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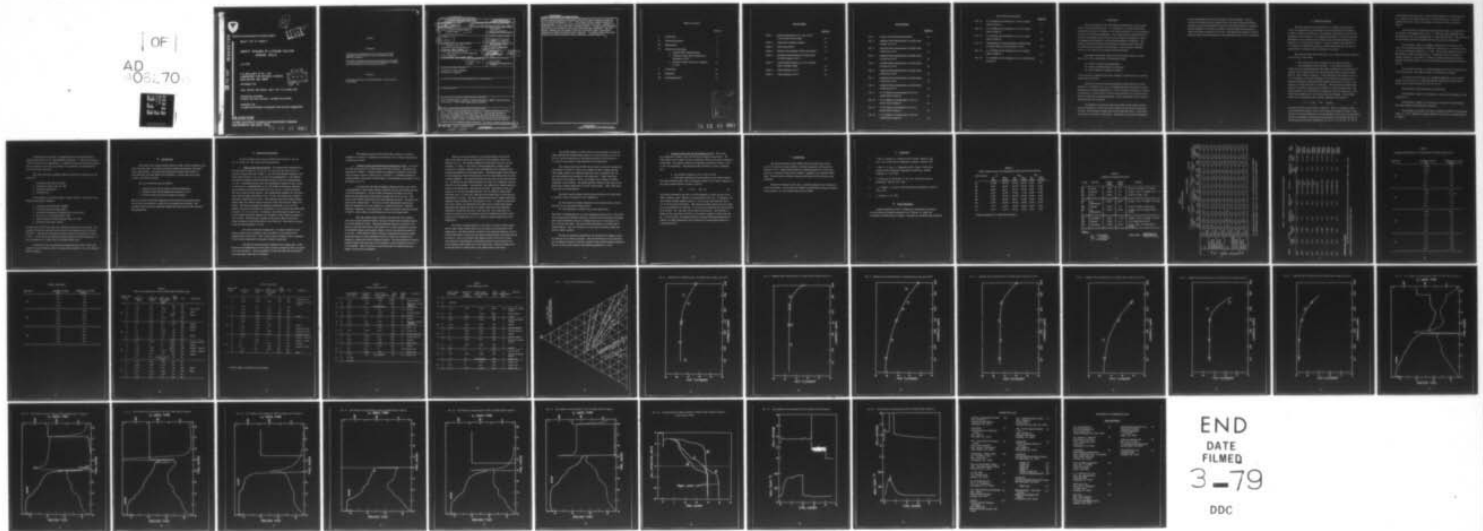
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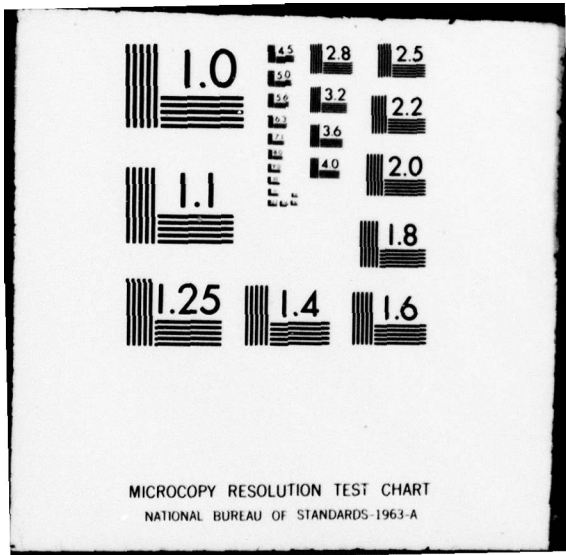
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Research and Development Technical Report

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SAFETY STUDIES OF LITHIUM - SULFUR  
DIOXIDE CELLS

A. N. DEY

P. R. MALLORY & CO., INC.  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The objective of this program was to improve the abuse resistance of Li/SO <sub>2</sub> cells. LO26S cells were chosen for the study. We studied the effect of cell design variables such as Li:SO <sub>2</sub> ratio, electrode configuration and electrolyte compositions on the abuse resistance as well as the performance of the LO26S cells in order to establish the trade-offs between the cell performance and the increased abuse resistance. We found several cell designs		

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which improved the abuse resistance of the LO26S cells for abuses consisting of a 2A forced discharge at  $-30^{\circ}\text{C}$ . This design entails a capacity penalty of approximately 3 A.Hr at low rates over the standard LO26S cells. However, at high rates (2A or more) there was no capacity penalty. Several design principles contributing to the safety of the Li/SO<sub>2</sub> cells have been identified. The cell design variables did not appear to have any significant effect on the abuse resistance of cells for abuses such as charging. In general LO26S cells of all designs were abuse resistant towards charging at currents below 2A.



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## I. Introduction

The Li/SO<sub>2</sub> battery is the most highly developed high energy density battery system obtainable today. It is available in a growing volume from several manufacturers in response to the rising demand for its use in industrial, consumer, and military applications. The rising demand is motivated by the need for a lightweight power source that has a high rate capability, a good low temperature performance, and good high temperature storability. The Li/SO<sub>2</sub> system has all these characteristics to a greater extent than does any other battery system and for this reason, it has acquired a dominant position in the emerging new primary battery technology.

Improvements have been made (1-4) and are being made at a rapid pace in the Li/SO<sub>2</sub> technology in the following areas:

- (a) Efficient manufacturing technology
- (b) Product reliability (hermetic structures)
- (c) Abuse tolerance (ventable structures)

In this program we addressed the abuse tolerance of state-of-the-art spirally-wound high rate Dcells.

Although the state-of-the-art hermetically sealed high rate D cells made by P. R. Mallory & Co. Inc. are sufficiently abuse resistant for various commercial and military applications, it was the object of this effort to explore the feasibility of improving the intrinsic abuse resistance of the system even further by chemical or mechanical means, so that the product may be rendered safe under all user conditions.

