capacity (%)	23.38	72.72	89.91	90.24
Storage Time (Days)	2.25	2.16	2.61	2.81
Meas. Temperature (°C)	71.1	48.7	22.4	19.0
Company E (AB₅ Prismatic Cells)				
Group No.	3	3	5	X
Cycle No.	40	37	40	X
Disch. Capacity, C _d (A-h)	1.350	2.313	2.723	X
Capacity (%)	44.53	75.59	88.27	X
Storage Time (Days)	2.30	2.20	2.16	X
Meas. Temperature (°C)	69.7	48.0	21.6	X
Company H (AB₂ Cylindrical Cells)				
Group No.	4	4	4	X
Cycle No.	46	43	26	X
Disch. Capacity, C _d (A-h)	0.037	0.377	1.310	X
Capacity (%)	2.82	27.58	75.37	X
Storage Time (Days)	1.60 ^a	2.16	1.83	X
Meas. Temperature (°C)	69.9	48.5	23.4	X

^a 1.60 days at 69.9 °C plus 1.07 days at 24 °C.

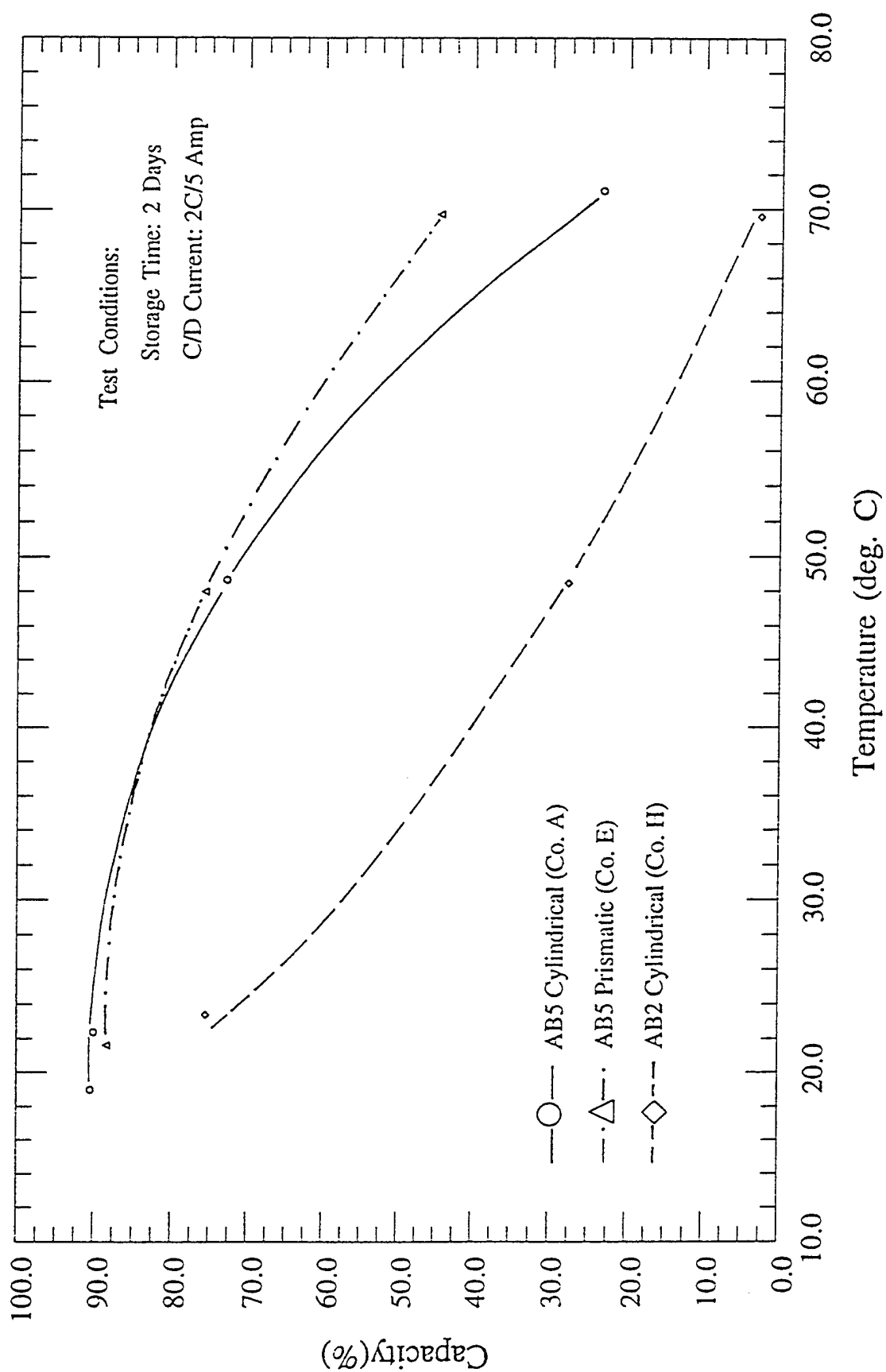


Figure 4.4.3-1. Self Discharge Capacity vs. Temperature

4.4.4. SD OBSERVATIONS AND SUMMARY

For comparison purposes between AB_2 and AB_5 cylindrical cells the cylindrical cell data from Figures 4.4.1-1 and 4.4.2-1 were combined and are presented in Figure 4.4.4-1. Comparisons of all the SD data at room temperature and above confirmed:

- The overall SD rate for both AB_5 and AB_2 cells at room temperature is 1-2.5 percent per day.
- AB_5 cylindrical cell manufacturers claims of 1 percent per day loss appear valid.
- The SD rate (Table/Figure 4.4-2) for AB_5 cells is highly dependent on the composition of the MH alloy. Substitution of lanthanide series elements for the lanthanum (A) and regular transition elements for the nickel (B) element in the alloy is beneficial in lowering the SD rate.
- The effect of different alloy manufacturing processes on SD rates was not verified. Cells from different manufacturing processes were not available and data on the manufacturing processes of the cells tested are proprietary to the manufacturer.
- Prismatic AB_5 cells (Figure 4.4.1-1) initially have a higher SD rate than their cylindrical counterparts but level off and as the data suggests, they may over longer periods have better SD characteristics than cylindrical cells.
- AB_2 cell SD data published by Ovonic Battery Co. [Ratnakumar, et al., 1993] were verified for Company D but not for Company H cells.
- Comparisons between AB_2 cylindrical and AB_5 cylindrical cells (Figure 4.4.4-1) show the best commercial AB_2 cells have a 2.5 higher SD rate than the best AB_5 commercial cells.
- Limited temperature studies on SD after approximately 2 days storage show AB_5 cells lose capacity much slower than the AB_2 cells tested with increasing temperature. This observation does not include data for AB_2 Company D cells which were not tested and which performed much better than the AB_2 Company H cells in the SD tests.
- At temperatures above 49 °C prismatic AB_5 cells retain capacity almost twice as well as cylindrical AB_2 cells.

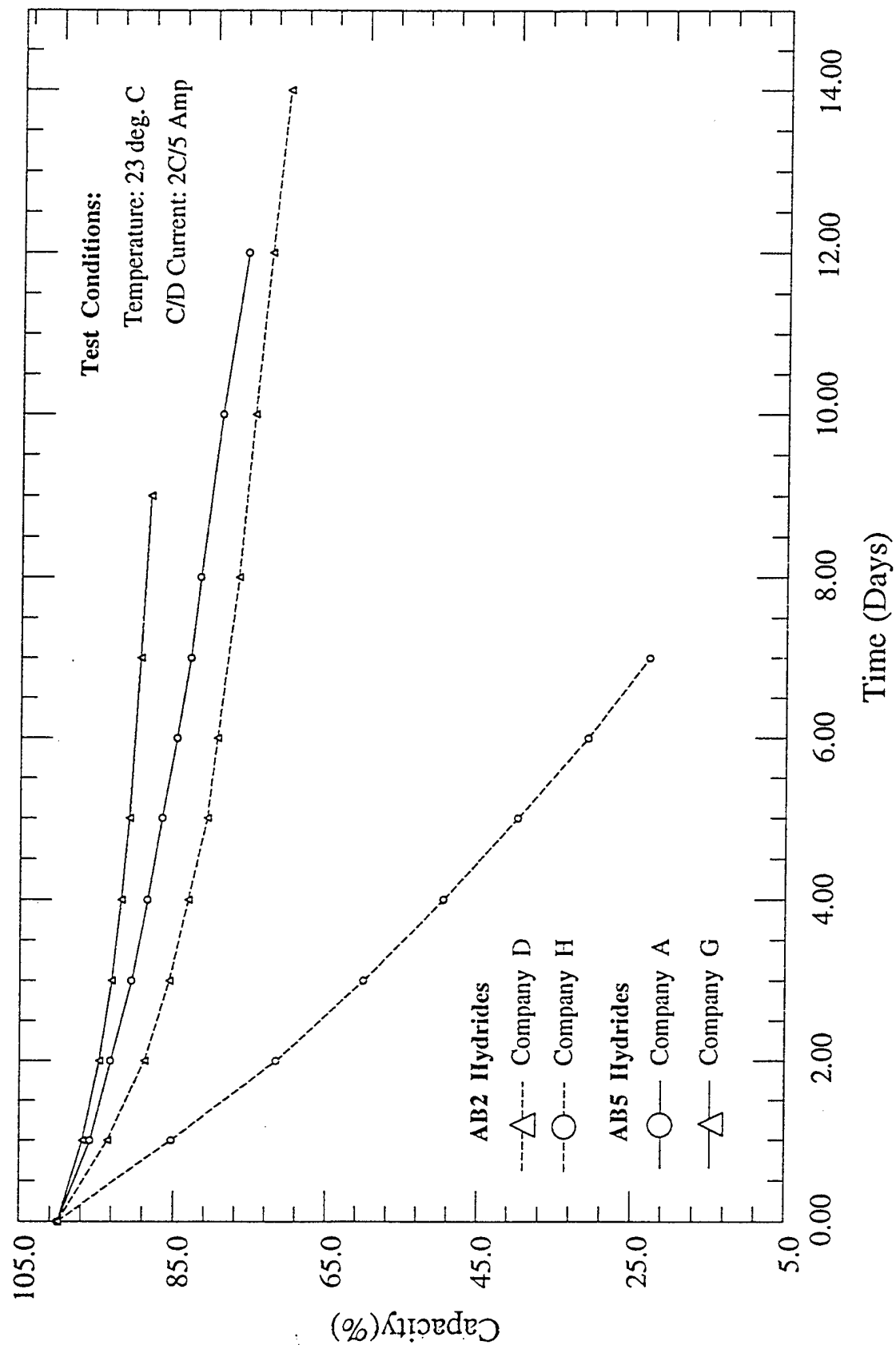


Figure 4.4.4-1. Self Discharge of Ni-MH Cylindrical Cells at Room Temperature

Summary At the present time, AB₅ cylindrical cells have the best SD characteristics of the cells and batteries tested. However, the data also suggests the prismatic cell design may retain capacity better than the cylindrical design for longer periods of storage at room temperature and definitely retains capacity better at elevated temperatures. However, SD rates of the commercial MH cells tested are higher than would be desirable for an aircraft battery application.

Lowering the SD rate at room temperature to 0.2 percent per day or better would be desirable and to at least 0.5 percent per day should be required in an aircraft battery development program. Retention of at least 75 percent of capacity after 2 days of storage above 49 °C is also a requirement. Such improvements may be accomplished through alloy chemistry optimization, alloy manufacturing process changes, and suitable cell design (bipolar, cylindrical or prismatic) and construction.

4.5 CONSTANT DISCHARGE CURRENT (CDC) TESTS This series of tests was designed to measure the capability of the cell to respond to different current loads at various temperatures consistent with an operational aircraft environment. Typical loads to open and close the canopy or to restart an engine electrically in an emergency can be as high as 10C for a few msec then drop to about 2-5C for longer seconds or even minutes. Other current loads can be as low as C/10. Temperature for these operations can range from -40 °C to possibly as high as 71 °C. Tests were conducted over the entire temperature range and the current was varied from 2C/5 to 10C based on the 2C/5 CT results for the different company cells.

The following procedure was established to perform the CDC tests on a four cell group¹ and used a 2C/5 charge current at room temperature prior to the discharge tests:

- Perform two conditioning cycles at room temperature. The cell temperature limit is 75°C during charging unless specified otherwise in Section 4.3.
- Equilibrate the cells on open circuit at the test temperature; recording the voltage (V) and temperature (°C) for each cell at 10 min. intervals. When two of the cells reached the test temperature begin the discharge.

¹ In the event there are less than three test samples, repeat the procedure three (3) times for only one cell or cell pack and two (2) times if there are two cells or cell packs under test.

- Discharge the cells at the specified CDC rate to a 0.90V cutoff.
- Record the voltage, current (A), discharge capacity, C_d (A-h), time (min.), and temperature for each cell during the discharge.
- Return the cells to room temperature for conditioning before the next test.
- From the measured capacity at each temperature and comparison with baseline capacity measurements (Tables 4.3.4-1 to -8), calculate the percent capacity during discharge at each test temperature.
- Plot percent capacity versus discharge current and temperature for each group of cells by manufacturer.

The results of the CDC tests are separated by AB_5 and AB_2 metal hydride alloy and are presented and discussed in the following sections.

4.5.1 AB_5 Battery and Single Cell Constant Discharge Current (CDC) Tests Five samples of AB_5 batteries and single cells from manufacturers A, C, E, F, and G were evaluated for their CDC characteristics. The results of the CDC tests by company are presented here.

4.5.1.1 Company A (AB_5 Cylindrical Cells) Company A cells exhibited extremely rugged performance while undergoing CDC tests. These cells always recovered from high currents and high and low temperatures after several FCR cycles with no observed ill effects. There were no observations of high or low resistance indicative of an open circuit or a shorted cell. Group performance, as with the SD tests (Section 4.4), was predictable and reliable with about 1-2 percent variation from cell to cell. These results are indicative of a well controlled manufacturing process and a robust cell design. The results of the CDC tests are presented in Table 4.5.1.1-1 to 4.5.1.1-3 and graphically in Figures 4.5.1.1-1 and 4.5.1.1-2.

4.5.1.2 Company C (AB_5 Prismatic Cells) The only cells from Company C subjected to CDC tests were the two undamaged replacement cells (Group 2). Tests of the damaged and used cell packs would have supplied erroneous data that would not have been representative of the capability of these cells. Since only two cells were available of this configuration, two determinations under each condition were necessary to obtain representative data. Variations

Table 4.5.1.1-1. Company A CDC Results at 71 and 49 °C

Nominal CDC (A)	1.0	2.4	4.8	12.0	24.0
71 °C					
Group 2					
Cycle No.	80	37	91	86	X ^a
Disch. Capacity, C _d (A-h)	2.516	2.368	2.308	1.524	X ^a
Capacity (%)	99.45	98.18	95.02	62.74	X ^a
Current (A)	0.928	2.40	4.81	12.01	X ^a
Temperature (°C)	70.2	68.5	70.7	70.0	X ^a
49 °C					
Group 2					
Cycle No.	63	32	66 69		X ^a
Disch. Capacity, C _d (A-h)	2.531	2.302	2.458 2.416		X ^a
Capacity (%)	99.29	95.44	96.43 94.78		X ^a
Current (A)	0.941	2.20	5.99 4.75		X ^a
Temperature (°C)	51.3	49.5	47.5 46.4		X ^a
Group 4					
Cycle No.	101				X ^a
Disch. Capacity, C _d (A-h)	2.256				X ^a
Capacity (%)	93.73				X ^a
Current (A)	0.961				X ^a
Temperature (°C)	52.7				X ^a
Group 5					
Cycle No.	101				X ^a
Disch. Capacity, C _d (A-h)	2.282				X ^a
Capacity (%)	93.60				X ^a
Current (A)	0.963				X ^a
Temperature (°C)	52.4				X ^a

^a Deleted: 24.0 amp discharge results at 23.3 °C.

Table 4.5.1.1-2. Company A CDC Results at 24 and 0 °C

Nominal CDC (A)	1.0	2.4	4.8	12.0	24.0
24 °C					
Group 1					
Cycle No.	Table 1		52	50	59
Disch. Capacity, C _d (A-h)	Table 1		2.237	2.122	0.000
Capacity (%)	100.00		94.23	89.38	00.00
Current (A)	0.978		4.79	9.61	24.0
Temperature (°C)	23.8		25.4	24.8	23.3
Group 2					
Cycle No.	Table 1				X ^a
Disch. Capacity, C _d (A-h)	Table 1				X ^a
Capacity (%)	100.00				X ^a
Current (A)	0.953				X ^a
Temperature (°C)	22.6				X ^a
Group 4					
Cycle No.	Table 1	21			X ^a
Disch. Capacity, C _d (A-h)	Table 1	2.180			X ^a
Capacity (%)	100.00	92.53			X ^a
Current (A)	0.952	2.40			X ^a
Temperature (°C)	24.0	25.9			X ^a
Group 5					
Cycle No.	Table 1	21			X ^a
Disch. Capacity, C _d (A-h)	Table 1	2.165			X ^a
Capacity (%)	100.00	91.08			X ^a
Current (A)	0.962	2.41			X ^a
Temperature (°C)	24.2	25.8			X ^a
0 °C					
Group 4					
Cycle No.	34	37	73		X ^a
Disch. Capacity, C _d (A-h)	2.240	2.164	2.065		X ^a
Capacity (%)	95.56	92.32	84.25		X ^a
Current (A)	0.921	2.39	4.77		X ^a
Temperature (°C)	-1.0	4.7	-0.1		X ^a
Group 5					
Cycle No.	34	37	73		X ^a
Disch. Capacity, C _d (A-h)	2.273	2.208	2.118		X ^a
Capacity (%)	94.95	92.23	85.64		X ^a
Current (A)	0.974	2.40	4.80		X ^a
Temperature (°C)	-0.8	4.6	0.2		X ^a

^a Deleted: 24.0 amp discharge results at 23.3 °C.

Table 4.5.1.1-3. Company A CDC Results at -18 and -40 °C

Nominal CDC (A)	1.0	2.4	4.8	12.0	24.0
-18 °C					
Group 4					
Cycle No.	70	42	83	X ^b	X ^a
Disch. Capacity, C _d (A-h)	2.192	1.887	0.906	X ^b	X ^a
Capacity (%)	89.32	80.20	36.95	X ^b	X ^a
Current (A)	0.917	2.38	4.78	X ^b	X ^a
Temperature (°C)	-17.6	-17.0	-18.1	X ^b	X ^a
Group 5					
Cycle No.	70	42	83	X ^b	X ^a
Disch. Capacity, C _d (A-h)	2.200	1.961	0.720	X ^b	X ^a
Capacity (%)	87.93	81.50	28.87	X ^b	X ^a
Current (A)	0.975	2.40	4.80	X ^b	X ^a
Temperature (°C)	-17.4	-16.9	-17.8	X ^b	X ^a
-40 °C					
Group 4					
Cycle No.	45	48	X ^c	X ^b	X ^a
Disch. Capacity, C _d (A-h)	0.209	0.020	X ^c	X ^b	X ^a
Capacity (%)	8.88	0.85	X ^c	X ^b	X ^a
Current (A)	0.963	2.35	X ^c	X ^b	X ^a
Temperature (°C)	-39.0	-39.3	X ^c	X ^b	X ^a
Group 5					
Cycle No.	45	48	X ^c	X ^b	X ^a
Disch. Capacity, C _d (A-h)	0.187	0.020	X ^c	X ^b	X ^a
Capacity (%)	7.77	0.83	X ^c	X ^b	X ^a
Current (A)	0.965	2.40	X ^c	X ^b	X ^a
Temperature (°C)	-39.0	-39.1	X ^c	X ^b	X ^a

^a Deleted: 24.0 amp discharge results at 23.3 °C.

^b Deleted: 4.8 amp discharge results at -18.0 °C.

^c Deleted: 2.4 amp discharge results at -39.1 °C.

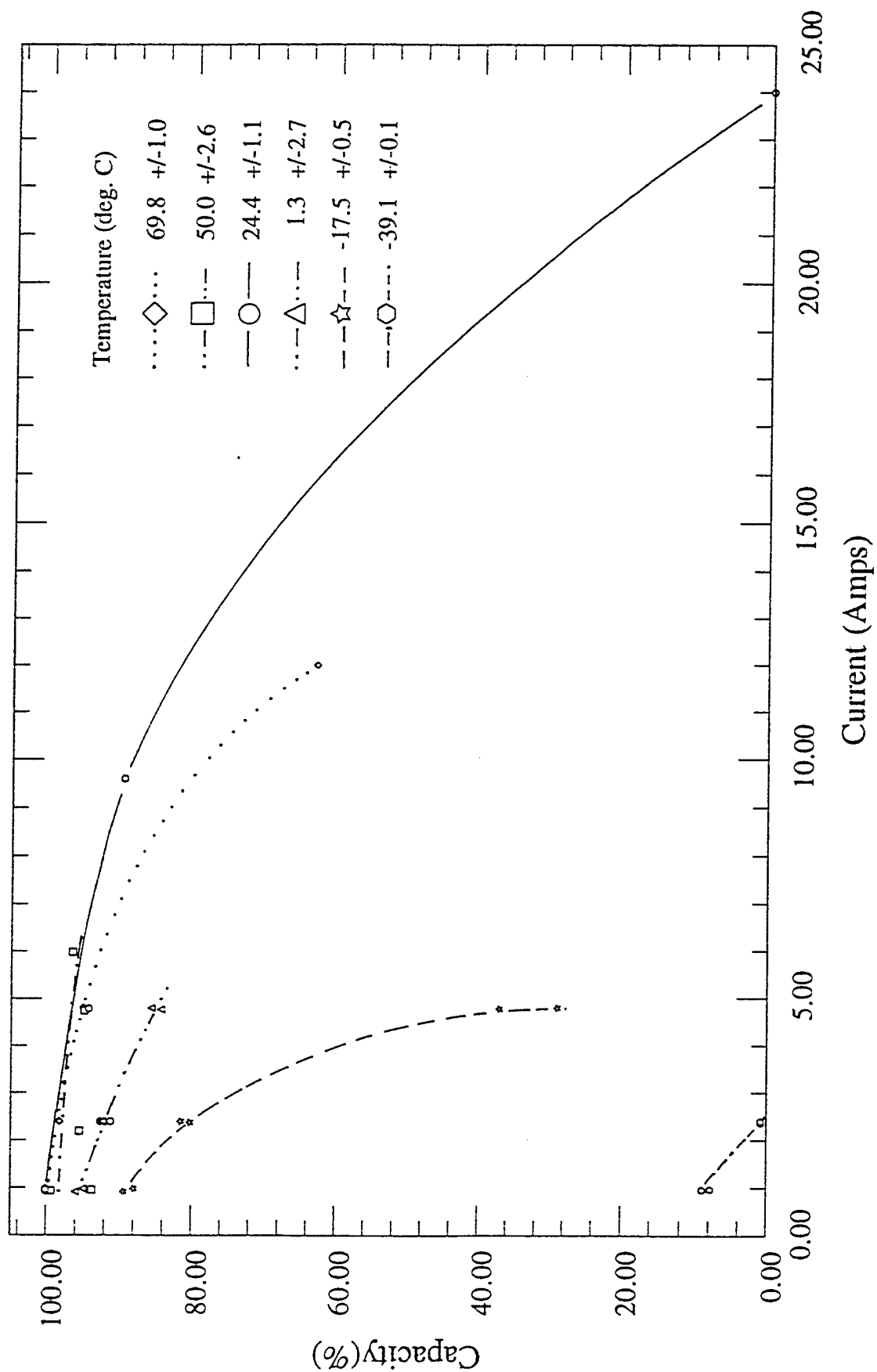


Figure 4.5.1.1-1. Company A CDC Capacity vs. Current

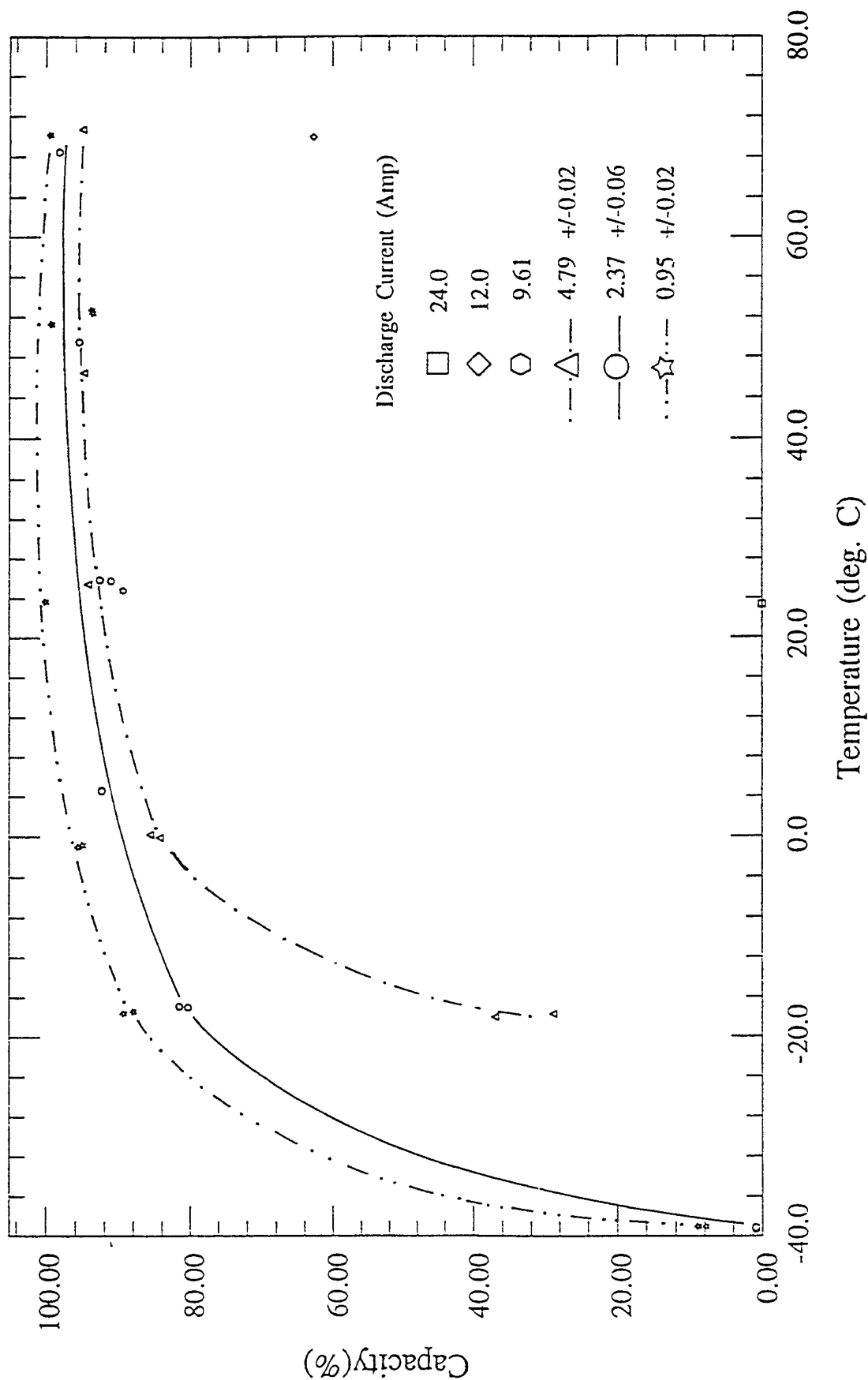


Figure 4.5.1.1-2. Company A CDC Capacity vs. Temperature

in the A-h capacity accepted during charge necessitated individual capacity determinations on the cycle prior to the CDC test. Cell discharge capacity would have shown less deviation if the manufacturer's upper limits on cell voltage and temperature increase during charge were improved and consistent with other AB₅ prismatic cell limits. In addition, due to the large capacity of these cells, tests were limited to a 5C discharge using rack 3 circuit 3 (Figure 3-1). The results of the CDC tests for Company C cells are reported in Table/Figure 4.5.1.2-1.

