

AD-A095 549

DURACELL INTERNATIONAL INC BURLINGTON MA LAB FOR PHYS--ETC F/G 9/1
ANALYSIS OF THE LITHIUM SULFUR DIOXIDE SYSTEM AT ULTRA-HIGH RAT--ETC(U)
FEB 81 R W HOLMES, A N DEY

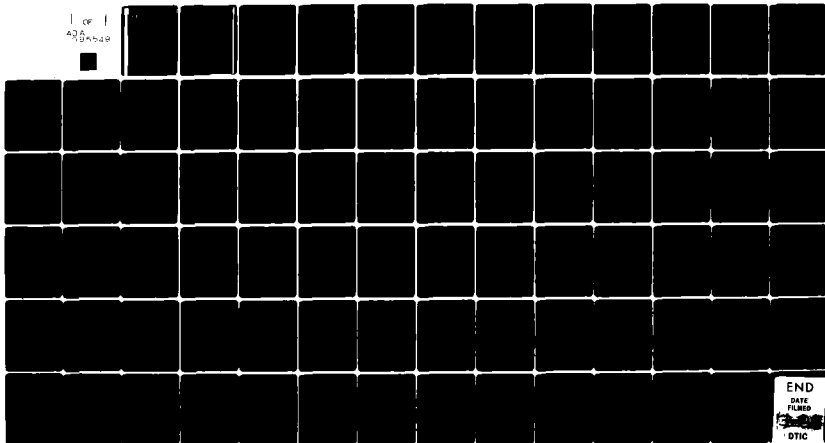
DAAK20-79-C-0273

NL

UNCLASSIFIED

DELET-TR-79-0273-F

1 of 1
ADA
205549



END
DATE
FILMED
DTIC

AD A095549



Research and Development Technical Report

DELET-TR-79-0273-F

ANALYSIS OF THE LITHIUM SULFUR
DIOXIDE SYSTEM AT ULTRA-HIGH
RATE DISCHARGES

R.W. HOLMES and A.N. DEY

DURACELL INTERNATIONAL INC.
LABORATORY FOR PHYSICAL SCIENCE
BURLINGTON, MA 01803

FEBRUARY 1981

FINAL REPORT FOR PERIOD 27 SEPT. 1979 TO 30 SEPT. 1980

DISTRIBUTION STATEMENT
APPROVED FOR PUBLIC RELEASE ; DISTRIBUTION UNLIMITED

PREPARED FOR:
US ARMY ELECTRONICS TECHNOLOGY AND DEVICES LABORATORY

ERADCOM

81 2 28 068

US ARMY ELECTRONICS RESEARCH AND DEVELOPMENT COMMAND
FORT MONMOUTH, NEW JERSEY 07703

DBG FILE COPY

DTIC
SELECTED
FEB 26 1981

NOTICES

Disclaimers

The citation of trade names and names of manufacturers in this report is not to be construed as official Government indorsement or approval of commercial products or services referenced herein.

Disposition

Destroy this report when it is no longer needed. Do not return it to the originator.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DELET-TR-79-0273-F	2. GOVT ACCESSION NO. AD-A095 549	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) Analysis of the Lithium Sulfur Dioxide System at Ultra-High Rate Discharges		5. TYPE OF REPORT & PERIOD COVERED Final Report. 27-01-79-9/27/79-9/30/80
7. AUTHOR(s) R. W./Holmes and A. N./Dey		8. CONTRACT OR GRANT NUMBER(s) DAAK20-79-C-0273
9. PERFORMING ORGANIZATION NAME AND ADDRESS Duracell International Inc. Laboratory for Physical Science Northwest Industrial Park - Third Ave. Burlington, MA 01803		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 16 1L162705AH94 11-765
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Elec. Tech. & Dvcs. Lab ATTN: DELET-PB Fort Monmouth, N.J. 07703		12. REPORT DATE 11 February 1981
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		13. NUMBER OF PAGES 70
		15. SECURITY CLASS. (of this report) Unclassified
16. DISTRIBUTION STATEMENT (of this Report) Approved for Public Release, Distribution Unlimited.		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Lithium, Sulfur Dioxide Battery, Organic Electrolyte, Safety, Abuse Testing, Ultra-High Discharge, D Cell, High Energy Density Battery, Electrolyte Study, High Temperature Storage.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The major objective of this program was to study the effects of electrolytes in Li/SO₂ cells, for use in high rate abusive discharge conditions. Five electrolytes were investigated based on previous differential thermal analysis (DTA) results. A standard type electrolyte using acetonitrile (AN) was included in the program for comparison. The work was performed at Duracell International Inc. using LO26SX cells made at the Lithium Systems Division in North Tarrytown, New York. The cells were filled and tested at the Laboratory for		

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. Abstract (continued)

Physical Science in Burlington, Massachusetts.

Two electrolytes, AN (standard) and AN/PC (90/10) were found satisfactory for use in high rate abuse discharge conditions. Cells with AN/AA (90/10) electrolyte were satisfactory when fresh but these cells evolved CO_2 on storage at 55°C and 72°C which led to severe cell leakage. The remaining electrolytes, AN/BL/DME (85/10/5), PC/DME (50/50) and BL/DME (50/50), were regarded unsatisfactory for use in Li/SO_2 cells for high rate abusive discharge conditions.

The use of copper foil as the anode substrate was studied in LO26SX cells filled with the standard AN electrolyte. These cells were effective in reducing the sharp voltage reversal during abusive forced discharge at 2.0A at -30°C . The abuse resistance of these cells was at least as good as that of the standard cells.

Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	☐
By _____	
Distribution/	
Availability Codes	
Dist	☒

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

Table of Contents

	<u>Page</u>
List of Tables	i.
List of Figures	iv.
1. Introduction	1
2. The Cell Package	3
3. Electrolytes and Cell Filling	4
4. Storage and Testing Regimes	6
5. Results and Discussion	8
6. Conclusions	18
7. Recommendations	22
8. References	23
Tables	24
Figures	55
Distribution List.	

List of Tables

<u>Table No.</u>		<u>Page</u>
Table 1.	Specifications and Data for the LO26SX, Li/SO ₂ Cell	24
Table 2A.	Composition of Electrolytes	25
Table 2B.	Composition of Electrolytes	26
Table 3.	Weight and Volume of Electrolytes in the Test Cells. Statistics from Samples of 15 Cells.	27
Table 4.	Constant Load Discharge Results for LO26SX Cells With PC/DME (50/50) Electrolyte. Fresh Cells.	28
Table 5.	Constant Load Discharge Results for LO26SX cells With PC/DME (50/50) Electrolyte. 72°C Storage 34 days.	29
Table 6.	Constant Load Discharge Results for LO26SX Cells With PC/DME (50/50) Electrolyte. Cells Stored 91 Days at 55°C.	30
Table 7.	Constant Load Discharge Results for LO26SX Cells With AN/PC (90/10) Electrolyte. Fresh Cells.	31
Table 8.	Constant Load Discharge Results for LO26SX Cells With AN/PC (90/10) Electrolyte. Cells Stored 31 Days at 72°C.	32
Table 9.	Constant Load Discharge Results for LO26SX Cells With AN/PC (90/10) Electrolyte. Cells Stored 91 Days at 55°C.	33
Table 10.	Constant Load Discharge Results for LO26SX Cells With AN Electrolyte. The Test Standard. Fresh Cells.	34
Table 11.	Constant Load Discharge Results for LO26SX Cells With AN Electrolyte. The Test Standard. Cells Stored 31 Days at 72°C.	35
Table 12.	Constant Load Discharge Results for LO26SX Cells with AN Electrolyte. The Test Standard. Cells Stored 91 Days at 55°C.	36
Table 13.	Constant Load Discharge Results for LC26SX Cells with AN/AA (90/10) Electrolyte. Fresh Cells.	37
Table 14.	Constant Load Discharge Results for LC26SX Cells with AN/AA (90/10) Electrolyte. Cells Stored 34 Days at 72°C. Cells Leaked During Storage.	38

List of Tables (continued)

<u>Table No.</u>		<u>Page</u>
Table 15.	Constant Load Discharge Results for LO26SX Cells With AN/AA (90/10) Electrolyte. Cells Stored 91 Days at 55°C. Cells Leaked During Storage.	39
Table 16.	Constant Load Discharge Results for LO26SX Cells With AN/BL/DME (85/10/5) Electrolyte. Fresh Cells.	40
Table 17.	Constant Load Discharge Results for LO26SX Cells With AN/BL/DME (85/10/5) Electrolyte. Cells Stored 31 Days at 72°C.	41
Table 18.	Constant Load Discharge Results for LO26SX Cells With AN/BL/DME (85/10/5) Electrolyte. Cells Stored 91 Days at 55°C.	42
Table 19.	Constant Load Discharge Results for LO26SX Cells With BL/DME (50/50) Electrolyte. Fresh Cells.	43
Table 20.	Constant Load Discharge Results for LO26SX Cells With BL/DME (50/50) Electrolyte. Cells Stored 31 Days at 72°C.	44
Table 21.	Constant Load Discharge Results for LO26SX Cells with BL/DME (50/50) Electrolyte. Cells Stored 91 Days at 55°C.	45
Table 22.	Constant Current Discharge Results for LO26SX Cells. Capacities to 2.0V Cutoff.	46
Table 23.	LO26SX Cells With Various Electrolytes Ranked by Average Standard Capacities With Standard Deviations.	47
Table 24.	LO26SX Cells With PC/DME (50/50) Electrolyte. Abuse Test: Forced Discharge at 2.0A at -30°C.	48
Table 25.	LO26SX Cells With AN/PC (90/10) Electrolyte. Abuse Test: Forced Discharge at 2.0A at -30°C.	49
Table 26.	LO26SX Cells With AN Electrolyte. The Test Standard. Abuse Test: Forced Discharge at 2.0A at -30°C.	50
Table 27.	LO26SX Cells With AN/AA (90/10) Electrolyte. Abuse Test: Forced Discharge at 2.0A at -30°C.	51

List of Tables (continued)

<u>Table No.</u>		<u>Page</u>
Table 28.	LO26SX Cells With AN/BL/DME (85/10/5) Electrolyte. Abuse Test: Forced Discharge at 2.0A at -30°C.	52
Table 29.	LO26SX Cells With BL/DME (50/50) Electrolyte. Abuse Test: Forced Discharge at 2.0A at -30°C.	53
Table 30A.	LO26SX Cells With Copper Foil Anode Current Collectors. AN Electrolyte. Abuse Test: Forced Discharge at 2.0A at -30°C. Fresh Cells.	54
Table 30B.	Results and Selected Data for LO26SX Cells With Li on Cu Foil Anodes and AN Electrolyte.	54
Table 31.	Voltage Delay Characteristics at 3.0A at -30°C.	55

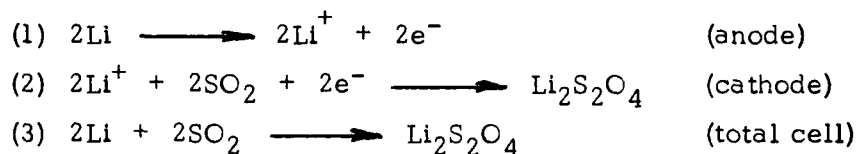
List of Figures

<u>Figure No.</u>		<u>Page</u>
Figure 1.	Capacity-Rate Curves of LO26SX Cells. Fresh Cells Discharged at Room Temperature.	56
Figure 2.	Capacity-Rate Curves of LO26SX Cells. Fresh Cells Discharged at -30°C .	57
Figure 3.	Capacity-Rate Curves of LO26SX Cells. Cells Stored 1 Month at 72°C , Discharged at Room Temperature.	58
Figure 4.	Capacity-Rate Curves of LO26SX Cells. Cells Stored 1 Month at 72°C , Discharged at -30°C .	59
Figure 5.	Capacity-Rate Curves of LO26SX Cells Stored 3 Months at 55°C , Discharged at Room Temperature.	60
Figure 6.	Capacity-Rate Curves of LO26SX Cells Stored 3 Months at 55°C , Discharged at -30°C .	61
Figure 7.	Capacity-Rate Curves of LO26SX Cells with PC/DME (50/50) Electrolyte.	62
Figure 8.	Capacity-Rate Curves of LO26SX Cells with AN/PC (90/10) Electrolyte.	63
Figure 9.	Capacity-Rate Curves of LO26SX Cells with AN Electrolyte.	64
Figure 10.	Capacity-Rate Curves of LO26SX Cells with AN/AA (90/10) Electrolyte.	65
Figure 11.	Capacity-Rate Curves of LO26SX Cells with AN/BL/DME (85/10/5) Electrolyte.	66
Figure 12.	Capacity-Rate Curves of LO26SX Cells with BL/DME (50/50) Electrolyte.	67
Figure 13.	Voltage and Temperature Profiles for LO26SX Cells Force-Discharged at 2.0A at -30°C . Fresh Cells.	68
Figure 14.	Voltage and Temperature Profiles for LO26SX Cells Force-Discharged at 2.0A at -30°C . Cells Stored 1 Month at 72°C .	69
Figure 15.	Voltage and Temperature Profile for LO26SX Cell with Copper Foil Anode Substrate Force-Discharged at 2.0A at -30°C . Fresh Cell No. Li/Cu 3.	70

1. Introduction

The Li/SO₂ system is the most highly developed high-energy density battery system available to date. This system is in great demand because of its high energy density, high rate capability, good low temperature performance and good capacity retention after storage at elevated temperatures. These favorable characteristics have resulted in the use of the Li/SO₂ system in a variety of military applications. Hermetically sealed Li/SO₂ cells made by Duracell International Inc. were found to be sufficiently abuse resistant for most of these applications (1-6), yet further improvements in the intrinsic abuse resistance of the system would make it even more desirable. The ultimate goal is a Li/SO₂ cell that is safe under all normal user conditions.

We have carried out differential thermal analysis (DTA) of the cell constituents of Li/SO₂ cells (7) in order to identify the chemical reactions that might be responsible for the thermal runaway in the cells. In that study we determined that unprotected lithium readily reacted with acetonitrile (AN) at or near room temperature. The heat generated by a discharging cell could initiate this reaction, once the protective SO₂ was depleted during the cell discharge according to the cell reaction:



The DTA studies also demonstrated that lithium could be protected from reacting with AN at temperatures up to about 100°C by adding other organic solvents to the system. Replacement of AN by other more inert solvents was also a viable alternative for the protection of lithium.

Our previous studies (7) suggested several possible solvent mixtures to replace AN in Li/SO₂ batteries. The candidate solvents were selected on the basis of favorable DTA results, and good ionic conductivity of the electrolyte containing 70% SO₂ and LiBr. Specifically, these candidate solvents did not

exhibit any strong exothermic reactions with lithium at temperatures below 90°C, and the specific conductivities of their SO₂ electrolytes were about $4 \times 10^{-2} \Omega^{-1} \text{cm}^{-1}$ or better at room temperature.

The major objective of this work involved the evaluation of the described, promising new electrolytes in Li/SO₂ D-cells by determining the performance and the abuse tolerance of these cells. Five new electrolytes were selected for study in the practical LO26SX D-cell configuration. A sixth group of cells, made as controls, contained a standard electrolyte with AN as the organic solvent.

Additional studies were conducted on Li/SO₂ cells with the AN electrolyte which contained modified anode structures. Copper foil was used as an anode substrate in these cells, and the effect on the abuse tolerance of the cells was examined.

The various experimental details and test results are reported herein.

2. The Cell Package

The cells used in this study were state-of-the-art LO26SX Li/SO₂ production line D-cells manufactured by the Lithium Systems Division of Duracell International Inc. in North Tarrytown, New York. The cells were filled with the six electrolytes chosen for study in this program at the Laboratory for Physical Science of Duracell International Inc. in Burlington, Massachusetts.

Table 1 describes the pertinent physical parameters of the production LO26SX, Li/SO₂ D-cells. The cells have a safety vent which opens on abusive short circuiting to prevent explosion.

The LO26SX cells were of the lithium limited design. The nominal Li/SO₂ ratio was 0.9/1 in these cells. It has been demonstrated (9) that this lithium-limited cell design is inherently safer than a lithium-rich cell design.

The largest source of variation in the dry cell package was the thickness of the electrodes. The weight range specification of the anode allowed a deviation of more than 10% in the anode thickness. Variations in the cathode thickness alone could account for the variation in weight of the unfilled cells.

3. Electrolyte Preparation and Cell Filling

The six electrolytes studied in this program are described in Tables 2A and 2B. The solvents used in the various electrolytes were treated as follows: Propylene carbonate (PC) and γ -butyrolactone (BL) were vacuum distilled and typically contained less than 20 ppm of water. Dimethoxyethane (DME) was distilled from calcium hydride and typically contained less than 50 ppm of water. Eastman X488 acetonitrile (AN) was used as delivered and contained less than 0.03% water. Fisher No. A-10 acetic anhydride was also used as delivered (98.4% assay). Matheson anhydrous sulfur dioxide (99.98% minimum, liquid phase) was distilled directly into the electrolyte cylinders during electrolyte preparation.

Electrolytes were made with the aim of keeping the relative volume of constituents constant. Therefore, the resulting electrolytes each contained 63.1% SO_2 and 36.9% organic solvents by liquid volume, and 379 grams of LiBr (about 0.87M). Weight percents varied accordingly from electrolyte to electrolyte due to the difference in density for the various organic solvents used.

Electrolytes were prepared as follows: 379.25g of lithium bromide (vacuum dried for 3-4 days at 150-155°C) were added to a 5-liter polypropylene cylinder in an argon filled dry box. In the same dry box, 1850 ml (total) of the appropriate organic solvents were added to the cylinder. Electrolyte preparation was completed by condensing $4532.5 \pm 5\text{g}$ of SO_2 into the cylinder. This step was accomplished by chilling the polypropylene cylinder in dry ice and distilling SO_2 from a supply cylinder.

The LO26SX cells were filled with appropriate SO_2 electrolytes from the 5-liter polypropylene electrolyte cylinders. Filling was accomplished from a system pressurized by the SO_2 in the electrolyte cylinder. Cells were filled until the electrolytes were exhausted. Approximately 155 cells could be filled from each batch of electrolyte.