The approach involved the study of the effect of the various cell construction parameters such as the relative amounts of the active material (Li, SO<sub>2</sub> AN), the electrolyte compositions and the electrode areas, on the abuse resistance of the LO26 (D size) cells. The details of the technical approach,

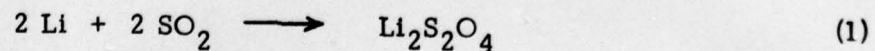
and the experimental results are described in this final report. We are carrying out detailed thermochemical studies using DTA (differential thermal analysis) of the various chemicals present in the Li/SO<sub>2</sub> system in a separate program (DAAB07-77-C-0472) in an effort to develop chemical approaches to improve the abuse resistance of the cells. The results are reported in monthly progress reports and are supportive of the approaches taken under this program.

## II. Technical Approach

The main objective of this program is to establish the dependence of the cell performance and cell safety on the cell composition and design; so that an optimum cell design can be developed with respect to both the cell performance and the safety. The underlying assumption is that the electrical performance can be traded for an increased abuse resistance (safety) and our objective is to optimize this tradeoff. In order to achieve this objective, it is necessary to identify the design and compositional elements that may be responsible for inadequate abuse resistance of the cells.

The design features which were shown (5) to affect the abuse resistance of the Li/SO<sub>2</sub> D cells were:

1. The Li/SO<sub>2</sub> ratio at the completion of the normal discharge.
2. The performance limiting process. It was shown (5) that low Li/SO<sub>2</sub> ratio and the polarization of the carbon cathode due to passivation (as opposed to SO<sub>2</sub> exhaustion) as the limiting process were the desired design features, from a safety standpoint. It was speculated that exhaustion of SO<sub>2</sub> at the completion of the cell discharge is most deleterious because of the possible exothermic chemical reaction between the excess Li and AN, in the absence of a protective film on Li from SO<sub>2</sub>. Thus the active materials most relevant to the abuse resistance of a cell are Li, SO<sub>2</sub> and acetonitrile. The relative safety of the cell will then be dependent upon the composition of the above three components at the various stages of discharge. The discharge results in the consumption of Li and SO<sub>2</sub> according to the reaction



whereas the amount of AN remains unchanged. Thus it is possible to draw cell discharge trajectories using a three component diagram as shown in Fig. 1, knowing the initial composition of a cell irrespective of the size and the design. We have specifically analyzed the data pertaining to the unbalanced cells of LO25S size and the design specified as 5A, 5B, 5C, 6A, 6B, 6C, 7A, 7B, 7C

in the monthly letter report #11, of the Contract DAAB07-76-C-1735 conducted by J. Barrella of the Mallory Battery Co. at North Tarrytown. The initial compositions of the various cell designs in gms and in A.Hrs are shown in Table 1.

The cell discharge trajectories calculated from Table 1 and reaction (1) are plotted in the diagram shown in Fig. 1. The ratios were calculated using the capacities of Li, SO<sub>2</sub> and AN based on 1 equiv/mole reaction. The trajectories of the standard LO26S and LO26SH cells are also shown for comparison.

The trajectory I leads to a complete exhaustion of Li and SO<sub>2</sub> at the end of the discharge provided the discharge is carried out at a very low current so that the utilization efficiency is 100%. All the cells except the ones in 7A had sufficient carbon to reduce all SO<sub>2</sub>. (A detailed study on the effect of cathode variables on the safety, as carried out earlier on the same contract showed insignificant effect). The only cell design that followed the trajectory I was 5A.

The trajectory II leads to a complete exhaustion of SO<sub>2</sub> and approximately 15% excess lithium. The cells of design 6C followed this trajectory.

The trajectory III also leads to a complete exhaustion of SO<sub>2</sub> and 49% excess Li in terms of A.Hr. This trajectory was followed by LO26-S cells as well as LO25-S cells of design 5B, 6B, 7A, 7B, 7C.

The trajectory IV was followed by LO26-SH cells.

The trajectory V leads to a 62% excess Li and this was followed by cells of design 5C.

The trajectory VI leads to a 66% excess Li at the end of the discharge. The cells of design 6A followed this trajectory.

The summary of the safety test data as reported in Table II of the monthly report no. 11 of J. Barrella on contract DAAB-07-76-C-1735, is reproduced here in Table 2.

According to the test data, it appears that the only cell design that showed some promise is 5A, which followed trajectory - I. This is encouraging, since it conforms to our expectations. It appears that the cell design corresponding to trajectory I or the ones lying above I are expected to be safer than the ones lying below trajectory I.

The other cell design variables which are believed to influence the cell safety are:

1. Electrolyte salt; LiBr and LiAsF<sub>6</sub>.
2. Electrolyte solvent; AN, PC + AN.
3. Electrode configuration.
4. Electrode area.

We developed a cell design matrix, shown in Table 3, consisting of the following cell design variables.

1. Electrode area (LO26S and LO26SH)
2. Li anode thickness (Li:SO<sub>2</sub> ratios)
3. Electrode configurations (cathode outer, anode outer)
4. SO<sub>2</sub> content in electrolyte (70%, 80%)
5. Organic solvents in the electrolyte (AN, PC + AN)
6. Electrolyte salt (LiBr, LiAsF<sub>6</sub>)

We chose the LO26 (D size) cell as a vehicle for carrying out our studies. The specific cell designs selected for this study and the design details are shown in Table 4. The reaction trajectories of these selected cell designs are shown in Fig. 1. Note that all the selected designs except 3a lie above trajectory - I and is expected to be 'safer' than the standard LO26S cells.

We planned to test the performance characteristics of these cells with respect to use and abuse in order to determine the tradeoffs, if any, for improved abuse resistance.

### III. Experimental

LO26 cells of the various designs shown in Table 4 were assembled at the North Tarrytown plant. The cells containing standard electrolytes were filled at the same facility. The cells with modified electrolytes were brought to LPS, Burlington and were filled at the Laboratory. All the cells were tested at LPS in the safety test area.

The tests carried out were as follows:

1. Capacity test at various loads at ambient temperature.
2. Constant current (2A) discharge and reversal at  $-30^{\circ}\text{C}$ .
3. Constant current (2A and 3A) charging at ambient.