Table 4.5.1.2-1. Company C Group 2 CDC Results at 24 °C.

Nominal CDC (A)	16	40	80	200	400
Cycle No.	37 44 70 74 81 87 90 93 109	38 45 71 75 82 88	91 94	110	X ^a
Disch. Capacity, C _d (A-h)	37.0 36.2 50.7 47.9 44.9 42.8 42.7 43.3 45.0	34.6 33.2 46.5 44.5 41.9 39.9	37.4 37.3	13.6	X ^a
Capacity (%)	100.00	93.5 91.7 91.7 92.9 93.3 93.2	87.6 86.1	30.2	X ^a
Current (A)	15.2	37.9	75.8	187.5	X ^a
Temperature (°C)	25.8	25.7	25.8	25.5	X ^a

^a Deleted: Test equipment limitations.

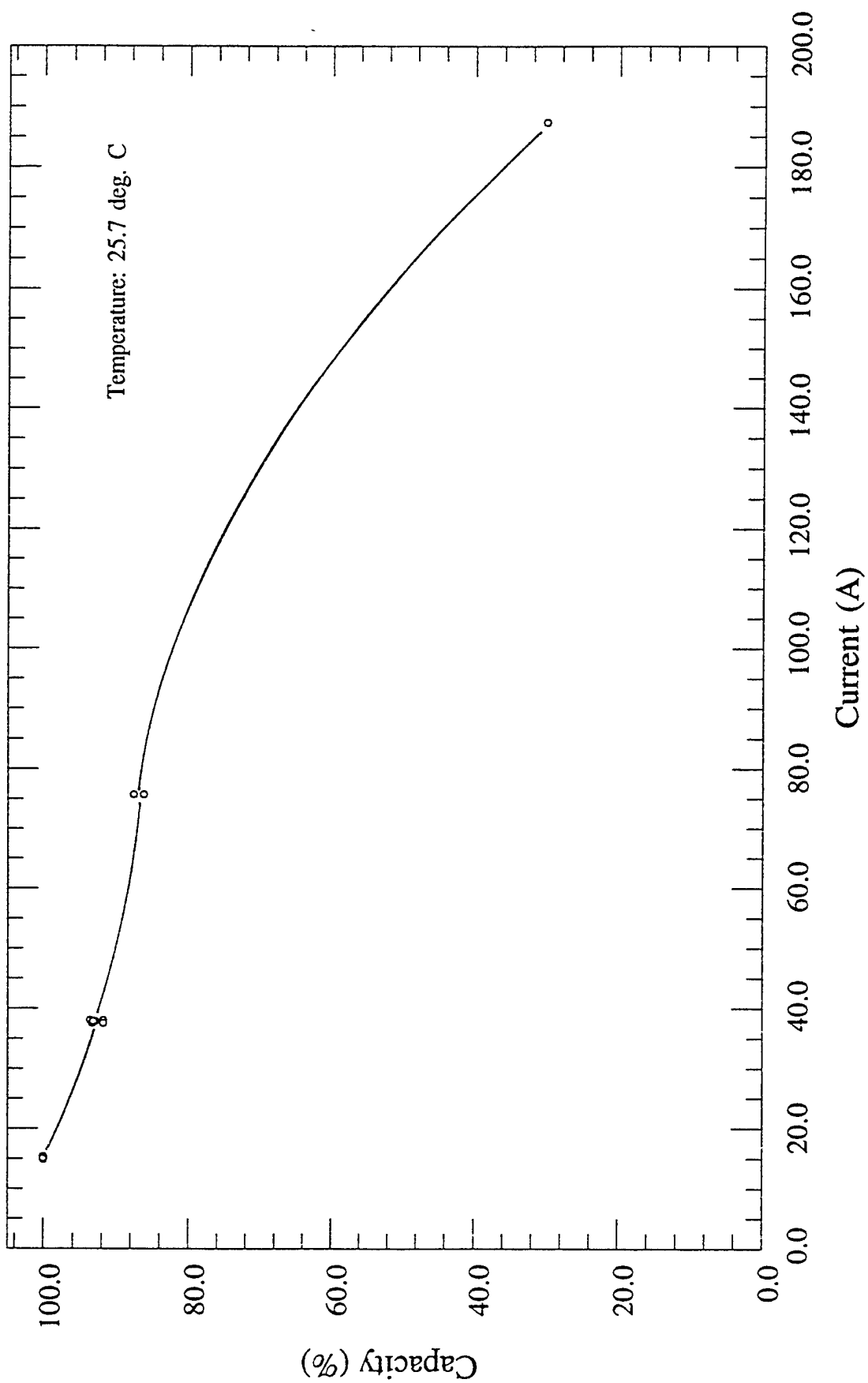


Figure 4.5.1.2-1. Company C Group 2 CDC Capacity vs. Current

4.5.1.3 Company E (AB₅ Prismatic Cells) Company E cells were unable to withstand a 5C discharge at 24 °C; two of the four cells shorted on the first attempt and one of the remaining two cells shorted on the second attempt. The cells did not recover after repeated FCR conditioning cycles. These cells also exhibited erratic performance on FCR conditioning cycles after exposure to 71 °C at a 3 A discharge current. The erratic performance was characterized as one or two cells would discharge normally for one or two cycles while the other two cells in the group would not then the other cells would discharge normally and the first one or two would not discharge.

Cell performance with temperature showed 75 percent retained capacity down to -20 °C at discharge currents less than 3 A and down to 5 °C for currents up to 6 A. Currents as high as 8 A could be maintained at 24 °C with up to 75 percent retained capacity. At temperatures above and below room temperature the maximum current that could be maintained was significantly lower. At or below -18 °C discharge performance significantly degraded with essentially no capacity at -40 °C. The results of CDC tests are tabulated in Tables 4.5.1.3-1 to 4.5.1.3-3 and graphically represented in Figures 4.5.1.3-1 and 4.5.1.3-2.

Table 4.5.1.3-1. Company E CDC Results at 71 and 49 °C

Nominal CDC (A)	1.2	3.0	5.0	6.0	15.0
71 °C (Group 3)					
Cycle No.		21	X ^b	X ^b	X ^a
Disch. Capacity, C _d (A-h)		2.972	X ^b	X ^b	X ^a
Capacity (%)		96.65	X ^b	X ^b	X ^a
Current (A)		3.00	X ^b	X ^b	X ^a
Temperature (°C)		69.2	X ^b	X ^b	X ^a
49 °C (Group 3)					
Cycle No.	46	15	49	52	X ^a
Disch. Capacity, C _d (A-h)	3.014	2.962	2.756	2.375	X ^a
Capacity (%)	100.33	96.32	91.74	79.06	X ^a
Current (A)	1.19	3.00	4.82	6.10	X ^a
Temperature (°C)	48.4	48.4	48.5	48.7	X ^a

^a Deleted results of 15 A discharge at 24 °C which shorted 3 of 4 cells.

^b Deleted results of cycle 21 test with erratic performance during subsequent FCR cycles.

Table 4.5.1.3-2. Company E CDC Results at 24 and 0 °C

Nominal CDC (A)	1.2	3.0	5.0	6.0	15.0
24 °C (Group 4)					
Cycle No.	Table 4.3.4-5	10		13	16 24
Disch. Capacity, C _d (A-h)	Table 4.3.4-5	2.915		2.580	1.972 2.502
Capacity (%)	100.00	93.82		81.93	62.6 80.4
Current (A)	1.202	3.004		6.026	15.02 15.00
Temperature (°C)	23.6	22.2		21.3	24.0 24.4
0 °C (Group 1)					
Cycle No.	18	21		55	X ^a
Disch. Capacity, C _d (A-h)	2.971	2.789		1.848	X ^a
Capacity (%)	98.22	91.86		62.75	X ^a
Current (A)	1.227	2.995		5.992	X ^a
Temperature (°C)	-0.9	3.9		-0.2	X ^a
0 °C (Group 2)					
Cycle No.	18	21		55	X ^a
Disch. Capacity, C _d (A-h)	3.034	2.814		2.084	X ^a
Capacity (%)	99.80	92.73		70.10	X ^a
Current (A)	1.203	2.988		5.990	X ^a
Temperature (°C)	-0.8	4.8		0.3	X ^a

^a Deleted results of 15 A discharge at 24 °C which shorted 3 of 4 cells.

Table 4.5.1.3-3. Company E CDC Results at -18 and -40 °C

Nom. Constant Disch. Current (A)	1.2	3.0	5.0	6.0	15.0
-18 °C (Group 1)					
Cycle No.		26		64	X ^a
Disch. Capacity, C _d (A-h)		2.120		0.113	X ^a
Capacity (%)		69.83		3.85	X ^a
Current (A)		2.992		6.016	X ^a
Temperature (°C)		-17.3		-18.3	X ^a
-18 °C (Group 2)					
Cycle No.		25		64	X ^a
Disch. Capacity, C _d (A-h)		2.242		0.050	X ^a
Capacity (%)		73.87		1.68	X ^a
Current (A)		2.988		5.994	X ^a
Temperature (°C)		-17.0		-17.8	X ^a
-40 °C (Group 1)					
Cycle No.	29	32	X ^b	X ^b	X ^b
Disch. Capacity, C _d (A-h)	0.056	0.012	X ^b	X ^b	X ^b
Capacity (%)	1.84	0.39	X ^b	X ^b	X ^b
Current (A)	1.213	2.994	X ^b	X ^b	X ^b
Temperature (°C)	-19.9	-39.5	X ^b	X ^b	X ^b
-40 °C (Group 2)					
Cycle No.	28	31	X ^b	X ^b	X ^b
Disch. Capacity, C _d (A-h)	0.050	0.012	X ^b	X ^b	X ^b
Capacity (%)	1.65	0.39	X ^b	X ^b	X ^b
Current (A)	1.204	3.005	X ^b	X ^b	X ^b
Temperature (°C)	-39.0	-39.0	X ^b	X ^b	X ^b

^a Deleted results of 6 A discharge at -18 °C.

^b Deleted results of 1.2 and 3 A discharges at -40 °C

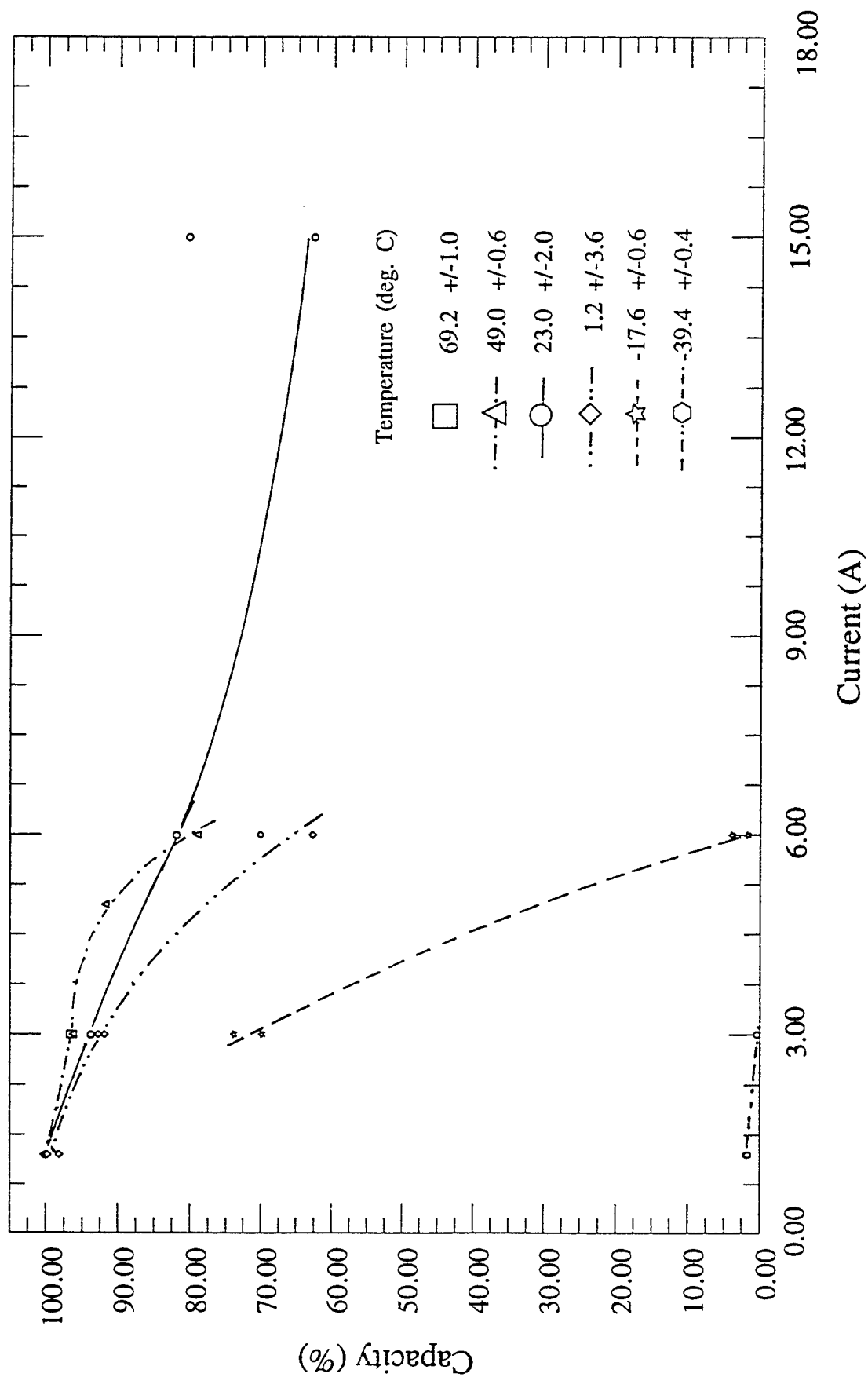


Figure 4.5.1.3-1. Company E CDC Capacity vs. Current

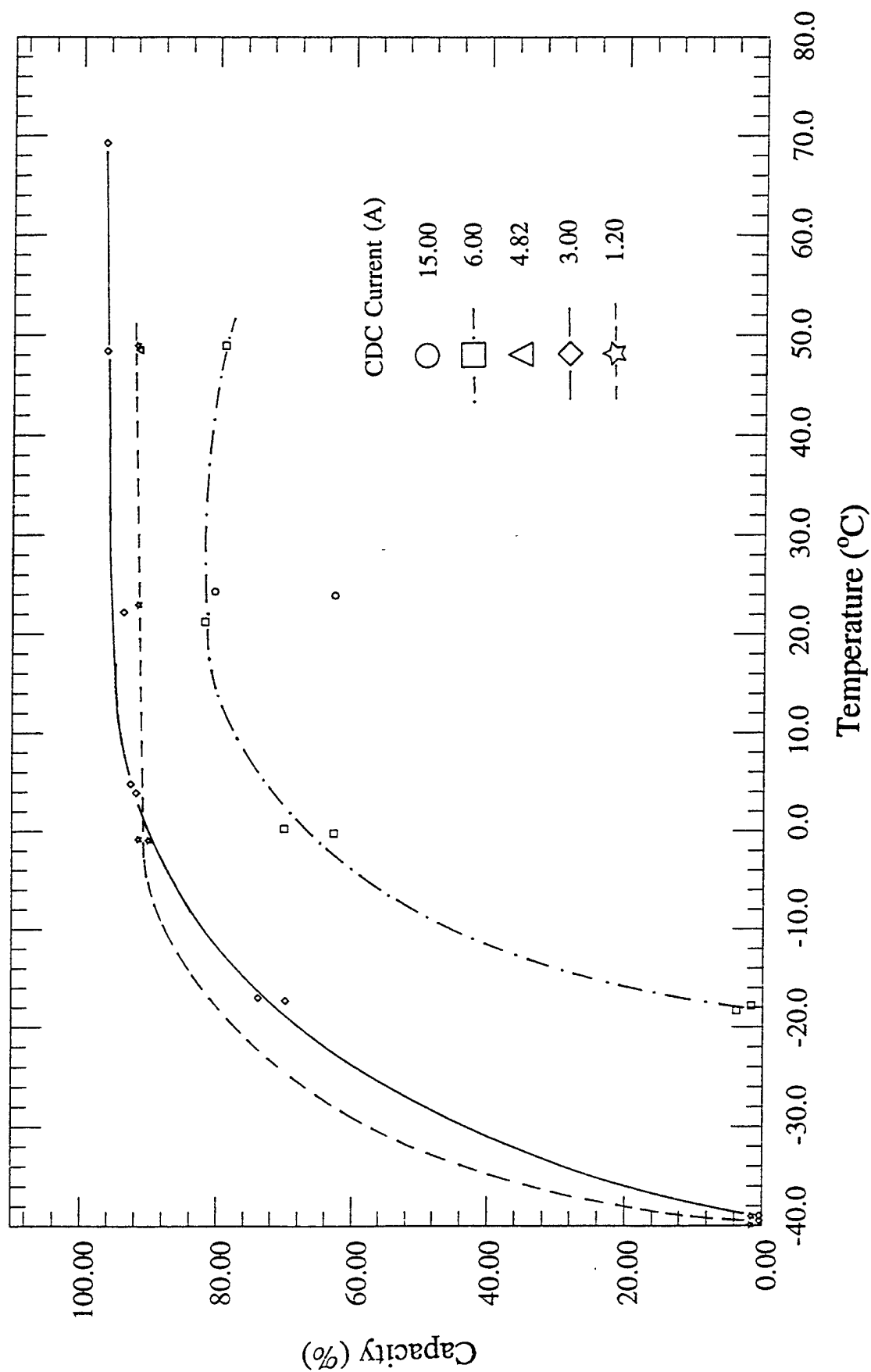


Figure 4.5.1.3-2. Company E CDC Capacity vs. Temperature

4.5.1.4 Company F (AB_5 Prismatic Cells) Company F cells exhibited extremely reproducible behavior from cell to cell. Capacity deviations for cells 1-3 were under 1 percent and for cells 1-3 and 5 deviations were approximately 0.8 percent. These results indicate very high quality control in the manufacturing process or all the cells came from the same batch with the same raw starting materials. Failure of cell 4 with markedly lower capacity (Table 4.3.4-6) is unexplained at this time. CDC test results for Company F are in Tables 4.5.1.4-1 and are graphically summarized in Figures 4.5.1.4-1 and 4.5.1.4-2.

The behavior of the cells on cycle 125 where three of four cells failed in a 5C rate discharge was unusual since cell performance had been predictable and reliable. Closer examination of the data revealed the cells that failed were no. 1, 2 and 3. Cell 5 was the only cell that showed any discharge capacity. This finding is significant since cell 5 had 68 fewer cycles than cells 1-3. It may be that cells 1-3 had developed a "set" or "memory" due to numerous cycles at 0.38 A and were no longer capable of sustaining a high discharge current. At cycle 125 cell 5 only had 57 cycles and may not have had time to develop a "set." Destructive physical analysis was not performed due to the limited no. of cells, which might have indicated a difference in the metal hydride particle size or other characteristic to explain the result. Subsequent tests at lower current densities did not show a similar effect.

CDC results at 0.94 A discharge current from -20 to 71 °C showed an unusual trend (Figure 4.5.1.4-2). The capacity peaked at 24 °C then fell off at 49 °C and rose again at 71 °C. Comparisons of the discharge data showed cell 5 had a lower capacity than cells 1-3 but not statistically capable of rejection. Excluding the cell 5 data would have raised the data points, but not enough to flatten the curve. Similarly, the data point at 24 °C is slightly high but appears accurate (see Figure 4.5.1.4-1) so there is no justification to exclude it. This analysis suggests the trend is real. Possibly the metal hydride may release additional hydrogen at 71 °C through a phase change in the hydride alloy. Proof would require destructive physical analysis to verify such a change, but this was not possible.

At temperatures below 24 °C discharge capacity shows a precipitous drop below 0 °C more so than with other AB_5 cells. This is probably attributable to electrolyte freezeout. Internal resistance (IR) measurements may confirm this possible explanation.

Table 4.5.1.4-1. Company F¹ CDC Results from 71 to -18 °C

Nominal CDC (A)	0.38	0.94	1.81	4.59	9.58
71 °C					
Cycle No.		144		X ^a	X ^a
Disch. Capacity, C _d (A-h)		0.895		X ^a	X ^a
Capacity (%)		92.94		X ^a	X ^a
Current (A)		0.921		X ^a	X ^a
Temperature (°C)		70.8		X ^a	X ^a
49 °C					
Cycle No.		108		X ^b	X ^b
Disch. Capacity, C _d (A-h)		0.846		X ^b	X ^b
Capacity (%)		88.12		X ^b	X ^b
Current (A)		0.925		X ^b	X ^b
Temperature (°C)		49.1		X ^b	X ^b
24 °C					
Cycle No.	Tbl. 4.3.4-6	57	62	125 ^a	X ^b
Disch. Capacity, C _d (A-h)	Tbl. 4.3.4-6	0.933	0.873	0.764	X ^b
Capacity (%)	100.00	99.15	92.68	79.92	X ^b
Current (A)	0.38	0.921	1.81	4.59	X ^b
Temperature (°C)	24.3	24.1	21.8	24.8	X ^b
0 °C					
Cycle No.		148		X ^b	X ^b
Disch. Capacity, C _d (A-h)		0.828		X ^b	X ^b
Capacity (%)		85.98		X ^b	X ^b
Current (A)		0.965		X ^b	X ^b
Temperature (°C)		-2.6		X ^b	X ^b
-18 °C					
Cycle No.		152	X ^c	X ^c	X ^b
Disch. Capacity, C _d (A-h)		0.142	X ^c	X ^c	X ^b
Capacity (%)		14.75	X ^c	X ^c	X ^b
Current (A)		0.971	X ^c	X ^c	X ^b
Temperature (°C)		-19.1	X ^c	X ^c	X ^b

¹ Only 5 cells were available for test. Cell 4 showed signs of early failure and was excluded from analysis. Cell 5 data was included after cycle 90. All data from cycles 1-90 are 3 cell averages and after cycle 91 are 4 cell averages unless specified otherwise.