When the first two batches of cells were filled (Electrolytes 1 and 2 in Table 2) we allowed about 2 ml of void space in the cells. This void volume was insufficient to accommodate the expansion of electrolyte at 72°C and

resulted in leakage of the cells through the vent which opened due to expansion of the PC/DME (50/50) electrolyte at 72°C. Due to the above leakage problem, the third and fourth batches of electrolyte were allowed over 2.5 ml of void space in the cells, and the fifth and sixth batches of electrolyte were allowed about 3 ml of void space in the cells.

The average volume of electrolyte and the standard deviation as determined from a sample of fifteen cells are shown in Table 3.

4. Storage and Testing Regimes

For each electrolyte system studied approximately 155 cells were filled for testing. The day after the cells were filled, they were allotted for use according to the following storage regime.

Storage Regimes:	1. 72°C storage for 1 month	= 30 cells
	2. 55°C storage for 3 months	= 30 cells
	3. Fresh cell discharge	= 30 cells
	4. Cells for delivery to ECOM	= 20 cells
	5. <u>Extras at RT storage, approx.</u>	<u>= 45 cells</u>
	TOTAL	= 155 cells

The above storage regimes allowed a few extra cells in each category in the event of leakage or catastrophic cell failure. Consequently the test regimes for each group of 30 cells from the storage regimes above were as follows:

Test Regimes:	1. RT discharge at various constant loads	= 9 cells
	2. -30°C discharge at various constant loads	= 9 cells
	3. Abuse test (force discharge) at -30°C at 2.0A	= 3 cells
	4. <u>Spares or other tests</u>	<u>= 9 cells</u>
	TOTAL	= 30 cells

In the test regimes, the cells of each type, from each storage condition, were discharged both at room temperature (RT) and at -30°C. Most of the data were obtained by discharge under a constant load wherein the capacity, Q , was determined by integrating the area under the voltage-time curve with a planimeter to the 2.0 volt cutoff. Capacity-rate curves were estimated from the resulting data for comparison of the performance of the various cell types.

To obtain a measure of the safety aspects of the test cells, the forced discharge abuse test at 2.0 amps at -30°C was run in triplicate for each cell type and storage condition. The effects of the abuse test on the ventable cells was observed.

5. Results and Discussion

A. Discharge Performance

The constant load discharge characteristics of LC26SX cells with various electrolyte systems and under different storage conditions are reported in Tables 4-21. The constant current discharge results of cells after a few months storage at room temperature at 7A at RT and at 3A at -30°C are presented in Table 22. Cell capacities as a function of discharge rate were determined from these data and are shown in Figures 1-12. Figures 1-6 show the capacity-rate curves of the six cell types at a given storage and discharge regime, while similar curves for cells with a given electrolyte system under various storage and discharge conditions are shown in Figures 7-12.

The capacity-rate curves for fresh cells discharged at room temperature are shown in Figure 1. The standard capacity data for these cells were analyzed statistically. The average standard capacities and standard deviations of fresh cells discharged at room temperature (RT) are reported in Table 23. These standard capacities do not necessarily coincide with the values in Figure 1 because the capacity-rate curves were also influenced by judgement using the data at the higher currents. The anomalous capacities at low currents were due to an extraneous cell construction variable. From Table 23 the pooled average standard capacity and standard deviation was 7.96 ± 0.41 A.h. In Figure 1, four of the six cell types fell within that range with the standard AN cells above this range and the AN/PC (90/10) cells below this range. The standard capacities between adjacent cell types however, did not exceed the pooled standard deviation of 0.41 A.h. Therefore, the apparent variation of the standard capacity from electrolyte to electrolyte is not considered significant.

Although the standard capacities of the D-cells with the various electrolytes are very similar, the rate capability of the cells, as determined by the current at which the capacities begin to decline, is dependent upon the electrolyte type. The rate capabilities of cells with PC/DME (50/50) and BL/DME (50/50) electrolytes are significantly inferior to those of cells with the standard

AN electrolyte. The addition of PC, AA and BL/DME to AN did not affect the rate capability of the fresh cells to a substantial extent at room temperature. Similar trends were observed at -30°C tests as well (Figure 2).

Figures 9 and 11 show the result for cells with AN (the test standard) and AN/BL/DME (85/10/5) electrolytes, respectively. These results were quite typical, in that the cells lost some capacity and rate capability after storage at 72°C for one month and at 55°C for 3 months. This behavior was reflected in discharge at both RT and -30°C discharge. Additionally, as expected, a slightly lower standard capacity and considerably inferior rate capability was observed at -30°C .

The cells with the AN/PC (90/10) electrolyte are shown in Figure 8. We noted the anomalous behavior that these cells performed relatively better after storage at elevated temperatures. The room temperature discharge characteristics of the cells stored at 55°C and 72°C were found to be about the same as fresh cells. At -30°C the cells which were stored for 1 month at 72°C demonstrated a superior rate capability compared to fresh cells or cells stored for 3 months at 55°C (see Figure 8). These cells had a better rate capability than standard AN cells when discharged at -30°C after 1 month storage at 72°C (Figure 4).

The fresh cells with the AN/AA (90/10) electrolyte performed well on discharge (Figure 10). A serious problem was encountered, however, during storage at elevated temperatures. After storage for 1 month at 72°C or for 3 months at 55°C all of these cells leaked. The vent motors were only slightly displaced indicating a gradual pressure buildup in the cells. Several cells survived storage for 77 days at 55°C and two of these cells were removed from the oven for analysis.

Gas chromatographic (GC) analysis was performed on the gaseous phase of the stored cells. A cell which leaked after 1 month storage at 72°C showed 67% SO_2 , 30% air and 3% CO_2 . A second cell which did not leak after 77 days at 55°C showed 40% SO_2 , 58% air and 0.7% CO_2 in its gaseous phase. Finally, as a control, a cell with the AN (standard) electrolyte was stored for 3 months

at 55°C, and its GC result showed that no CO₂ was present. It is apparent that the pressure buildup in the stored AN/AA (90/10) cells was at least partially due to CO₂ evolution, and that a decomposition reaction which produces CO₂ is responsible for the leakage of these cells. A suspected reaction was the decomposition of acetic anhydride, possibly catalyzed by water which produced CO₂. The presence of H₂ was suspected but not confirmed.

Two cell types were made with electrolytes that did not contain AN in the electrolyte. Figure 7 shows cells with the PC/DME (50/50) electrolyte and Figure 12 shows cells with the BL/DME (50/50) electrolyte. The PC/DME (50/50) cells had only small performance losses after storage at the elevated temperatures. At -30°C discharges however, these cells had a very large, significant loss in rate capability that was much more than cells containing AN in their electrolytes. The RT result for cells stored at 72°C for 1 month (dashed line, Figure 7) were marred by the fact that these cells leaked during storage. The amount of electrolyte lost by the test cells is shown in Table 5. Without the leakage problem, the performance of these cells would be expected to be similar to the cells stored for 3 months at 55°C.

The cells with the BL/DME (50/50) electrolyte (Figure 12) gave the least desirable discharge performance of the six electrolyte systems studied in this work. After storage at 55°C or 72°C, these cells showed large losses in both capacity and rate capability as compared to fresh cells. Similar to the PC/DME (50/50) electrolyte, cells with the BL/DME (50/50) electrolyte had a drastically reduced rate capability when discharged at -30°C.

A comparison of the discharge performance of the various cell types is shown in Figures 1 through 6 for the given storage and discharge conditions.

The fresh cell results at room temperature as shown in Figure 1, were discussed in the analysis at the beginning of this section. We showed that the standard capacities for the various cell types were different at the extremes but the differences were not outstanding. The cells containing AN in the electrolyte all had good rate capability while the cells without AN, particularly the BL/DME (50/50) cells were inferior in rate capability.

When the fresh cells were discharged at -30°C as shown in Figure 2, the sizable decrease in rate capability for the PC/DME (50/50) and the BL/DME (50/50) cells became even more apparent. The AN/PC (90/10) system did not perform as well as the other AN containing electrolyte systems at -30°C . The four cell types containing AN were just different enough in Figure 2 to lead one to believe that they were slightly different in the order shown.

The discharge results at RT after 1 month storage at 72°C are shown in Figure 9. We noted that the cells with AN in their electrolytes behaved almost alike. An extremely poor performance was observed however for the cells with the BL/DME (50/50) electrolyte. The leaky PC/DME (50/50) cells performed quite well considering the leakage problem. These cells actually vastly outperformed the BL/DME (50/50) cells, but were far inferior to the cells with AN in rate capability.

Figure 4 shows the -30°C discharge results after 1 month storage at 72°C . Again the BL/DME (50/50) cells performed extremely poorly. The discharge of PC/DME (50/50) cells were not carried out under this condition due to the leakage problem at 72°C . In view of the other results it is expected that these cells would have performed similar to, or slightly better than the cells with the BL/DME (50/50) electrolyte. Among the cells with AN in the electrolyte it appeared that the cells with AN (standard) electrolyte had a slightly better capacity at low rates while the cells with AN/PC (90/10) electrolyte showed a slightly better rate capability. The latter after 1 month storage at 72°C was a surprise since fresh AN/PC (90/10) cells tended to be slightly inferior to other cells filled with AN containing electrolytes.

The RT discharge after 3 months storage at 55°C is shown in Figure 5. These results once again indicate that the AN containing electrolytes gave much better rate capability than that of the BL/DME (50/50) and the PC/DME (50/50) electrolyte systems. At low rates, PC/DME (50/50) electrolyte was found to be comparable to the AN containing electrolytes in terms of cell capacity.

Cell discharge curves at -30°C after 3 months at 55°C storage are presented in Figure 6 which clearly show a dichotomy between electrolytes with and without AN present. Again, a much larger loss of rate capability

at -30°C discharge in the cells without AN was noted.

In summary, the discharge data revealed only relatively small differences between the four electrolytes containing AN. These cell types were quite superior however to the two cell types which did not contain AN, particularly at -30°C discharge.

B. Safety Aspects

In order to evaluate the safety aspects of the LC26SX cells, a standard abuse test was conducted in triplicate for each cell type. In the abuse test, the cells were force discharged at 2.0A constant current at -30°C . Cell voltage and wall temperature were monitored. This test is realistic in relation to a single cell in a battery which becomes totally discharged earlier than the rest, resulting in the forced discharge of that single cell.

The major safety aspect of the abuse tests concerns venting and/or explosion. The results of the force-discharge abuse tests are listed in Tables 24 to 29. The terminologies adopted are defined as follows:

The "Initial Voltage Excursion" defines the lowest potential reached by the force-discharged cell. The initial voltage excursion is seen as a sharp severe drop after the cell potential goes below zero volts. This voltage drop is related to the depletion or disconnection of lithium at the anode and is most probably the trigger point for cell venting.

The "Maximum Wall Temperature" is the highest temperature read by the 0.003" iron-constantin thermocouple which is attached to the center of the outside cell wall. The maximum temperature almost always occurs in conjunction with the initial voltage excursion.

The "Continuing Voltage" and the "Continuing Wall Temperature" are used to describe the steadier states (approximate average) attained by the cell voltage and wall temperature following the initial "maximum" values. If these parameters are not reasonably steady, a range of values is shown.

A study of the venting characteristics of the test cells (Tables 24 to 29) indicated only occasional venting for cells which did not contain DME. One cell with standard AN electrolyte and one cell with AN/PC (90/10) electrolyte vented during the abuse test after three months storage at 55°C. Fresh cells with the AN/AA (90/10) electrolyte did not leak on the abuse test. These cells all leaked, however, on storage at elevated temperatures, thus preempting abuse tests on the AN/AA (90/10) cells after storage at 55°C and 72°C.

The cells with the ternary electrolyte, AN/BL/DME (85/10/5), did not vent on the abuse test when they were fresh, but two out of three vented after storage at 72°C for one month, and all three vented after storage at 55°C for three months.

Both cell types which contained fifty percent DME in the electrolyte solvent performed poorly during the abuse test. Eight out of nine cells with PC/DME (50/50) or BL/DME (50/50) electrolytes vented in our study.

Some insight into the venting mechanism can be attained by studying the cell voltages and cell wall temperatures during the abuse test. Figure 13 shows (1) a fresh cell with AN/AA (90/10) electrolyte (cell 610), a cell type which did not vent, compared to (2) a fresh cell with BL/DME (50/50) electrolyte (cell 1102), a cell type which vented during the fresh cell abuse test. According to the terminology used by Dey (8), the non-venting cell with the AN/AA (90/10) electrolyte had a Class I voltage profile. The Class I cell showed a gradual voltage decline past the two volt cutoff to zero volts, where the cell reaction still produced $\text{Li}_2\text{S}_2\text{O}_4$ product. Upon reaching zero volts at 8.3 A.h the cell almost immediately went in to deep reversal which indicated little or no plating of active lithium onto the cathode. Although the initial voltage excursion went beyond -7 volts and the maximum cell wall temperature reached 84°C, the cell did not vent.

The cell with BL/DME (50/50) electrolyte, which vented, had a Class III voltage profile (8). This cell reached zero volts after only 6 A.h of discharge. During this period resistive heating of the cell was higher due to the higher resistivity of the BL/DME (50/50) electrolyte. Below zero volts, this cell

had a voltage plateau lasting over one hour during which lithium was deposited on the cathode. Subsequently, the deep voltage plunge occurred and the cell vented as the wall temperature reached 87°C.

A similar analysis can also be rendered for the cells stored for one month at 72°C prior to the abuse test (Figure 14). Again the Class I voltage profile was observed for the non-vented cell (1) with the AN (electrolyte)(cell 324), and the Class III voltage profile was observed for the cell which vented (2), which contained PC/DME (50/50) electrolyte (cell 118).

The consistent venting of the cells containing DME can be attributed to the higher resistivity and the lower cathode efficiency of the electrolytes. The venting was most pronounced in the cells with fifty percent DME in the electrolyte solvent, but it also occurred in the stored cells with the ternary electrolyte which contained only five percent DME in the solvent mixture. By comparison, venting during the forced-discharge was only infrequent for the cell types which did not contain any DME.

A comparison of the cell wall temperatures during the force-discharge abuse tests was unrevealing. The maximum cell wall temperatures varied between 35°C and 95°C with an occasional cell running over 100°C. Temperatures in excess of 150°C were registered for some vented cells. Cells which did not vent sometimes registered higher temperatures than cells that did vent, because of cooling due to evaporation and expansion of electrolyte upon venting.

C. Anode Current Collectors

The use of copper foil anode current collectors was briefly attempted. The fabrication of anodes was carried out in an argon filled dry box on a rolling mill with both rollers driven. The rolling mill was designed for making shorter and thicker anodes and consequently problems were encountered in fabricating anodes with 1-mil copper foil sandwiched between lithium sheets. Attempts at gross reductions in thickness to produce good Li-Cu bonding were unsuccessful due to shredding, crushing, curving and washboarding of the anodes. The resulting anodes were unusable.

We succeeded in making some usable anodes by rolling two or three 1-5/8 inch wide by 3-mil thick lithium foils onto 1-inch wide by 1-mil thick etched copper substrates. The anodes were reduced by about 1-1/2 mils on a single pass through the rollers between two sheets of 1/32 inch polypropylene. The resulting anodes were coherent, although firm Li-Cu bonding was not accomplished.

The new anode structures were placed into LO26SX cells for testing. Two cells had 6-mil thick anodes and two cells had 9-mil thick anodes. All of these cells were filled with the AN electrolyte.

The cells with the copper foil anode current collectors were placed on the force-discharge abuse test at 2.0A at -30°C. The results and data sheet for these experiments are shown in Table 30. A typical cell voltage and wall temperature profile during the force discharge test is shown for Li/Cu cell 3 in Figure 15. These cells discharged at just above or just below 2V, causing the discrepancy in the capacities reported in Tables 30A and 30B. There was no obvious reason for the low operating voltages. The discharge capacities to the inflection points were comparable to regular LO26SX cells with the AN electrolyte.

An examination of the discharge data for these cells revealed that the Li/Cu anodes were quite effective in diminishing the sharp voltage drop at the end of discharge. The absence of the trigger point was reflected in the somewhat lower cell wall temperatures recorded for these cells, as reflected in Figure 15. The increase in cell temperature that coincides with the trigger point is presumed responsible for initiating exothermic chemical reactions and subsequent venting. None of these cells vented on the abuse test which was comparable to standard cells.

In general these cells ran at slightly lower temperatures than cells without the copper anode substrate. This was due in part to the heat sink effect of the copper foil. Also, the electrochemical dissolution of the copper anode substrate contributed to the cooler running of these cells during forced-discharge. The cells ran cooler because the copper dissolution prevented the development of high cell impedance and the consequent I^2R heating effect. The evidence for the dissolution of copper was very apparent in the discharged

cells where copper deposits were found through the separator and in the cathodes.

D. Voltage Delay

Inherent in the classical Li/SO₂ battery system, is a lower than normal operating voltage which occurs just as a cell is placed on discharge. This initial polarization has been termed the voltage delay and it is most pronounced at low service temperatures. A typical cell, discharged at 2A at -30°C, has an initial momentary operating voltage of around 1.5 volts. The operating voltage rapidly recovers and exceeds 2V in about a half-minute. The maximum operating voltage is usually approached even more slowly.

The voltage delay was briefly studied in this work as a function of electrolyte composition. The voltage delay was observed for 3.0A constant current discharges at -30°C. The results are shown in Table 31.

Three categories of voltage delay behavior were observed at 3A at -30°C. First was the normal voltage delay exhibited by standard cells with AN electrolyte and similarly by cells with the AN/PC (90/10) electrolyte. Here, the voltage dropped to below 1V and took about 1 minute to recover to above 2V.

The second category included cells with the AN/AA (90/10) electrolyte and the AN/BL/DME (85/10/5) electrolyte. These cells had a less severe voltage delay than the standard cells. For these cells, the voltage dropped to just below 2V and recovered to over 2V in less than 15 seconds.

The third category of cells had a more severe voltage delay problem than the standard cells. This category included cells with fifty percent DME in the electrolyte solvent, PC/DME (50/50) and BL/DME (50/50). At 3A constant current these cells were driven into reversal upon startup. The large polarization was attributed to a heavy anode film which vastly increased the internal impedance of these cells. After starting at less than zero volts, these cells took over 2 minutes to recover to the 2V operating voltage.