Both the voltage and the wall temperature of the cells were monitored during all the above tests except 1, where only the voltage was monitored. The condition of the cells were examined visually after the tests and was recorded photographically.

#### IV. Results and Discussion

We have completed the testing of LO26S cells of type 1a, 2a, 3a, 1b, 1g, 2g and 3g. The results are discussed here.

1. Capacity-Rate Characteristics: The capacity-rate characteristics of LO26S cells of type 1a, 2a, 3a, 1b, 1g, 2g and 3g are shown in Fig. 2 through 8 respectively and in Table 5. Note that the maximum capacity of the LO26S cells of type 1a, 2a, 1b, 1g and 2g is approximately 7 A.Hr whereas the maximum capacity of the LO26S cells of type 3a and 3g is approximately 10 A.Hr. Considering the fact that the stoichiometric capacity of  $\text{SO}_2$ , based on reaction (1), is approximately 10-11 A.Hr (Table 4) for all the cell types, the low capacity of the LO26S cells of type 1a, 2a, 1b, 1g and 2g indicate that these cells are anode limited. The stoichiometric capacity of Li for these latter types of cells varied from 9.2 to 9.9 A.Hr. thus giving rise to lithium utilization efficiencies of 70-76%. This indicates that the so-called lithium limited cells must contain excess unused Li at the end of the low current discharge. The amount of excess Li remaining varied from 2.2 to 2.9 A.Hr whereas the amount of excess  $\text{SO}_2$  varied from 3 to 4.4 A.Hr for the LO26S cells of type 1a, 2a, 1b, 1g and 2g. In contrast, the LO26S cells of type 3a and 3g are cathode and/or  $\text{SO}_2$  limited; the utilization of  $\text{SO}_2$  based on reaction (1) was 90-100%. Thus there was virtually no  $\text{SO}_2$  left at the end of the low current discharge of the LO26S cells of type 3a and 3g. The amount of excess Li left was approximately 1.5 A.Hr.

The type of electrode configuration, viz. exterior cathode versus interior cathode does not appear to have any effect on the capacity-rate characteristics of the cells. LO26S cells of type 1g appears to be an exception in that the rate capability of this group of cells is quite poor.

The effect of the electrolyte variables such as  $\text{LiAsF}_6$  salt, on the capacity-rate characteristics of the cells at ambient temperature does not appear to be very significant. The rate capability of the cells with 80%  $\text{SO}_2$  appears to be marginally lower than the standard.

The capacity penalty of the LO26S cells of type 1a, 2a and 1b compared to 3a and 3g is significant at low rates, (0.1-1.0A) but insignificant at high rates (2-10A).

2. Constant Current (2A) Discharge and Reversal at -30°C: We tested six cells from each type of LO26S cells under this condition. The results are summarized in Table 6. Typical voltage and temperature profiles of the LO26S cells of various types are shown in Fig. 9 through 15. Simplified qualitative voltage profiles of all types of LO26S cells on 2A discharge and reversal at -30°C are shown in Fig. 16.

In general the cell wall temperature changed with the cell voltage in approximately a mirror image fashion indicating that the cell heating was due to the cell polarization. The most rapid cell heating occurred at the point where the cell experienced deep reversal towards the end of the test. This was the point where venting and/or fire and explosion occurred. We define this point as the "trigger point". We did not see any spontaneous cell heating after the completion of the test leading to a venting and/or fire. Whatever happened, happened at this trigger point. There are several instances as shown in Table 6, when nothing untoward happened even at the trigger point.

The cell voltage reflects primarily the potential of the cathode since the Li anode potential remains constant throughout the discharge because of its high exchange current. The electrochemical reactions occurring in the cell up to the zero volt result in the formation of Li salts according to reaction (1) (primarily  $\text{Li}_2\text{S}_2\text{O}_4$  and possibly others), and the consumption primarily of Li and  $\text{SO}_2$ . These reactions may be viewed as deactivating processes which reduce the amount of active materials such as Li which can initiate and/or propagate a combustive and/or explosive process. The electrochemical reactions occurring below zero volt result in the formation of active materials such as Li on the cathode. This Li may be in a very active form to initiate and/or propagate a fire and/or an explosion.

Based on the above analysis, the voltage profiles of the LO26S cells of the various types can be grouped into four different classes as shown in Fig. 16. The voltage profiles of LO26S cells of type 1a, 2a and 2g belong to Class I. The Class I voltage profile has a plateau above 2 volts and a stepwise decline to zero volt followed by an immediate deep reversal corresponding to the trigger point. The deep reversal occurs because of the consumption and/or disconnection of the Li anode which does not have a current collector. The interval between the zero volt and the deep reversal ( $t_3 - t_2$ ; Table 6) is very small indicating very little or no formation of active form of Li on the cathode. Consequently, the cells did not exhibit explosion or fire at the trigger point; only venting occurred. The amount of  $\text{SO}_2$  consumed up to zero volt was approximately 7-8 A.Hr (Table 6) which meant that there was 2-3 A.Hr of  $\text{SO}_2$  still left at the trigger point to cool the cell sufficiently on venting. The cells exhibiting this type of voltage profile had excellent abuse resistance on 2A reversal at  $-30^\circ\text{C}$ . It should be noted that for a given current and temperature the amount of Li and the anode design determines the trigger point ( $t_3$ ); the carbon cathode and the electrolyte composition determines the time to zero volt ( $t_2$ ). For a safe cell  $t_3 - t_2$  must be as close to zero as possible; also the stoichiometric amount (A.Hr) of  $\text{SO}_2$  must be higher than  $t_3 \times i$  ( $i$  = current) to ensure excess  $\text{SO}_2$  at the trigger point.

The Class II voltage profile is very similar to Class I profile except that the cell voltage lingers below zero volt quite a bit longer prior to the trigger point. The above analysis conforms to the observed explosion and fire of the LO26S cells of type 3a and 3g whose voltage profiles on reversal belong to Class II. The  $t_3 - t_2$  of these cells (Table 6) was 1 hr (2 A.Hr) or more thus resulting in the formation of significant amounts of active forms of Li on the cathode which caught fire at the trigger point. This was because the anode had excess Li which made  $t_3$  (the trigger point) much longer.