^a Three cells failed immediately; result is for one cell only.

^b Deleted: Results of 4.59 A discharge at 24 °C; three cells out immediately.

^c Deleted: Results of 0.941 A discharge at -18 °C.

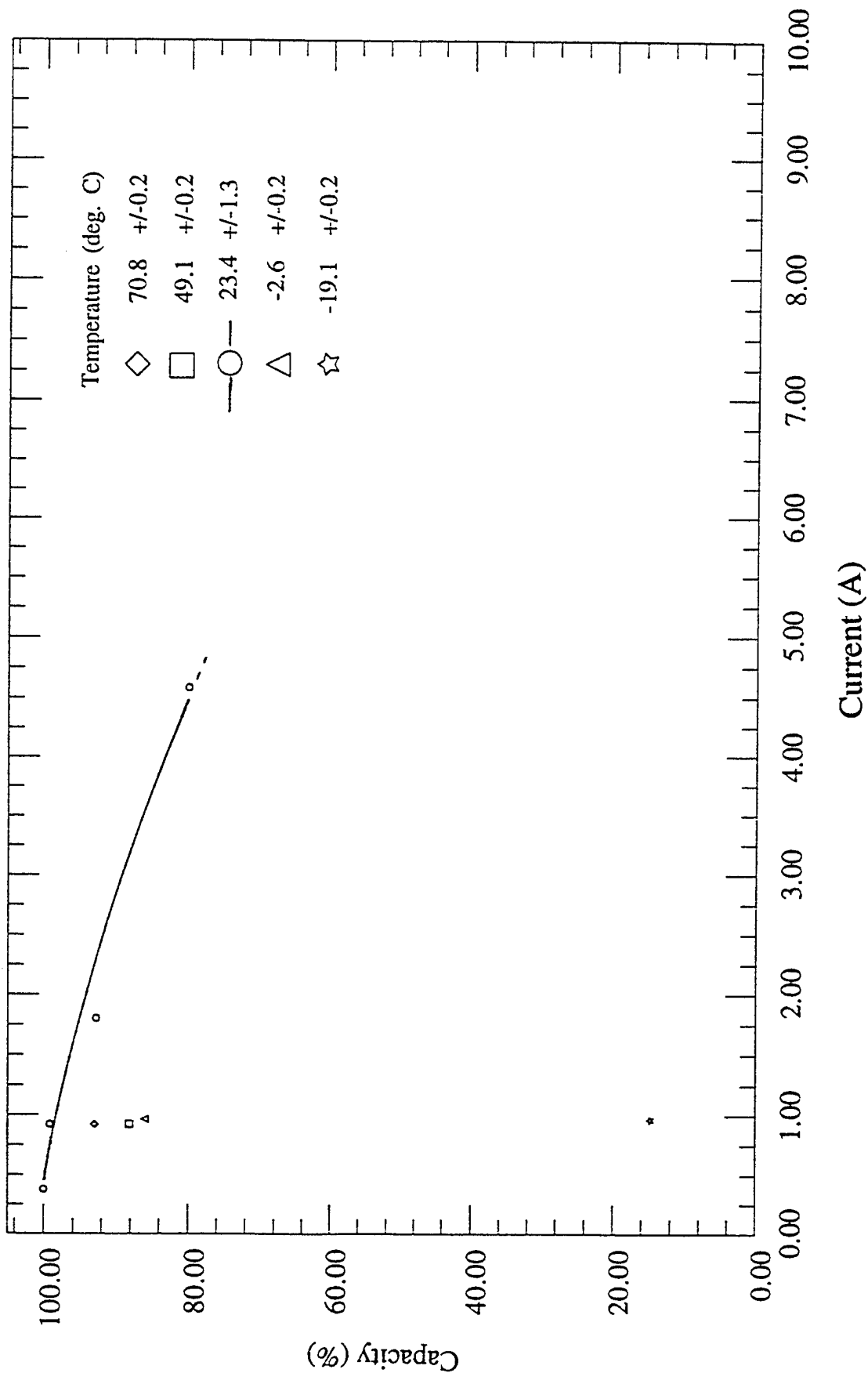


Figure 4.5.1.4-1. Company F CDC Capacity vs. Current

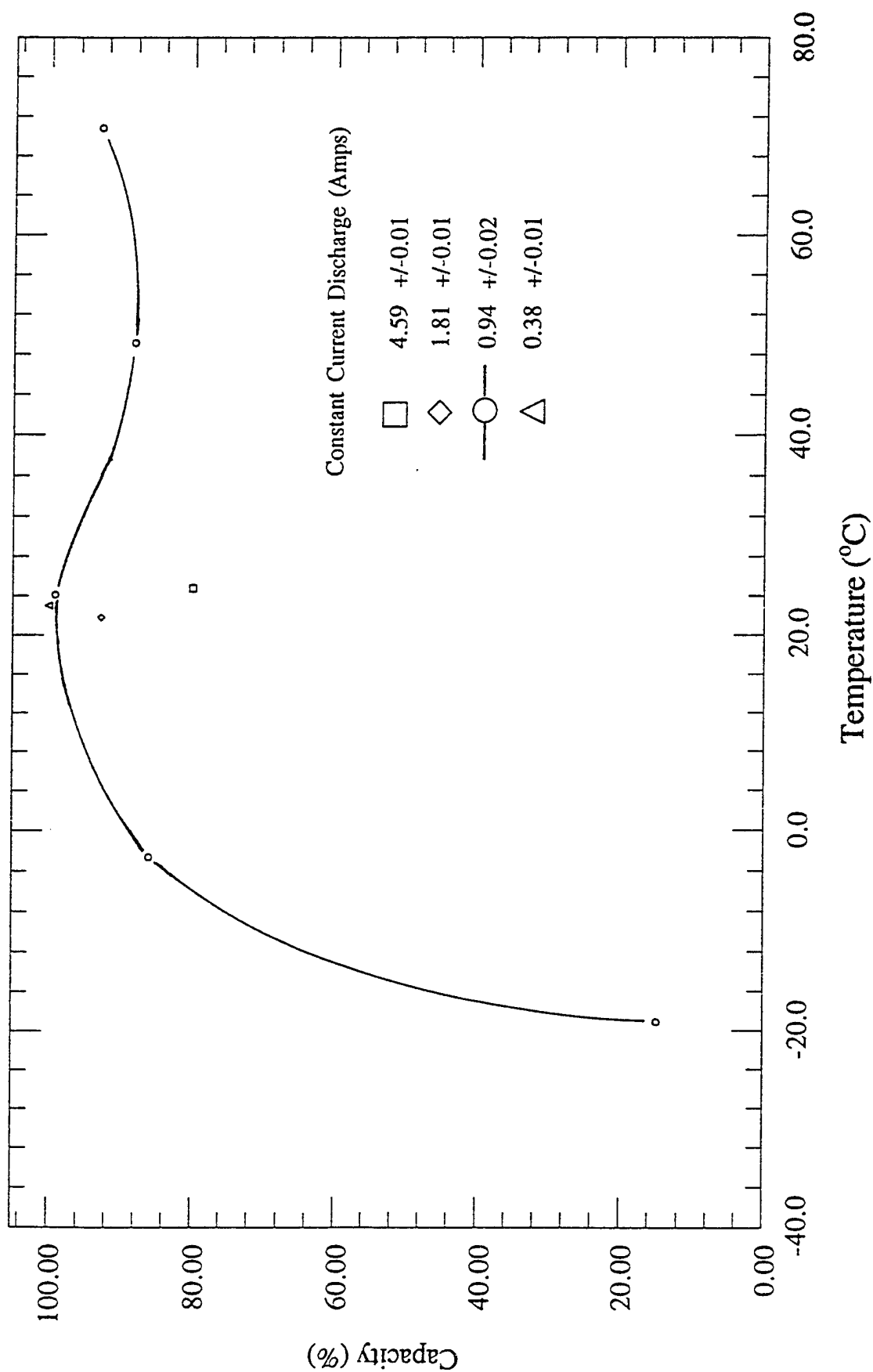


Figure 4.5.1.4-2. Company F CDC Capacity vs. Temperature

4.5.1.5 Company G (AB₅ Cylindrical Cells) Company G cells exhibited very reproducible results from group to group and within groups. Due to the temperature and current limit switches in the nine cell battery packs CDC tests on the battery pack were not possible and CDC tests were done using cells from the disassembled battery packs. Capacity deviations within groups were within 1-1.5 percent and indicate good quality control in the manufacturing process. CDC results for Company G are in Tables 4.5.1.5-1 through 4.5.1.5-3. Graphical summaries of the CDC capacities versus current and temperature are in Figures 4.5.1.5-1 and 4.5.1.5-2 respectively.

Examination of Figure 4.5.1.5-1 shows a 75 percent capacity window of operation out to an 11 A discharge current (approximately 4.4 C) at or near room temperature. The data at 49 °C parallel the room temperature but additional data are needed at 7 and 9 A discharges to extend the range. Tests of the cells at 71°C shows a falloff in capacity at low current discharges suggestive of a loss due to accelerated self discharge during the 2 hour discharge time required. At higher currents capacity falls off more rapidly than at 49 or 24 °C but additional data is needed at 7 and 9 A discharge currents to extend the range. Discharges at 0 ° and -18 °C show similar behavior to other cells tested.

The CDC capacities versus temperature plots (Figure 4.5.1.5-2) show a fairly large temperature window from 20 ° to 71 °C for discharge rates equivalent to 2C/5, C and 2C. Below 20 °C the capacity falls off as the current increases and the temperature decreases consistent with decreased hydrogen mobility due to an increase in internal resistance of the electrolyte as the temperature is lowered. Internal resistance tests of these cells and electrolyte analysis after cell disassembly would provide further information on the limiting mechanism at the lower temperatures. WL/POOB personnel are continuing tests of Company G cells beyond the scope of this report.

Table 4.5.1.5-1. Company G CDC Results at 71 °C

Nominal CDC (A)	1.0	2.5	5.0	12.5	25.0
Group 2					
Cycle No.	88	57	61 ^c	X ^b	X ^a
Disch. Capacity, C_d (A-h)	2.553	2.603	2.454	X ^b	X ^a
Capacity (%)	96.63	98.71	92.85	X ^b	X ^a
Current (A)	1.004	1.815	5.076	X ^b	X ^a
Temperature (°C)	72.7	71.3	73.2	X ^b	X ^a

^a Deleted: 18.0 A discharge at 25.9 °C.

^b Deleted: 12.5 A discharge at 24 °C.

Table 4.5.1.5-2. Company G CDC Results at 49 °C

Nominal CDC (A)	1.0	2.5	5.0	12.5	25.0
Group 2					
Cycle No.	92	71	42 53	X ^b	X ^a
Disch. Capacity, C _d (A-h)	2.651	2.642	2.602 2.619	X ^b	X ^a
Capacity (%)	101.2	99.77	97.93 99.32	X ^b	X ^a
Current (A)	0.990	2.535	5.080 5.066	X ^b	X ^a
Temperature (°C)	49.5	51.5	49.6 49.5	X ^b	X ^a
Group 4					
Cycle No.	30			X ^b	X ^a
Disch. Capacity, C _d (A-h)	2.570			X ^b	X ^a
Capacity (%)	98.96			X ^b	X ^a
Current (A)	1.013			X ^b	X ^a
Temperature (°C)	51.2			X ^b	X ^a
Group 5					
Cycle No.	21	7		X ^b	X ^a
Disch. Capacity, C _d (A-h)	2.673	2.584		X ^b	X ^a
Capacity (%)	102.1	100.2		X ^b	X ^a
Current (A)	1.011	2.508		X ^b	X ^a
Temperature (°C)	49.0	48.4		X ^b	X ^a

^a Deleted: 18.0 A discharge at 25.9 °C.^b Deleted: 12.5 A discharge at 24 °C.^c Two of four cells failed.

Table 4.5.1.5-3. Company G CDC Results at 24, 0 and -18 °C

Nominal CDC (A)	1.0	2.5	5.0	12.5	25.0
24 °C (Group 2)					
Cycle No.	Table 4.3.4-7	45			
Disch. Capacity, C _d (A-h)	Table 4.3.4-7	2.599			
Capacity (%)	100.0	97.82			
Current (A)	1.020	2.535			
Temperature (°C)	22.5	22.4			
24 °C (Group 3)					
Cycle No.	Table 4.3.4-7	19 45	22	30 ^a	36
Disch. Capacity, C _d (A-h)	Table 4.3.4-7	2.608 2.642	2.580	1.558	0.075
Capacity (%)	100.0	98.38 98.44	97.03	58.59	2.80
Current (A)	1.020	2.568 2.531	5.034	12.65	18.01
Temperature (°C)	22.5	22.2 22.0	22.6	23.8	25.9
24 °C (Group 5)					
Cycle No.	Table 4.3.4-7			13	
Disch. Capacity, C _d (A-h)	Table 4.3.4-7			1.615	
Capacity (%)	100.0			61.76	
Current (A)	1.020			12.65	
Temperature (°C)	22.5			23.1	
0 °C					
Group No.	4	2	4	X ^d	X ^b
Cycle No.	62	76	54 ^c	X ^d	X ^b
Disch. Capacity, C _d (A-h)	2.479	2.206	1.758	X ^d	X ^b
Capacity (%)	94.08	83.31	67.12	X ^d	X ^b
Current (A)	1.013	2.554	5.044	X ^d	X ^b
Temperature (°C)	-0.1	-0.2	-1.8	X ^d	X ^b
-18 °C					
Group No.	5	2	4	X ^d	X ^b
Cycle No.	17	49	58	X ^d	X ^b
Disch. Capacity, C _d (A-h)	2.250	0.804	0.000	X ^d	X ^b
Capacity (%)	86.04	30.26	0.00	X ^d	X ^b
Current (A)	1.005	2.554	5.055	X ^d	X ^b
Temperature (°C)	-18.2	-18.1	-18.8	X ^d	X ^b

^a One cell failed.

^b Deleted: Results of 18.01 A discharge at 25.9 °C.

^c Two cells failed.

^d Deleted: Results of 12.65 A discharge at 23.5 °C.

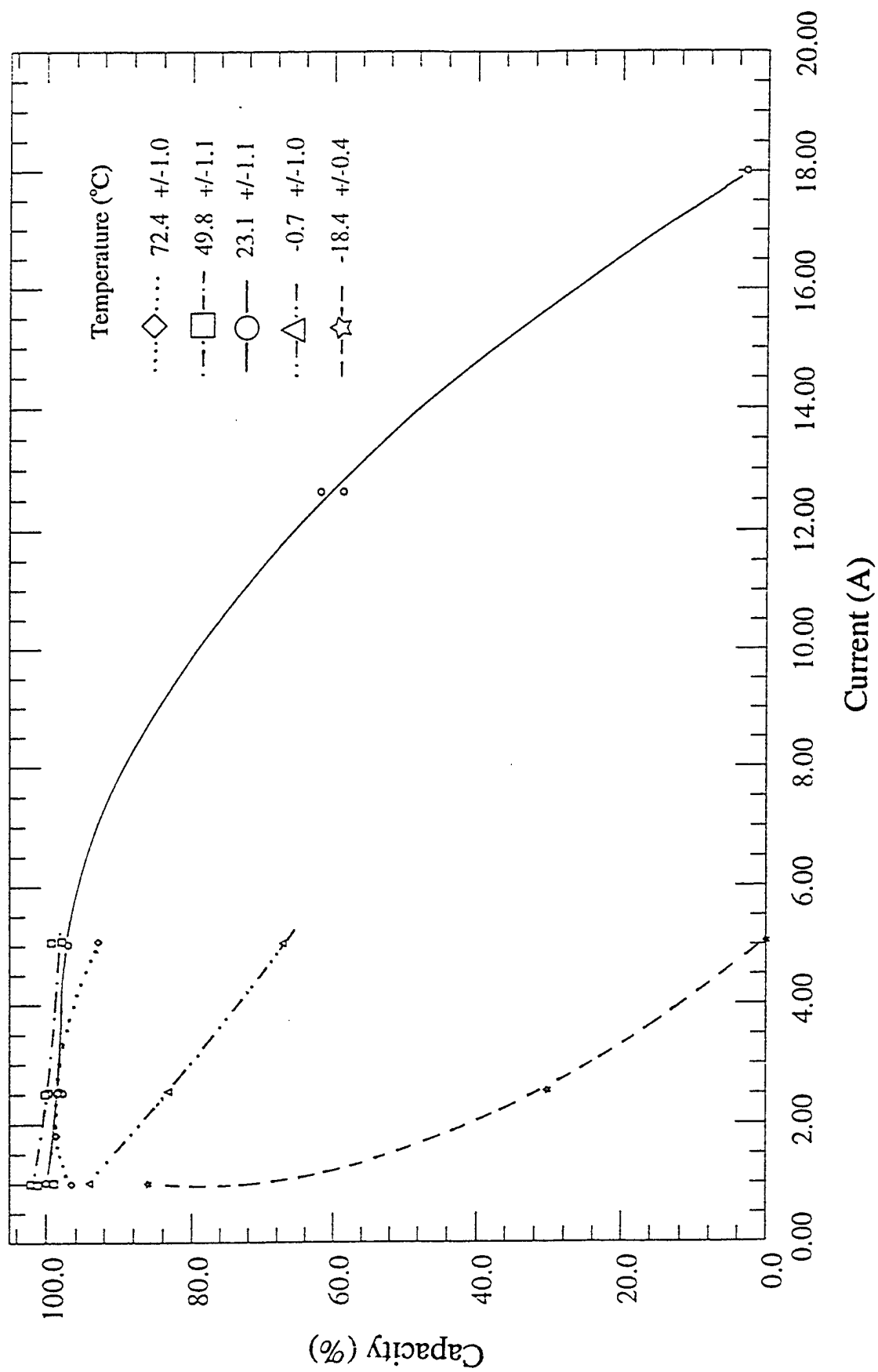


Figure 4.5.1.5-1. Company G CDC Capacity vs. Current

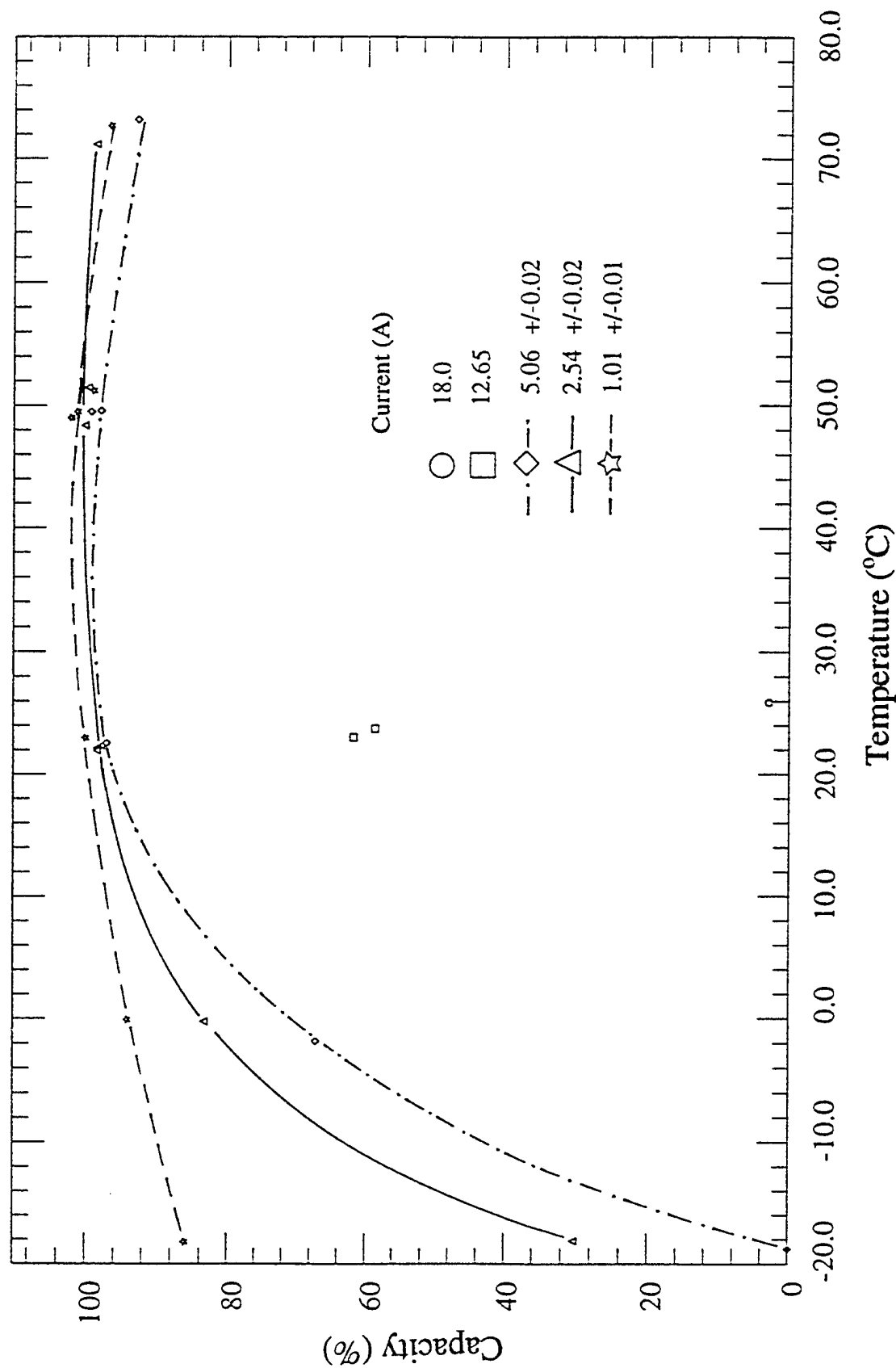


Figure 4.5.1.5-2. Company G CDC Capacity vs. Temperature

4.5.2 AB₂ Single Cell CDC Tests Two samples of AB₂ single cells from manufacturers D and H were evaluated for their CDC characteristics. Both sets of cells were cylindrical construction. The results of the CDC tests by company are presented here.

4.5.2.1 Company D (AB₂ Cylindrical Cells) Company D cells exhibited erratic behavior from group to group during the capacity tests (see Figure 4.3.4-4) and within each group the deviation was much larger than with the AB₅ cells. Discussions with Company D personnel and the manufacturer's literature indicates that Company D is using a small batch manufacturing process. This allows the company to alter the metal hydride chemistry during the manufacturing process based on input data from the customer on the load and type of use the battery will receive. Conceivably, since the requisition for Company D cells was for only 25 cells, the company made up the order with available left over assets which may explain the large variation in cells from group to group. The CDC results for Company D cells are in Table 4.5.2.1-1 Graphical presentations of the CDC capacities vs. current and temperature are in Figures 4.5.2.1-1 and 4.5.2.1-2 respectively.

During the CDC tests at room temperature the highest discharge current used was 8.83 A (5C) and the capacity obtained was 0.046 A-h. This low value precluded further discharge tests at or above 5C currents and at all test temperatures from 71 ° to -40 °C. Similarly, after observing the trend in capacity with current at 0 °C, tests at -18 ° and -40 °C were eliminated from the test program. Despite the limited test envelope, discharges at constant temperature from 0.7 A to 3.6 A (Figure 4.5.2.1-1) show better performance at 49 °C than at room temperature. A capacity plot at 71 °C shows some usable capacity below 2.5 A but exposure to this temperature reduces the capacity of the cells and is not recoverable. This loss of capacity is consistent with transition of the metal hydride alloy to a different phase with lower storage capacity. Similarly at 0 °C there is essentially no usable capacity.

The CDC test results at various temperatures show a capacity plateau between 35 °C and 50 °C with a fairly rapid fall off above 50 °C. Although the fall off at low temperatures for Company D cells is not as extreme as at high temperature, it is much faster than the corresponding AB₅ cylindrical cells (see Figures 4.5.1.1-2 and 4.5.1.5-2) which have an approximate 10-15 °C lower temperature limit.

Table 4.5.2.1-1: Company D CDC Results from 71 to 0 °C.