It is interesting that the AN/AA (90/10) electrolyte and the AN/BL/DME (85/10/5) electrolytes resulted in cells with improved performance with respect to the voltage delay phenomenon. Presumably, the additive solvents in these electrolytes prevented or slowed down the growth of very thick $\text{Li}_2\text{S}_2\text{O}_4$ passivating films on the anode. Alternatively, but less likely, the additive solvents aided in the more rapid dissolution of the anode film. Regardless of the mechanism, the diminished voltage delay was a positive feature of these electrolyte types.

6. Conclusions

The results of the tests of the LC26SX cells with the various electrolytes can best be concluded with the aid of the following review.

1. AN/PC (90/10): These cells used propylene carbonate, a traditional Li/SO₂ cell additive, as a protective solvent for the lithium in the cells. Less than half of the traditional amount of PC was in this electrolyte. These cells had the lowest fresh, RT standard capacity of all the cell types, 1.3 A.h, or 15% less than that of the AN (standard) cells. This difference was of borderline significance in view of the experimental error. The fresh cells were the same as AN (standard) cells at room temperature at the higher discharge rates, but they were relatively inferior to the fresh AN cells at -30°C. After storage at the elevated temperatures the cells with AN/PC (90/10) performed equally to the standard cells. One cell out of nine (stored at 55°C) vented during the 2.0A, -30°C abuse test which is comparable to the behavior of the standard AN cells. The voltage delay for these cells was only slightly higher than that observed for the AN cells.

Overall, the AN/PC (90/10) electrolyte appeared to be equivalent to or perhaps very slightly inferior to the standard AN electrolyte.

2. AN/AA (90/10): The potential use of acetic anhydride (AA) as an additive for Li/SO₂ cells was suggested by our earlier DTA studies. The initial fresh cell discharge results for this electrolyte were very encouraging. The fresh cells were equivalent to standard AN cells in most aspects while giving slightly higher open circuit and operating voltages. The cells displayed marginally superior rate capability over fresh AN cells at -30°C discharge. On the 2.0A, -30°C abuse test, none of three fresh cells vented. The voltage delay was reduced markedly with the AN/AA (90/10) electrolyte while the start-up voltage plunged less. These cells had the best voltage delay characteristics of all the cells tested.

On the negative side, all the cells with the AN/AA (90/10) electrolyte vented during the programmed storage routines at 55°C and 72°C. AA is quite corrosive and it reacts slowly with water to form acetic acid. A slow, unidentified CO₂ gas producing reaction was causing the pressure buildup and subsequent

venting of these AN/AA (90/10) cells.

Fresh cells with the subject electrolyte are rated overall as slightly superior to fresh AN cells. The use of this electrolyte severely is limited however, by the disastrous gassing during storage which related to the use of AA in the electrolyte.

3. AN/BL/DME (85/10/5): A glance at the various capacity-rate curves indicated that the discharge performance of cells with the ternary electrolyte was slightly inferior to that of the standard AN cells. A very slight tendency to lose rate capability at lower discharge temperatures was also indicated in our results. On the 2.0A, -30°C abuse test, the AN/BL/DME (85/10/5) cells did not vent when they were tested fresh. Almost universal abuse test venting occurred however, after these cells were stored for 1 month at 72°C and for 3 months at 55°C. Thus, these cells were simply unacceptable based on the abuse test. One positive aspect of this electrolyte was the reduced voltage delay characteristics. In this respect, these cells were better than the AN cells and equivalent to the AN/AA (90/10) cells.

The overall performance rating of these cells seemed to be slightly inferior to standard cells despite their advantageous voltage delay characteristics. The loss of abuse tolerance after storage at higher temperatures is the principle negative factor.

4. PC/DME (50/50): This was one of two electrolytes in this study which contained no acetonitrile at all. Cells with AN are believed to form cyanide (9), an event which has negative environmental implications for the Li/SC₂ system. The cells with the PC/DME (50/50) electrolyte were slightly inferior to standard cells in rate capability at room temperature. At -30°C discharges the rate capability of these cells was vastly inferior. Similar effects were observed for the 55°C storage condition. These cells also fared very poorly on the 2.0A, -30°C abuse test where almost universal venting occurred. The voltage delay characteristics of these cells were also inferior. The voltage delay problem was significantly worse than that encountered in standard cells.

The PC/DME (50/50) electrolyte was far less desirable than the standard AN electrolyte in all respects. It was clearly unacceptable for high rate, potentially abusive discharge regimes.

5. BL/DME (50/50): This was the second test electrolyte which contained no acetonitrile. The fresh cell discharge performance of cells with the BL/DME (50/50) electrolyte was about the same as its companion electrolyte, PC/DME (50/50). The BL/DME (50/50) electrolyte however, showed much greater loss in discharge performance after high temperature storage conditions. In general, the discharge performance was also vastly inferior to standard cells. These cells almost universally vented on the 2.0A, -30°C abuse test and the voltage delay characteristics were intolerable. These poor performances mirrored the results obtained with the PC/DME (50/50) electrolyte.

A review of the BL/DME (50/50) electrolyte showed that it was also clearly unacceptable, in comparison to standard electrolytes which contained AN.

Based on the above review of the various electrolytes, we may draw the following conclusions:

The standard AN electrolyte and the AN/PC (90/10) electrolyte are acceptable for use in high rate Li/SO₂ batteries where abuse tolerance is an asset. No electrolyte was found to clearly outperform the standard electrolyte in all areas of concern.

The AN/AA (90/10) electrolyte has shown several advantages over the standard AN cells. The immediate implementation of this electrolyte is aborted however, by the unfortunate high temperature leakage problem suffered by these cells. This electrolyte would be very promising in the absence of the leakage problem.

The behavior of AN/BL/DME (85/10/5) electrolyte was considered to be unsatisfactory. This electrolyte generally performed slightly poorer than standard electrolyte and cell venting at the 2.0A, -30°C abuse test became a problem especially after high temperature storage.

The PC/DME (50/50) electrolyte and the BL/DME (50/50) electrolyte and the BL/DME (50/50) electrolyte were clearly unacceptable for use in high rate abuse tolerant Li/SO₂ batteries. These cell types were demonstrably

poorer in all phases of interest as compared to standard cells.

The use of copper foil anode substrates was studied briefly and found to favorably decrease both the deep voltage reversal and cell operating temperature in the test cells. None of the test cells vented during the 2.0A, -30°C abuse test. These safety-oriented tests had positive implications but more demanding tests are required in order to determine if this type of cell refinement results in cells which are superior to the standard LO26SX cells.

7. Recommendations

Although no imminently useful new electrolytes were found in this study, the approach of altering the electrolyte in SO_2 cells remains valid. Some favorable aspects were observed among the several electrolytes studied and hopefully one may develop a future electrolyte with improved safety and discharge characteristics.

It is recommended that future work of this nature be confined to a more limited number of tests on individual cell types while broadening the scope to enable the study of a wider variety of unknowns. By this method a wider range of samples could be screened through carefully chosen tests to define a limited number of promising candidates for more detailed study.

Along this line, screening methods should not be constricted to user oriented test regimes. More important are tests which strongly differentiate between cell types, thus giving the clearest possible picture of the relative merits of the candidates. Preferably, these tests would be more stringent than that required for the user applications.

The most productive near-term approach in constructing improved high rate, abuse resistant Li/SO_2 cells lies in the arena of physical cell design. This approach would include the study of electrode materials, fabrication methods and cell structures. The purpose to this approach would be the design of cells which operate at lower current densities through the use of longer, thinner electrodes while using the most efficient electrode structures possible.

8. References

1. P. Bro, R. Holmes, N. Marincic and H. Taylor, Paper No. 45, Proc. Intl. Power Sources Symposium, Brighton, England, 1974.
2. P. Bro, H. Y. Kang, C. Schlaikjer and H. Taylor, Tenth Intersociety Energy Conversion Engineering Conference, Newark, Delaware, p. 432 (1975).
3. H. Taylor and B. McDonald, p. 66, Proc. 27th Power Sources Symposium, Atlantic City, 1976.
4. E. S. Brooks, p. 42, Proc. 26th Power Sources Symposium, Atlantic City, 1974.
5. G. DiMasi, p. 75, Proc. 27th Power Sources Symposium, Atlantic City, 1976.
6. H. F. Hunger, and J. A. Christopulos, R&D Technical Report, ECOM-4292, February 1975.
7. A. N. Dey and R. W. Holmes, R&D Technical Report, "Analysis of Pressure Producing Reactions in Lithium-Sulfur Dioxide Cells", DELET-TR-77-0472-F (ERADCOM), P. R. Mallory & Co. Inc., November 1979.
8. A. N. Dey, "Safety Studies of Lithium Sulfur Dioxide Cells", Final Report DELET-TR-77-0458-F (ERADCOM), P. R. Mallory & Co. Inc., Nov. 1978.
9. A. H. Taylor, W. L. Bowden and J. Barrella, "Li/SO₂ Cells of Improved Stability", Proc. 28th Power Sources Symposium, Atlantic City, 1978.

TABLE 1.

Specifications and Data for the LO26SX, Li/SO₂ CellPackage: D-cell, venting can typeNominal Volume: 3.2 in³ or 52.3 cm³

Length, maximum: 2.268 inches (including bent fill port)

Diameter, maximum: 1.315 inches

Anti-corrosion treatment: Halar coated G/M seal

Separator:

Polypropylene, 1 mil thick with reaction barrier strip.

Electrolyte:Volume, approximate: 28 cm³63% SO₂ (volume): 10.6 A.h SO₂Anode:

Length:	21.000 ±0.125 inches
Width:	1.625 ±0.010 inches
Thickness, nominal:	0.008 inches
Weight Range Specification:	2.07 to 2.72 grams
Calculated Li Capacity:	8.0 to 10.5 A.h

Cathode:

Length:	23.500 ±0.125 inches
Width:	1.625 ±0.031 inches
Thickness:	0.036 ±0.004 inches
Weight:	9.00 ±0.60 grams

TABLE 2A
Composition of Electrolytes

1. PC/DME (50/50)	Components	Milliliters	Grams	Weight Pct.
Lithium bromide	LiBr	----	379	3.6
Propylene Carbonate	PC	925	1114	16.3
Dimethoxyethane	DME	925	798	11.7
Sulfur dioxide	SO ₂	3158	4528	66.4
Total		5008 ml	6819g	100%

Approximate Density, PC/DME (50/50): 1.36 g/cm³

2. AN/PC (90/10)	Components	Milliliters	Grams	Weight Pct.
Lithium bromide	LiBr	----	379	5.9
Acetonitrile	AN	1665	1308	20.3
Propylene Carbonate	PC	185	223	3.5
Sulfur dioxide	SO ₂	3162	4534	70.4
Total		5012 ml	6444g	100%

Approximate Density, AN/PC (90/10): 1.29g/cm³

3. AN (standard type)	Components	Milliliters	Grams	Weight Pct.
Lithium bromide	LiBr	----	379	6.0
Acetonitrile	AN	1850	1454	22.8
Sulfur Dioxide	SO ₂	3163	4536	71.2
Total		5013 ml	6369g	100%

Approximate Density, AN: 1.27 g/cm³

TABLE 2B
Composition of Electrolytes

4. AN/AA (90/10)	Components	Milliliters	Grams	Weight Pct.
Lithium bromide	LiBr	----	379	5.9
Acetonitrile	AN	1665	1308	20.4
Acetic Anhydride	AA	185	200	3.1
Sulfur Dioxide	SO ₂	3162	4535	70.6
Total		5012 ml	6422g	100%

Approximate Density, AN/AA (90/10): 1.28 g/cm³

5. AN/BL/DME (85/10/5)	Components	Milliliters	Grams	Weight Pct.
Lithium bromide	LiBr	----	379	5.9
Acetonitrile	AN	1573	1236	19.2
γ-Butyrolactone	BL	185	209	3.2
Dimethoxyethane	DME	92	80	1.2
Sulfur Dioxide	SO ₂	3165	4539	70.4
Total		5015 ml	6443g	100%

Approximate Density, AN/BL/DME (85/10/5): 1.28 g/cm³

6. BL/DME (50/50)	Components	Milliliters	Grams	Weight Pct.
Lithium bromide	LiBr	----	379	5.6
γ-Butyrolactone	BL	925	1044	15.5
Dimethoxyethane	DME	925	798	11.8
Sulfur Dioxide	SO ₂	3162	4535	67.1
Total		5012	6756	100%

Approximate Density, BL/DME (50/50): 1.35 g/cm³

Note: (1) The approximate densities above were calculated with the assumption that the LiBr did not contribute to the volume of the final electrolyte.

(2) Based on (1) the electrolytes are 0.87M LiBr.

TABLE 3.

Weight and Volume of Electrolytes in the Test Cells.

Statistics From Samples of 15 Cells.

No.	Electrolyte Type	Electrolyte Weight	Electrolyte Volume
1.	PC/DME (50/50)	39.5 $\pm$ 0.4 g	29.0 $\pm$ 0.3 ml
2.	AN/PC (90/10)	37.1 $\pm$ 0.4	28.8 $\pm$ 0.3
3.	AN (standard)	35.3 $\pm$ 0.8	27.8 $\pm$ 0.6
4.	AN/AA (90/10)	36.2 $\pm$ 0.7	28.2 $\pm$ 0.5
5.	AN/BL/DME (85/10/5)	35.1 $\pm$ 0.8	27.4 $\pm$ 0.6
6.	BL/DME (50/50)	37.0 $\pm$ 0.9	27.4 $\pm$ 0.7

TABLE 4

Constand Load Discharge Results for LO26SX Cells
With PC/DME (50/50) Electrolyte. Fresh Cells

Capacities Determined by Integration to 2.0V Cutoff

R.T. Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0 Volts	Average Current
33	202.8 Ω	565.0 hr	1641.03 V.h	8.09 A.h	0.0143 A
94	100.9	274.8	788.39	7.81	0.0284
74	30.69	83.8	237.55	7.74	0.0924
16	14.745	31.2	85.55	5.80	0.1860
124	5.046	14.70	39.664	7.86	0.54
115	2.020	6.315	16.981	8.41	1.33
95	1.012	3.06	7.832	7.74	2.53
130	0.596	1.636	4.301	6.76	4.13
131	0.194	0.283	0.630	3.25	11.47

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0 volts	Average Current
73	202.8 Ω	534.3 hr	1490.06 V.h	7.35 A.h	0.0138 A
71	100.9	270.9	726.71	7.20	0.0266
108	30.69	64.6	169.93	5.54	0.0857
93	14.745	28.5	71.61	4.86	0.1704
72	5.046	7.49	18.426	3.65	0.49
77	2.020	2.57	4.335	2.15	0.84
84	1.012	1.43	3.303	3.26	2.28
68	0.596	0.802	1.791	3.00	3.75
69	0.194	0.230	0.397	2.05	8.91

Note: Cells at 0.194 Ω load, vented

TABLE 5
Constant Load Discharge Results for LO26SX Cells With
PC/DME (50/50) Electrolyte. 72°C Storage 34 days.

Capacities Determined by Integration to 2.0V Cutoff

R. T. Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Fours	Capacity, Q, to 2.0 Volts	Average Current	Weight Lost @ 72°C
128	30.69 Ω	86.05 hr	242.32 V.h	7.90 A.h	0.0918A	0.44 g
135	14.75	39.13	108.64	7.37	0.188	0.92
87	5.046	6.73	16.70	3.31	0.492	10.57
90	2.020	0	0	0	-----	13.49
103	1.012	1.26	3.123	3.09	2.449	8.86
141	0.596	0.766	1.858	3.12	4.070	9.08
149	0.194	0.159	0.341	1.76	11.04	19.65

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Fours	Capacity, Q, to 2.0 Volts	Average Current	Weight Lost @ 72°C
86	30.69 Ω	27.58 hr	64.52 V.h	2.10 A.h	0.0762A	9.21 g
112	14.75	15.15	35.87	2.43	0.161	8.64
28	5.046	5.45	13.24	2.62	0.481	----
151	2.020	2.63	6.206	3.07	1.168	----
43	1.012	1.64	3.935	3.89	2.371	0.11
19	0.596	1.136	2.550	4.28	3.766	0
25	0.194	0.285	0.511	2.63	9.242	7.40

TABLE 6

Constant Load Discharge Results for LO26SX Cells with PC/DME (50/50)
Electrolyte. Cells Stored 91 Days at 55°C.

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
8	202.8 Ω	479.60 hr	1370.84 V.h	6.76 A.h	0.0141A
117	100.9	216.32	609.03	6.04	0.0279
85	30.69	79.26	220.00	7.17	0.0904
9	14.745	39.24	107.74	7.31	0.1862
102	5.046	14.88	30.65	7.86	0.528
137	2.020	5.63	14.43	7.14	1.268
100	1.012	2.79	6.04	5.97	2.139
120	0.596	1.37	3.26	5.47	4.003
2	0.194	0.196	0.506	2.61	13.312

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
89	202.8 Ω	564.30 hr	1513.29 V.h	7.46 A.h	0.0132A
10	100.9	252.73	668.13	6.62	0.0262
3	30.69	55.64	136.52	4.45	0.0799
98	14.745	20.98	51.10	3.47	0.1652
99	5.046	6.57	15.50	3.07	0.467
107	2.020	1.94	4.30	2.13	1.096
101	1.012	1.14	2.45	2.42	2.125
106	0.596	0.684	1.417	2.38	3.475
1	0.194	0	0	0	--

TABLE 7
Constant Load Discharge Results for LO26SX Cells
With AN/PC (90/10) Electrolyte. Fresh Cells

Capacities Determined by Integration to 2.0V Cutoff

R.T. Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0 Volts	Average Current
308	202.8 Ω	463.6 hr	1296.77 V.h	6.39 A.h	0.0138 A
259	100.9	245.3	703.48	6.97	0.0284
236	30.69	68.7	193.16	6.29	0.0916
321	14.745	35.6	100.90	6.84	0.1922
353	5.046	13.2	36.90	7.31	0.554
212	2.020	5.51	14.86	7.36	1.336
284	1.012	3.04	8.090	7.99	2.630
207	0.596	1.883	4.844	8.13	4.316
219	0.194	0.345	0.787	4.06	11.76

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0 Volts	Average Current
277	202.8 Ω	494.7 hr	1388.38 V.h	6.85 A.h	0.0138A
247	100.9	269.2	738.32	7.32	0.0272
220	30.69	85.6	224.64	7.32	0.0855
238	14.745	39.7	102.45	6.95	0.1750
261	5.046	10.7	26.63	5.28	0.493
294	2.020	3.37	8.129	4.02	1.194
351	1.012	1.48	3.523	3.48	2.344
287	0.596	0.932	2.206	3.70	3.972
323	0.194	0.258	0.532	2.74	10.62

TABLE 8

Constant Load Discharge Results for LO26SX Cells With
AN/PC (90/10) Electrolyte. Cells Stored 31 Days at 72°C.