The voltage profiles of LO26S cells of type 1g belongs to Class III where although the stoichiometric amount of Li was the same as in 1a, 2a, and 2g, the poor performance of the cathode resulted in the increase of  $t_3-t_2$  and the consequent unsafe behavior at the trigger point.

The voltage profiles of LO26S cells of type 1b was quite exceptional and belongs to Class IV. This is very similar to Class I except that the cell voltage remains at a relatively high level prior to reaching zero volt and the immediate deep reversal at the trigger point. These cells were also safe on 2A reversal at  $-30^\circ\text{C}$ , since there was no chance of lithium deposition on the cathode. The higher operating voltage of this type of cell gives them a longer useful life to a given cutoff voltage. These cells have  $\text{LiAsF}_6$  salt as the electrolyte.

The above results indicate that the abuse resistance of LO26S cells on constant current reversals at  $-30^\circ\text{C}$  depends on

- (a) The absence of lithium deposition on the cathode prior to the exhaustion of Li on the anode (trigger point).
- (b) The availability of excess  $\text{SO}_2$  at the trigger point.

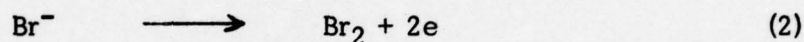
The former is accomplished by using the appropriate amount of Li on the anode and by improving the cathode utilization such that the cell reaches the trigger point (deep reversal) as soon as it reaches zero volt as in the case of 1a, 2a, 2g and 1b type cells. The poor cathode utilization in 1g cells lead to unsafe behavior. The use of excess Li in the case of 3a and 3g cells also lead to unsafe condition.

The type of electrode configuration (1a and 2a) did not appear to have an influence on the abuse resistance. The use of 80%  $\text{SO}_2$  in the electrolyte did not improve the abuse resistance because of the inferior cathode utilization. The use of  $\text{LiAsF}_6$  salt improved the cathode performance at  $-30^\circ\text{C}$ .

3. Constant Current (2A and 3A) charging at 25°C: The results are summarized in Table 7 and 8 for 2A and 3A charging respectively. The cell designs did not appear to have a significant effect on the abuse resistance of the cells. Two typical voltage and temperature profiles are shown in Figs. 17 and 18 respectively. The processes that are likely to occur on charging are:

- a. The cathodic deposition of Li on the Li anode.
- b. The anodic oxidation of the electrolyte on the carbon cathode.

With LiBr electrolyte salt, (as in all designs except 1b) the anodic oxidation on the carbon cathode leads to bromine evolution.



With LiAsF<sub>6</sub> electrolyte salt (as in 1b) the oxidation of Al tab and grid of the carbon cathode ensues leading to a disconnection (Fig. 18). On charging, the cell voltage initially remains stable at 3.5-4 volt for cells with LiBr and at 4.5-5 volt for cells with LiAsF<sub>6</sub>. The subsequent sharp voltage rise was either due to the exhaustion of LiBr (Fig. 17) or due to the corrosion and disconnection of Al tab (Fig. 18). The cell venting occurs at this point. The dendritic Li formed on the anode may then lead to a fire when it comes in contact with the air. At low currents, the charging may be continued for prolonged periods (3) without any sharp polarization of the cathode and consequently without any venting and/or fire.

## V. Conclusions

The results obtained to date indicate that the LO26S cells of type 1a, 2a, 1b and 2g are quite resistant to abuses consisting of 2A forced discharge at  $-30^{\circ}\text{C}$ . These designs lead to a capacity penalty of 3 A.Hr at low rates and no penalty at rates of 2A or higher, compared to the standard LO26S cells. Several design principles governing the safety of the cells have been identified.

The abuse resistance of the cells on charging appears to be independent of the cell designs. All the cells are capable of withstanding prolonged charging at low currents but not at high currents (2A or higher).

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## VII. Acknowledgement

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TABLE 1

Initial Compositions of Li, SO<sub>2</sub> and AN of the Various Cell Designs

Cell Designs	Li		SO <sub>2</sub>		AN	
	wt (gm)	cap. (A.Hr)	wt (gm)	cap (A.Hr)	wt (gm)	cap* (A.Hr)
5A	2.646	10.22	24.85	10.40	8.29	5.42
5B	3.97	15.33	24.85	10.40	8.29	5.42
5C	4.96	19.17	24.85	10.40	8.29	5.42
6A	3.97	15.33	17.99	7.53	6.00	3.93
6B	3.97	15.33	24.85	10.40	8.29	5.42
6C	3.31	12.78	28.0	11.72	9.34	6.10
7A	3.97	15.33	24.85	10.40	8.29	5.42
7B	3.97	15.33	24.85	10.40	8.29	5.42
7C	3.97	15.33	24.85	10.40	8.29	5.42

\*Taken arbitrarily on 1 equiv/mole reaction

TABLE 2  
Unbalanced Parameter Summary

Group	Identity	Ratio* Li:SO <sub>2</sub>	Ratio* C:SO <sub>2</sub>	Remarks
5A	Low Li	.99:1	1:1	No fire 5.0 amps or 3.3 amps
5B	Control	1.49:1	1:1	5 amps - fire, 3.3 amps 1 of 6 - fire
5C	Hi Li	1.86:1	1:1	5 and 3.3 amps - fire
6A	Lo Electrolyte	2.03:1	1.36:1	5 amps - fire, 3.3 amps - no vent
6B	Control	1.49:1	1:1	5 and 3.3 amps, same as 5B
6C	Hi Electrolyte	1.08:1	1.14:1	5 amps - fire, 3.3 amps >300°F., no fire
7A	Lo Carbon	1.49:1	.77:1	5 amps - fire, 3.3 amps - no fire
7B	Control	1.49:1	1:1	5 & 3 amps same as 5B
7C	Hi Carbon	1.49:1	1.16:1	5 amp - fire, 3.3 amps 300°F., no fire