Nominal CDC (A)	0.72	1.8	3.6	9.0	18.0
71 °C					
Group No.		5	5	X ^a	X ^a
Cycle No.		16 ^c	20 ^c	X ^a	X ^a
Disch. Capacity, C _d (A-h)		1.150	0.827	X ^a	X ^a
Capacity (%)		70.68	50.83	X ^a	X ^a
Current (A)		2.551	3.546	X ^a	X ^a
Temperature (°C)		70.0	70.9	X ^a	X ^a
49 °C					
Group No.	2	4	3	X ^a	X ^a
Cycle No.	27	24	23	X ^a	X ^a
Disch. Capacity, C _d (A-h)	1.852	1.905	1.655	X ^a	X ^a
Capacity (%)	104.6	101.6	92.15	X ^a	X ^a
Current (A)	0.698	1.766	3.423	X ^a	X ^a
Temperature (°C)	49.6	49.1	48.7	X ^a	X ^a
24 °C					
Group No.	1-5	2	4	1	X ^a
Cycle No.	Table 4.3.4-3	20	17	28	X ^a
Disch. Capacity, C _d (A-h)	Table 4.3.4-3	1.604	1.308 ^b	0.046	X ^a
Capacity (%)	100.00	91.66	73.32	2.55	X ^a
Current (A)	0.71	1.770	3.528	8.83	X ^a
Temperature (°C)	22.7	25.3	23.0	23.9	X ^a
0 °C					
Group No.	4	3	2	X ^a	X ^a
Cycle No.	20	19	23	X ^a	X ^a
Disch. Capacity, C _d (A-h)	0.821 ^b	0.272	0.045	X ^a	X ^a
Capacity (%)	46.02	15.15	2.54	X ^a	X ^a
Current (A)	0.890	1.777	3.556	X ^a	X ^a
Temperature (°C)	-0.1	-0.2	0.0	X ^a	X ^a

^a Deleted: Results of 8.83 A discharge at 24 °C.

^b Three cells failed; single data point

^c Two cells failed.

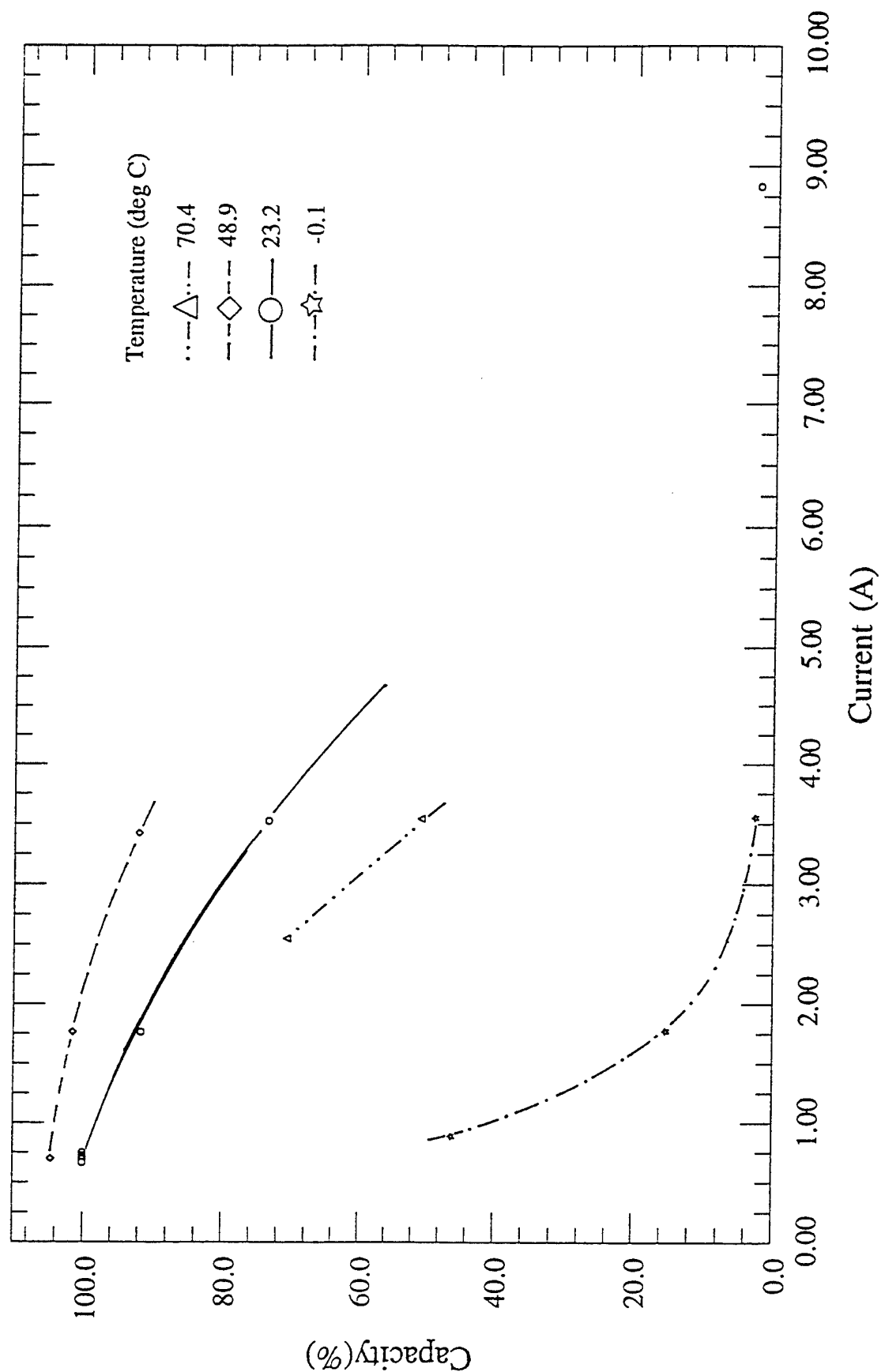


Figure 4.5.2.1-1. Company D CDC Capacity vs. Current

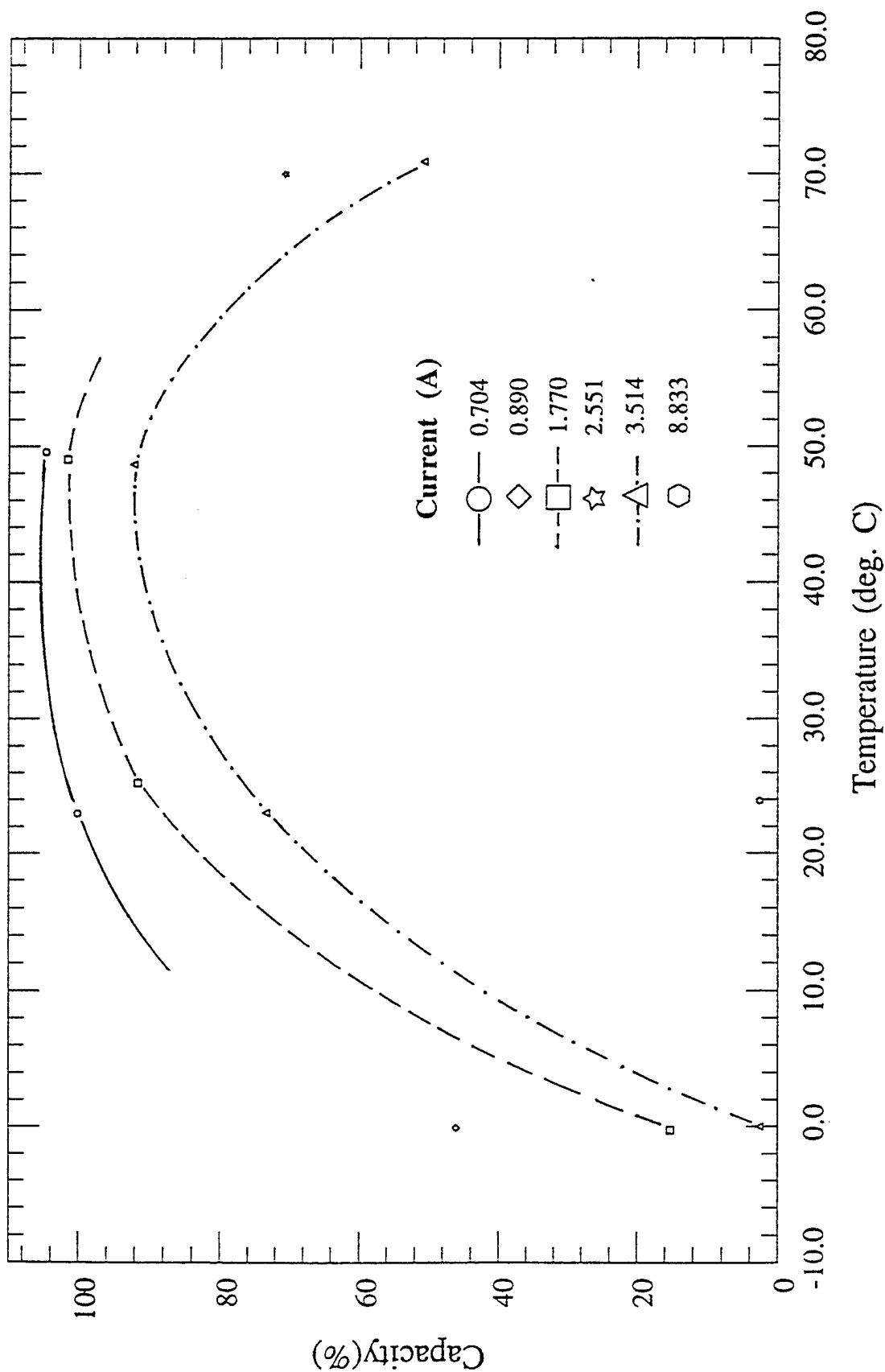


Figure 4.5.2.1-2. Company D CDC Capacity vs. Temperature

4.5.2.2 Company H (AB₂ Cylindrical Cells) Similar to the Company D cells, Company H cells showed large group to group variations in capacity (Figure 4.3.4-8) which made interpretation of the data from the CDC tests more difficult. In addition, when CDC and CCC experiments were conducted at 71 °C the cells were damaged and the capacity severely and permanently degraded during subsequent FCR cycles. The CDC results for Company H cells are in Tables 4.5.2.2-1 and 4.5.2.2-2. Graphical presentation of the CDC capacities versus current and temperature are presented in Figures 4.5.2.2-1 and 4.5.2.2-2 respectively and are discussed in the following paragraphs.

Plots of capacity versus current (Figure 4.5.2.2-1) at different temperatures indicate the best performance with these cells occurs at room temperature. Unlike Company D cells which showed a parallel but better performance at 49 °C out to a 6 A discharge current, company H cell data indicates a faster degradation of performance at 49 °C with increasing current, compared to the 24 °C curve, when the current is higher than 2 A. These cells, however, did show unusual performance at 71 °C, with a higher capacity at the 1C (1.82 A) rate compared to the 2C/5 rate (0.74 A). It is probable that the longer exposure to 71 °C during the 2C/5 rate discharge allows sufficient time for the cells to lose capacity through self discharge. Alternatively, the breakdown in the AB₂ alloy at 71 °C may be releasing additional hydrogen which is electrochemically active at the higher 1C discharge current, but is not at the 2C/5 discharge current and diffuses away through self discharge.

The temperature plots of the CDC results (Figure 4.5.2.2-2) show a linear, but slow, increase in capacity at the 2C/5 current from 0 °C to 71 °C and a sharp drop in capacity below 0 °C. At the higher 1C rate, the drop occurs at a higher temperature, approximately 5-10 °C, and is linear only from 24 - 49 °C. The capacity then rises sharply at 71 °C which may be due to one of the explanations offered in the previous paragraph. Destructive physical analysis of the AB₂ alloy after exposure to 71 °C and hydrogen absorption capacity studies would clarify the mechanism for the higher temperature behavior.

Table 4.5.2.2-1: Company H CDC Results from 71 to 0 °C.

Nominal CDC (A)	0.72	1.8	3.6	9.0	18.0
71 °C					
Group No.	4	4	X ^b	X ^a	X ^a
Cycle No.	71	28	X ^b	X ^a	X ^a
Disch. Capacity, C _d (A-h)	1.211	1.687	X ^b	X ^a	X ^a
Capacity (%)	107.74	116.51	X ^b	X ^a	X ^a
Current (A)	0.796	1.810	X ^b	X ^a	X ^a
Temperature (°C)	72.2	69.8	X ^b	X ^a	X ^a
49 °C					
Group No.	4	4		X ^a	X ^a
Cycle No.	53	15		X ^a	X ^a
Disch. Capacity, C _d (A-h)	1.158	1.687		X ^a	X ^a
Capacity (%)	105.46	91.54		X ^a	X ^a
Current (A)	0.748	1.816		X ^a	X ^a
Temperature (°C)	49.4	49.2		X ^a	X ^a
24 °C					
Group No.	5	5	5	5	X ^a
Cycle No.	Table 4.3.4-8	15	18	21	X ^a
Disch. Capacity, C _d (A-h)	Table 4.3.4-8	1.658	1.438	0.113	X ^a
Capacity (%)	100.00	98.28	85.24	6.94	X ^a
Current (A)	0.890	1.828	3.528	9.013	X ^a
Temperature (°C)	23.4	24.0	23.6	24.1	X ^a
0 °C					
Group No.	1	1	1	X ^a	X ^a
Cycle No.	16	19	68	X ^a	X ^a
Disch. Capacity, C _d (A-h)	1.855	0.621	0.086	X ^a	X ^a
Capacity (%)	90.36	30.25	5.77	X ^a	X ^a
Current (A)	0.722	1.799	3.598	X ^a	X ^a
Temperature (°C)	-1.2	-1.3	0.6	X ^a	X ^a

^a Deleted: Results of 9.01 A discharge at 24.1 °C.

^b Deleted: Results of 1.80 A discharge at 69.8 °C.

Table 4.5.2.2-2: Company H CDC Results at -18 and -40 °C.

Nominal CDC (A)	0.72	1.8	3.6	9.0	18.0
-18 °C					
Group No.	1	1	X ^b	X ^a	X ^a
Cycle No.	77	24	X ^b	X ^a	X ^a
Disch. Capacity, C _d (A-h)	0.240	0.093	X ^b	X ^a	X ^a
Capacity (%)	16.11	4.53	X ^b	X ^a	X ^a
Current (A)	0.724	1.816	X ^b	X ^a	X ^a
Temperature (°C)	-17.8	-17.8	X ^b	X ^a	X ^a
-40 °C					
Group No.	1	1	X ^b	X ^a	X ^a
Cycle No.	27	30	X ^b	X ^a	X ^a
Disch. Capacity, C _d (A-h)	0.016	0.000	X ^b	X ^a	X ^a
Capacity (%)	0.78	0.00	X ^b	X ^a	X ^a
Current (A)	0.715	1.819	X ^b	X ^a	X ^a
Temperature (°C)	-39.3	-38.8	X ^b	X ^a	X ^a

^a Deleted: Results of 9.01 A discharge at 24.1 °C.

^b Deleted: Results of 3.60 A discharge at 0.6 °C.

4.5.3 CDC Observations and Summary For comparison purposes between AB₂ and AB₅ cells the CDC results versus current at room temperature for all the cells are plotted in Figure 4.5.3-1. A similar plot versus temperature at a standard 1C discharge rate is shown in Figure 4.5.3-2. The 75 percent capacity line has been marked on each Figure. The data for these plots were extracted from the individual best fit curves for each set of cells and do not represent actual data points. Comparisons of these two figures and the discussions in sections 4.5.1 and 4.5.2 indicate:

- None of the AB₅ cells tested can deliver 75 percent of capacity below -20 °C. Similarly the limit for AB₂ cells is about 10 °C. Insulation and/or heating would be required to operate an aircraft battery with either type of hydride battery.
- The data for both types of Ni-MH batteries suggest low temperature performance can be enhanced with alloy chemistry improvements.