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
349	202.8 Ω	356.9 hr	1013.67 V.h	5.00 A.h	0.0140 A
314	100.0	265.5	752.00	7.45	0.0281
246	30.69	73.0	207.61	6.76	0.0927
296	14.745	35.0	99.35	6.74	0.1925
286	5.046	12.47	34.99	6.93	0.556
298	2.020	5.49	14.97	7.41	1.349
341	1.012	3.02	8.05	7.96	2.634
290	0.596	1.85	4.63	7.76	4.196
348	0.194	0.275	0.601	3.10	11.271

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
297	202.8 Ω	467.62 hr	1314.58 V.h	6.48 A.h	0.0139 A
352	100.9	172.25	468.39	4.64	0.0269
317	30.69	67.9	181.29	5.91	0.0870
320	14.745	40.0	103.61	7.03	0.1755
224	5.046	13.43	34.23	6.78	0.505
327	2.020	4.30	10.63	5.26	1.224
322	1.012	2.39	5.81	5.74	2.402
209	0.596	1.147	2.67	4.48	3.903
339	0.194	0.498	1.048	5.40	10.845

TABLE 9

Constant Load Discharge Results for LO26SX Cells with AN/PC (90/10)
Electrolyte. Cells Stored 91 Days at 55°C.

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
282	202.8 Ω	453.95 hr	1255.22 V.h	6.19 A.h	0.0137A
342	100.9	211.60	564.39	5.59	0.0264
302	30.69	66.97	188.26	6.13 A.h	0.0916
312	14.745	34.84	97.16	6.59	0.1891
318	5.046	12.56	34.74	6.88	0.548
221	2.020	5.48	14.72	7.29	1.330
306	1.012	3.03	7.97	7.88	2.601
223	0.596	1.84	4.60	7.72	4.203
283	0.194	0.347	0.764	3.94	11.347

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
340	202.8 Ω	339.75 hr	862.97 V.h	4.26 A.h	0.0125
243	100.9	215.50	533.42	5.29	0.0245
225	30.69	80.25	209.94	6.84	0.0852
346	14.745	39.21	99.61	6.76	0.1723
319	5.046	9.83	24.13	4.78	0.486
299	2.020	2.70	6.34	3.14	1.162
311	1.012	1.56	3.70	3.66	2.346
285	0.596	0.960	2.22	3.73	3.883
303	0.184	0.260	0.545	2.81	10.795

TABLE 10

Constant Load Discharge Results for LO26CX Cells With
AN Electrolyte. The Test Standard. Fresh Cells

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
464	202.8 Ω	608.80 hr	1741.67 V.h	8.59 A.h	0.0141 A
442	100.9	310.00	887.74	8.80	0.0284
522	30.69	91.53	259.87	8.47	0.0925
473	14.745	46.57	130.97	8.88	0.191
431	5.046	15.00	41.44	8.21	0.548
514	2.020	6.46	17.66	8.74	1.354
549	1.012	3.35	8.90	8.80	2.626
447	0.596	2.052	5.213	8.75	4.262
532	0.194	0.405	0.929	4.79	11.82

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
468	202.8 Ω	581.23 hr	1618.58 V.h	7.98 A.h	0.0137 A
488	100.9	298.77	827.10	8.20	0.0274
482	30.69	91.69	249.55	8.13	0.0887
484	14.745	47.44	124.90	8.47	0.179
418	5.046	13.81	35.26	6.99	0.506
471	2.020	4.36	10.79	5.34	1.225
443	1.012	2.27	5.665	5.60	2.466
548	0.596	1.193	2.916	4.89	4.101
467	0.194	0.250	0.550	2.83	11.33

TABLE 11

Constant Load Discharge Results for LO26SX Cells with AN Electrolyte.

The Test Standard. Cells Stored 31 Days at 72°C.

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
509	202.8 Ω	521.8 hr	1458.06 V.h	7.19 A.h	0.0138 A
533	100.9	250.0	695.74	6.90	0.0276
411	30.69	78.6	220.64	7.19	0.0914
485	14.745	38.5	107.87	7.32	0.1900
428	5.046	14.29	39.56	7.84	0.549
490	2.020	5.31	13.85	6.85	1.291
552	1.012	3.06	8.01	7.91	2.589
495	0.596	1.818	4.53	7.60	4.180
551	0.194	0.352	0.779	4.02	11.413

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
441	202.8 Ω	298.58 hr	832.26 V.h	4.10 A.h	0.0138 A
401	100.9	173.20	470.71	4.67	0.0269
405	30.69	91.6	238.06	7.76	0.0847
502	14.745	44.2	113.03	7.67	0.1732
407	5.046	12.49	31.36	6.21	0.498
493	2.020	3.84	9.26	4.59	1.194
462	1.012	1.96	4.44	4.39	2.236
478	0.596	1.044	2.47	4.14	3.969
489	0.194	0.293	0.606	3.13	10.669

TABLE 12

Constant Load Discharge Results for LO26SX Cells with AN
Electrolyte. The Test Standard: Cells Stored 91 Days at 55°C

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
492	202.8 Ω	573.03 hr	1579.87 V.h	7.79 A.h	0.0136A
534	100.9	245.00	660.64	6.55	0.0267
554	30.69	87.50	245.29	7.99	0.0913
529	14.745	37.07	103.23	7.00	0.1889
429	5.046	14.39	39.73	7.87	0.547
496	2.020	6.06	16.48	8.16	1.346
499	1.012	3.32	8.61	8.50	2.562
446	0.596	1.88	4.62	7.75	4.120
507	0.194	0.378	0.849	4.38	11.578

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
410	202.8 Ω	437.48 hr	1135.22 V.h	5.60 A.h	0.0128A
459	100.9	314.15	772.39	7.65	0.0244
433	30.69	88.50	225.81	7.36	0.0831
487	14.745	38.37	94.84	6.43	0.1676
409	5.046	12.90	32.58	6.46	0.501
465	2.020	3.84	9.51	4.71	1.226
449	1.012	2.22	5.15	5.09	2.292
544	0.596	0.990	2.31	3.87	3.910
475	0.194	0.352	0.692	3.57	10.128

TABLE 13

Constant Load Discharge Results for LO26SX Cells with AN/AA (90/10) Electrolyte.
Fresh Cells.

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
659	202.8 Ω	595.16 hr	1703.22 V.h	8.40 A.h	0.0141 A
658	100.9	302.72	866.06	8.58	0.0284
628	30.69	86.2	244.90	7.98	0.0926
621	14.745	44.4	125.29	8.50	0.1912
631	5.046	14.79	41.10	8.14	0.551
649	2.020	5.96	16.03	7.93	1.330
667	1.012	3.30	8.58	8.48	2.569
665	0.596	1.923	4.82	8.08	4.202
662	0.194	0.347	0.777	4.00	11.539

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
655	202.8 Ω	574.77 hr	1616.25 V.h	7.97 A.h	0.0139 A
636	100.9	315.03	876.90	8.69	0.0276
603	30.69	98.9	265.93	8.67	0.0876
623	14.745	44.6	118.06	8.01	0.1795
650	5.046	14.37	37.16	7.36	0.512
642	2.020	5.19	13.11	6.40	1.249
680	1.012	2.45	6.01	5.94	2.426
617	0.596	1.318	3.19	5.35	4.057
656	0.194	0.392	0.859	4.43	11.300

TABLE 14.

Constant Load Discharge Results for LO26SX Cells with AN/AA (90/10)
Electrolyte. Cells Stored 34 Days at 72°C. Cells Leaked During Storage.

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
-	30.69 Ω	54.58 hr	139.23 V.h	4.54 A.h	0.0831 A
-	14.745	26.15	66.71	4.52	0.1730

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
-	30.69 Ω	72.86 hr	187.61 V.h	6.11 A.h	0.0839 A
-	14.745	20.62	47.35	3.21	0.1558

TABLE 15.

Constant Load Discharge Results for LO26SX Cells with AN/AA (90/10)
Electrolyte. Cells Stored 91 Days at 55°C. Cells Leaked During Storage.

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
714	30.69 Ω	71.48 hr	195.10 V.h	6.36 A.h	0.0889A
697	14.745	24.03	64.00	4.34	0.1806

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
700	30.69 Ω	43.88 hr	115.10 V.h	3.75 A.h	0.0855A
709	14.745	35.86	90.97	6.17	0.1720

TABLE 16

Constant Load Discharge Results for LO26SX Cells with AN/BL/DME (85/10/5)
Electrolyte. Cells Stored

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
814	202.8 Ω	575.9 hr	1636.38 V.h	8.07 A.h	0.0140 A
870	100.9	269.3	757.93	7.51	0.0279
880	30.69	82.0	228.52	7.45	0.0908
804	14.745	42.8	117.16	7.94	0.1855
946	5.046	14.45	39.33	7.79	0.539
930	2.020	5.98	16.06	7.95	1.330
868	1.012	3.39	9.01	8.90	2.625
878	0.596	1.939	4.92	8.25	4.254
941	0.194	0.397	0.890	4.59	11.560

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
929	202.8 Ω	586.0 hr	1603.09 V.h	7.90 A.h	0.0135 A
892	100.9	267.6	769.03	7.62	0.0285
905	30.69	85.5	225.29	7.34	0.0859
825	14.745	40.2	103.61	7.03	0.1746
926	5.046	13.14	33.77	6.69	0.509
948	2.020	4.09	10.09	5.00	1.221
943	1.012	1.97	4.76	4.70	2.388
955	0.596	1.777	4.32	7.26	4.084
931	0.194	0.304	0.635	3.27	10.764

TABLE 17

Constant Load Discharge Results for LO26SX Cells with AN/BL/DME (85/10/5)
Electrolyte. Cells Stored 31 Days at 72°C.

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
937	202.8 Ω	454.35 hr	1273.03 V.h	6.28 A.h	0.0138A
925	100.9	251.13	709.42	7.03	0.0280
933	30.69	57.85	162.58	5.30	0.0916
808	14.745	39.33	108.77	7.38	0.1876
877	5.046	14.50	39.35	7.80	0.5379
947	2.020	5.76	15.34	7.60	1.319
951	1.012	2.91	7.39	7.31	2.511
940	0.596	1.606	3.97	6.66	4.147
932	0.194	0.334	0.730	3.76	11.271

Note: Cell #933 failed abruptly. Bad cell, probably electrode disconnection.

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
938	202.3 Ω	442.00 hr	1220.38 V.h	6.02 A.h	0.0136 A
953	100.9	246.80	655.22	6.49	0.0263
916	30.69	80.85	209.29	6.82	0.0843
919	14.745	35.88	90.71	6.15	0.1715
954	5.046	11.27	27.15	5.38	0.4774
927	2.020	3.59	8.63	4.27	1.190
901	1.012	1.76	3.51	3.47	1.971
944	0.596	1.092	2.57	4.32	3.953
958	0.194	0.353	0.741	3.82	10.815

TABLE 18

Constant Load Discharge Results for LO26SX Cells with AN/BL/DME (85/10/5)
Electrolyte. Cells Stored 91 Days at 55°C

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
911	202.8 Ω	503.60 hr	1389.42 V.h	6.85 A.h	0.0136A
903	100.9	270.00	732.90	7.26	0.0269
924	30.69	68.56	193.81	6.31	0.0921
908	14.745	36.89	103.35	7.01	0.1900
917	5.046	12.17	34.06	6.75	0.555
869	2.020	5.43	14.75	7.30	1.345
915	1.012	2.91	7.69	7.60	2.611
845	0.594	1.581	3.98	6.70	4.237
813	0.194	0.313	0.717	3.70	11.815

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
890	202.8 Ω	518.21 hr	1361.80 V.h	6.72 A.h	0.0130A
860	100.9	277.90	688.51	6.82	0.0246
904	30.69	78.00	205.29	6.69	0.0858
910	14.745	36.65	94.84	6.43	0.1755
920	5.046	10.82	27.08	5.37	0.496
851	2.020	3.06	7.43	3.68	1.202
923	1.012	1.71	4.13	4.08	2.386
853	0.594	1.052	2.511	4.23	4.018
918	0.194	0.274	0.586	3.02	11.020

TABLE 19

Constant Load Discharge Results for LO26SX Cells with BL/DME(50/50)
Electrolyte. Fresh Cells.

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
1119	202.8 Ω	519.1 hr	1459.09 V.h	7.19 A.h	0.0139 A
1154	100.9	274.0	768.77	7.62	0.0278
1111	30.69	82.24	231.61	7.55	0.0918
1072	14.745	46.07	121.55	8.24	0.1789
1035	5.046	14.53	39.06	7.74	0.5327
1058	2.020	5.36	13.86	6.86	1.280
1012	1.012	2.322	5.88	5.81	2.504
1103	0.594	1.280	3.19	5.36	4.184
1070	0.194	0.287	0.617	3.18	11.077

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
1027	202.8 Ω	552.0 hr	1477.67 V.h	7.29 A.h	0.0132 A
1105	100.9	276.5	724.90	7.18	0.0260
1158	30.69	55.10	142.45	4.64	0.0842
1149	14.745	26.73	68.13	4.62	0.1729
1015	5.046	6.46	15.79	3.13	0.4847
1024	2.020	2.67	6.37	3.16	1.180
1054	1.012	1.482	3.43	3.39	2.288
1079	0.594	0.914	2.05	3.44	3.761
1083	0.194	0.274	0.493	2.54	9.273

TABLE 20

Constant Load Discharge Results for LO26SX Cells with BL/DME (50/50)
Electrolyte. Cells Stored 31 Days at 72°C

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
1143	202.8	484.51 hr	1360.84 V.h	6.76 A.h	0.0140A
1029	100.9	112.25	298.32	2.06	0.0263
1046	30.69	21.11	54.19	1.77	0.0836
1129	14.745	14.90	37.81	2.56	0.1721
1091	5.046	4.73	10.71	2.12	0.449
1093	2.020	1.68	4.16	2.06	1.224
1003	1.012	1.07	2.59	2.56	2.395
1033	0.596	0.556	1.311	2.20	3.956
1109	0.194	0	0	0	--

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
1081	202.8	493.18 hr	1319.48 V.h	6.51 A.h	0.0132A
1032	100.9	216.99	563.35	5.58	0.0257
1067	30.69	46.01	113.94	3.71	0.0807
1050	14.745	16.00	38.32	2.60	0.1624
1145	5.046	3.61	7.67	1.52	0.421
1126	2.020	1.74	3.87	1.92	1.101
1160	1.012	0	0	0	--
1036	0.596	0	0	0	--
1115	0.194	0	0	0	--

TABLE 21

Constant Load Discharge Results for LO26SX Cells with BL/DME (50/50)
Electrolyte. Cells Stored 91 Days at 55°C.

Capacities Determined by Integration to 2.0V Cutoff

Room Temperature Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
1037	202.8 Ω	498.12 hr	1310.97 V.h	6.46 A.h	0.0130 A
1131	100.9	219.75	569.03	5.64	0.2566
1097	30.69	45.13	120.77	3.94	0.0872
1011	14.745	28.88	77.94	5.29	0.1830
1082	5.046	8.32	21.88	4.34	0.521
1125	2.020	0	0	0	--
1137	1.012	1.31	3.471	3.43	2.618
1075	0.594	0.762	1.811	3.05	4.002
1098	0.194	0.229	0.366	1.89	8.249

-30°C Discharge

Cell No.	Load Resistance	Discharge Time	Integrated Volt-Hours	Capacity, Q, to 2.0V	Average Current
1085	202.8 Ω	67.10 hr	176.52 V.h	0.87 A.h	0.0130 A
1123	100.9	59.73	155.61	1.54	0.0258
1130	30.69	46.12	116.52	3.80	0.0823
1140	14.745	16.55	40.52	2.75	0.1660
1117	5.046	4.67	11.277	2.23	0.479
1076	2.020	1.67	3.871	1.92	1.147
1092	1.012	0.90	1.987	1.96	2.182
1006	0.594	0.456	0.870	1.46	3.211
1134	0.194	0	0	0	--

TABLE 22

Constant Current Discharge Results for LC26SX Cells.
Capacities to 2.0V Cutoff.

Cells Discharged at 7.0A at RT.

Cell No.	Electrolyte	Storage	Capacity
14	PC/DME (50/50)	3 months @ 55° C	3.72 A.h
305	AN/PC (90/10)	3 months @ 55° C	6.78
498	AN (Standard)	3 months @ 55° C	5.94
914	AN/BL/DME (85/10/5)	3 months @ 55° C	5.57
1124	BL/DME (50/50)	3 months @ 55° C	2.81
50	PC/DME (50/50)	195 days @ RT	4.86
267	AN/PC (90/10)	180 days @ RT	6.55
480	AN (Standard)	167 days @ RT	5.62
699	AN/AA (90/10)	154 days @ RT	5.01
812	AN/BL/DME (85/10/5)	127 days @ RT	5.76
1043	BL/DME (50/50)	113 days @ RT	4.26

Cells Discharged at 3.0A at -30° C.