**\*Note:**

Li - 3.86 AH/gm  
SO<sub>2</sub> - .418 AH/gm  
C - 1.83 AH/gm

$$\text{Li:SO}_2 \text{ Ratio} = \frac{\text{Theoretical Li}}{\text{Theoretical SO}_2}$$

Table 3  
CELL DESIGN MATRIX

		Electrode Variables											
		LO-26S						LO-26SH					
		Li Thickness 0.008"		Li Thickness 0.01"		Li Thickness (to be determined later)		Li Thickness 0.005"		Li Thickness 0.008"		Li Thickness (to be determined later)	
Cath. Outer	Cath. Inner	Cath. Outer	Cath. Inner	Cath. Outer	Cath. Inner	Cath. Outer	Cath. Inner	Cath. Outer	Cath. Inner	Cath. Outer	Cath. Inner		
70% SO <sub>2</sub>	AN	LiBr	2 <sub>X</sub> a	3 <sub>X</sub> a	4a	5a	6a	7 a	8 a	9 a	10a	11a	12a
		LiAsF <sub>6</sub>	2b	3b	4b	5b	6b	7b	8b	9 b	10b	11b	12b
		LiBr	2c	3c	4c	5c	6c	7c	8c	9c	10c	11c	12c
	New (to be determined later)	LiAsF <sub>6</sub>	2d	3d	4d	5d	6d	7d	8d	9d	10d	11d	12d
		LiBr	2e	3e	4e	5e	6e	7e	8e	9e	10e	11e	12e
		LiAsF <sub>6</sub>	2f	3f	4f	5f	6f	7f	8f	9f	10f	11f	12f
80% SO <sub>2</sub>	AN	LiBr	2g <sub>X</sub>	3g <sub>X</sub>	4g	5g	6g	7 g	8g	9g	10g	11g	12g
		LiAsF <sub>6</sub>	2h	3h	4h	5h	6h	7h	8h	9h	10h	11h	12h
		LiBr	2i	3i	4i	5i	6i	7i	8i	9i	10i	11i	12i
	New (to be determined later)	LiAsF <sub>6</sub>	2j	3j	4j	5j	6j	7j	8j	9j	10j	11j	12j
		LiBr	2k	3k	4k	5k	6k	7k	8k	9k	10k	11k	12k
		LiAsF <sub>6</sub>	2l	3l	4l	5l	6l	7l	8l	9l	10l	11l	12l

(a) Production Type Cathodes: 0.027"-0.037" for LO-26S and 0.024" ±2 mil for LO-26SH

(b) Other Cathode Variables: (porosity, etc.) will be considered on a separate matrix.

Table 4. DETAILS OF THE SELECTED LO26S CELL DESIGNS

Design	Li Anode Length (inch)	Li Anode Thickness (inch)	Stoichiometric Capacity of Li (A.Hr)	Cathode Length (inch)	Electrolyte	Stoichiometric Capacity of SO <sub>2</sub> (A.Hr)	Li:SO <sub>2</sub> Stoich. Ratio	Type of Roll
1(a)	21.0	0.008	9.2	23.5	34.2 g (70% SO <sub>2</sub> ) std	10.0	1:1.08	Exterior Cathode
1(a)	21.0	0.008	9.2	23.5	36.5 g (70% SO <sub>2</sub> ) std	10.7	1:1.16	Exterior Cathode
2(a)	22.5	0.008	9.9	21.0	36.5 g (70% SO <sub>2</sub> ) std	10.7	1:1.08	Exterior Anode
3(a)	21.0	0.01	11.5	23.5	34.2 g (70% SO <sub>2</sub> ) std	10.0	1:1.15:1	Exterior Cathode
1(b)	21.0	0.008	9.2	23.5	34.2 g (LiAsF <sub>6</sub> )	10.0	1:1.08	Exterior Cathode
1(c)	21.0	0.008	9.2	23.5	34.2 g (PC + AN)	10.0	1:1.08	Exterior Cathode
1(g)	21.0	0.008	9.2	23.5	34.2 g (80% SO <sub>2</sub> )	11.4	1:1.24	Exterior Cathode
2(g)	22.5	0.008	9.9	21.0	34.2 g (80% SO <sub>2</sub> )	11.4	1:1.15	Exterior Anode
3(g)	21.0	0.01	11.5	23.5	34.2 g (80% SO <sub>2</sub> )	11.4	1:1	Exterior Cathode

Special Design Features:

The cells with exterior cathode have two Ni tabs on the Li anode, placed 12" apart and have a polypropylene insulating jacket outside the electrode stack.

Table 5

## Discharge Characteristics of LO26S Cells of Various Types at 25°C

Cell Type	Discharge Current (A)	Capacity to 2.0 Volt (A.Hr)
1a	0.095	6.5
	0.28	7.5
	0.90	7.3
	1.0	7.2
	3.0	6.0
	5.0	6.8
	10.0	4.7
2a	0.26	6.8
	0.90	7.3, 6.8
	2.4	7.2
	3.0	7.2
	5.0	7.1
	10.0	4.7
3a	0.10	10.1
	0.30	9.0
	1.0	8.4
	2.0	7.2
	3.0	6.3
	7.0	6.6
	10.0	4.6
1b	0.1	6.9
	0.3	6.8
	1.0	6.9
	3.0	6.6
	10.0	3.9

Table 5 (continued)

Cell Type	Discharge Current (A)	Capacity to 2.0 Volt (A, Hr)
1g	0.1	7.1
	0.3	7.3
	1.0	4.6
	3.0	2.4
2g	0.1	6.9
	0.3	6.9
	1.0	6.9
	2.0	7.3
	3.0	3.3
3g	0.1	9.6
	0.3	9.5
	1.0	9.0
	2.0	8.5
	3.0	7.2