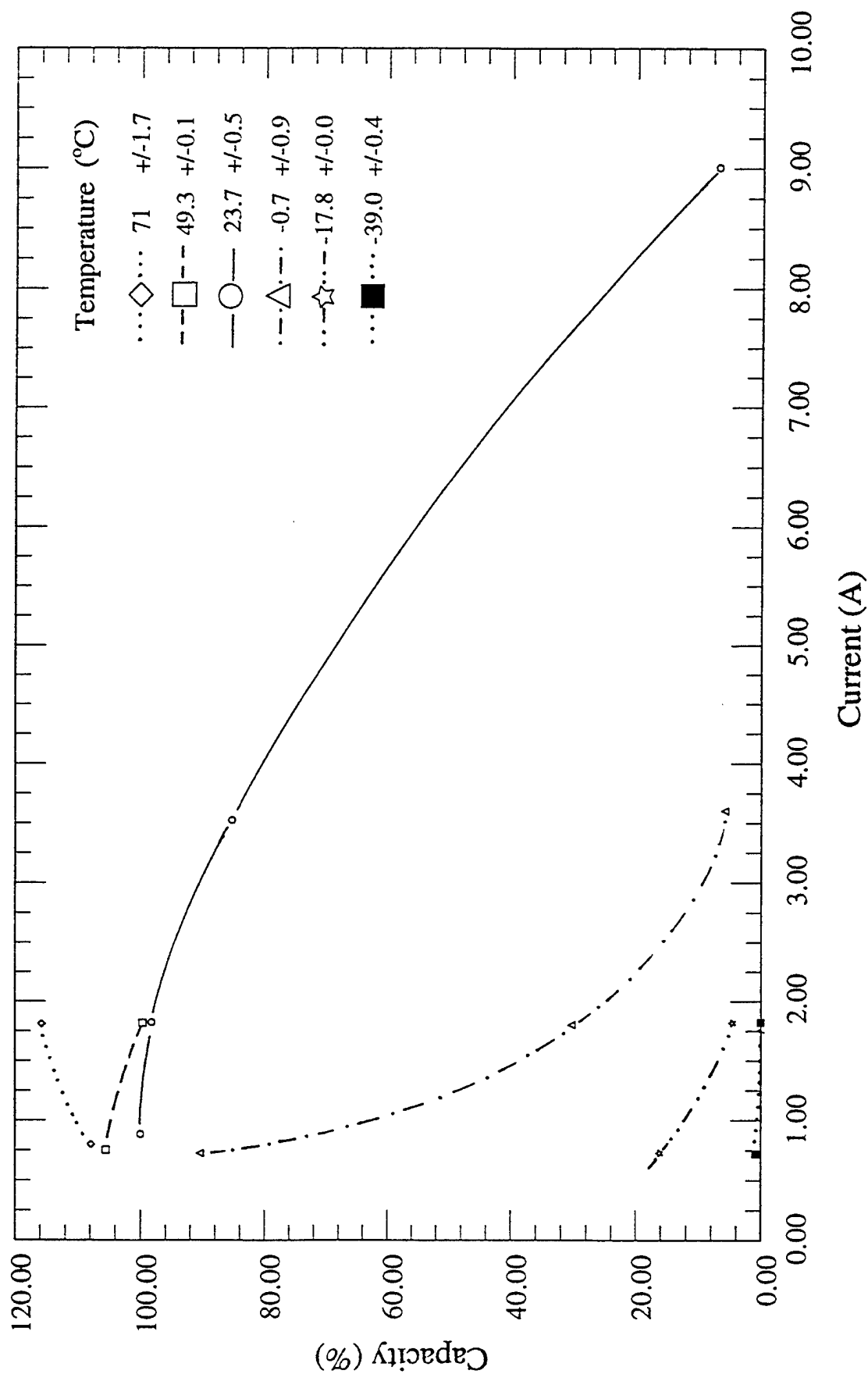


Figure 4.5.2.2-1. Company H CDC Capacity vs. Current

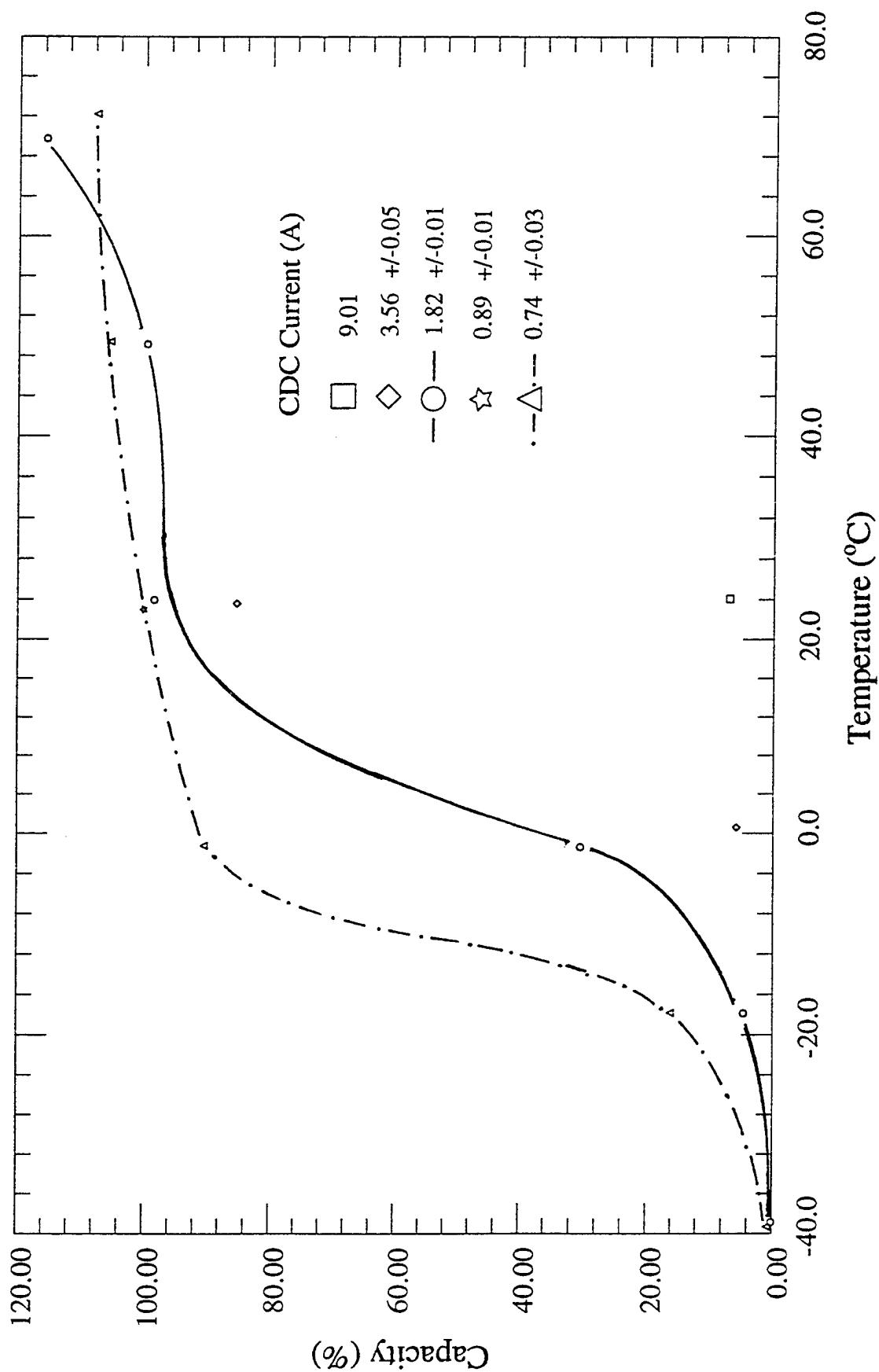


Figure 4.5.2.2-2. Company H CDC Capacity vs. Temperature

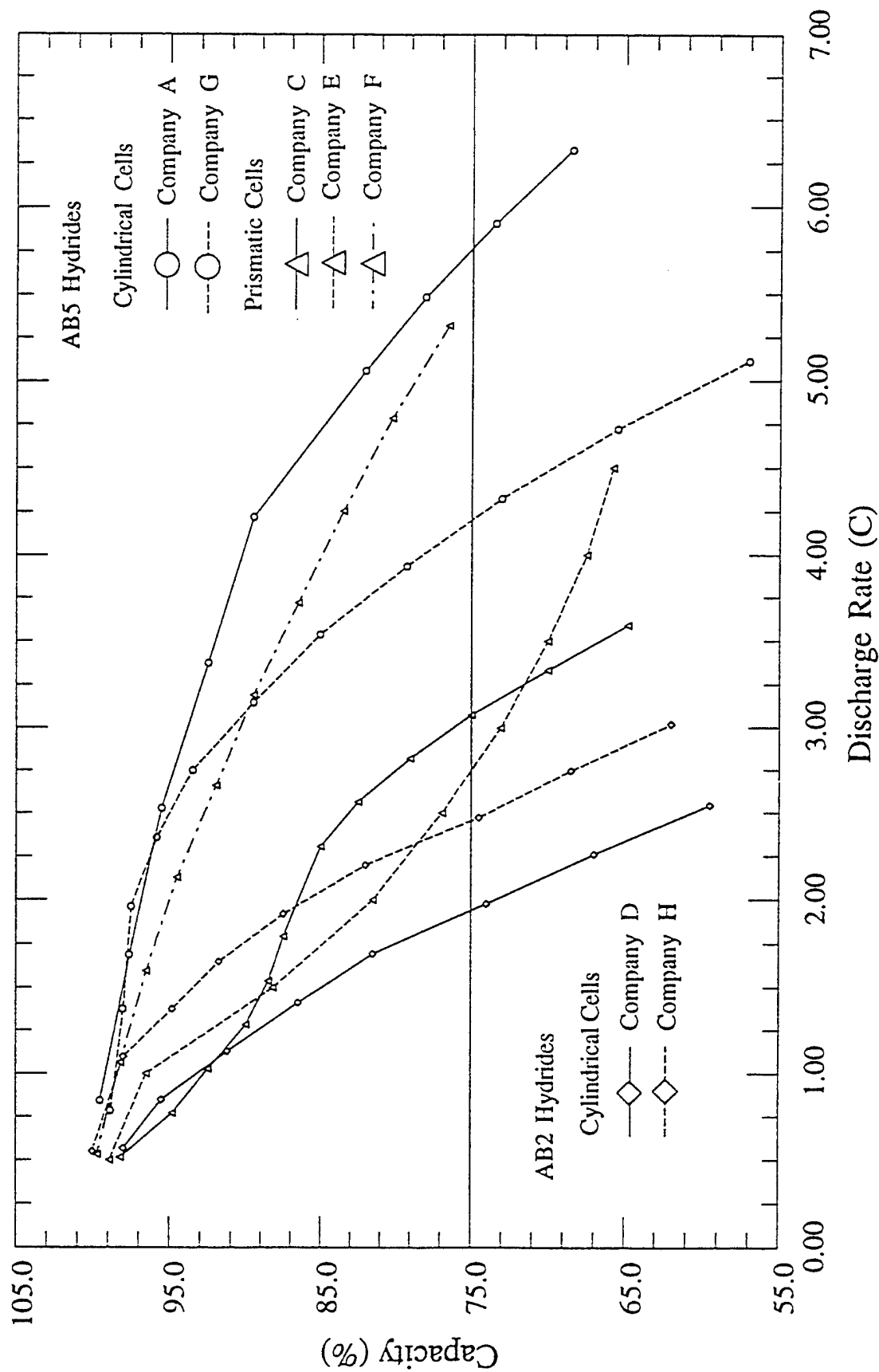


Figure 4.5.3-1. CDC Capacity vs. Discharge Rate at Room Temperature

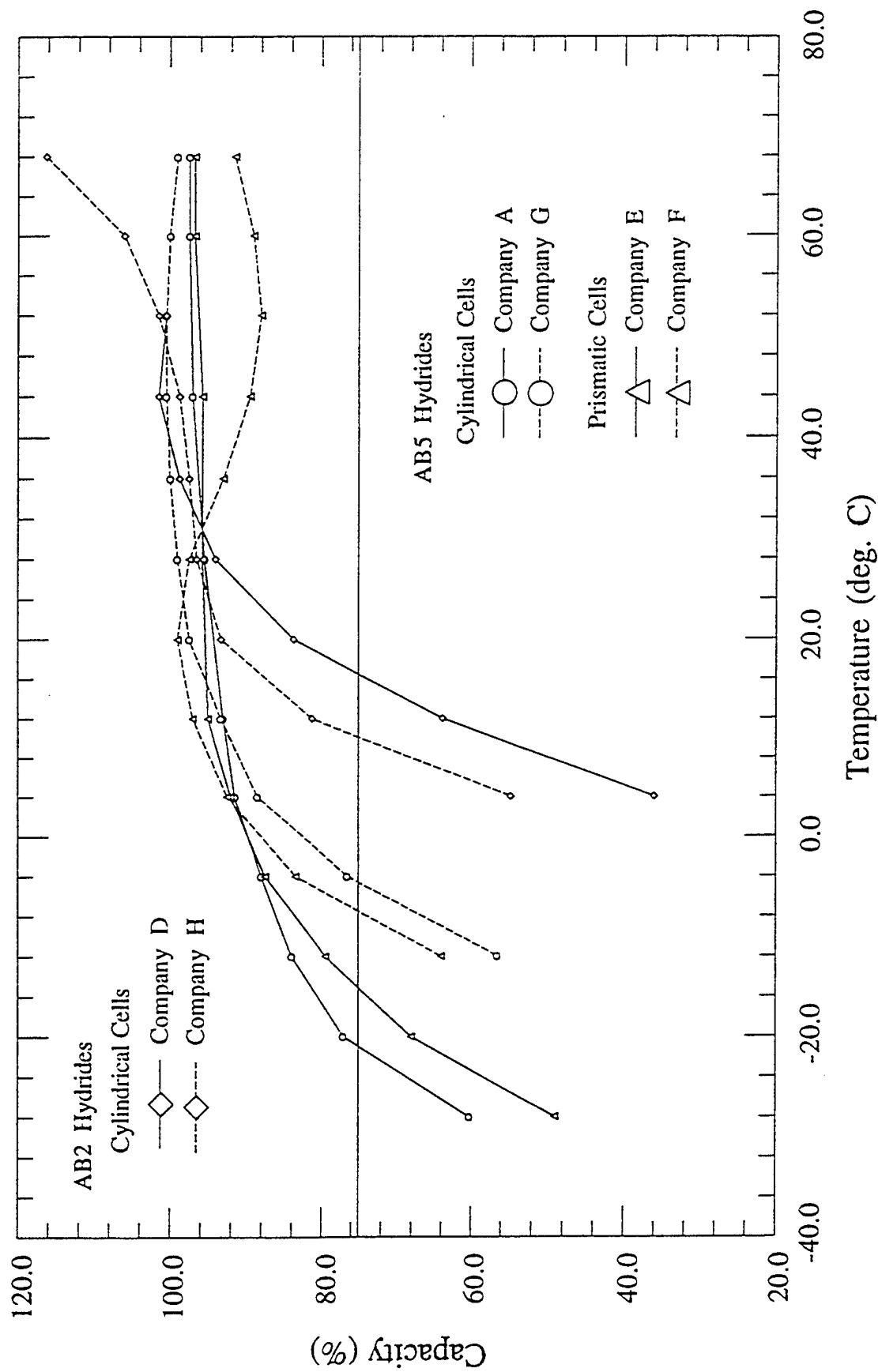


Figure 4.5.3-2. CDC Capacity vs. Temperature at the 1C Discharge Rate

- High temperature performance, up to 49 °C for all cells tested, is adequate up to a 2C discharge current.
- AB₅ cells may be able to operate at 71 °C, depending on the alloy formulation, but the current commercial AB₂ cells are irreparably damaged at that temperature.
- A Ni-MH aircraft battery of either type would require cooling and/or insulation to safely operate above 49 °C.
- All of the AB₅ cells can sustain a 3-5C discharge current at room temperature and deliver at least 75 percent of the design capacity; the upper current limit for AB₂ cells is approximately 2C.

Summary AB₅ batteries both cylindrical and prismatic have better discharge performance characteristics than AB₂ batteries. Both types of batteries would require heating to maintain operations below 0 °C and cooling to safely operate above 49 °C. None of the batteries could sustain a 10C discharge current for aircraft operations but high current performance of the AB₅ cells is 50 - 100 percent better than the AB₂ cells tested. AB₅ cells have a 15 - 20 °C lower operating temperature than AB₂ cells. Alloy optimization and improvements could enhance the temperature range and high current performance of both types of batteries.

4.6 CONSTANT CHARGE CURRENT (CCC) TESTS This series of tests was designed to measure the capability of the cell to respond to different charge currents at various temperatures from -40 °C to as high as 71 °C in a typical airfield environment. Charge currents varied from as low as C/5 up to 5C and were set to provide a 10 percent overcharge based on the previous cycle capacity test measurement.

The following procedure was established to perform the CCC tests on a four cell group¹ and used a standard 2C/5 discharge current at room temperature on the subsequent discharge to provide a standard for comparison between different company cells:

- Perform 2 conditioning cycles at room temperature.
- Discharge the cell at a 2C/5 current at room temperature.

¹ In the event there are less than three test samples, repeat the procedure three (3) times for only one cell or cell pack and two (2) times if there are two cells or cell packs under test.

- Equilibrate the cells at the test temperature. Record the OCV and temperature for each cell at 10 min. intervals. When at least two of the cells have reached the test temperature begin the charge.
- Charge the cells at the specified rate to a 10 percent overcharge based on the discharge capacity measured in step 2. The cell charge temperature limit is 75 °C unless specified otherwise in Section 4.3.
- Rest the cells on open circuit until two of the cells have reached room temperature. Record the OCV and temperature for each cell at 10 min. intervals.
- Discharge the cells at room temperature at the 2C/5 CDC rate to a 0.90V cutoff.
- From the measured capacity and comparison with the baseline capacity measurements (Tables 4.3.4-1 to 4.3.4.1-8) calculate the percent capacity during the discharge cycle immediately after the CCC cycle.
- Plot percent discharge capacity versus charge current and temperature for each group of cells by manufacturer.

The results of the CCC tests are separated by AB₅ and AB₂ metal hydride alloy and are presented and discussed in the following sections.

4.6.1 AB₅ Single Cell Constant Charge Current (CCC) Tests Four samples of AB₅ single cells from manufacturers A, E, F, and G were evaluated for their CCC characteristics and are presented here by company.

4.6.1.1 Company A (AB₅ Cylindrical Cells) Company A cells behaved predictably as had been observed with the SD and CDC tests discussed in previous sections. Difficulties arose when the charge experiments were conducted at 71 °C and at higher currents at 49 °C. During the charge the cell temperatures increased and reached the upper temperature limit of 75 °C before the full 10 percent overcharge was accepted by the cells and the charge terminated. This was not unexpected so the discharge data reported and percent capacities plotted under the high temperature conditions are low principally for this reason. At no time however, did the Company A cells show signs of degraded capacity due to high temperature and current exposure and continued to function normally when returned to room temperature

conditions. The data for Company A cells are presented in Table 4.6.1.1-1 and 4.6.1.1-2 and in Figures 4.6.1.1-1 and 4.6.1.1-2. Each figure has the 75 percent capacity line marked.

At room temperature, Company A cells accepted charges as high as 2C and delivered full capacity on discharge. Capacity began to decline above the 2C charge current but 75 percent capacity was still available up to 4C. The temperature data (Figure 4.6.1.1-2) show a peak in charge acceptance around 12 °C and a 75 percent capacity window from -15 °C to 42 °C for a 1C charge current. The limited data at the 2C charge current parallel the 1C results.

Table 4.6.1.1-1. Company A CCC Results at 2.4 A (1C) and at 4.8 A (2C)

Nominal Temp. (°C)	71	49	49	24	0	-18	-40
Charge Current 2.4 A (1C)							
Group No.	2	2		1	4 & 5	4 & 5	4 & 5
Cycle No.	46/47	43/44		75/76	50/51 50/51	55/56 55/56	60/61 61/62
Disch. Capacity (A-h)	1.070	1.521		2.425	2.260 2.313	1.538 1.602	0.022 0.024
Capacity (%)	43.34	61.60		98.62	96.05 96.14	64.40 65.71	0.90 0.98
Current (A)	2.39	2.41		2.40	2.41 2.41	2.40 2.40	2.41 2.40
Temperature (°C)	70.2	50.5		23.2	0.9 0.7	-18.2 -18.3	-39.0 -39.2
Charge Current 4.8 A (2C)							
Group No.		4	5	1			
Cycle No.		93/94 96/97	94/95 97/98	66/67 71/72			
Disch. Capacity (A-h)		1.463 1.484	1.500 1.524	2.383 2.391			
Capacity (%)		60.78 61.65	61.53 62.51	98.07 98.40			
Current (A)		4.81 4.79	4.81 4.80	4.79 4.79			
Temperature (°C)		49.4 49.5	49.1 48.9	23.3 23.1			

Table 4.6.1.1-2. Company A CCC Results at 49 and 24 °C

Nominal CCC (A)	0.5	1.0	2.4	4.8	4.8	8.0	12.0
49 °C							
Group No.			2	4	5		
Cycle No.			43/44	96/97	97/98		
Disch. Capacity (A-h)			1.521	1.484	1.524		
Capacity (%)			61.60	61.65	62.51		
Current (A)			2.41	4.79	4.80		
Temperature (°C)			50.5	49.5	48.9		
24 °C							
Group No.	1	2	1	1		1	1
Cycle No.	85/86	28/29	75/76	66/67 71/72		78/79	81/82
Disch. Capacity (A-h)	2.401	2.363	2.425	2.383 2.391		1.912	0.229
Capacity (%)	97.13	98.54	98.62	98.07 98.40		77.76	9.26
Current (A)	0.470	0.959	2.40	4.79 4.79		8.04	11.99
Temperature (°C)	23.6	23.0	23.2	23.3 23.1		23.2	24.0

4.6.1.2 Company E (AB₅ Prismatic Cells) Originally CCC tests were planned with Company E cells up to a 15 A charge current (5C), however, the results of the CDC tests (Section 4.5.1.3) which destroyed four cells while attempting a 15 A discharge canceled CCC tests at that current. During the course of the CCC tests, particularly at temperatures below room temperature, capacities fell off very fast even at the 1.2 A charge current. Examination of the data showed the cells were not receiving a full 10 % overcharge which resulted in the lower capacities than expected. Apparently cell resistance increases rapidly below room temperature either due to the design or to the electrolyte causing cell voltage to rise rapidly and the charge terminated at the preset charging voltage limit of 1.60 V. This termination of charge also occurred on the group 2 cells in the experiment at 49 °C using a 6 A charging

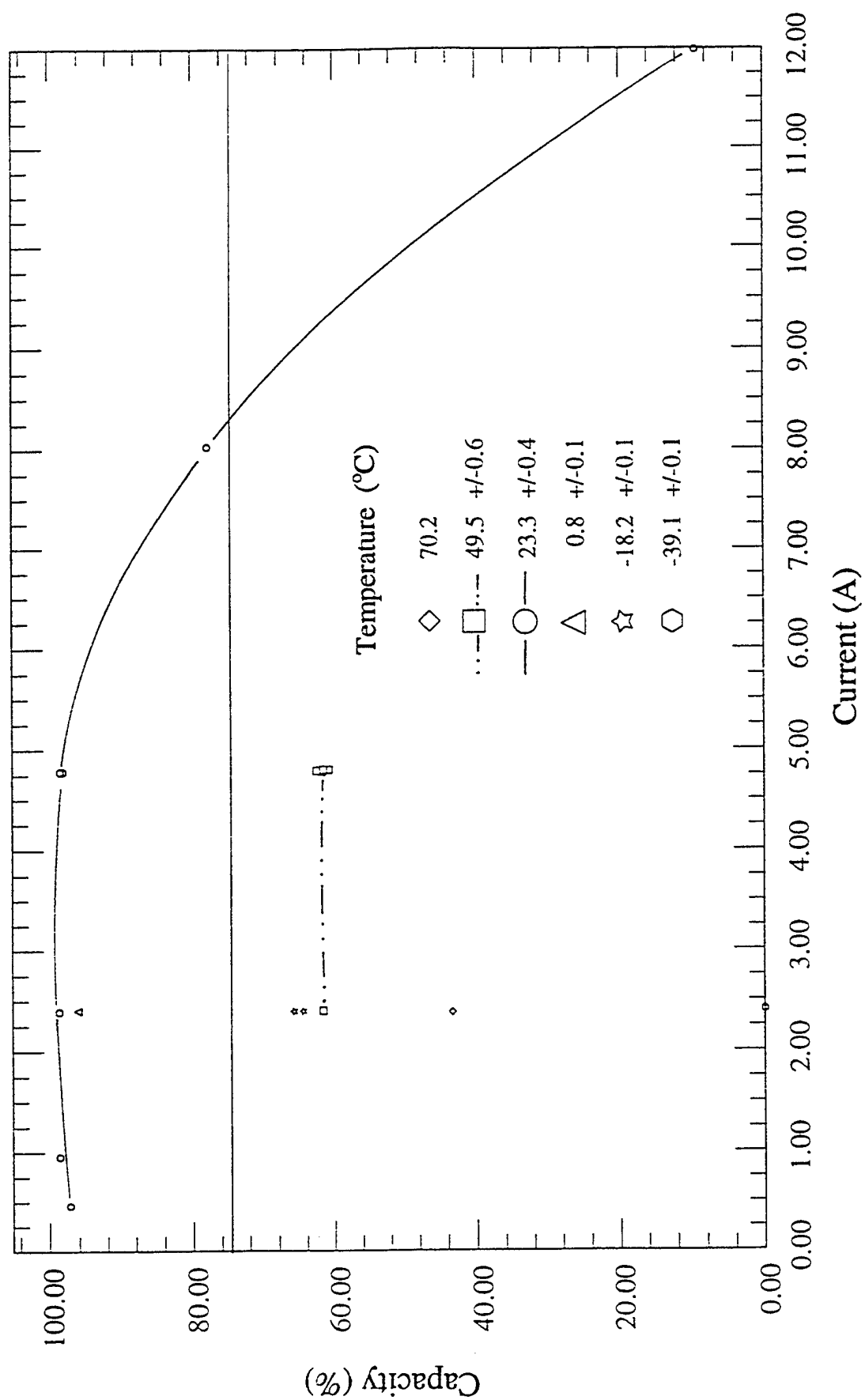


Figure 4.6.1.1-1. Company A CCC Capacity vs. Current

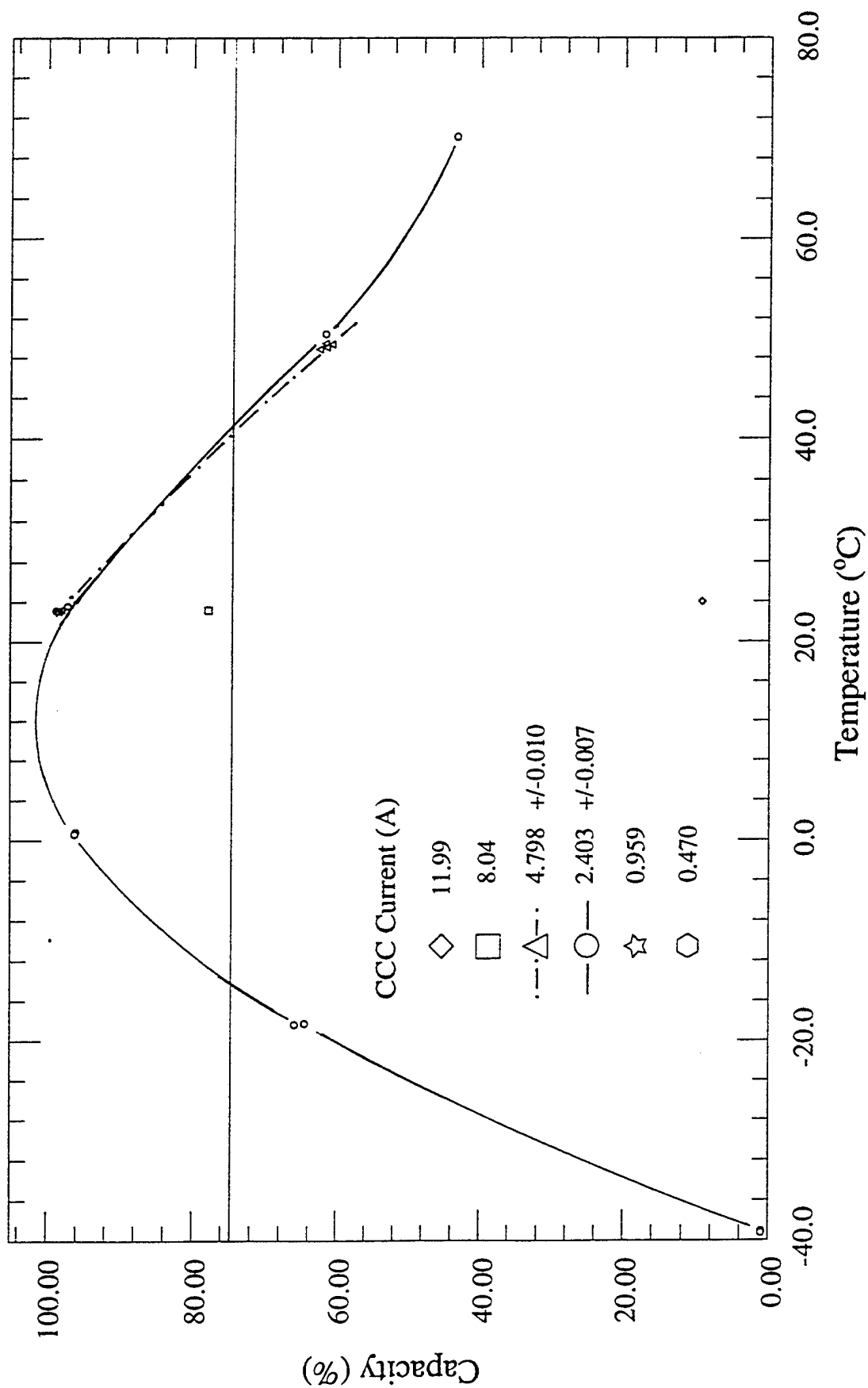


Figure 4.6.1.1-2. Company A CCC Capacity vs. Temperature

current. The group 1 cells that were in the same environmental chamber functioned normally and received a full 10 % overcharge. Comparison of the data for those two groups in Table 4.6.1.2-1 shows the group 1 cells had a higher discharge capacity than the group 2 cells.

The test run at 71 °C on the group 3 cells was modified to raise the temperature limit cutoff to 85 °C due to the problems encountered with experiments on Company A cells at that temperature. This change was successful and the cell temperatures never rose above 83 °C.

Examination of the summary figures for Company E cells shows a very limited temperature range for cell charging due to the voltage limit cutoff at 1.6 V. However, the cells accept up to a 6 A charge current at room temperature with very little change in the discharge capacity. Discharge capacity begins to fall below 75 percent when the cells are used at 49 °C. The data for Company E cells are presented in Table 4.6.1.2-1 and 4.6.1.2-2 and in Figures 4.6.1.2-1 and 4.6.1.2-2. Each figure has the 75 percent capacity line marked.

Table 4.6.1.2-1. Company E CCC Results at 71 and 49 °C.

Nominal CCC (A)	0.6	1.2	3.0	6.0	6.0
71 °C					
Group No.			3		
Cycle No.			30/31		
Disch. Capacity (A-h)			0.953		
Capacity (%)			31.14		
Current (A)			3.001		
Temperature (°C)			70.5		
49 °C					
Group No.			3	1	2 ^a
Cycle No.			27/28	77/78	77/78
Disch. Capacity (A-h)			2.770	2.332	2.230
Capacity (%)			91.21	79.56	75.03
Current (A)			2.980	5.998	5.990
Temperature (°C)			49.5	49.6	49.0

^a Group 2 cells terminated the charge due to the 1.6 V limit on the cell voltage during charge.

Table 4.6.1.2-2. Company E CCC Results from 24 to -40 °C^a

Nominal CCC (A)	0.6	1.2	1.2	3.0	3.0	6.0	6.0
24 °C							
Group No.	5	5		5		5	
Cycle No.	29/30	26/27		18/19		21/22	
Disch. Capacity (A-h)	2.951	2.950		2.982		2.904	
Capacity (%)	97.81	97.78		96.98		95.62	
Current (A)	0.594	1.191		2.996		5.989	
Temperature (°C)	23.7	23.7		22.9		23.3	
0 °C							
Group No.				1	2	1	2
Cycle No.				34/35	34/35	86/87	86/87
Disch. Capacity (A-h)				2.277	2.374	0.041	0.044
Capacity (%)				74.80	77.63	1.46	1.50
Current (A)				3.004	3.006	6.020	6.003
Temperature (°C)				0.5	0.7	-0.3	-0.3
-18 °C							
Group No.				1	2	X ^b	X ^b
Cycle No.				39/40	39/40	X ^b	X ^b
Disch. Capacity (A-h)				0.205	0.538	X ^b	X ^b
Capacity (%)				6.74	17.60	X ^b	X ^b
Current (A)				3.004	2.996	X ^b	X ^b
Temperature (°C)				-18.2	-18.2	X ^b	X ^b
-40 °C							
Group No.		1	2	X ^b	X ^b	X ^b	X ^b
Cycle No.		42/43 45/46	42/43 45/46	X ^b	X ^b	X ^b	X ^b
Disch. Capacity (A-h)		0.015 0.045	0.022 0.062	X ^b	X ^b	X ^b	X ^b
Capacity (%)		0.49 1.48	0.72 2.03	X ^b	X ^b	X ^b	X ^b
Current (A)		1.200	1.193	X ^b	X ^b	X ^b	X ^b
Temperature (°C)		-39.8 -39.4	-40.1 -39.2	X ^b	X ^b	X ^b	X ^b

^a For all cell tests at 0 °C and below, the cells terminated the charge at the 1.60 V limit prior to accepting a 10 % overcharge.

^b Deleted: Cell voltage limit during charge.