Cell No.	Electrolyte	Storage	Capacity
304	AN/PC (90/10)	3 months @ 55° C	3.65 A.h
497	AN (Standard)	3 months @ 55° C	4.08
909	AN/BL/DME (85/10/5)	3 months @ 55° C	3.64
1133	BL/DME (50/50)	3 months @ 55° C	1.61
59	PC/DME (50/50)	208 days @ RT	2.81
280	AN/PC (90/10)	193 days @ RT	4.38
477	AN (Standard)	180 days @ RT	3.87
666	AN/AA (90/10)	167 days @ RT	6.45
864	AN/BL/DME (85/10/5)	140 days @ RT	3.59
1089	BL/DME (50/50)	126 days @ RT	3.15

TABLE 23

LO26SX Cells with Various Electrolytes Ranked by Average
Standard Capacities with Standard Deviations

Room Temperature Discharge, Fresh Cells

Rank	Electrolyte Type	Std. Cap'y Std. Dev.	No. of Data	Maximum Current for Data Tabulation
1	AN	8.66 ± 0.22 A.h	8	4.3A
2	AN/AA (90/10)	8.26 ± 0.26	8	4.3
3	AN/BL/DME (85/10/5)	7.98 ± 0.46	8	4.3
4	PC/DME (50/50)	7.94 ± 0.26	6	2.6
5	BL/DME (50/50)	7.67 ± 0.38	5	0.52
6	AN/PC (90/10)	7.16 ± 0.67	8	4.3
	Pooled Ave & Std. Dev.	7.96 ± 0.41		

-30° C Discharge, Fresh Cells

Rank	Electrolyte Type	Std. Cap'y Std. Dev.	No. of Data	Maximum Current for Data Tabulation
1	AN/AA (90/10)	8.34 ± 0.40	4	0.18A
2	AN	8.20 ± 0.21	4	0.18
3	AN/BL/DME (85/10/5)	7.47 ± 0.37	4	0.18
4	PC/DME (50/50)	7.28 ± 0.11	2	0.027
5	BL/DME (50/50)	7.24 ± 0.08	2	0.027
6	AN/PC (90/10)	7.11 ± 0.25	4	0.18

TABLE 24
 1C26SX Cells With PC/DME (50/50) Electrolyte
 Abuse Test: Forced Discharge at 2.0A at -30°C

Fresh Cells

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
4	2.00 A.h	2.00 A.h	-3.6V	-1.9V	35°C	decline to 7°C
5	0	3.00	-2.5	open circuit	37	decline to ambient
111	0	2.14	-4.4	-1.6	48	decline to -3°C

Note: Cell 4 was restarted when power cut off.
 All three cells bulged and vented.

Cells Stored 34 Days at 72°C

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
116	1.78 A.h	1.83 A.h	-5.4V (A)	N.A.	92°C	N.A.
118	2.38	2.52	Steady decline	to -3.2	56	37 (B)
144	3.28	3.32	-3.0	vented, end of run	68	vented upon initial voltage excursion

Note: Cells 118 and 144 vented. (A) = after steady decline to -2.5V
 Cell 116 did not vent. (B) = before venting
 N.A. = not applicable

Cells Stored 91 Days at 55°C

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
123	2.29 A.h	2.29 A.h	< -7V	Cpen circuit	150°C	Decline to ambient
105	2.38	2.38	-5.8V	-4.0V	66	51°C
104	2.36	2.36	< -7	-3.8V	86	58

Note: All three cells severely bulged and vented.

TABLE 25
 LC26SX Cells With AN/PC (90/10) Electrolyte
 Abuse Test: Forced Discharge at 2.0A at -30°C

Fresh Cells

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
218	0 A.h	3.14 A.h	-5.1V	-4 to -2V	41°C	40 to 16°C
313	3.19	3.19	-4.0	-1.7	68	12
350	0	3.14	-5.9	-4 to -6V	73	54 to 68

Note: No cell vented.

Cells Stored 31 Days @ 72°C

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
228	6.03 A.h	6.03 A.h	<-7V	-6 to <-7V(E)	74°C	72°C
300	3.75	3.75	-3.2	-1.6	66	16
324	4.02	4.02	-4.7	-4.0	79	60

Note: No Cells Vented.

(E) = Erratic, poorly defined potential

Cells Stored 91 Days at 55°C

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
347	3.10 A.h	3.10 A.h	<-7V	-5.0 to -5.6V	128°C	102°C
309	2.66	2.66	<-7	-4.6	118	79
326	3.65	3.65	<-7	-4.2 to -5.6	63	54

Note: Cell 347 bulged and vented.

Cell 326 max. temp. occurred 2-1/2 hours after initial voltage excursion.

TABLE 26
 LC26SX Cells With AN Electrolyte. The Test Standard
 Abuse Test: Forced Discharge at 2.0A at -30°C

Fresh Cells

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
403	4.45 A.h	5.48 A.h	-5.8V	-3 to -5V(E)	61°C	60 to 33°C
455	3.92	4.51	-5.1	-4.8	63	62 to 50
540	0	6.40	-3.2	-3.6	43	30

Note: No cells Vented

(E) = erratic, poorly defined potential.

Cells Stored 31 Days at 72°C

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
435	3.50 A.h	3.50 A.h	<-7V	<-7V	42°C	declined to ambient
528	4.05	4.05	<-7V	-3.2	108	41°C
425	3.42	3.42	-3.4	-1.0	56	-3

Note: No cells vented.

Cell 528 lost about .3g during storage at 72°C

Cells Stored 91 Days at 55°C

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
434	3.72 A.h	3.72 A.h	-5.4V	-2.6 to -3.2V	80°C	39°C
486	4.11	4.11	<-7V	-3 to <-7V	111	63
506	4.05	4.05	<-7V	3.0	127	37

Note: Cell 486 bulged and vented.

TABLE 27

LO26SX Cells With AN/AA (90/10) Electrolyte.

Abuse Test: Forced Discharge at 2.0A at -30°C

Fresh Cells

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
629	5.14 A.h	5.14 A.h	-6.7	-3 to -5V(E)	97°C	80°C
604	5.78	5.78	-3.2	-0.8	78	decline to -3°C
610	5.50	5.50	<-7.0	-6.8	84	65°C

Note: No cells vented

(E) = erratic, poorly defined potential

Cells Stored 34 Days @ 72°C

Cell No.	Capacity to 2.0V	Capacity Inflection	Weight Lost When Tested
620	0 A.h	0.78 A.h	18.4g
609	0	0	21.5
614	0	0.30	22.7

Note: These cells had vented during storage. Cells no good.

Cells Stored 91 Days @ 55°C: Leaked during storage.

TABLE 28
 LC2FSX Cells With AN/BI/DME (85/10/5) Electrolyte.
 Abuse Test: Forced Discharge at 2.0A at -30°C

Fresh Cells

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
891	5.92 A.h	5.92 A.h	<-7V	-6.1 V (E)	91°C	decline to 83°C
952	3.94	3.94	-3.7	Discontinuity	65	decline to ambient
887	6.11	6.11	<-7	<-7V	58	25°C

Note: No cells vented.

(E) = erratic, poorly defined potential.

Cells Stored 31 Days at 72°C

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
935	3.38 A.h	3.39 A.h	<-7V	<-7V	62°C	declined to ambient
816	2.99	2.99	<-7	<-7	67	"
907	3.17	3.17	-4.0	-4.1	73	51°C

Note: 935 did not vent

816 vented

907 bulged and vented

Cells Stored 91 Days at 55°C

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
840	3.24 A.h	3.24 A.h	-2.2V	-2.2V	45°C	25°C
855	3.37	3.37	<-7	-4.2 to -5.4	95	80
876	3.50	3.05	-4.4	-1.2	54	5

Note: Cells 840 and 876 bulged and vented

Cell 855 no vent.

TABLE 29

LO26SX Cells With BL/DME (50/50) Electrolyte.

Abuse Test: Forced Discharge at 2.0A at -30°C

Fresh Cells

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
1038	3.67 A.h	3.67 A.h	-2.3V	-0.2V	52°C	-25°C
1102	4.23	4.23	-3.0	Discontinuity	87	declined to ambient
1080	3.90	3.90	-5.0	-1.6V	97	13°C

Note: Cells 1038 and 1102 vented.
Cell 1080 did not vent

Cells Stored 31 Days at 72°C

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
1017	1.95 A.h	1.95 A.h	-5.4V	-5.7	119°C	99°C
1159	1.77	1.77	< -7	-2.1	61	20
1150	1.73	1.73	< -7	< -7	>150	declined to ambient

Note: All three cells bulged severely and vented.

Cells Stored 91 Days at 55°C

Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
1088	1.80 A.h	1.80 A.h	< -7V	< -7V	63°C	decline to ambient
1059	2.10	2.10	< -7	< -7	53	decline to ambient
1114	2.03	2.03	< -7	< -7	Est. >200	decline to ambient

Note: All three cells severely bulged and vented.
Cell 1114: evidence of fire.

TABLE 30A

LO26SX Cells With Copper Foil Anode Current Collectors. AN Electrolyte.

Abuse Test: Forced Discharge at 2.0A at -30°C

Fresh Cells

Li on Cu Cell No.	Capacity to 2.0V	Capacity Inflection	Initial Voltage Excursion	Continuing Voltage	Maximum Wall Temp.	Continuing Wall Temp.
1	0.0 A.h	6.00 A.h	-1.0V	-1.0V	23°C	-21°C
3	3.60	4.80	-1.5	-1.1	30	-20
4	3.72	4.50	-4.2	-1.6	36	- 2
6	0.0	3.72	-6.3	-2.5	62	27

Note: no cells vented.

TABLE 30B

Results and Selected Data for LO26SX Cells WithLi on Cu Foil Anodes and AN Electrolyte.

Li/Cu Cell No.	1	3	4	6
Anode Thickness	9-mils	9-mils	6-mils	6-mils
Li Capacity	10.0 A.h	10.0 A.h	7.0 A.h	~6.5 A.h
Electrolyte Volume	29.0 ml	29.3 ml	30.8 ml	30.8 ml
SO ₂ Capacity	11.0 A.h	11.1 A.h	11.6 A.h	11.6 A.h
Realized Capacity*	6.0 A.h	4.8 A.h	4.5 A.h	3.7 A.h
Utilization vs. Li **	60%	48%	64%	57%

* Realized capacity at 2.0A, -30°C, to inflection point

** Cells 1 and 4 had sharp voltage drops and more characteristic utilizations.

TABLE 31

VOLTAGE DELAY CHARACTERISTICS AT 3.0A AT -30°C

Table Shows Time to Recover to 2V, and Lowest Voltage at Startup

<u>Electrolyte Type</u>	<u>RT Stored 4-6 Months</u>		<u>55°C Stored 3 Months</u>	
	<u>Delay Time</u>	<u>Minimum Volts</u>	<u>Delay Time</u>	<u>Minimum Volts</u>
AN (Standard)	64 sec	0.3V	35 sec.	1.5V
AN/PC (90/10)	90	0.6	44	1.3
AN/AA (90/10)	8	1.9	no test cells	
AN/BL/DME (85/10/5)	12	1.9	7	1.9
PC/DME (50/50)	127	< - .6 *	no test cells	
BL/DME (50/50)	153	< -1.1 *	121	-3.1

* Note: Due to excessive cell impedance, power supply delivered less than three amps for several seconds.

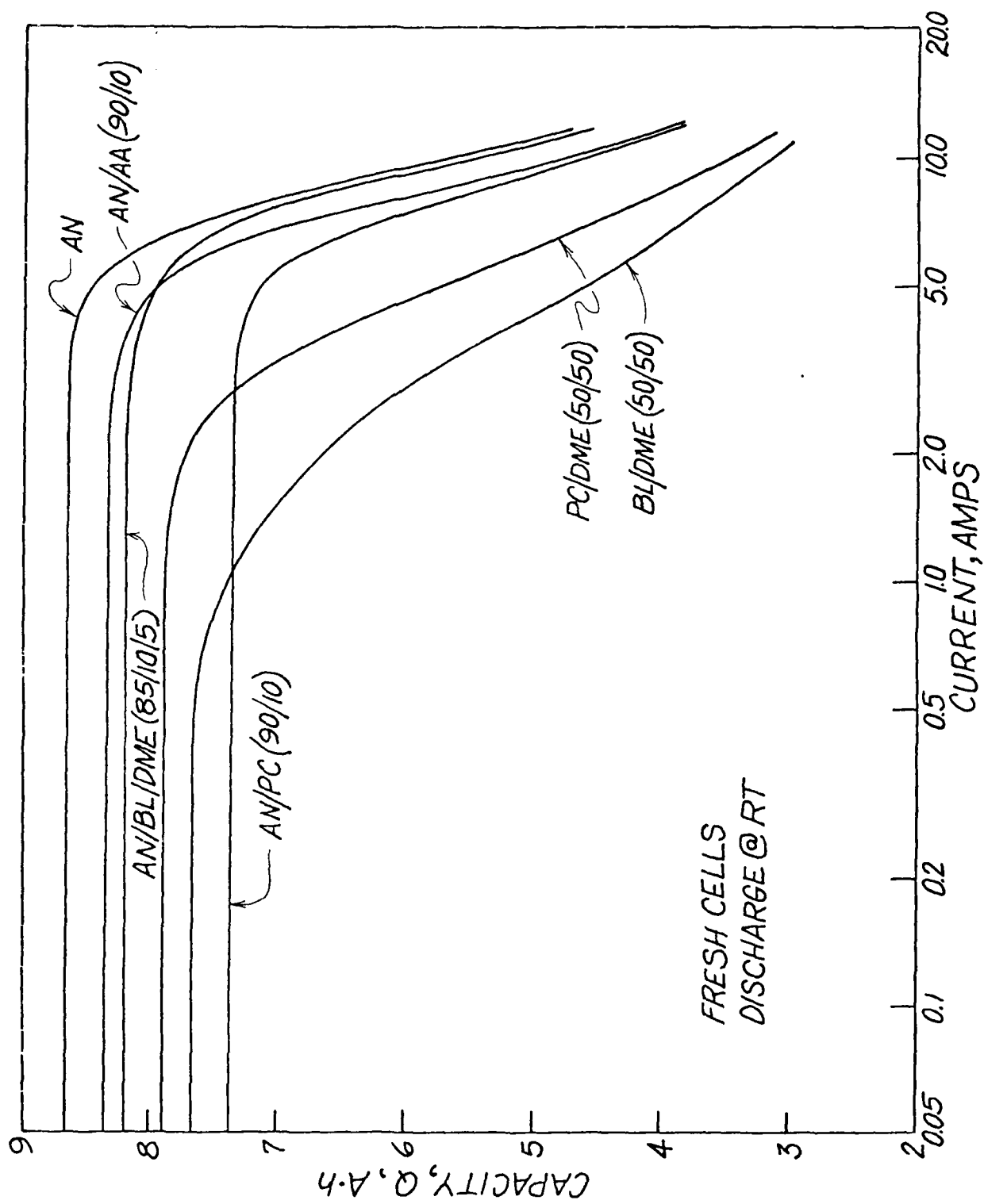


Figure 1. Capacity-Rate Curves of LO26SX Cells. Fresh Cells Discharged at Room Temperature.

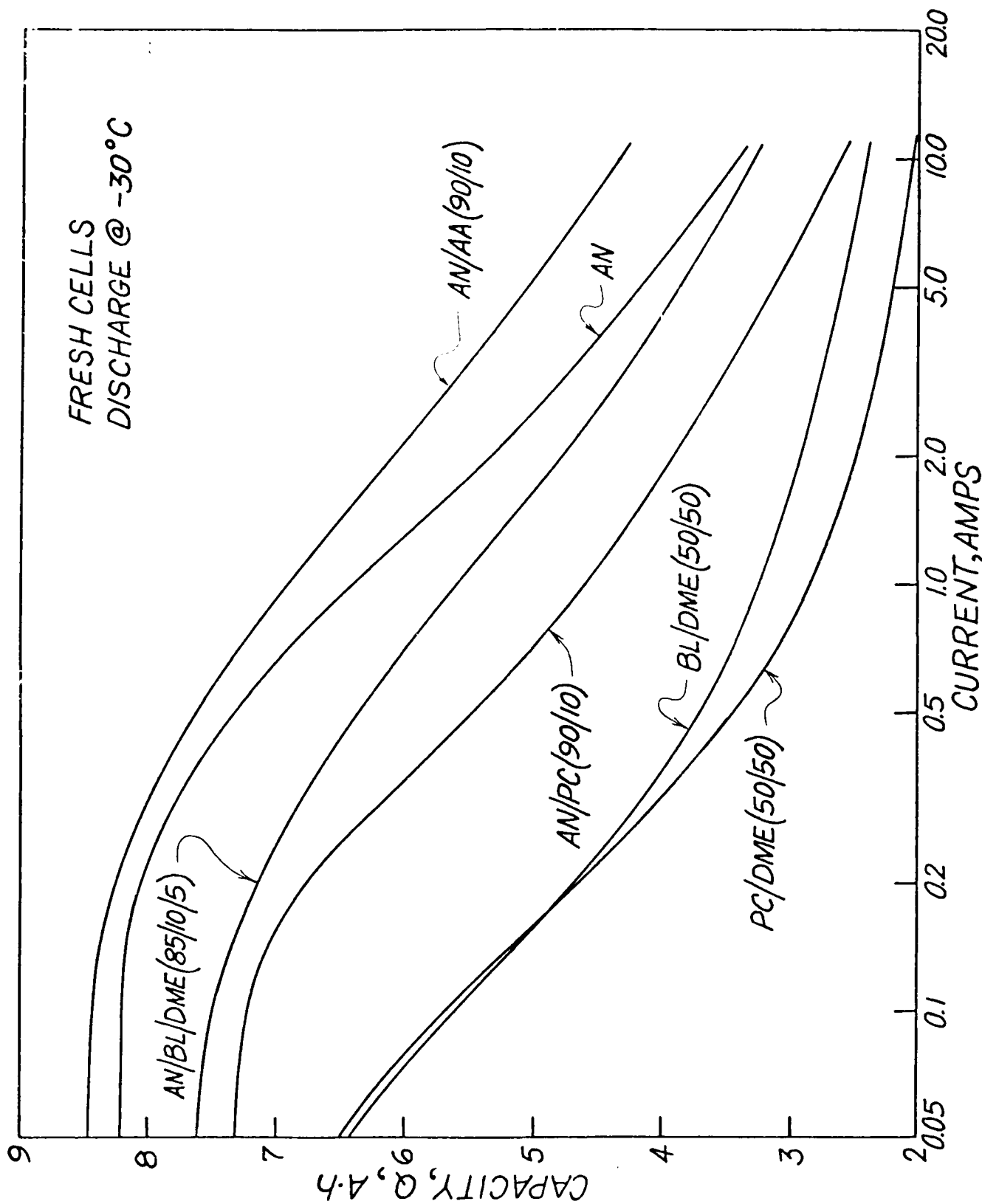


Figure 2. Capacity-Rate Curves of IO26SX Cells. Fresh Cells Discharged at -30°C .