Table 6  
2 Amp Voltage Reversal at -30°C of LO26S Cells of Various Types

LO26S Cell Types	t <sub>1</sub> Time to 2V (hrs)	t <sub>2</sub> Time to 0V (hrs)	t <sub>3</sub> Time to Deep V Reversal (hrs)	Max. Temp. C	Vent	Comments*	
1a	1.	1.7	3.6	4.	106	Yes	
	2.	1.35	3.6	3.95	77	Yes	Slight Split
	3.	1.6	3.7	3.85	43	Yes	Slight
	4.	1.6	3.9	4.	>140	Yes	Slight
	5.	1.3	3.6	3.65	---	Yes	
	6.	1.3	3.8	4.	77	No	
2a	1.	1.5	3.6	3.7	103	Yes	Slight
	2.	2.	4.7	4.7	---	Yes	Bulged
	3.	1.5	3.6	3.85	78	Yes	Slight
	4.	1.6	3.6	3.65	137	No	
	5.	1.6	3.8	3.8	80	Yes	Slight
	6.	1.67	3.7	4.	104	No	
3a	1.	1.4	3.56	5.	>150	Yes	Bulged, Charred
	2.	1.4	4.	6.5	>150	Yes	Bulged
	3.	1.48	3.88	6.	>294	Yes	Bulged - Charred
	4.	1.52	3.84	5.56	>150	Yes	Bulged - Charred
	5.	1.56	3.9	5.6	186	Yes	Bulged
	6.	1.5	3.8	Level at -0.8V 7 hrs.	26	No	
1b	1.	1.92	3.64	3.76	122	No	
	2.	2.48	3.36	3.76	69	No	
	3.	2.88	3.8	3.8	49	Yes	Slight
	4.	2.16	3.72	3.88	57	Yes	Slight
	5.	2.8	3.56	3.56	65	No	
	6.	3.28	3.4	3.4	86	No	

Table 6 (continued)

LO26S Cell Types	t <sub>1</sub> Time to 2V (hrs)	t <sub>2</sub> Time to 0V (hrs)	t <sub>3</sub> Time to Deep V Reversal (hrs)	Max. Temp. C	Vent	Comments *	
	1.	1.16	2.48	4.	236	Yes	Top blown out
	2.	1.24	3.16	4.28	28	Yes	Hole burnt through bottom
1g	3.	1.16	3.4	4.2	51	Yes	" " " "
	4.	1.16	3.	4.72	55	Yes	" " " "
	5.	1.28	3.08	4.75	158	Yes	
	6.	1.24	3.44	4.84	168	Yes	Slight
	1.	1.88	3.68	3.68	88	No	
	2.	1.64	3.72	4.	82	No	
2g	3.	1.2	3.64	4.08	114	Yes	Slight
	4.	1.24	3.52	4.	73	Yes	Bulged severely
	5.	1.2	3.2	4.48	45	Yes	Bulged severely
	6.	1.24	3.24	3.84	34	Yes	Bulged severely
	1.	2.08	4.	5.	201	Yes	Bulged - Charred
	2.	3.	4.08	6.	47	Yes	Bulged - Charred
3g	3.	2.	4.2	4.92	179	Yes	Charred
	4.	<2.	4.	5.24	60	Yes	Bulged-Charred
	5.	1.12	3.8	5.08	123	Yes	
	6.	2.4	4.	5.	103	Yes	Slight

\* "Slight" refers to the extent of vent opening.

Table 7  
2 Amps Charging at 25°C

		Initial Voltage On Charge	Duration of Charge vs (hours)	Time to Vent and/or Explosion (hours)	Max. Temp. C	Voltage After Test	Comments
1a	1.	3.55	4.5	1.86	>200	0	Vented-charred
	2.	3.4	1.86	1.8	>200	0	Hole burnt through bottom
	3.	3.75	6.	Not apparent	97	-	Slight vent
2a	1.	3.8	7.3	0.5	99	3.4	Vented
	2.	3.8	7.15	1.45	164	0	Vented-charred
	3.	3.6	7.	0.55	96	3.4	Vented
3a	1.	3.75	4.	2.	97	0	Vented
	2.	3.75	2.4	1.84	85	0	Hole burnt through bottom
	3.	3.75	7.64	2.4	113	0	Slight vent
1b	1.	5.	7.	0.64	95	1.6	Slight vent
	2.	5.05	0.84	0.52	89	4.6	Slight vent
	3.	5.	7.	1.	150	-0.7	Lg hole-charred
1g	1.	3.8	6.64	2.64	220	0	Bulged-charred
	2.	3.85	6.72	1.84	359	0	Charred
	3.	3.7	6.8	0.64	95	0	Slight vent
2g	1.	3.8	5.36	2.64	140	0	Vented
	2.	4.4	5.4	1.	83	0.99	Slight vent
	3.	3.8	6.48	1.92	91	0	Slight vent
3g	1.	3.85	7.32	Not apparent	98	2.4	Slight vent
	2.	No test					
	3.	No test					

Table 8  
3 Amps Charging at 25°C

		Initial Voltage On Charge	Duration of Charge vs (hours)	Time to Vent and/or Explosion (hrs)	Max. Temp. C	Cell Voltage After Test	Comments
	1.						
1a	2.	No Tests					
	3.						
	1.	3.85	0.32	0.32	>168	-0.8	Hole burnt through bottom
2a	2.	3.8	5.	0.64	>168	---	Vent-charred
	3.	3.8	6.28	0.75	294	0	Vented
	1.	3.85	0.5	0.42	280	0	Hole burnt through bottom
3a	2.	3.85	0.83	0.66	132	0	Vented
	3.	3.85	0.5	0.5	318	0	Vented-charred
	1.	5.	0.32	0.24	138	0	Bottom blown out
1b	2.	5.	1.88	0.84	262	0	Vented
	3.	5.	0.3	----	150	0	Did not vent
	1.	3.9	0.88	0.6	240	0	Hole burnt through bottom
1g	2.	3.9	0.88	0.84	308	0	" " " "
	3.	3.9	7.	1.	137	0	Vented
	1.	3.9	7.	----	158	-	Did not vent
2g	2.	3.85	0.64	0.28	222	0	Hole burnt through bottom
	3.	3.9	6.5	Not apparent	126	0	Slight vent
	1.	4.	6.	0.76	168	0	Slight vent
3g	2.	3.9	6.	0.6	123	0	Slight vent
	3.	3.9	6.14	0.64	132	0	Slight vent