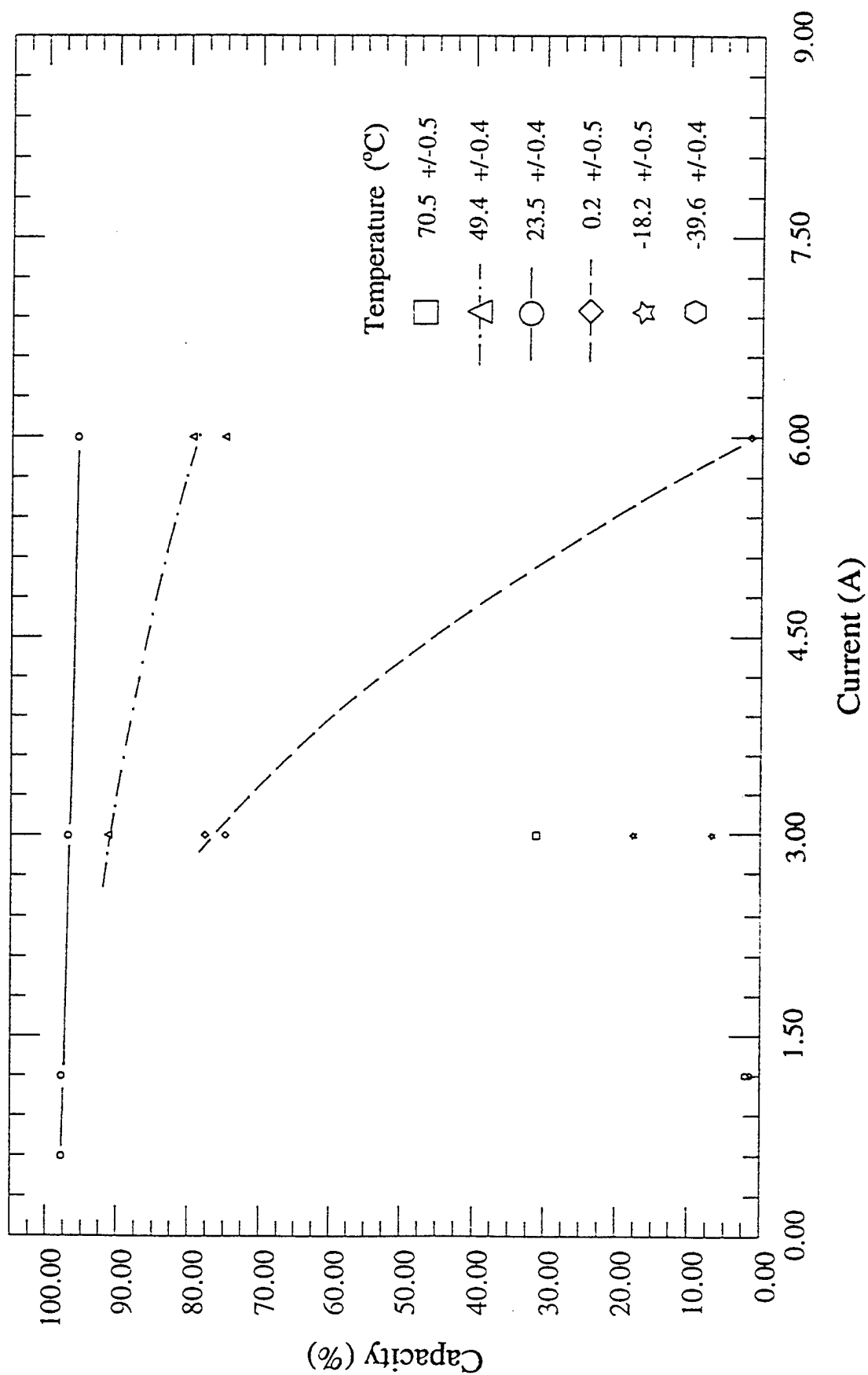


Figure 4.6.1.2-1. Company E CCC Capacity vs. Current

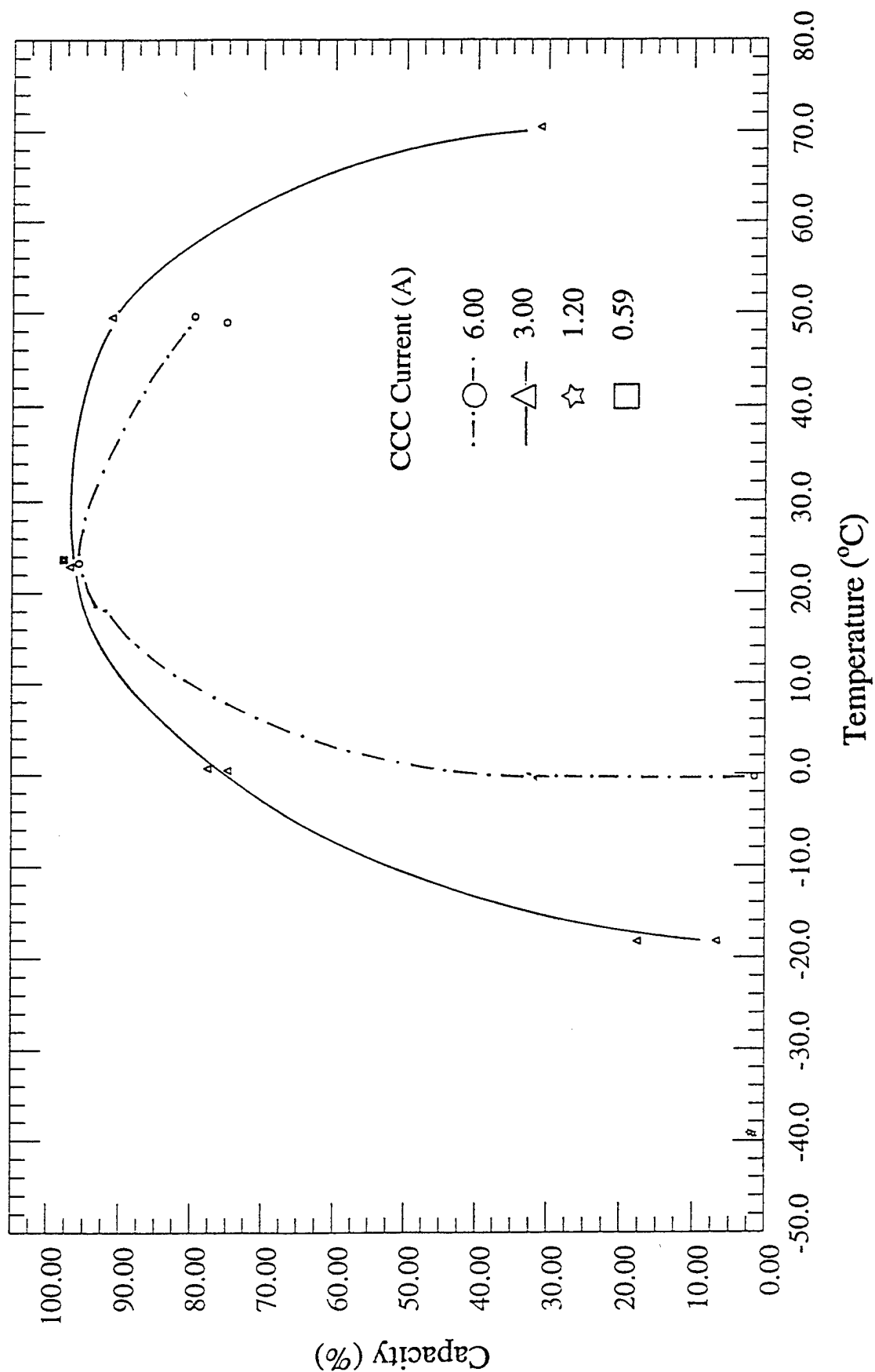


Figure 4.6.1.2-2. Company E CCC Capacity vs. Temperature

4.6.1.3 Company F (AB₅ Prismatic Cells) Company F cells responded well to the different charge currents used during the tests. Limited testing was done at the higher currents because there were only four cells available to do all the testing which also slowed the test process. There were no unusual characteristics noted other than the more cycles on the cells the higher the cell voltages became as the cells were charged. Company F CCC results are presented in Tables 4.6.1.2-1 and 4.6.1.2-2. The CCC test results versus current are summarized in Figures 4.6.1.2-1 and over the temperature range tested in Figure 4.6.1.2-2.

Comparisons of the two figures shows a crossover between the room temperature and 49 °C curves that indicates the cells perform better at higher currents at higher temperatures. Similarly, the plot of CCC capacity versus temperature at a given charge current shows better performance at higher currents. These two observations and the CDC capacity versus temperature curve (Figure 4.51.4-2) suggest the Company F cells have a different AB₅ alloy compared to the others tested in this program.

Table 4.6.1.3-1. Company F CCC Results at 71 and 49 °C.

Nominal CCC (A)	0.2	0.4	0.9	1.8	4.6
71 °C					
Cycle No.			111 ^a /112		
Disch. Capacity (A-h)			0.322		
Capacity (%)			33.44		
Current (A)			0.938		
Temperature (°C)			71.1		
49 °C					
Cycle No.		103/104	99/100	115/116 135/136	
Disch. Capacity (A-h)		0.721	0.838	0.853 0.879	
Capacity (%)		75.10	86.93	88.58 90.25	
Current (A)		0.373	0.938	1.851 1.851	
Temperature (°C)		49.1	49.0	49.0 48.9	

^a Temperature limited short charge; only 34 percent instead of 110 percent.

Table 4.6.1.3-2. Company F CCC Results at 24 and 0 °C

Nominal CCC (A)	0.2	0.4	0.9	1.8	4.6
24 °C					
Cycle No.	87/88	77/78	73/74	80/81	
Disch. Capacity (A-h)	0.919	0.911	0.926	0.832	
Capacity (%)	95.33	95.69	97.27	86.31	
Current (A)	0.198	0.369	0.928	1.802	
Temperature (°C)	22.3	22.0	20.3	22.8	
0 °C					
Cycle No.		139/140	90 ^b /91 93 ^b /94	X ^a	X ^a
Disch. Capacity (A-h)		0.794	0.428 ^b 0.299 ^b	X ^a	X ^a
Capacity (%)		82.36	44.40 ^b 31.02 ^b	X ^a	X ^a
Current (A)		0.373	0.938 0.938	X ^a	X ^a
Temperature (°C)		-0.3	-0.3 -0.3	X ^a	X ^a

^a Deleted: Results of 0.94 A charge at 0 °C.

^b Low overcharge due to faulty mechanical switch setting.

4.6.1.4 Company G (AB₅ Cylindrical Cells) Company G cells experienced some problems with both the voltage limit (1.60 V) and the temperature limit which had been mechanically set to 60 °C instead of the normal 75 °C. The temperature limit was deliberately set low because the manufacturer recommended not charging the cells above 45 °C for the cell packs which were the source for the individual cells. Company G cells would not accept a 12.5 A charge, but the cells were not damaged in the process and exhibited normal behavior during subsequent FCR cycles, which resulted in cancellation of 12.5 A charge tests at all temperatures. In tests at the 5.0 A (2C) charge rate two of the four cells in group 2 would not accept the charge. All of the group 2 cells recovered on subsequent FCR cycles. The CCC

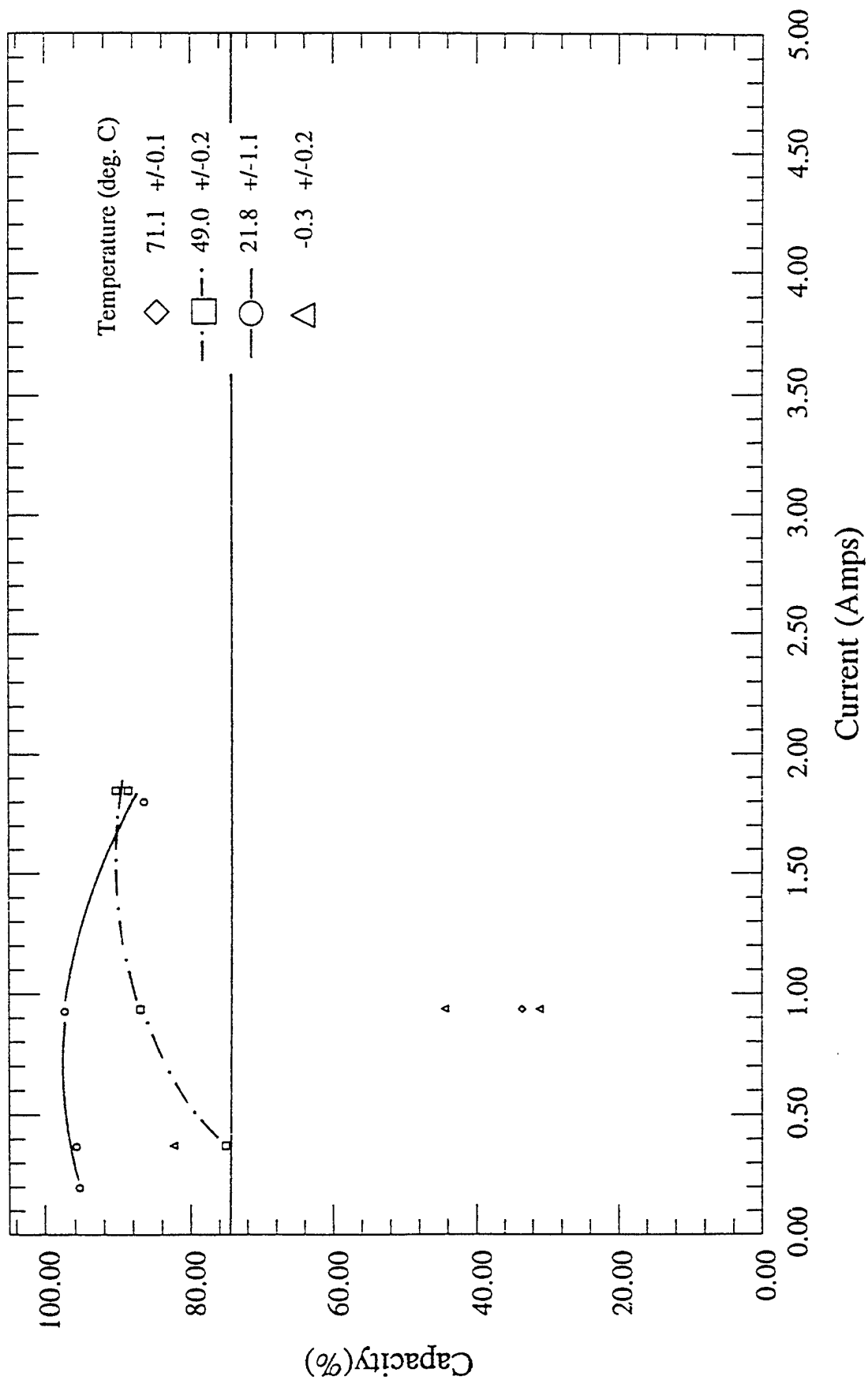


Figure 4.6.1.3-1. Company F CCC Capacity vs. Current

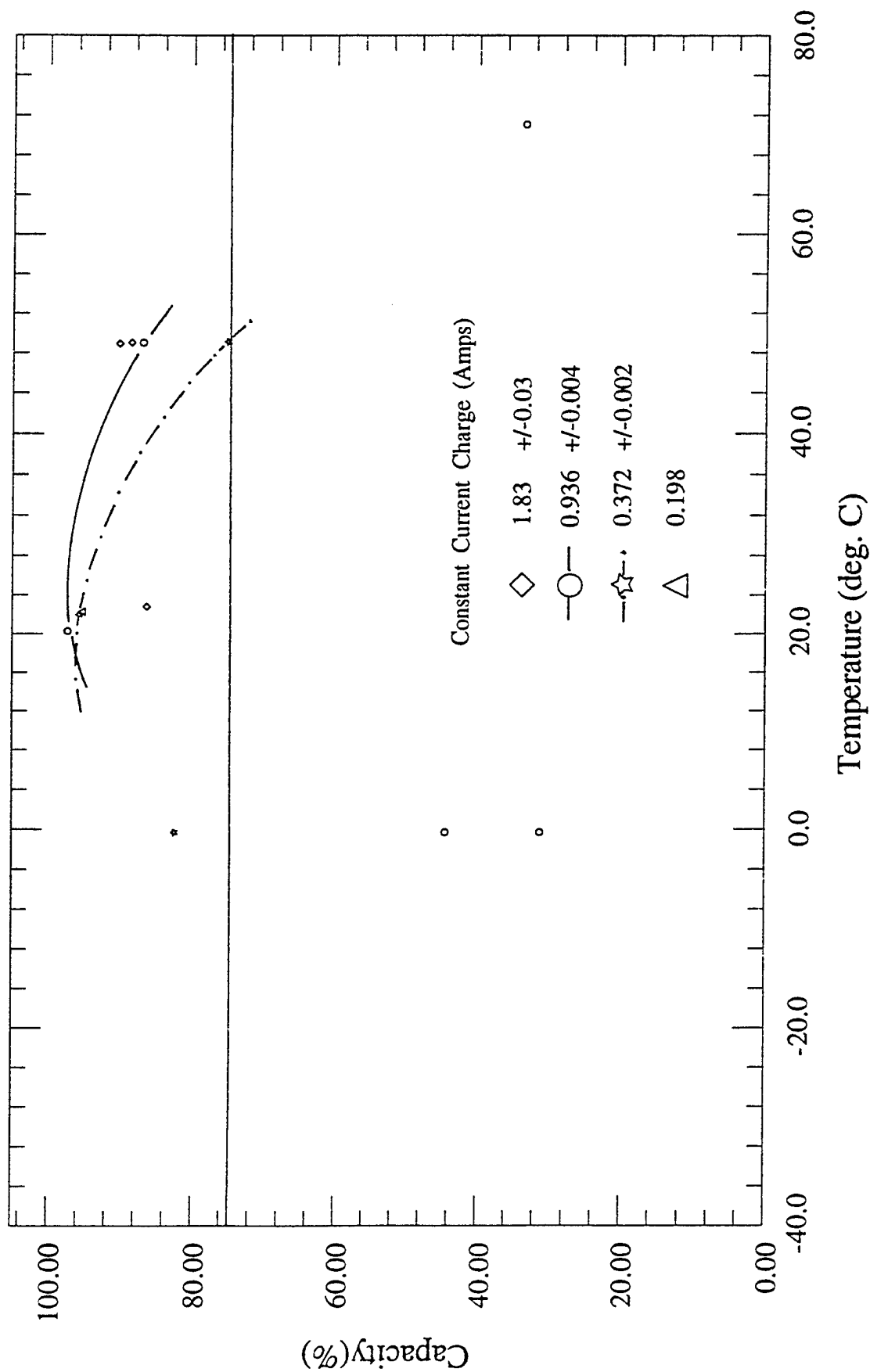


Figure 4.6.1.3-2. Company F CCC Capacity vs. Temperature

results for Company G cells are shown in Tables 4.6.1.4-1 and 4.6.1.4-2. The CCC capacities vs. charge rate and temperature are presented in Figures 4.6.1.4-1 and 4.6.1.4-2.

The Company G CCC capacity versus current graphs (Figure 4.6.1.4-1) show normal behavior with no unusual characteristics. The 75 percent capacity line suggests 5 A (2C) is the upper limit for charging under aircraft conditions at room temperature. The chart of CCC capacities over the temperature range indicates a peak in the charge efficiency near 35 °C and a one hour charge rate temperature window from 10 ° to 60 °C.

Table 4.6.1.4-1. Company G CCC Results at 71 and 49 °C

Nominal CCC (A)	0.5	1.0	2.5	5.0	12.5
71 °C (Group 5)					
Cycle No.			24 ^d /25 33 ^d /34	X ^c	X ^b
Disch. Capacity (A-h)			0.920 0.921	X ^c	X ^b
Capacity (%)			35.14 35.10	X ^c	X ^b
Current (A)			2.525 2.525	X ^c	X ^b
Temperature (°C)			71.0 70.7	X ^c	X ^b
49 °C (Group 4)					
Cycle No.		70/71	9 ^a /10 12 ^a /13	X ^c	X ^b
Disch. Capacity (A-h)		2.349	2.291 2.336	X ^c	X ^b
Capacity (%)		89.15	89.45 90.40	X ^c	X ^b
Current (A)		1.014	2.529 2.529	X ^c	X ^b
Temperature (°C)		50.0	51.0 50.2	X ^c	X ^b

^a T limit cutoff (60 °C) reached on cells 9, 11 and 12 before 10% overcharge completed.

^b Deleted: 12.64 amp charge result at 24 °C.

^c Deleted: 5.06 amp charge results at 24 °C.

^d Cells 21 and 22 would not accept the charge.

Table 4.5.1.4-2. Company G CCC Results at 49 and 24 °C

Nominal CCC (A)	0.5	1.0	2.5	5.0	12.5
24 °C					
Group No.		2	2	2	
Cycle No.		10/11	7 ^a 8	13 ^a /14	
Disch. Capacity (A-h)		2.531	2.442 ^a	2.162 ^a	
Capacity (%)		98.83	95.35	83.19	
Current (A)		0.998	2.523	5.064	
Temperature (°C)		23.5	23.5	20.0	
24 °C					
Group No.	4			3	3
Cycle No.	46/47			41 ^a /42	48 ^b /49
Disch. Capacity (A-h)	2.550			1.964 ^a	0.193 ^b
Capacity (%)	97.85			73.17	7.19
Current (A)	0.503			5.057	12.64
Temperature (°C)	23.5			22.8	22.6
0 °C					
Group No.		2	2	4	X ^b
Cycle No.		99 ^a /100	95 ^a /96	33/34	X ^b
Disch. Capacity (A-h)		2.302 ^a	1.182 ^a	0.057	X ^b
Capacity (%)		87.86	45.11	2.20	X ^b
Current (A)		1.030	2.523	5.093	X ^b
Temperature (°C)		-0.9	-0.2	1.2	X ^b
-18 °C					
Group No.			4	X ^d	X ^c
Cycle No.			65 ^a /66	X ^d	X ^c
Disch. Capacity (A-h)			0.042 ^a	X ^d	X ^c
Capacity (%)			1.59	X ^d	X ^c
Current (A)			2.555	X ^d	X ^c
Temperature (°C)			-17.7	X ^d	X ^c

^a Voltage limit cutoff (1.60 V/cell) reached before 10% overcharge completed.

^b Would not accept charge.

^c Deleted: 12.64 amp charge result at 24 °C.

^d Deleted: 5.09 amp charge result at 0 °C.