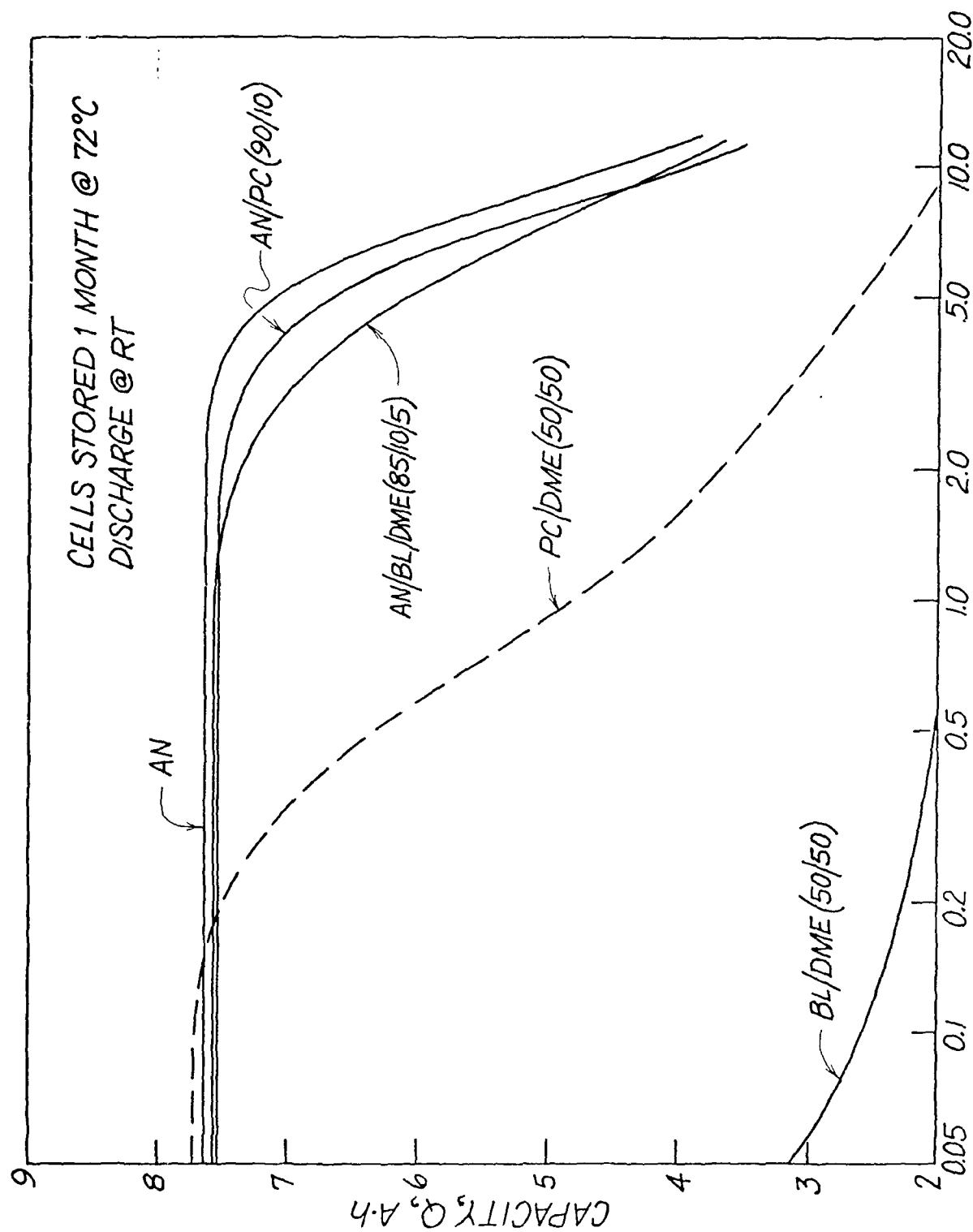


Figure 3. Capacity-Rate Curves of LC 268X Cells. Cells Stored 1 Month at 72°C, Discharged at Room Temperature.

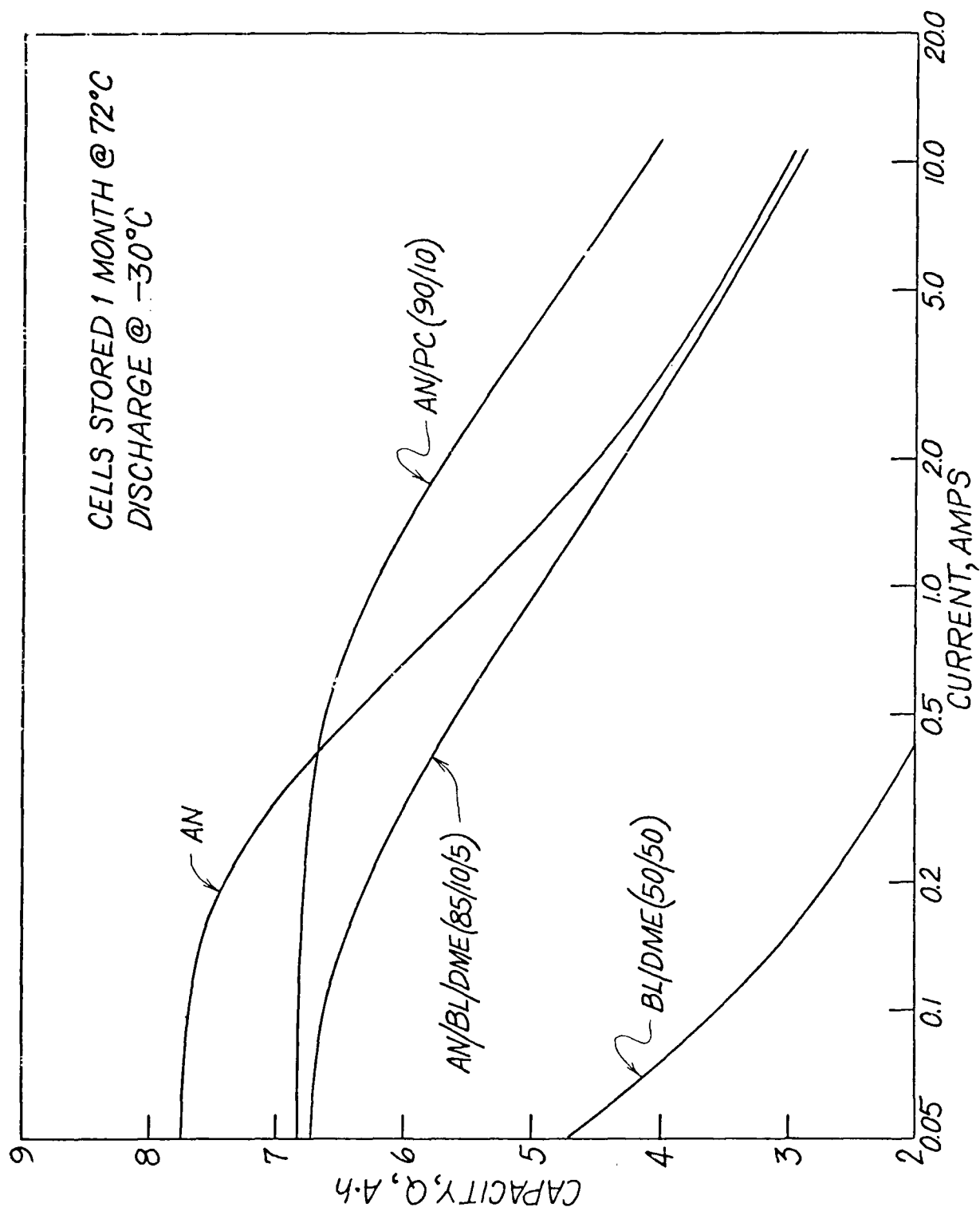


Figure 4. Capacity-Rate Curves of LG26SX Cells. Cells Stored 1 Month at 72°C, Discharged at -30°C.

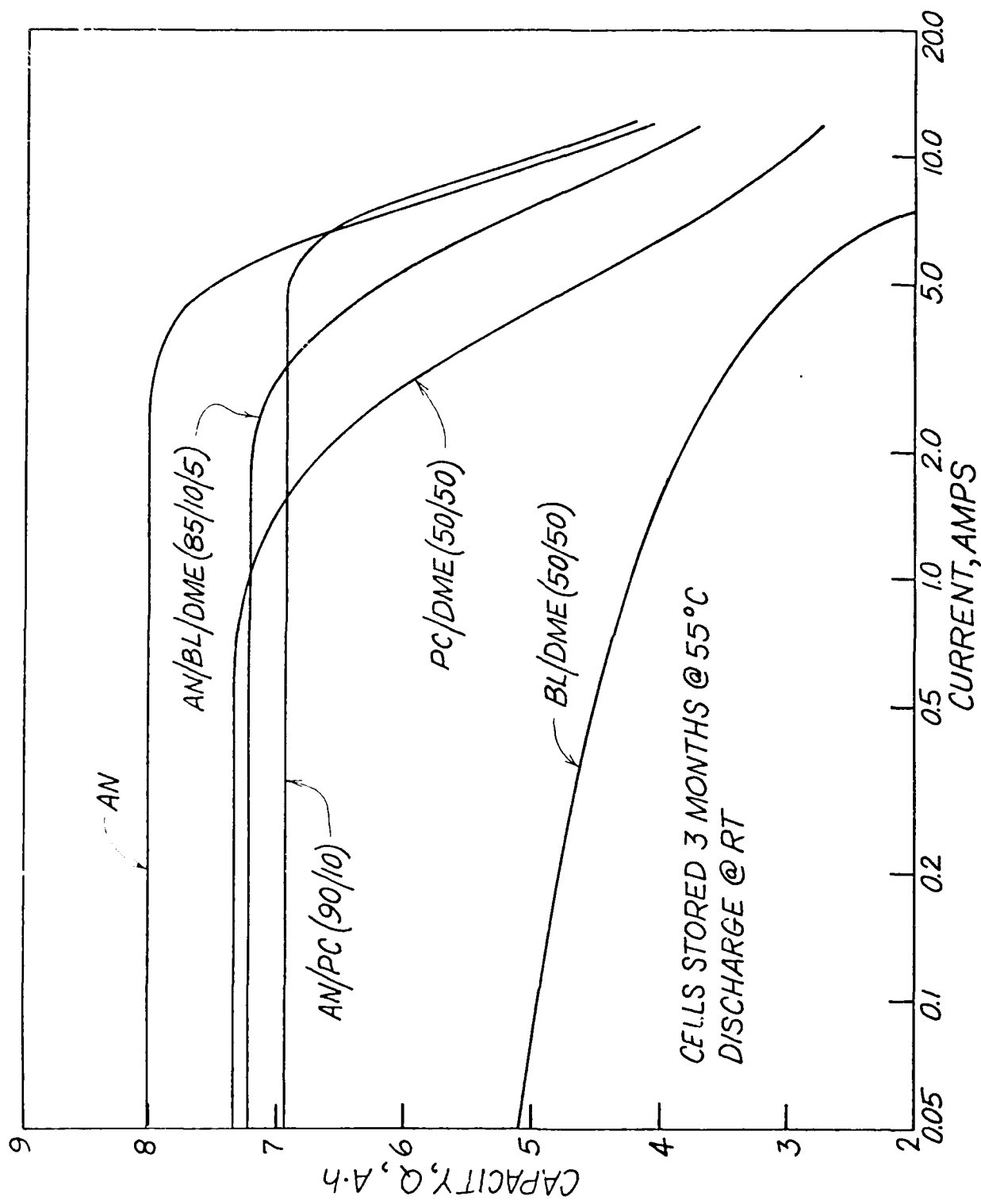


Figure 5. Capacity-Rate Curves of LO26SX Cells Stored 3 Months at 55°C, Discharged at Room Temperature.

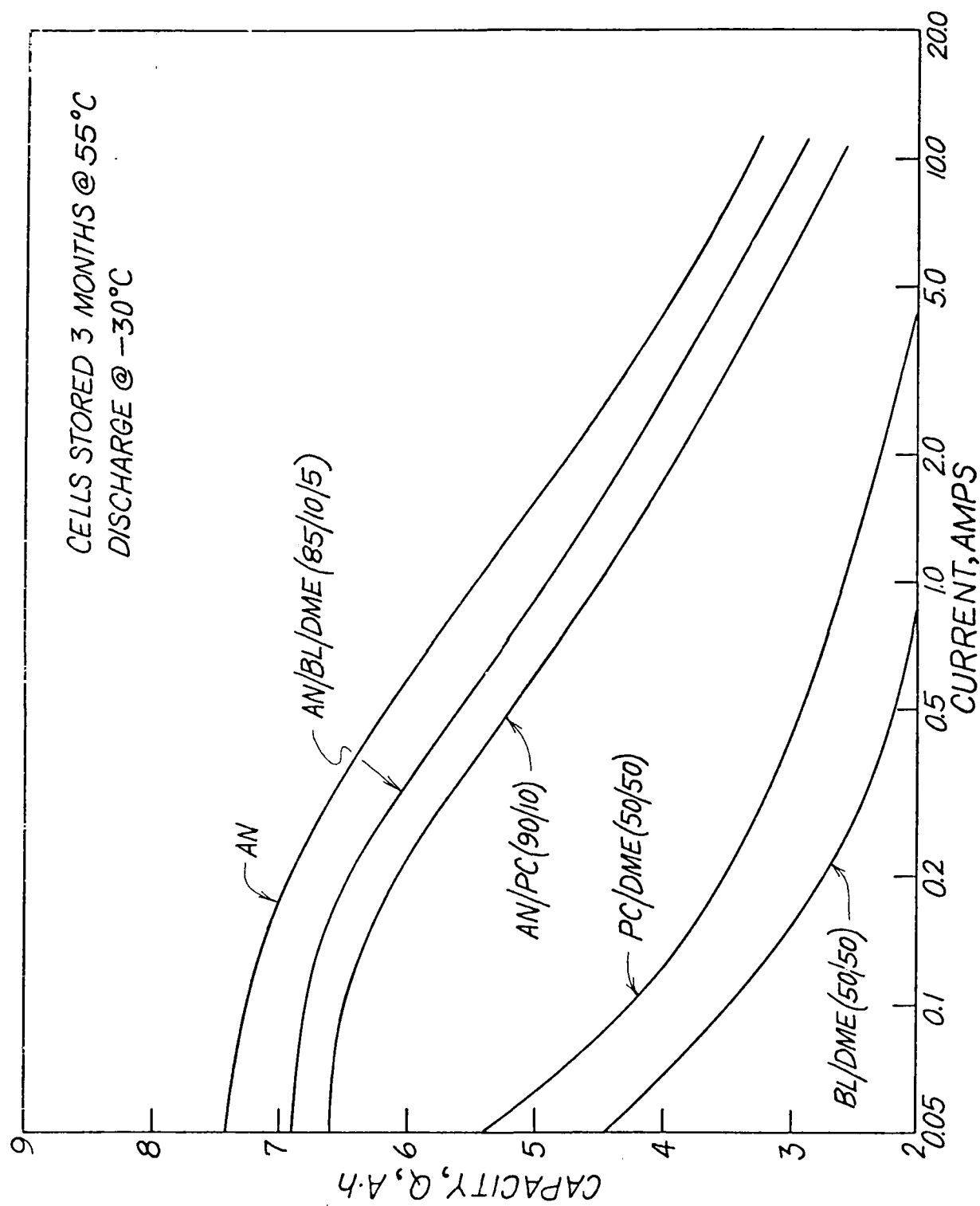


Figure 6. Capacity-Rate Curves of LO26SX Cells Stored 3 Months at 55°C, Discharged at -30°C.

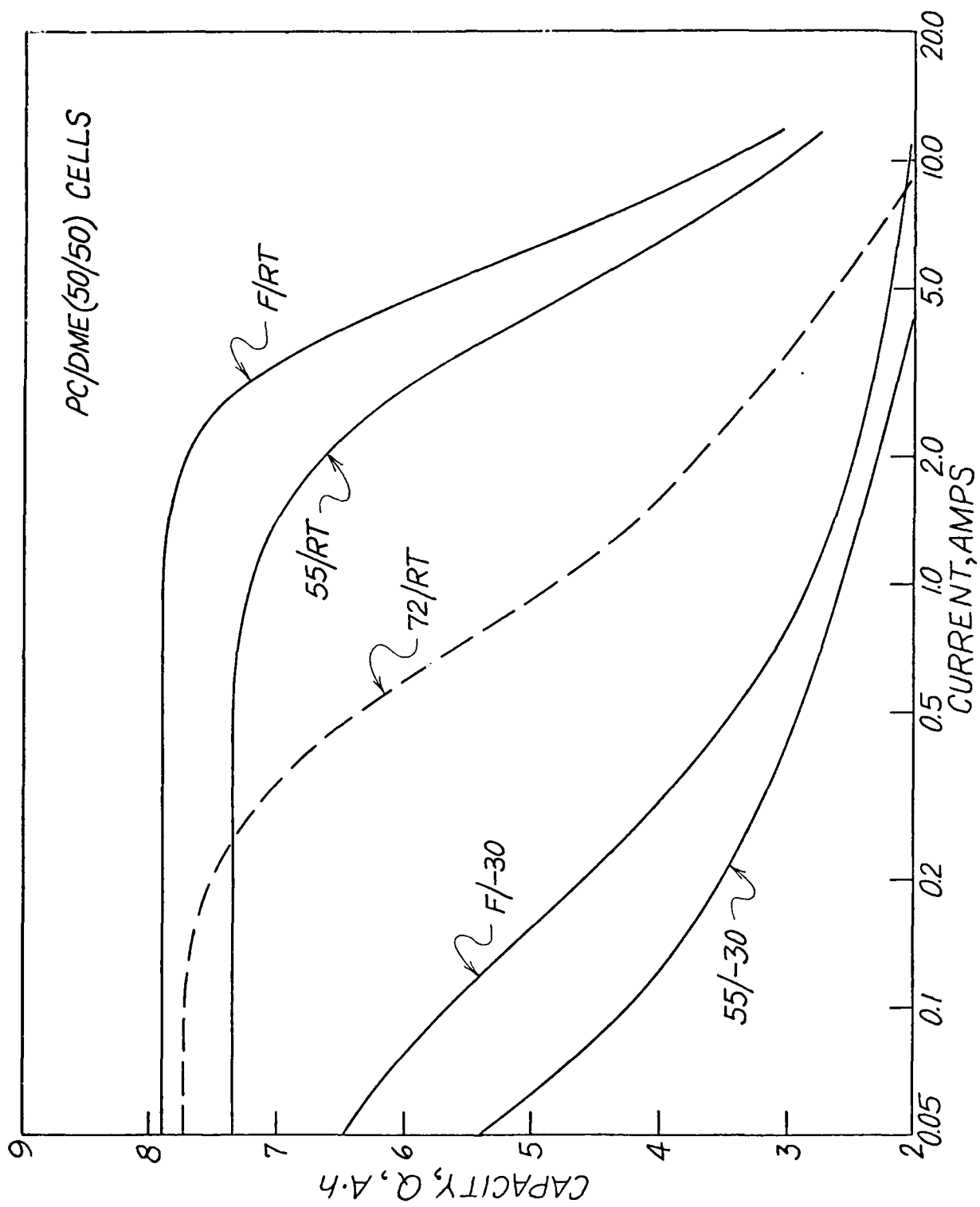


Figure 7. Capacity-Rate Curves of IO26SX Cells with PC/DME (50/50) Electrolyte.