Fig. 1. Li/SO<sub>2</sub> Cell Discharge Trajectories

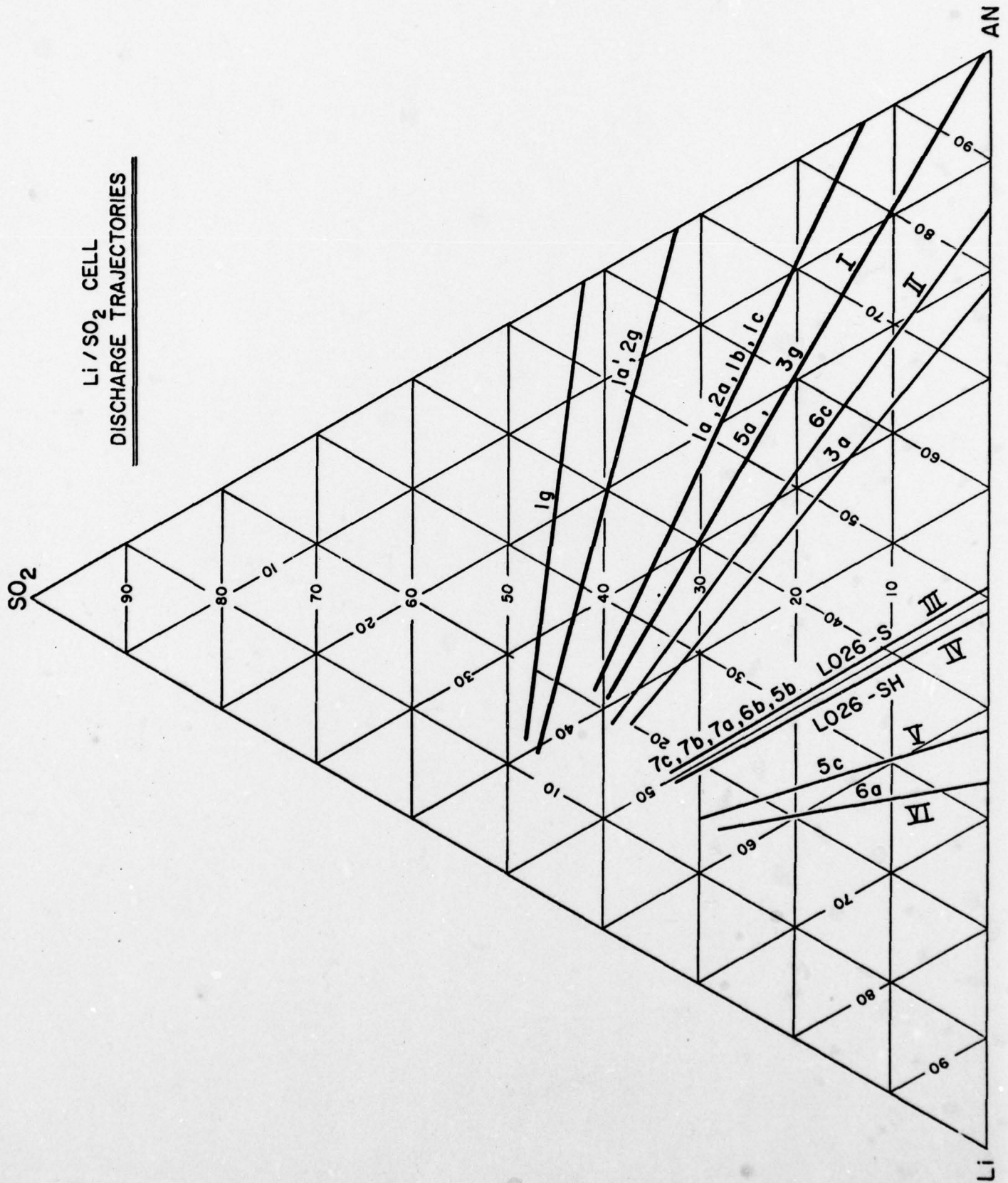


Fig. 2. Capacity-Rate Characteristics of LO26S Cells of Type 1a at 25°C

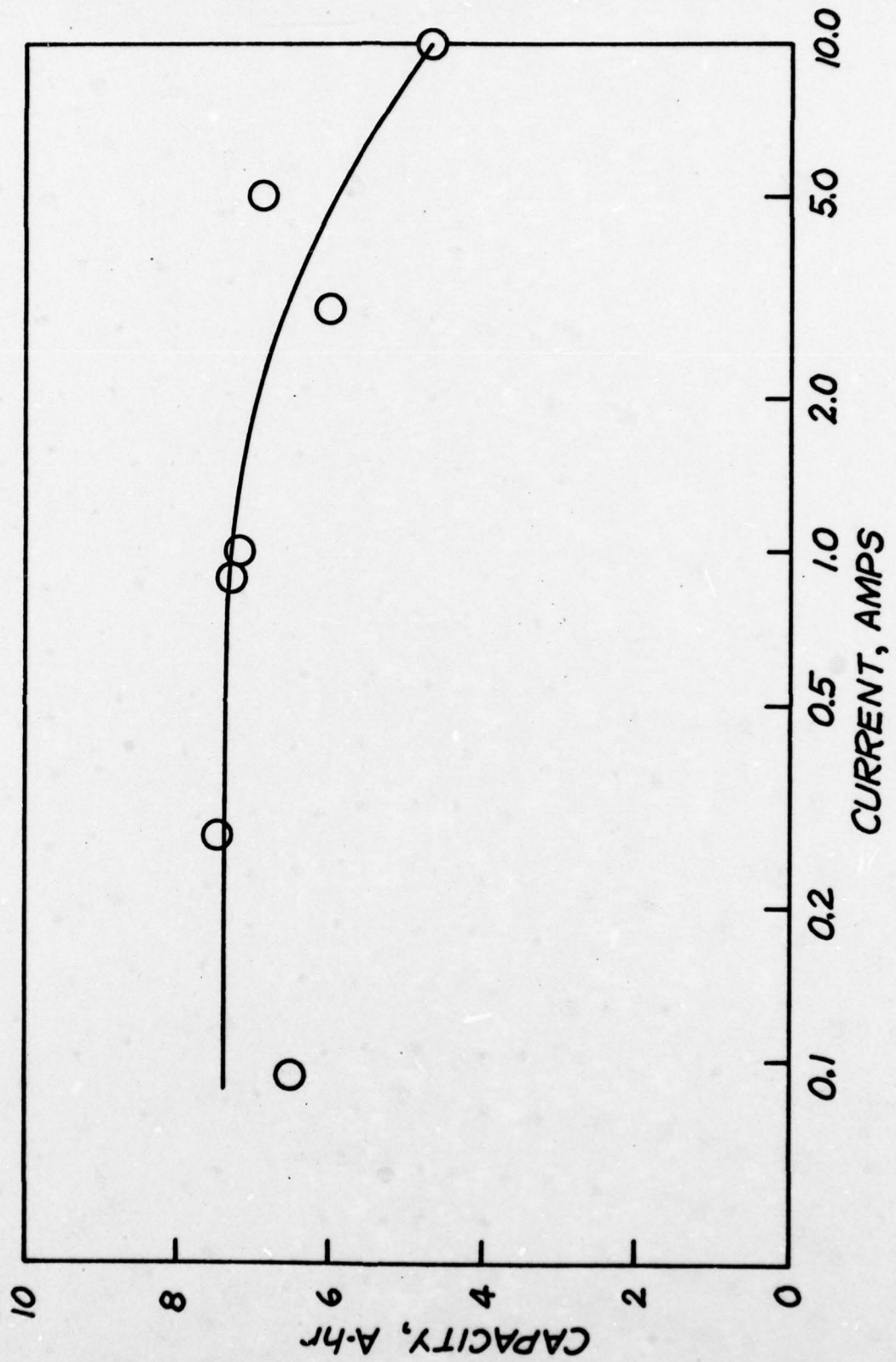