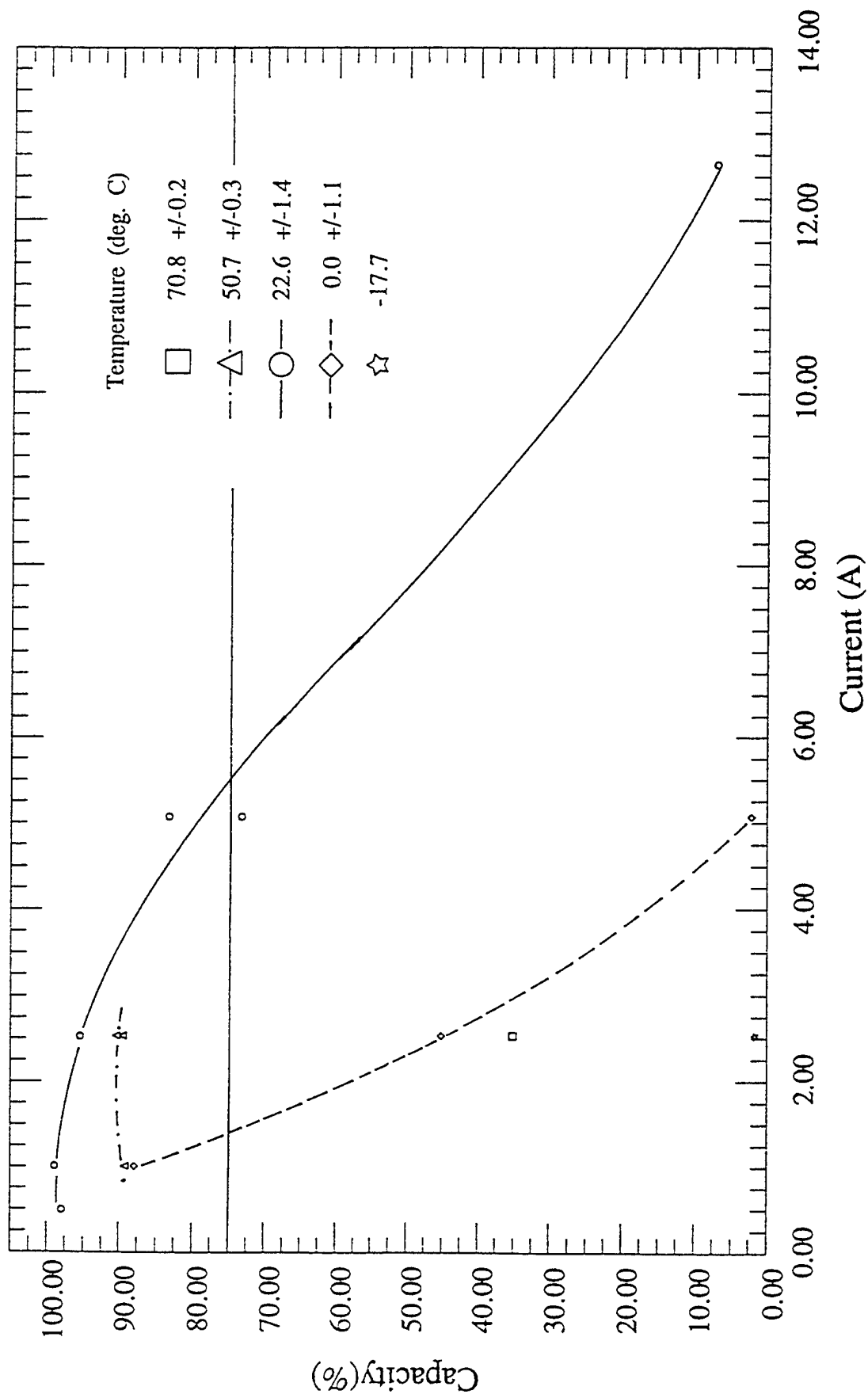


Figure 4.6.1.4-1. Company G CCC Capacity vs. Current

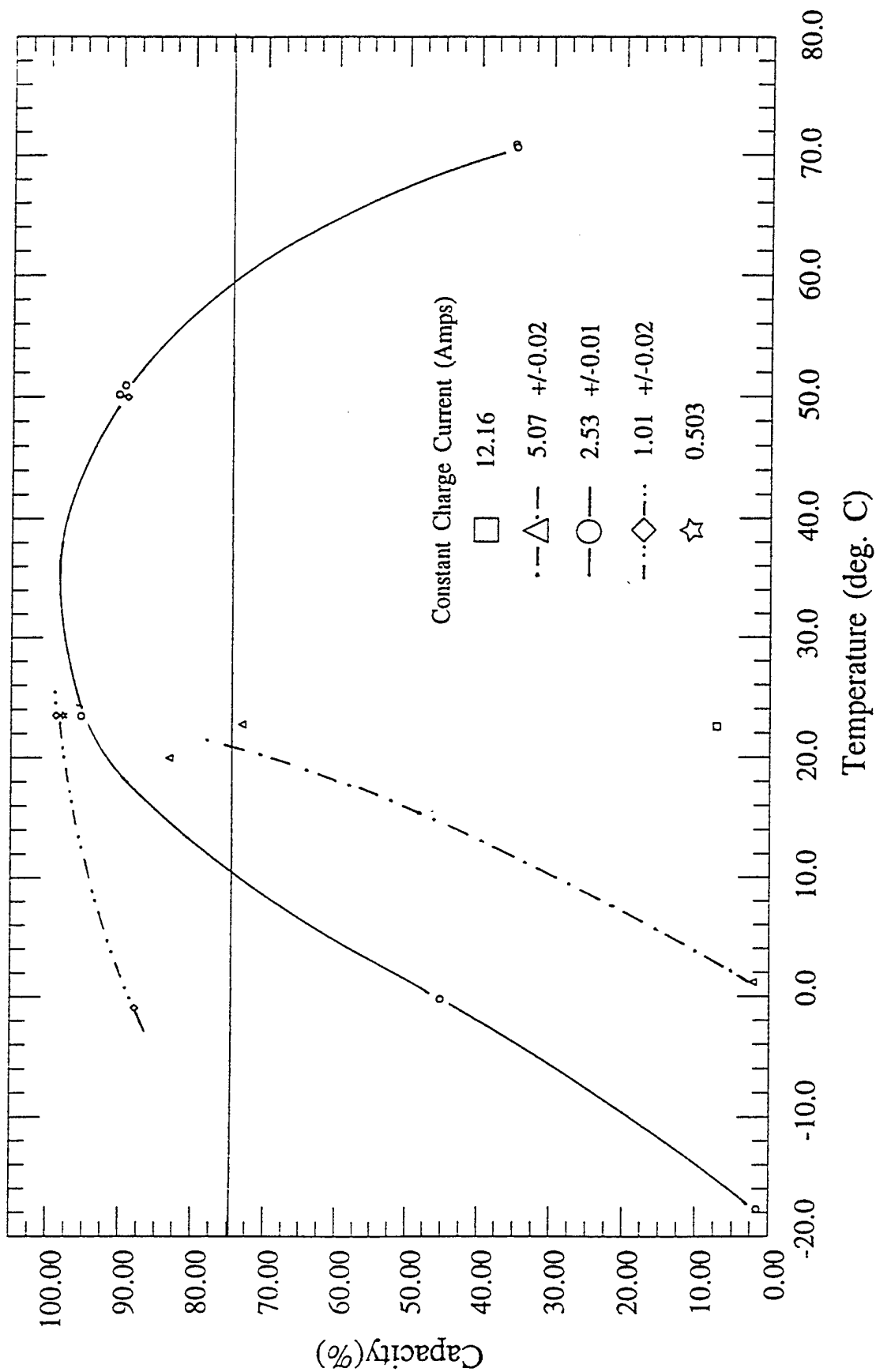


Figure 4.6.1.4-2. Company G CCC Capacity vs. Temperature

4.6.2 AB₂ Single Cell Tests Two samples of AB₂ single cells from manufacturers D and H were evaluated for their Constant Charge Current (CCC) characteristics. Both sets of cells were cylindrical construction. The results of the CCC tests by company are presented here.

4.6.2.1 Company D (AB₂ Cylindrical Cells) Company D cells experienced the same type of difficulties with voltage and temperature limits on charge that Company G did, but unlike the AB₅ cells tested they did not recover their full capacity when exposed to high temperatures and high charge currents. Company D CCC results are tabulated in Tables 4.6.2.1-1 and 4.6.2.1-2. Graphical presentations of the test data versus current at room temperature are in Figure 4.6.2.1-1 and over the temperature range tested in Figure 4.6.2.1-2. Both figures have the 75 percent capacity level marked on the graphic.

Comparisons of the two figures shows an approximate 3 - 4.5 A limit on charging that will return 75 percent of the charged capacity at room temperature and at 49 °C. At 0 °C the upper limit for charge is 1 A. There is no obvious reason for the drop in charge efficiency below 0.8 A but it is present at both 49 °C and at 23.3 °C. Encouragingly, however, plots at various charge rates over the temperature region tested show a fairly broad flat charging window from about -10 °C to slightly higher than 50 °C for currents from C/5 to 1C. Above 1C charge rates the temperature and voltage limits degrade the charging characteristics. The best charge retention was at 0.7 A (2C/5).

Table 4.6.2.1-1. Company D CCC Results at 71 °C.

Nominal CCC (A)	0.35	0.7	1.8	1.8	3.6	9.0
Group No.			2	5	3	X ^a
Cycle No.			49 ^b /50	23 ^b /24 ^c	45 ^b /46	X ^a
Disch. Capacity (A-h)			0.931	0.457	0.277	X ^a
Capacity (%)			51.69	28.53	14.84	X ^a
Current (A)			1.767	1.768	3.537	X ^a
Temperature (°C)			71.0	71.5	70.1	X ^a

^a Deleted: Results of 3.6 A charge at 49 °C.

^b Charge terminated due to voltage and temperature limits before attaining 10 % overcharge.

^c Two cells failed during the measurement discharge and did not recover.

Table 4.6.2.1-2. Company D CCC Results at 49 and 24 °C.

Nominal CCC (A)	0.35	0.35	0.7	1.8	3.6	3.6	9.0
49 °C							
Group No.	3	5	2	3	2	3	X ^b
Cycle No.	41/42	7/8	41/42	37/38	45 ^a /46	49 ^a /50	X ^b
Disch. Capacity (A-h)	1.505	1.339	1.598	1.659	0.896	0.255	X ^b
Capacity (%)	81.35	87.80	88.73	89.68	49.75	13.66	X ^b
Current (A)	0.345	0.354	0.708	1.762	3.534	4.590	X ^b
Temperature (°C)	48.5	49.6	49.3	48.4	49.7	49.0	X ^b
24 °C							
Group No.	1		1	1			1
Cycle No.	46/47		43/44	37/38 40.41			50 ^c /51
Disch. Capacity (A-h)	1.557		1.771	1.745 1.726			0.133
Capacity (%)	86.55		98.44	96.25 95.94			7.39
Current (A)	0.336		0.702	1.759 1.778			8.846
Temperature (°C)	22.2		23.2	24.0 24.2			23.0

^a Charge terminated due to voltage and temperature limits before attaining 10 % overcharge.

^b Deleted: Results of 3.6 A charge at 49 °C.

^c Hit voltage limit almost immediately.

Table 4.6.2.1-3. Company D CCC Results at 0 and -18 °C.

Nominal CCC (A)	0.35	0.7	0.7	1.8	3.6
0 °C					
Group No.	3	3	2	2	X ^b
Cycle No.	31/32 ^c	28/29	32/33	38 ^a /39	X ^b
Disch. Capacity (A-h)	1.775	1.523	1.372	0.206	X ^b
Capacity (%)	95.95	84.80	76.18	11.44	X ^b
Current (A)	0.357	0.699	0.718	1.766	X ^b
Temperature (°C)	-1.0	-1.0	-0.7	-0.5	X ^b
-18 °C					
Group No.		5	X ^d	X ^d	X ^b
Cycle No.		11/12	X ^d	X ^d	X ^b
Disch. Capacity (A-h)		0.260	X ^d	X ^d	X ^b
Capacity (%)		17.05	X ^d	X ^d	X ^b
Current (A)		0.704	X ^d	X ^d	X ^b
Temperature (°C)		-18.4	X ^d	X ^d	X ^b

^a Charge terminated due to voltage and temperature limits before attaining 10 % overcharge.

^b Deleted: Results of 1.8 A charge at 0 °C.

^c One cell failed during the measurement discharge and did not recover.

^d Deleted: Results of 0.7 A charge at -18 °C.

4.6.2.2 Company H (AB₂ Cylindrical Cells) Company H charging tests were limited due to the poor results obtained at high currents and both high and low temperatures during the discharge tests (Section 4.5.2.2). The data are presented in Tables 4.6.2.2-1 and 4.6.2.2-2 and are graphically summarized in Figures 4.6.2.2-1 and 4.6.2.2-2. The limited data shows an upper current limit at 23 °C of 1.60 A and indications of a slightly higher limit at 49 °C of 1.80 A. Additional testing is needed to characterize these cells at lower currents and at 49 °C.

The temperature results for a given charge current (Figure 4.6.2.2-2) are not very promising for an aircraft application. The 1.81 A charge curve shows a 75 percent maximum in the charge efficiency around 49 °C. The shapes of the two curves at 0.8 and 0.4 A respectively, are speculative pending additional data at 10 degree intervals between 20 °C and -30 °C. Additional testing of these cells is underway by WL/POOB personnel covering both charge and discharge experiments at these lower temperatures.

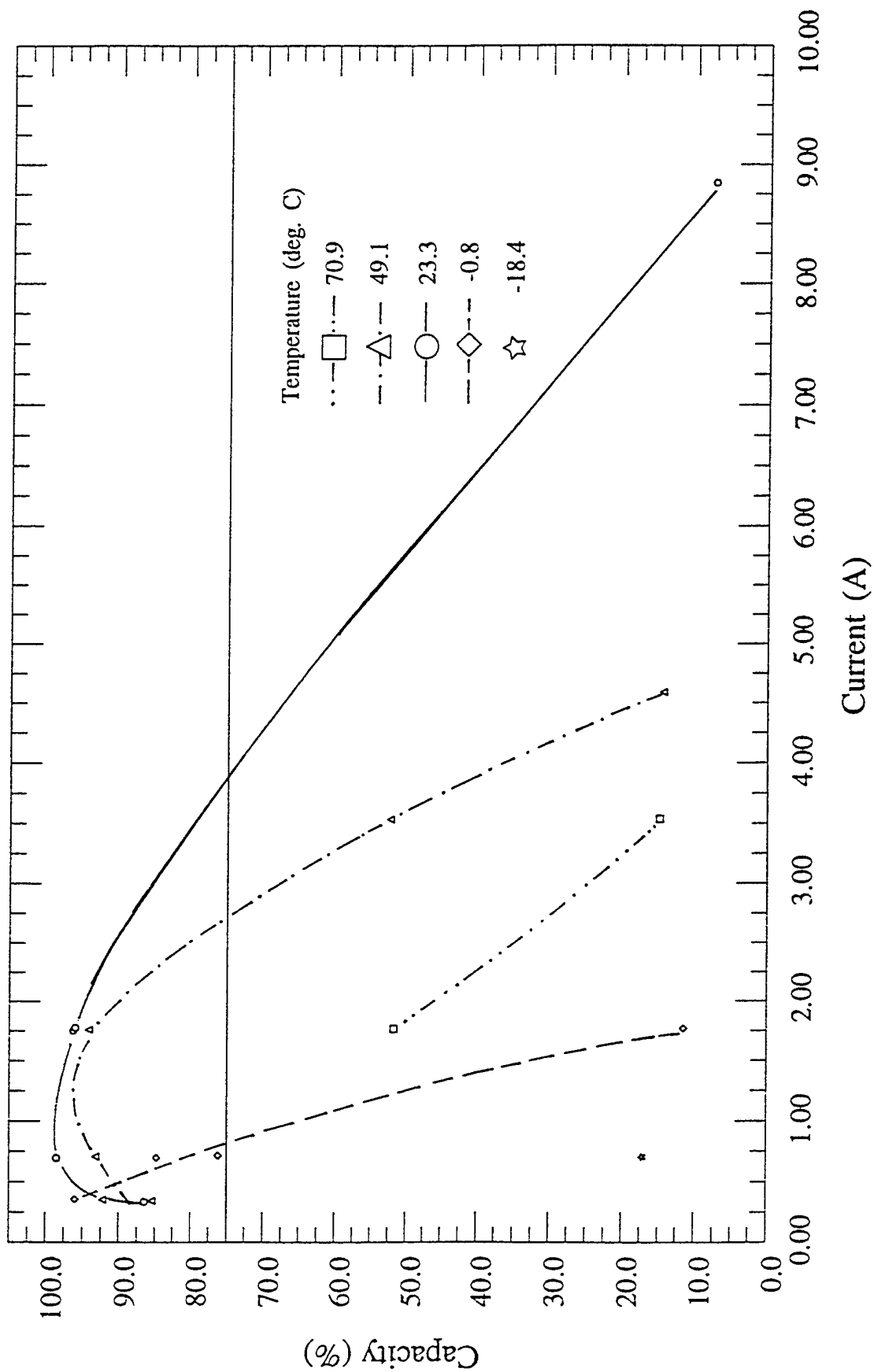


Figure 4.6.2.1-1. Company D CCC Capacity vs. Current

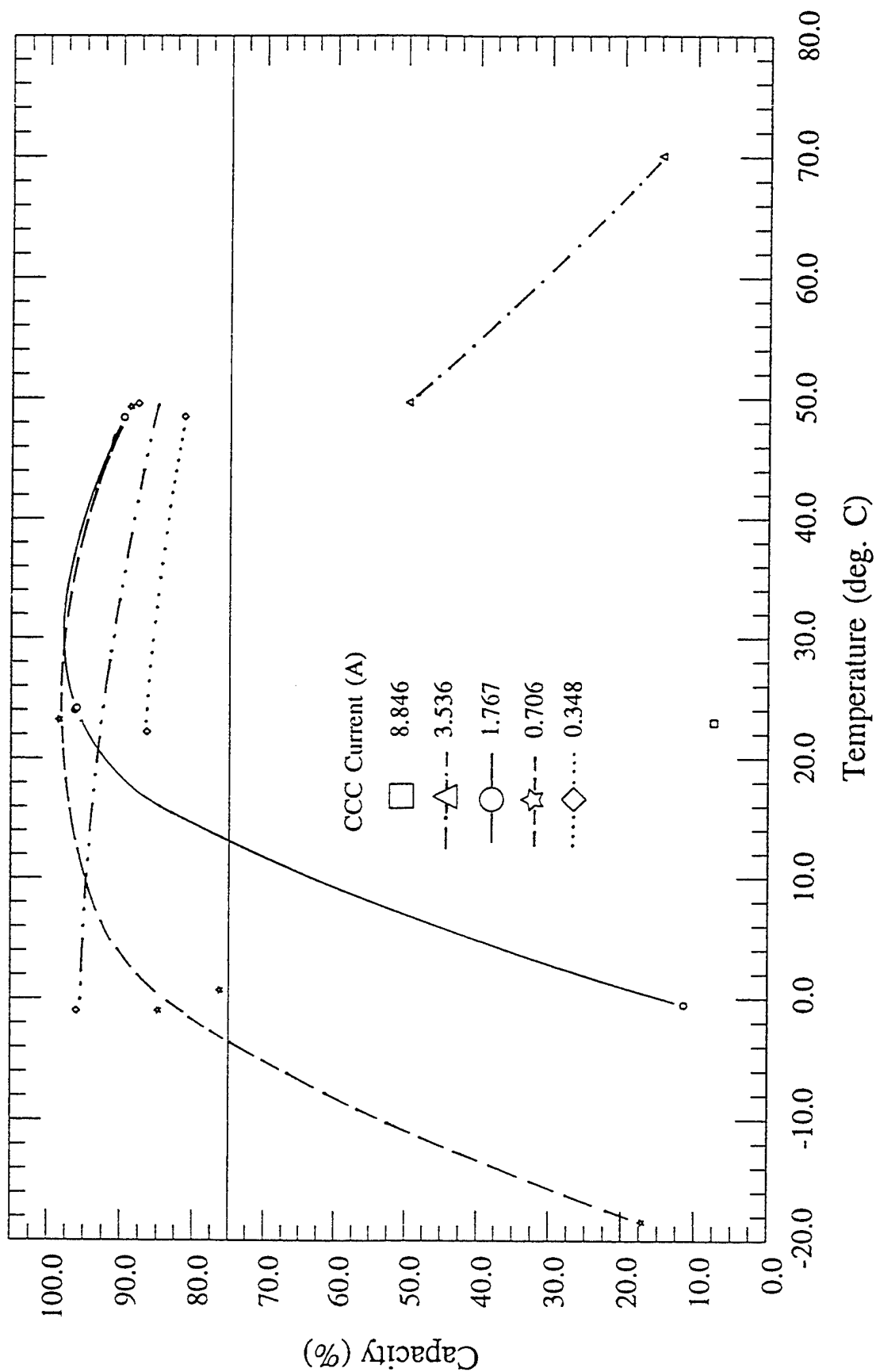


Figure 4.6.2.1-2. Company D CCC Capacity vs. Temperature

Table 4.6.2.2-1. Company H CCC Results from 71 to -40 °C.

Nominal CCC (A)	0.36	0.72	1.8	3.6	9.0
71 °C (Group 4)					
Cycle No.	X ^e	X ^e	36/37	X ^e	X ^a
Disch. Capacity (A-h)	X ^e	X ^e	1.132	X ^e	X ^a
Capacity (%)	X ^e	X ^e	67.02	X ^e	X ^a
Current (A)	X ^e	X ^e	1.796	X ^e	X ^a
Temperature (°C)	X ^e	X ^e	70.0	X ^e	X ^a
49 °C (Group 4)					
Cycle No.			33/34		X ^a
Disch. Capacity (A-h)			1.253		X ^a
Capacity (%)			74.19		X ^a
Current (A)			1.797		X ^a
Temperature (°C)			49.0		X ^a
24 °C (Group 5)					
Cycle No.	35/36	33/34	25/26	28/29	X ^a
Disch. Capacity (A-h)	1.694	1.618	1.040	0.112	X ^a
Capacity (%)	102.92	98.30	63.88	6.88	X ^a
Current (A)	0.433	0.870	1.808	3.592	X ^a
Temperature (°C)	24.0	23.1	23.2	23.3	X ^a
0 °C (Group 1)					
Cycle No.			32/33	X ^b	X ^b
Disch. Capacity (A-h)			0.175	X ^b	X ^b
Capacity (%)			8.61	X ^b	X ^b
Current (A)			1.810	X ^b	X ^b
Temperature (°C)			2.1	X ^b	X ^b
-18 °C (Group 1)					
Cycle No.		37/38	X ^c	X ^b	X ^b
Disch. Capacity (A-h)		0.151	X ^c	X ^b	X ^b
Capacity (%)		7.43	X ^c	X ^b	X ^b
Current (A)		0.722	X ^c	X ^b	X ^b
Temperature (°C)		-17.3	X ^c	X ^b	X ^b
-40 °C (Group 1)					
Cycle No.	43/44	X ^d	X ^c	X ^b	X ^b
Disch. Capacity (A-h)	0.033	X ^d	X ^c	X ^b	X ^b
Capacity (%)	1.64	X ^d	X ^c	X ^b	X ^b
Current (A)	0.358	X ^d	X ^c	X ^b	X ^b
Temperature (°C)	-39.9	X ^d	X ^c	X ^b	X ^b

^a Deleted: Results of 3.6 A charge test at 24 °C.

^b Deleted: Results of 1.8 A charge test at 0 °C.

^c Deleted: Results of 0.7 A charge test at -18 °C.

^d Deleted: Results of 0.35 A charge test at -40 °C.

^e Deleted: Results of discharge tests in Section 4.5.2.2 at 71 °C.