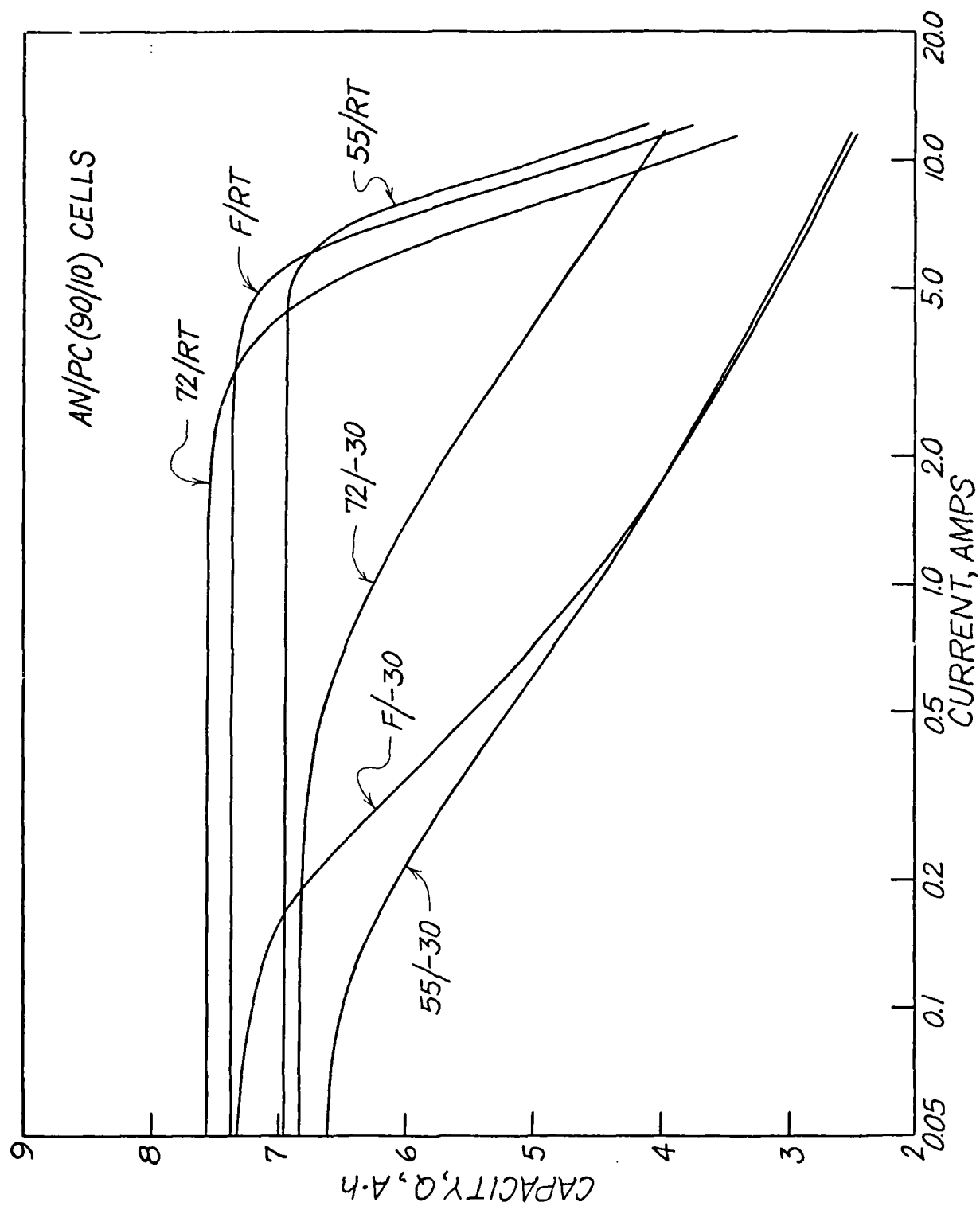


Figure 8. Capacity-Rate Curves of LO26SX Cells with AN/PC (90/10) Electrolyte.

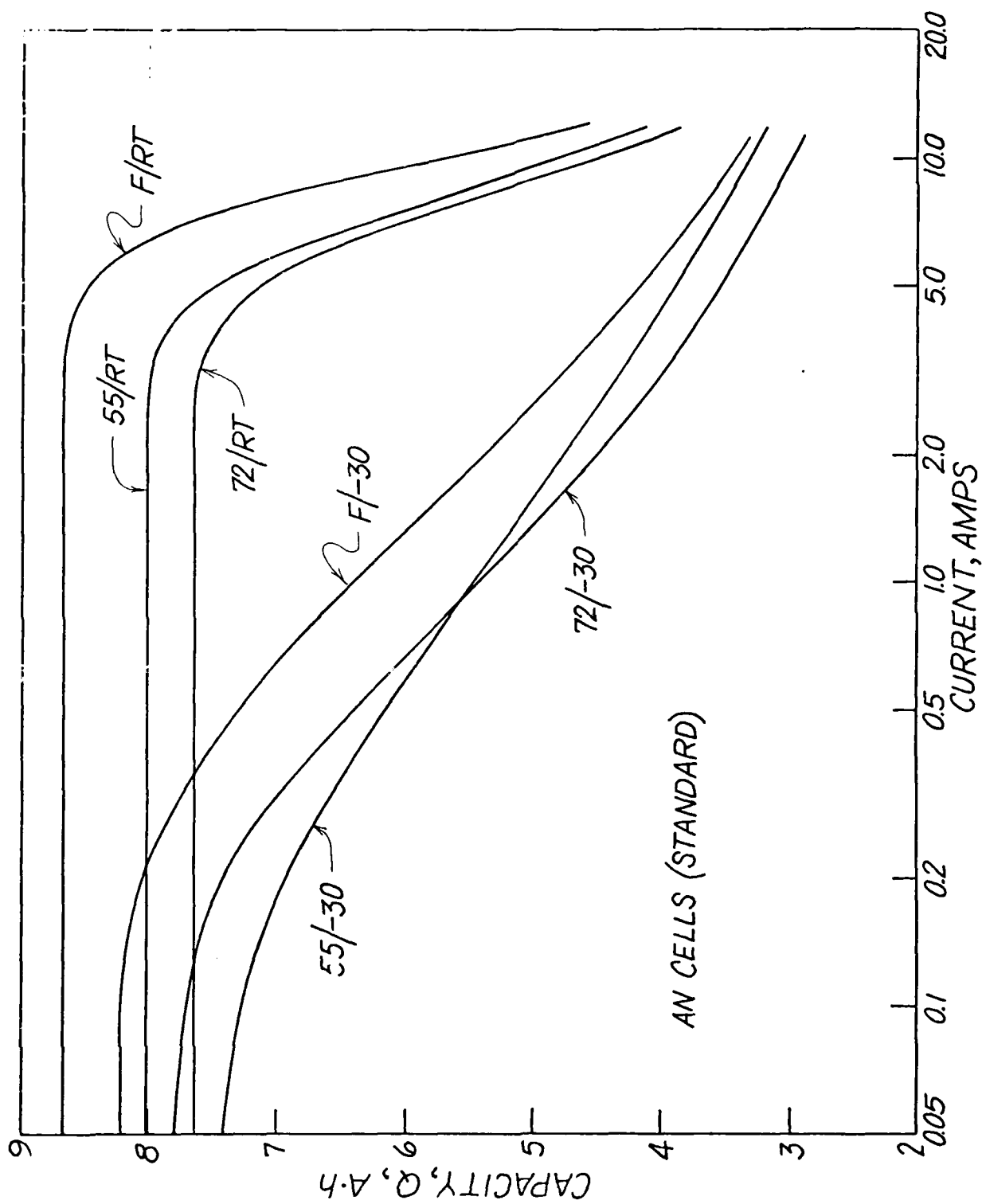


Figure 9. Capacity-Rate Curves of LO26SX Cells with AN Electrolyte.

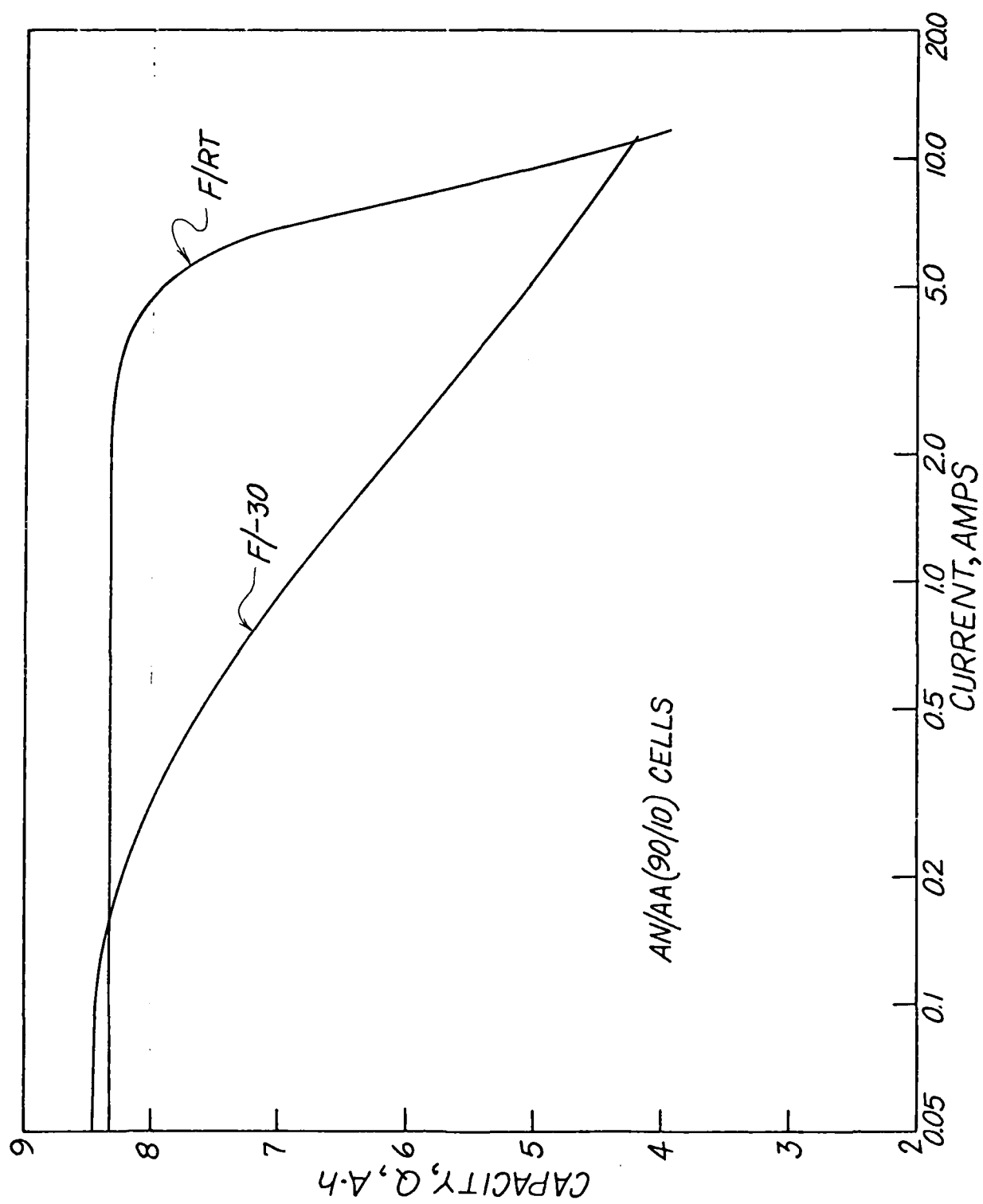


Figure 10. Capacity-Rate Curves of LO26SX Cells with AN/AA (90/10) Electrolyte.

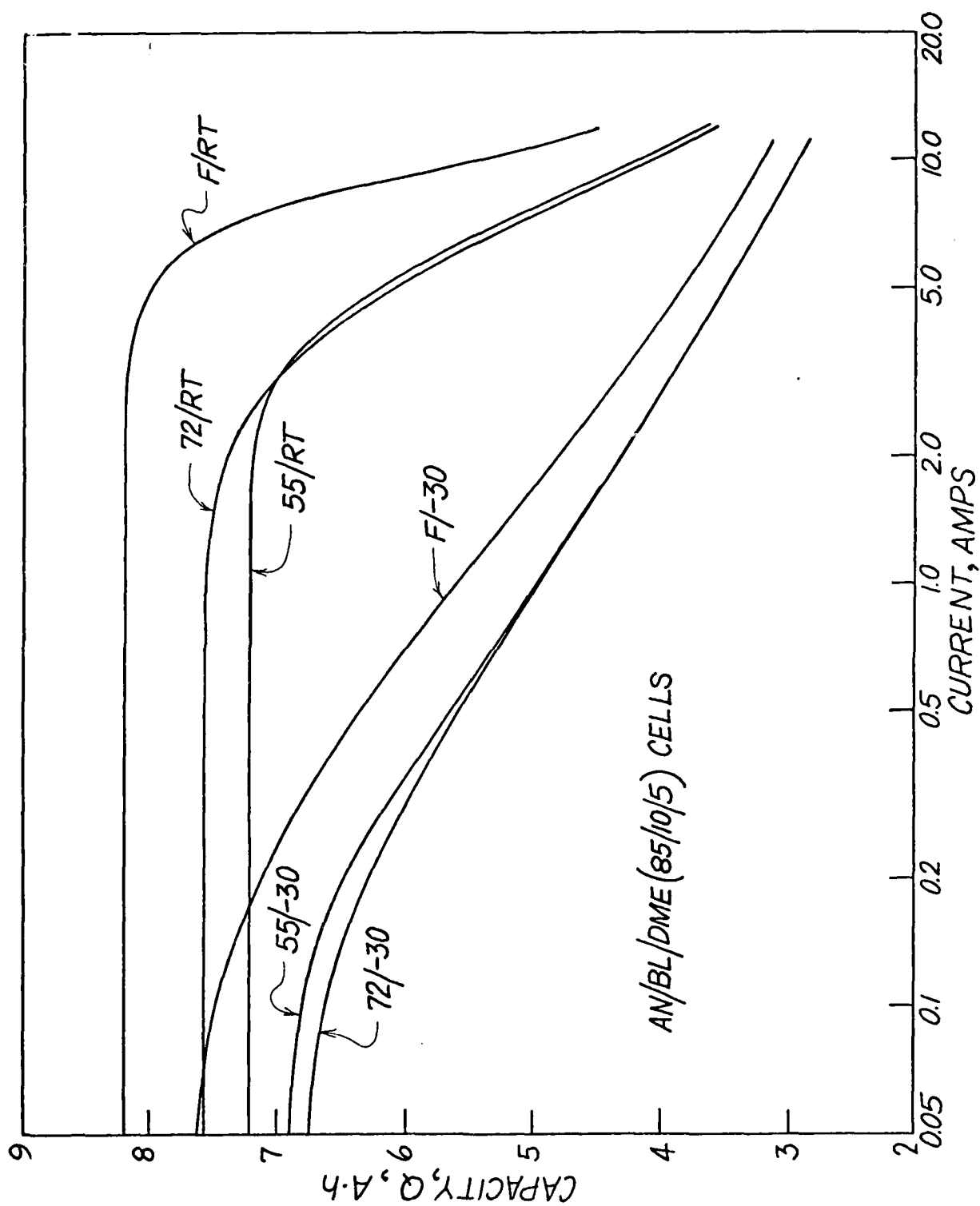


Figure 11. Capacity-Rate Curves of IG26SX Cells with AN/BL/DME (85/10/5) Electrolyte.

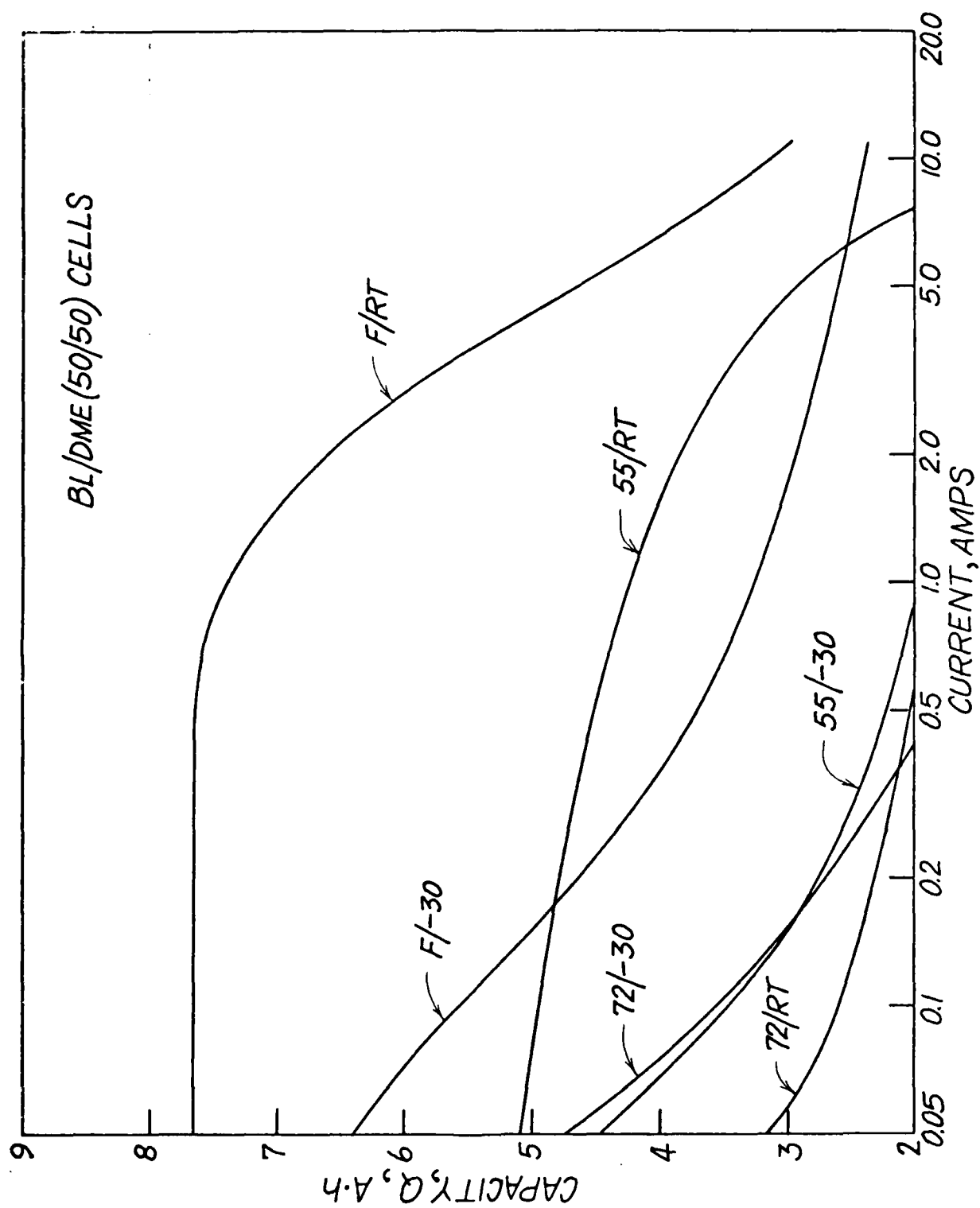


Figure 12. Capacity-Rate Curves of LO26SX Cells with BL/DME (50/50) Electrolyte.

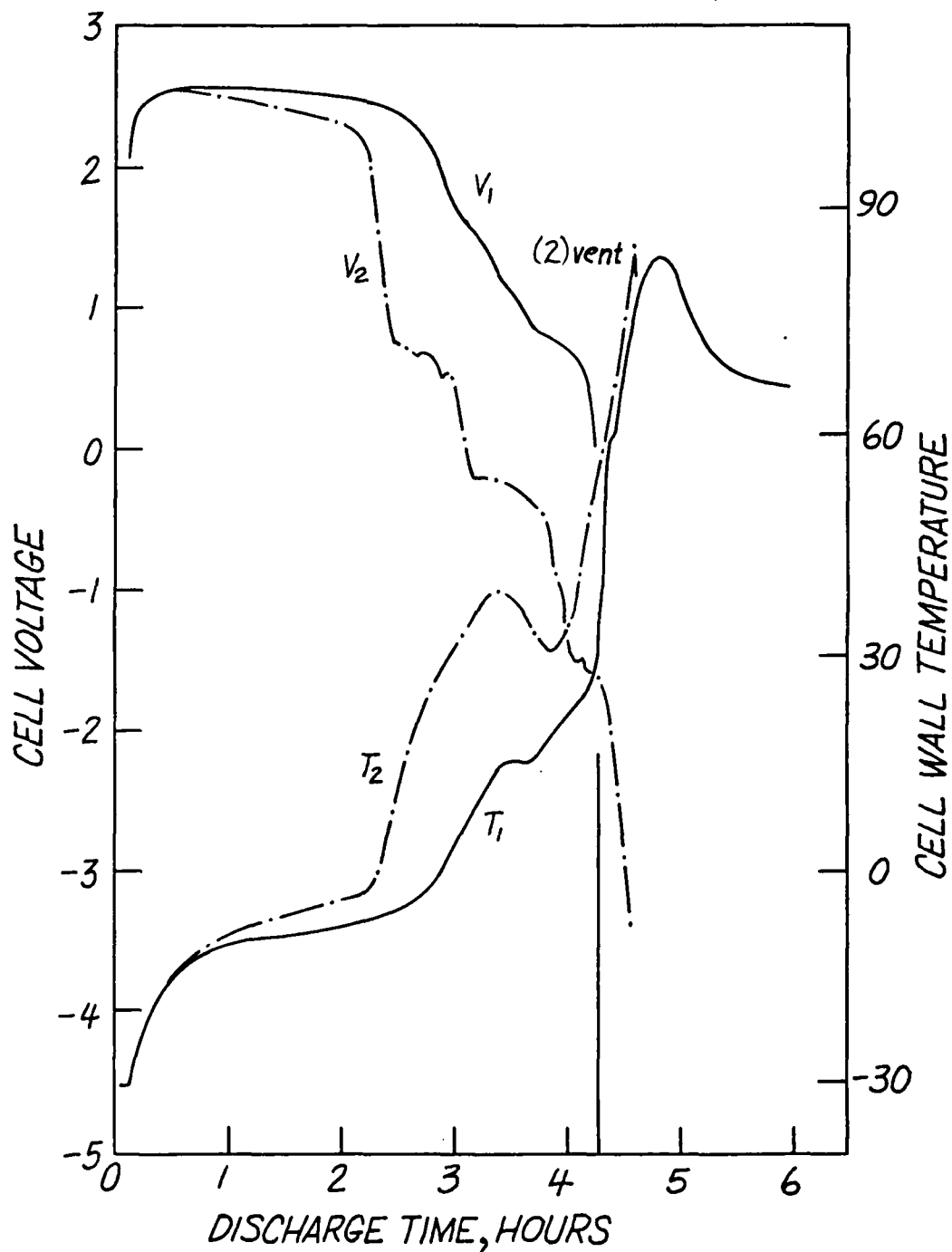


Figure 13. Voltage and Temperature Profiles for LO26SX Cells Force-Discharge at 2.0A at -30°C . Fresh Cells.

- (1): Cell 610, AN/AA (90/10) Electrolyte.
- (2) Cell 1102, BL/DME (50/50) Electrolyte.

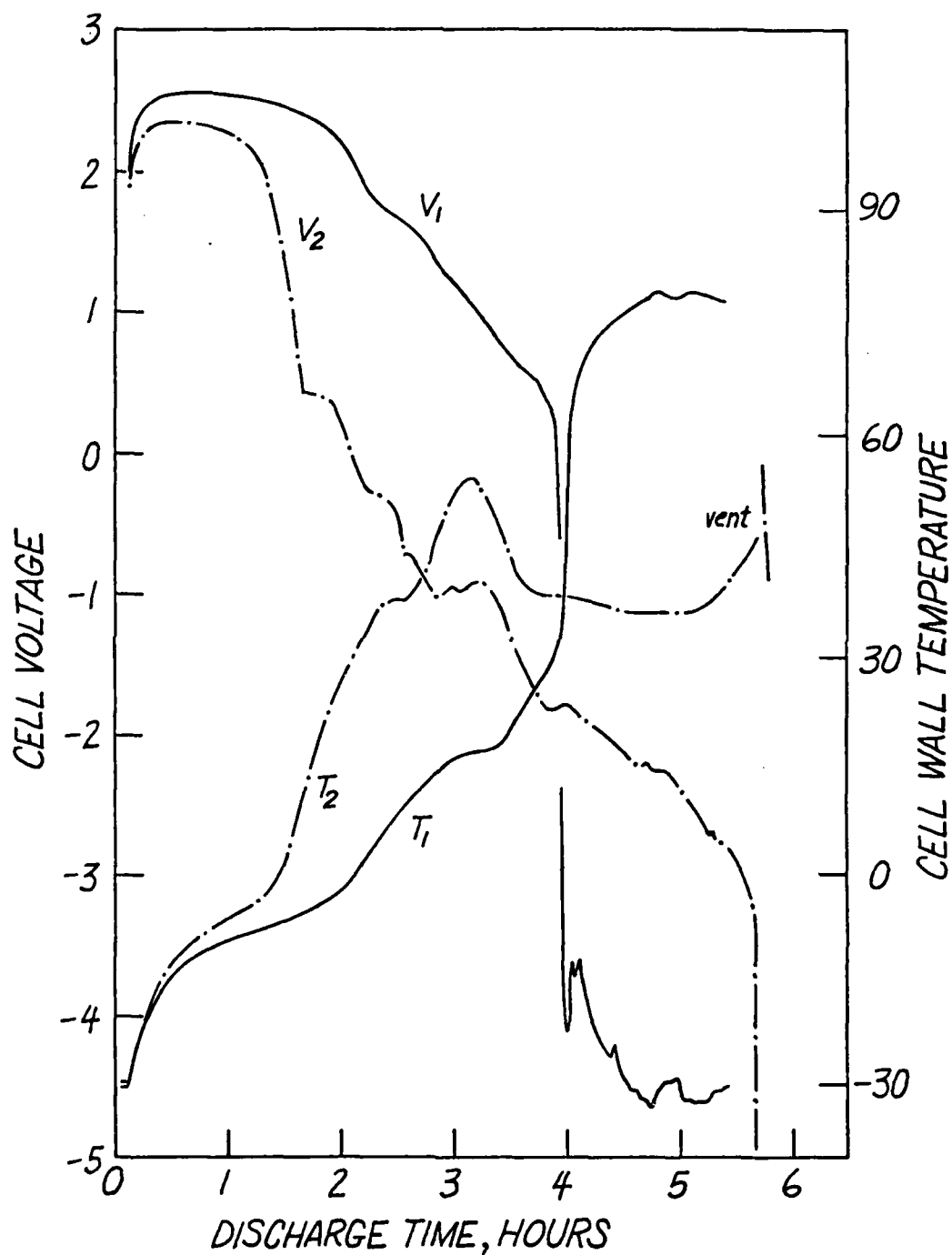


Figure 14. Voltage and Temperature Profiles for LO26SX Cells Forced-Discharged at 2.0A at -30°C . Cells Stored 1 Month at 72°C .

(1): Cell 324, AN Electrolyte.

(2): Cell 118, PC/DME (50/50) Electrolyte.

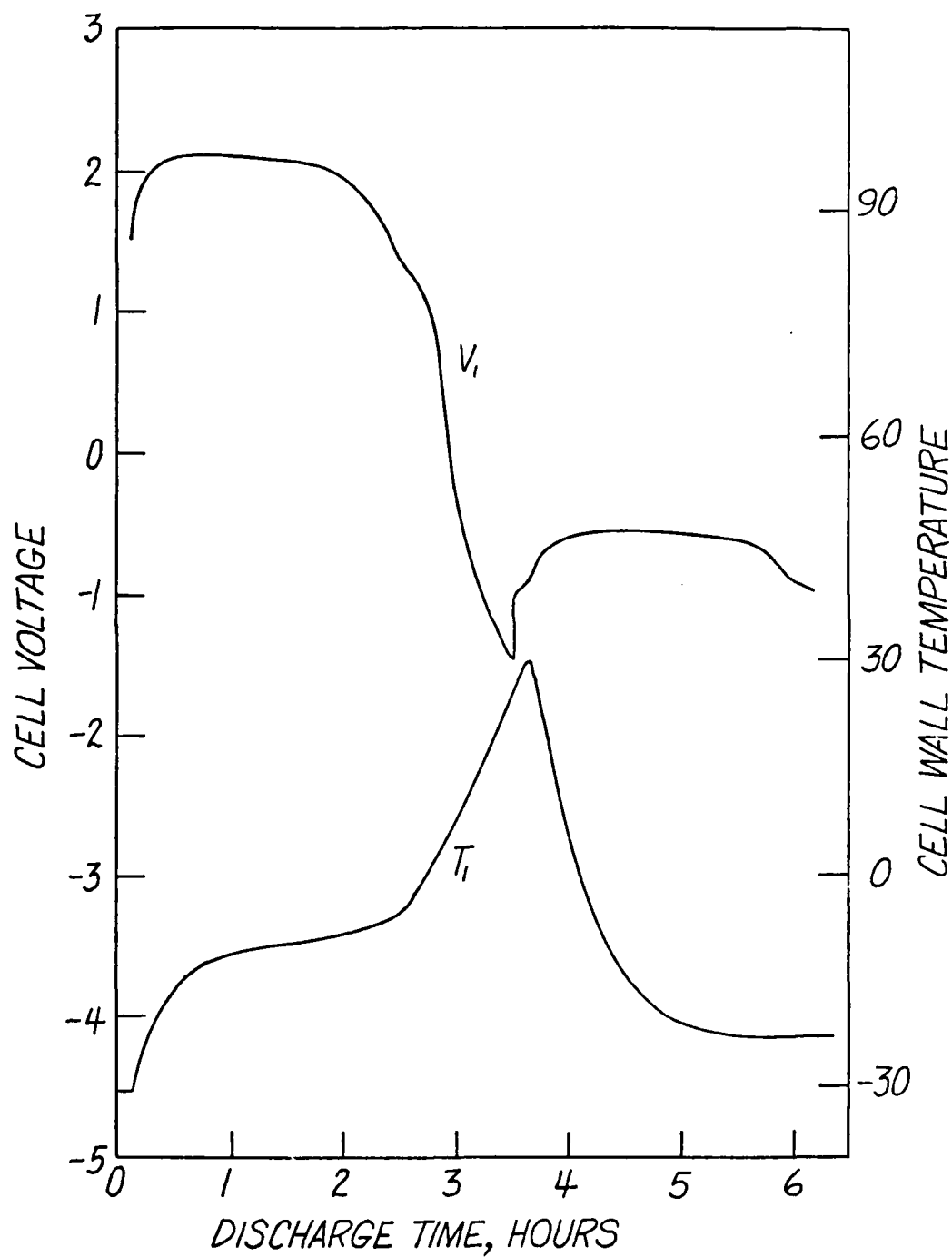


Figure 15. Voltage and Temperature Profile for LO26SX with Copper Foil Anode Substrate, Force-Discharged at 2.0A at -30°C . Fresh Cell No. Li/Cu 3. AN Electrolyte.

13 November 1979

ELECTRONICS TECHNOLOGY AND DEVICES LABORATORY

MANDATORY CONTRACT DISTRIBUTION LIST

101	Defense Technical Information Center ATTN: DTIC-TCA Cameron Station (Bldg. 5)	579	Cdr, PM Concept Analysis Centers ATTN: DRCPM-CAC Arlington Hall Station
012	Alexandria, VA 22314	001	Arlington, VA 22212
203	GIDEP Engineering & Support Dept TE Section PO Box 398	602	Cdr, Night Vision & Electro-Optics ERADCOM ATTN: DELNV-D
001	NORCO, CA 91760	001	Fort Belvoir, VA 22060
205	Director Naval Research Laboratory ATTN: CODE 2627	603	Cdr, Atmospheric Sciences Lab ERADCOM ATTN: DELAS-SY-S
001	Washington, DC 20375	001	White Sands Missile Range, NM 88002
301	Rome Air Development Center ATTN: Documents Library (TILD)	607	Cdr, Harry Diamond Laboratories ATTN: DELHD-CO, TD (In Turn)
001	Griffiss AFB, NY 13441	001	2800 Powder Mill Road Adelphi, MD 20783
437	Deputy for Science & Technology Office, Asst Sec Army (R&D)	609	Cdr, ERADCOM ATTN: DRDEL-CG, CD, CS (In Turn)
001	Washington, DC 20310	001	2800 Powder Mill Road Adelphi, MD 20783
438	HQDA (DAMA-ARZ-D/Dr. F. D. Verderame)	612	Cdr, ERADCOM ATTN: DRDEL-CT
001	Washington, DC 20310	001	2800 Powder Mill Road Adelphi, MD 20783
482	Director US Army Materiel Systems Analysis Actv ATTN: DRXSY-T	680	Commander US Army Electronics R&D Command
001	Aberdeen Proving Ground, MD 21005	000	Fort Monmouth, NJ 07703
563	Commander, DARCOM ATTN: DRCDE	1	DELEW-D
001	5001 Eisenhower Avenue Alexandria, VA 22333	1	DELET-DD
564	Cdr, US Army Signals Warfare Lab ATTN: DELSW-OS	1	DELS-D-L (Tech Library)
001	Vint Hill Farms Station Warrenton, VA 22186	2	DELS-D-L-S (STINFO)
		35	DELET-PB (Mr. DiMasi)
		681	Commander US Army Communications R&D Command ATTN: USMC-LNO
		001	Fort Monmouth, NJ 07703
		705	Advisory Group on Electron Devices 201 Varick Street, 9th Floor
		002	New York, NY 10014

DISTRIBUTION LIST (continued)

Union Carbide Corporation (1)
ATTN: Mr. R. Powers
12900 Snow Road
Parma, OH 44130

Honeywell, Inc. (1)
ATTN: Mr. T. Bierman
104 Rock Road
Horsham, Pa 19044

ESB, Inc. (1)
Ray-O-Vac Division
ATTN: Mr. P. Albert
212 East Washington Avenue
Madison, WI 53703

Eagle-Picher Industries, Inc. (1)
Electronics Division
Couples Department
P. O. Box 47
Joplin, MO 64801

Power Conversion, Inc. (1)
ATTN: Mr. B. Jagid
70 MacQuesten Parkway South
Mount Vernon, NY 10550

GTE Sylvania (1)
520 Winter Street
Waltham, MA 02154
ATTN: Dr. Ronald McDonald

**DAT
FILM**