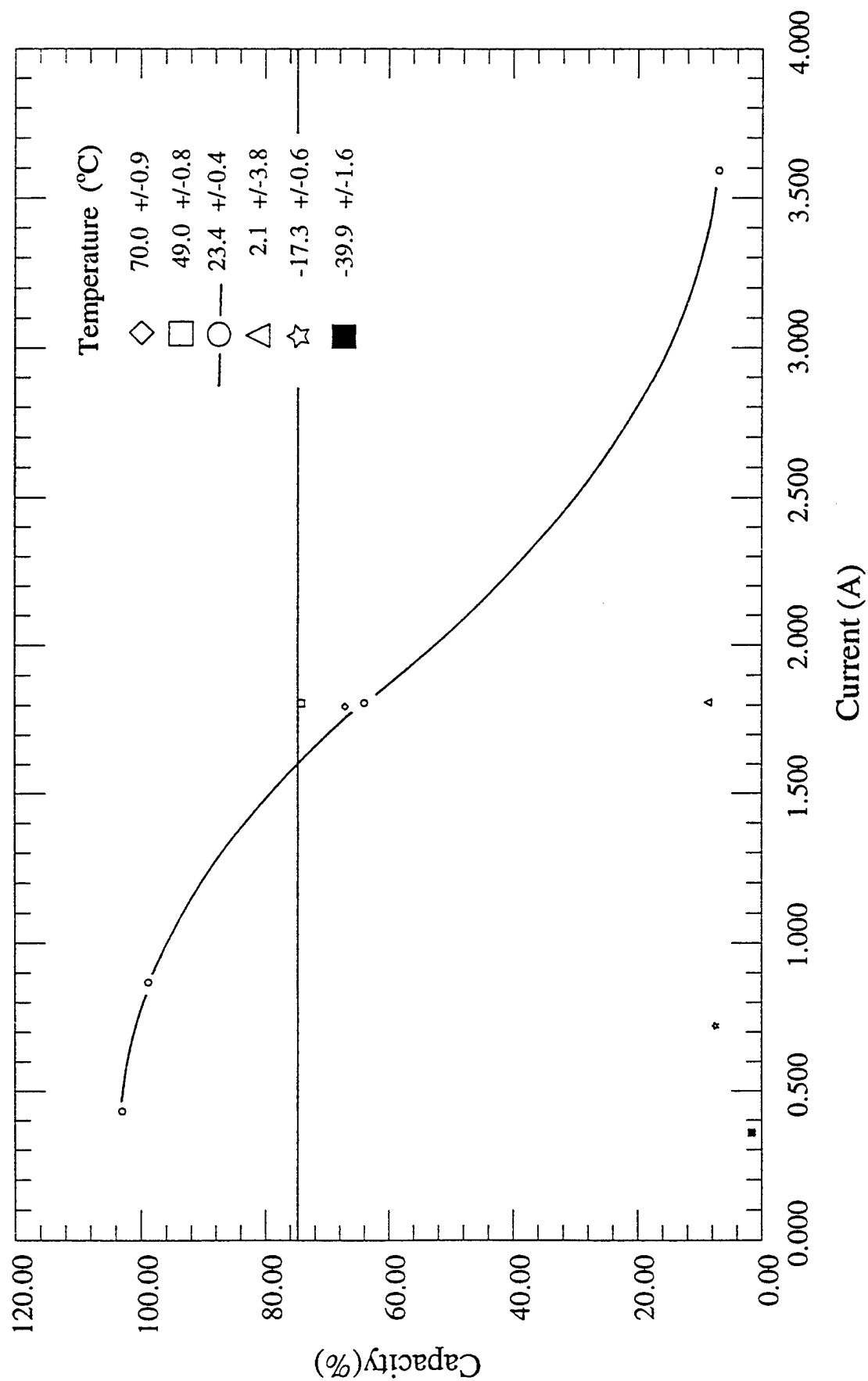


Figure 4.6.2.2-1. Company H CCC Capacity vs. Current

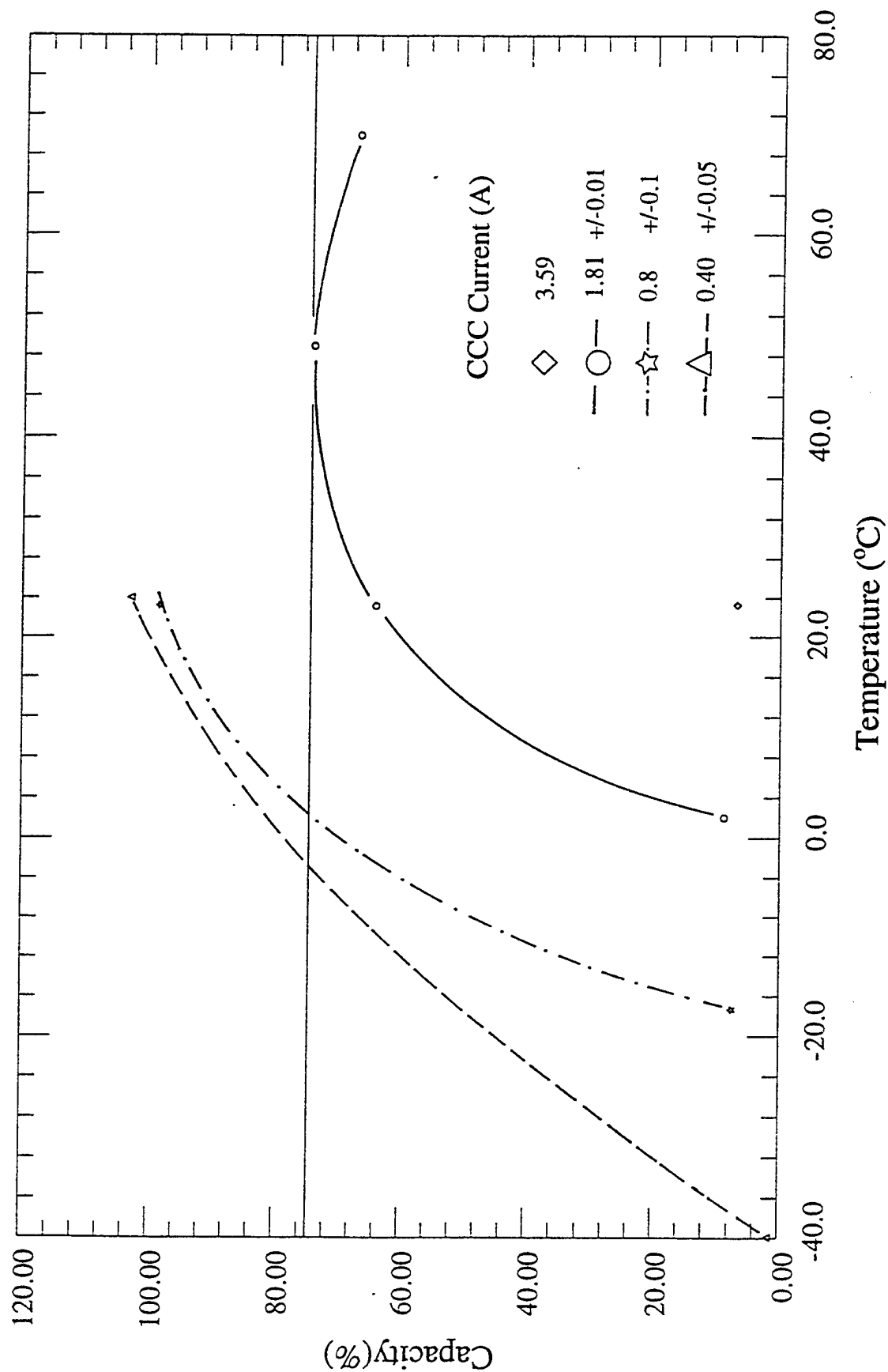


Figure 4.6.2.2-2. Company H CCC Capacity vs. Temperature

4.6.3 CCC Observations and Summary For comparison purposes between AB₂ and AB₅ cells the constant charge test results versus current at room temperature for all the cells are plotted in Figure 4.6.3-1. A similar plot versus temperature at a standard 1C charge rate is shown in Figure 4.6.3-2. The 75 percent charge retention capacity line has been marked on each figure. It is stressed that the data used to generate these two figures were extracted from the best fit curves for each set of cells and are not actual data points measured in this study. Comparisons of these two figures and the discussions in Sections 4.6.3.1 and 4.6.3.2 furnish the following observations:

- None of the Ni-MH cells has a charge efficiency above 75 percent below -15 °C at the 1C charge rate. AB₅ cylindrical cells have a lower limit of -10 to -15 °C whereas the limit for the prismatic cells is 0 °C. AB₂ cylindrical cells from Company D have a lower limit of 15 °C, whereas Company H cells just managed to attain 75 percent efficiency around 45 °C.
- AB₅ cells have a 2C and possibly higher charge capability.
- AB₂ cells from Company D have a 1C charge capability and Company H cells have a 2C/5 charge capability.
- AB₅ cells are more rugged than AB₂ cells and although have low charge efficiency at temperatures above 49 °C they will still function after exposure to the higher temperatures and high charge currents.
- AB₂ cells are damaged and lose capacity when exposed to either high charge currents (over 2C) or temperatures above 49 °C.
- The data for the AB₅ cells suggest the cell design and probably the MH alloy has an effect on charge efficiency and the lower temperature charge limit.
- Insulation and/or heating or cooling would be required to charge cells above or below the observed charging temperature limits.
- For an aircraft application, improvement in the charge rate to at least 3C and preferably 4C would be required for either type of MH cell.

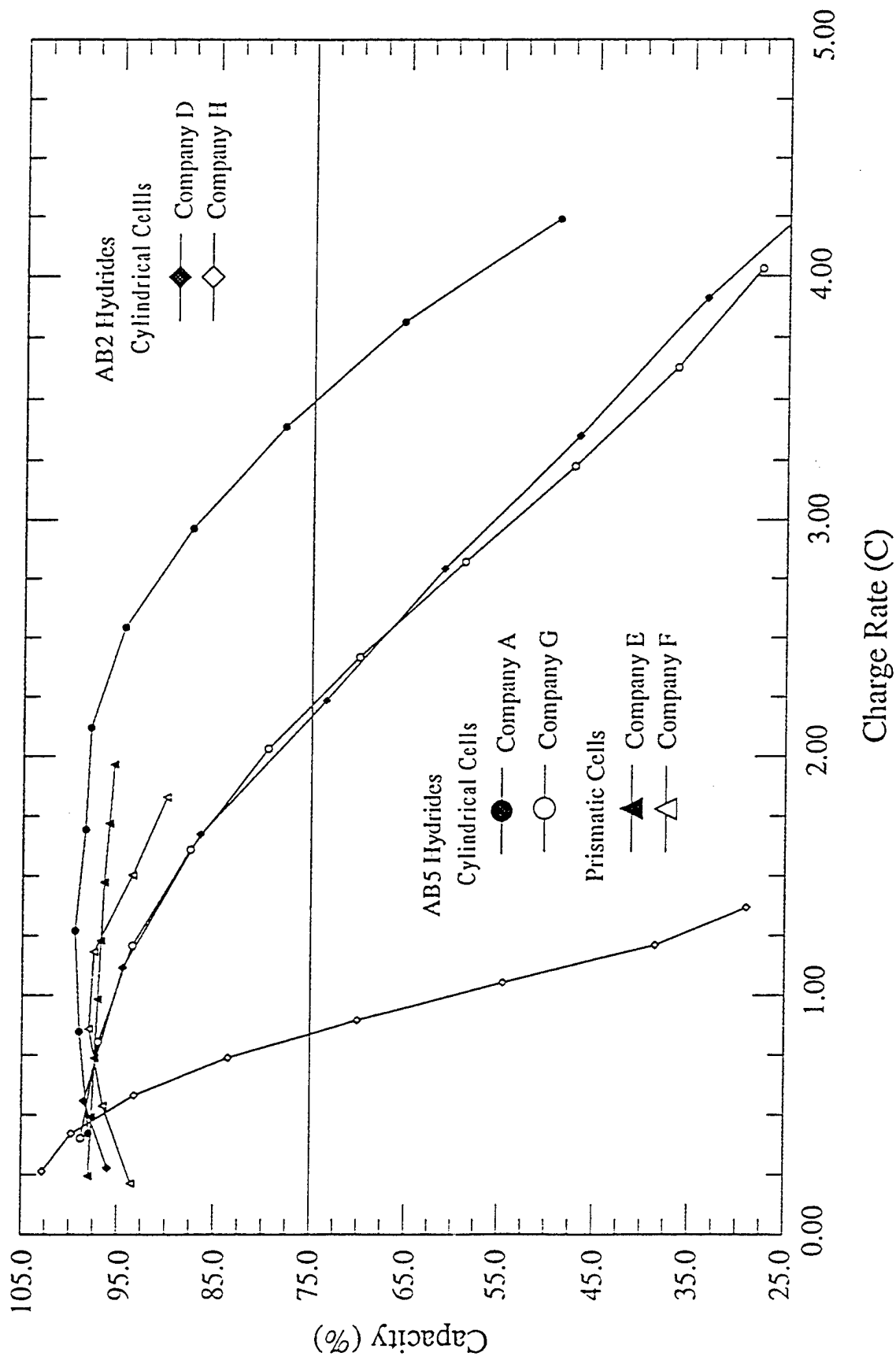


Figure 4.6.3-1. CCC Capacity vs. Charge Rate at Room Temperature

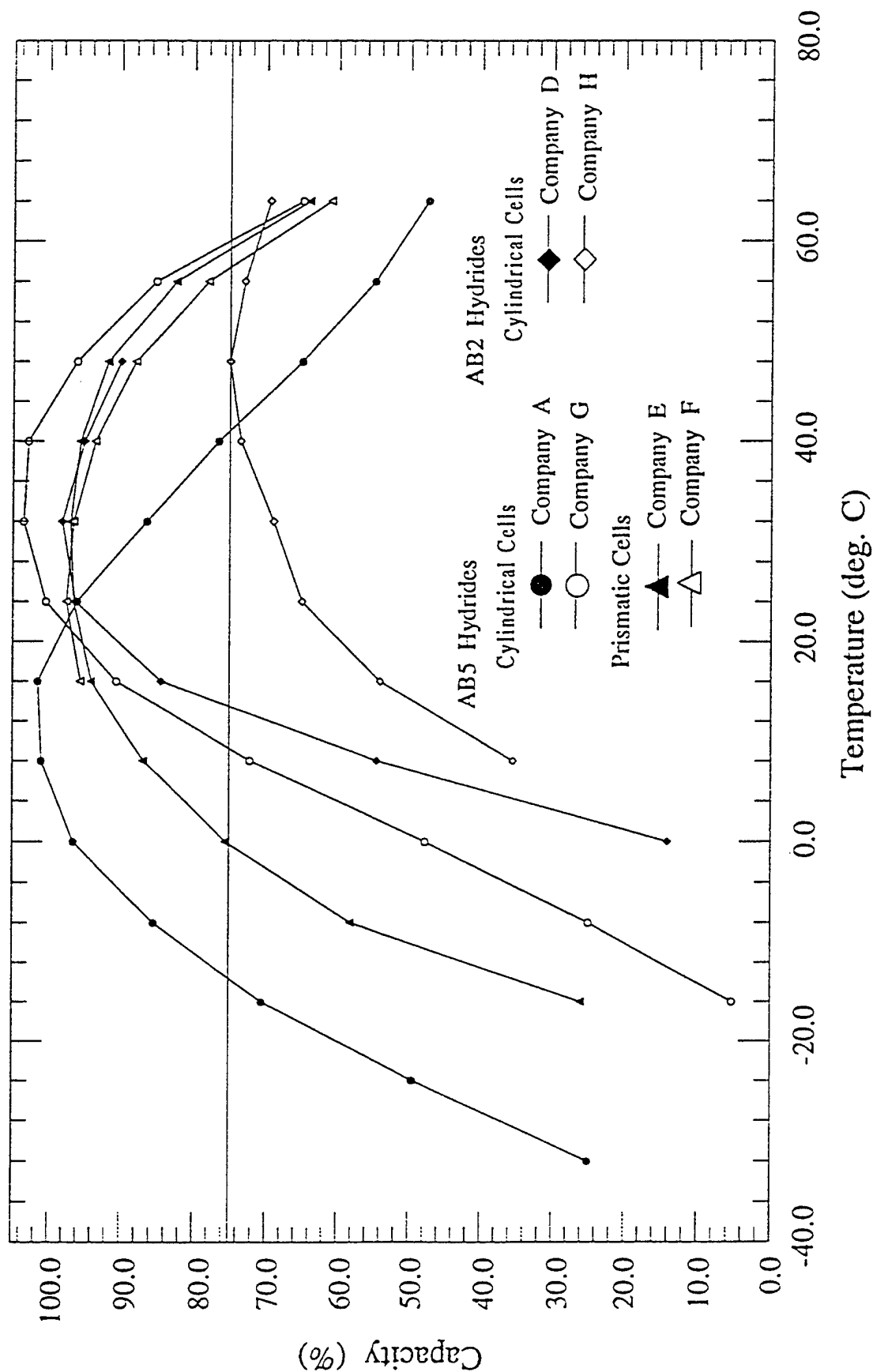


Figure 4.6.3-2. CCC Capacity vs. Temperature at the 1C Charge Rate

- At room temperature all the cells had a 2C charge acceptance with 75 percent efficiency except Company A and Company H. Company A cells can accept a 3.5C charge current while Company H cells can only accept a 1C charge current.

Summary AB₅ batteries both cylindrical and prismatic have better charge characteristics and are more rugged than AB₂ batteries. Both types of batteries would require cooling to safely operate at 49 °C safely and heating to maintain charge efficiency below 10 °C. None of the batteries could sustain a 5C charge current but the Company A cylindrical AB₅ cells had the highest charge current capability at 3.5C. Similar to the discharge tests, the AB₅ cells had a 15 to 25 degree lower operating temperature minimum during charge than the best AB₂ cells. Among AB₅ cells, the cylindrical cells had a 10 degree lower operating temperature than the prismatic cells. Alloy improvements are needed for both alloys to enhance the temperature range for charging, but more importantly an increase in the charge current to 4 - 5C is needed for aircraft applications.

4.7 INTERNAL RESISTANCE (IR) TESTS Internal resistance (IR) for batteries is a determining factor in charge and discharge efficiency, duration of discharge and determines the operational cycle life for batteries and how hot the battery becomes during charge in the case of Ni-MH batteries. For high efficiency a low IR is needed and estimates of IR at the beginning of and during discharge and charge can provide information on the reaction mechanism underway in the battery.

Based on the differences in the discharge and charge characteristics of the batteries under test an experiment was constructed to measure internal resistance of the cells during discharge. The procedure developed depended on the speed of the WL/POOS-2 data acquisition system and a complex computer controlled discharge profile during the actual experiments. These experiments were conducted using a standard 2C/5 discharge current at various temperatures which typically took approximately 2.5 hours to the 0.9 V termination. The procedure required the technicians to:

- Collect voltage, current, temperature and time data at 3-5 sec. intervals during the first 2 minutes of battery discharge and at 5 min. intervals thereafter.

- Interrupt the discharge and allow the cells to float on open circuit for 15 minutes starting at 10 minutes into the discharge (collect data at 3-5 sec. intervals).
- Resume the discharge at 25 minutes (collect data at 3-5 sec. intervals for the first two minutes and at 5-10 minutes thereafter).
- Interrupt the current at 105 minutes (equivalent to 90 minutes or 60 percent of a standard discharge) and allow the voltage to float on open circuit for another 15 minutes (collect data at 3-5 sec. intervals).
- Resume the discharge at 120 minutes (collect data at 3-5 sec. intervals for the first two minutes and at 5-10 minute intervals thereafter) until completion.

The data acquisition system proved susceptible to overload and would either terminate storing the data or stop the test at one of the change points in the test. Some data were collected during the process of debugging the procedure, but the data are too fragmentary to use for quantitative measurements. Future IR tests using the current system would require using a slower data acquisition rate which would yield questionable results. Alternatively, the slow speed small strip chart recorders in the test racks would have to be replaced with high resolution, high speed recorders to obtain a continuous analog trace of the voltage, current and temperature during each test. Since the current data acquisition system was in the process of replacement with a high speed Sun computer system, further IR tests were postponed until the new computer system became operational. The new computer system was not operational by the time this study ended so further IR tests were not conducted.

Qualitative observations on the fragmentary IR data collected indicate:

- The resistance increases during the discharge as is typical of all battery discharges. At the 10 min. break the resistance does not appear markedly different than when the cell is first discharged but the break at the 105 min. point shows an approximate increase in the resistance by a factor of two.
- The AB₅ cells overall seemed to have lower resistance than the AB₂ cells.
- Differences within the AB₅ and the AB₂ cells were noticeable and could be the result of either the alloy, the cell construction, and the electrolyte in the cells or a combination of all three factors.

5.0 CONCLUSIONS

GRCI developed a baseline analysis of the commercial Ni-MH battery capability for future planning of a military aircraft battery development program using this technology. In conjunction with this analysis, GRCI maintained cognizance of EPA activities and regulations related to hazardous materials for battery manufacturing that could impact a USAF Ni-MH battery development program. Results, conclusions, and recommendations were documented throughout the duration of the study in quarterly program and monthly technical reviews. Appropriate recommendations to overcome technical and environmental limitations of the commercial technology in a military environment were identified and documented. The technical developments, cost and schedule requirements for a military aircraft Ni-MH battery development program were documented.

Based on the original objectives of the commercial Ni-MH battery technology evaluation program, GRCI concluded:

- The baseline Ni-MH battery technology available is not adequate to replace existing USAF Ni-Cd and Lead-Acid batteries using commercial off the shelf (COTS) technology. Specific developments are needed in metal hydride alloys, packaging, cooling, heating and insulation to use Ni-MH batteries in a military aircraft application. Details of specific areas for battery development for AB₅ and AB₂ batteries are discussed in Sections 5.1 and 5.2.
- Existing and proposed materials and chemicals used in Ni-MH batteries are not an environmental hazard. This conclusion is based on NREL TP-463-5475, August 1993 on the "Current Status of Environmental, Health, and Safety Issues of Nickel Metal-Hydride Batteries for Electric Vehicles" which is discussed in more detail in Section 4.1.1.
- A Ni-MH battery development program can build on the commercial technology that is available in the US. The program details are discussed in Section 6.1.
- The US Ni-MH industrial base consists of seven companies with experience in commercial battery development and production. Five companies are experienced with AB₅ batteries for commercial use and also have necessary experience in

military development and production. Only two companies have commercial development experience with AB_2 batteries and neither of these has any experience with military battery development. The commercial business base in the US is sufficient to support a military Ni-MH battery through the development and production phases but such a development would require government support to fund such a development.

5.1 AB_5 METAL HYDRIDE BATTERIES

Evaluation of AB_5 batteries and single cells indicates the commercial development of this technology is well understood and those developments can be exploited in a military aircraft battery development program. Specific AB_5 alloy improvements needed include:

- Changes to the metal hydride alloy that will reduce self discharge to at least 0.5 percent per day or better. This could be due to changes in the chemistry of the alloy or to new or modified manufacturing processes to make the alloy.
- Increase the discharge current to 10C for aircraft operations, but as a minimum 75 percent of the capacity must be available at the 5C discharge rate.
- Increase charge currents to 5C with 75 percent efficiency during the subsequent discharge.
- A wider temperature range on charge and discharge at the 75 percent level.

In addition to the above recommendations for alloy improvement, existing insulation, charging and monitoring equipment, and operational cooling and heating procedures for Ni-Cd and Lead-Acid in an aircraft must be adapted for use with AB_5 battery technology.

5.2 AB_2 METAL HYDRIDE BATTERIES

Commercial AB_2 battery technology is relatively new and shows variations in the manufacturing processes and lack of production experience that produces a rugged, dependable product. Existing production batteries tested show extreme variations in operational performance, low charge efficiencies and limited operational temperatures. Areas that need improvement for AB_2 alloy cells include:

- Self discharge which is approximately twice as high as the AB_5 counterparts.

- Higher voltage and temperature limits during charging that will permit overcharging without damage to the battery.
- Higher temperature alloys that can withstand exposure to temperatures above 49 °C without degrading.
- Higher charge and discharge currents over a wider temperature range; preferably near 5C for charge and 10C for discharge.

The same conclusion on adapting existing aircraft Ni-Cd and Lead-Acid battery packaging, monitoring and charging technologies for AB₅ batteries applies to AB₂ batteries for aircraft applications.

6.0 RECOMMENDATION

GRCI recommends that WL/POOB initiate a 6.2 funded military aircraft Ni-MH battery development program to begin in FY97. The program should take approximately 36 months for the technical effort with 4 months for a final report. Development funds to support this program are estimated at \$3.5 - 4.0 million. These funds should be allocated by FY as indicated in Table 6.0-1. The suggested overall technical content of the development program is presented in Section 6.1.

Table 6.0-1. 6.2 Development Program Fund Allocation

<u>PROGRAM TITLE</u>	<u>6.2 Development Funds (\$K)</u>			
	<u>FY97</u>	<u>FY98</u>	<u>FY99</u>	<u>FY00</u>
Ni-MH Aircraft Battery Development	250 - 500	1,000	1,500	750 - 1,000

6.1 Nickel-Metal Hydride (Ni-MH) Aircraft Battery Development Program

Development of an environmental military aircraft battery replacement for current Ni-Cd and Lead-Acid batteries based on the commercial Ni-MH technology will require technology development in several areas. Currently there are two types of Ni-MH battery using either the AB₂ or AB₅ chemical formula of the hydride material. The AB₅ batteries are widely used throughout the world and are a well developed commercial product in both cylindrical and prismatic configurations with a bipolar configuration in development through the DoD SBIR program. AB₂ batteries are commercially available in small cylindrical cell configuration, but there are only two known sources both based on the development work of Ovonic Battery Co., Troy, MI. Ovonic is developing the AB₂ prismatic battery in conjunction with the US Advanced Battery Consortium (USABC) and the DOE for electric vehicle applications. As of this date no commercial battery using the AB₂ prismatic design is available for test and evaluation.

Development areas for military aircraft applications of Ni-MH technology include:

- Alloy development for both AB₅ and AB₂ type metal hydrides. Increased charge (5C) and discharge (10C) current capability consistent with a fighter aircraft application is needed. In addition, a reduction in self discharge rates to equal that

of current Ni-Cd aircraft batteries is required, preferably to as low as 0.2 percent per day at room temperature and no more than 0.5 percent per day at 49 °C.

- Increased alloy temperature range and possible electrolyte changes to improve low and high temperature performance for either MH alloy. For AB₂ batteries, emphasis should eliminate the observed degraded performance at temperatures above 49 °C which will probably mean a significant change in alloy composition.
- Evaluation of different cell designs. Cylindrical cells are good for small portable applications, but have not been made in large configurations suitable for an aircraft application. Prismatic cells are commonly used for aircraft batteries and some R&D cells have been made for electric vehicle use with AB₅ hydride cathodes. A bipolar design is also in development that may offer a 30 percent improvement in energy density due to a reduction in packaging requirements.
- Adaptation of existing packaging, charging and monitoring technology used in aircraft batteries to the Ni-MH technology and incorporation of smart charging techniques and designs from commercial systems.
- Evaluation of new alloys for self discharge, charge, discharge, and internal resistance characteristics and possible “memory” effects in prototype aircraft single cell configurations. Subsequent tests should use modular cell packs to finalize cell designs prior to building a complete battery.
- Design and build at least five (5) prototype R&D full size aircraft batteries for government test and evaluation prior to establishing a final design.
- Evaluate production process changes and costs needed to produce the replacement Ni-MH battery on existing Ni-Cd and/or Lead-Acid aircraft battery production lines. Alternatively, what changes and costs would be incurred to adapt existing Ni-MH production lines to large aircraft batteries?

In addition to the technical developments, an aircraft user group consisting of government R&D development and aircraft system personnel, industry OEMs and the battery developers is needed to review designs and test results, establish a test program and select an implementation target(s) for battery design and test.

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