Fig. 3. Capacity-Rate Characteristics of LO26S Cells of Type 2a at 25°C

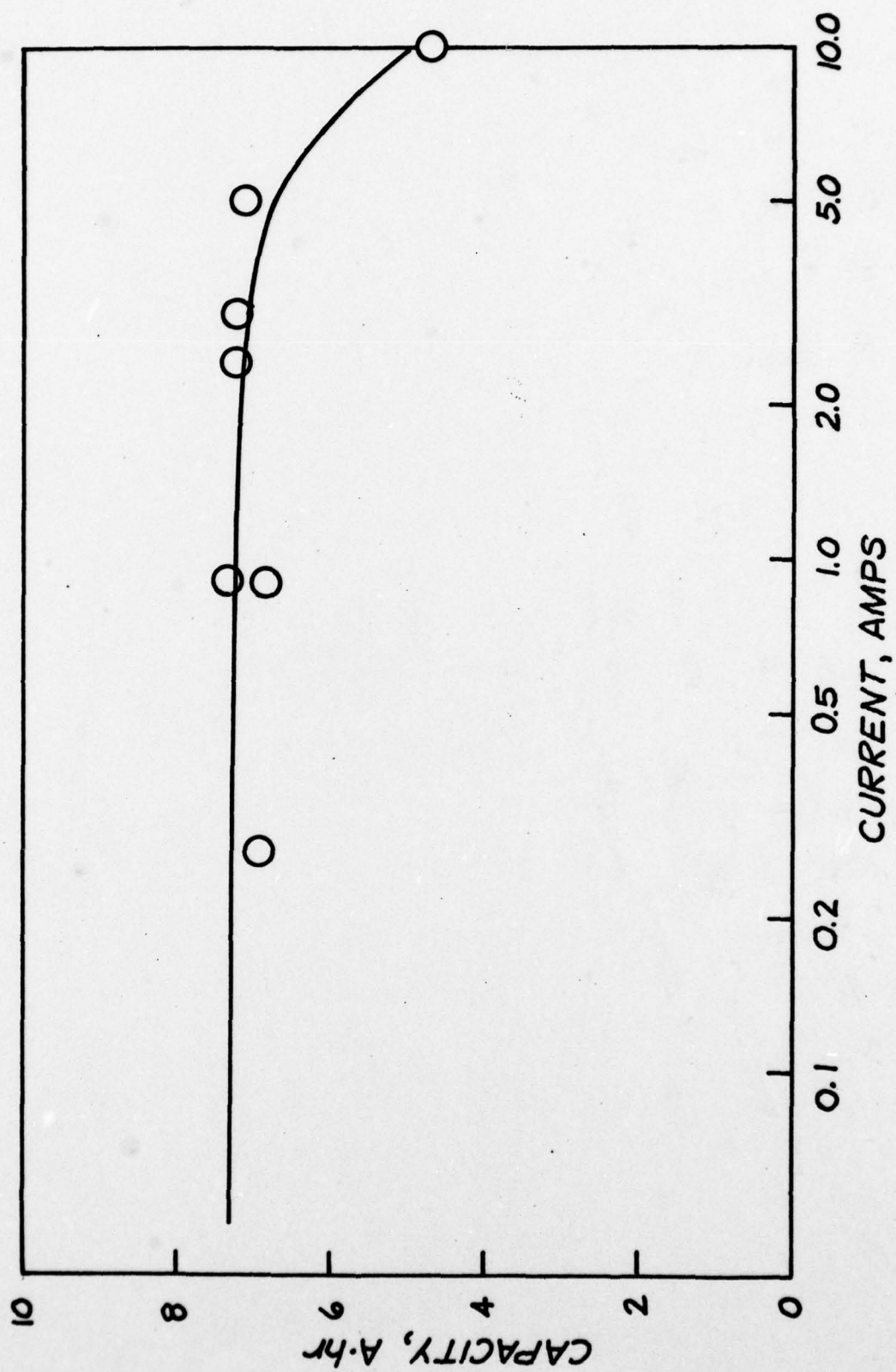


Fig. 4. Capacity-Rate Characteristics of LO26S Cells of Type 3a at 25°C

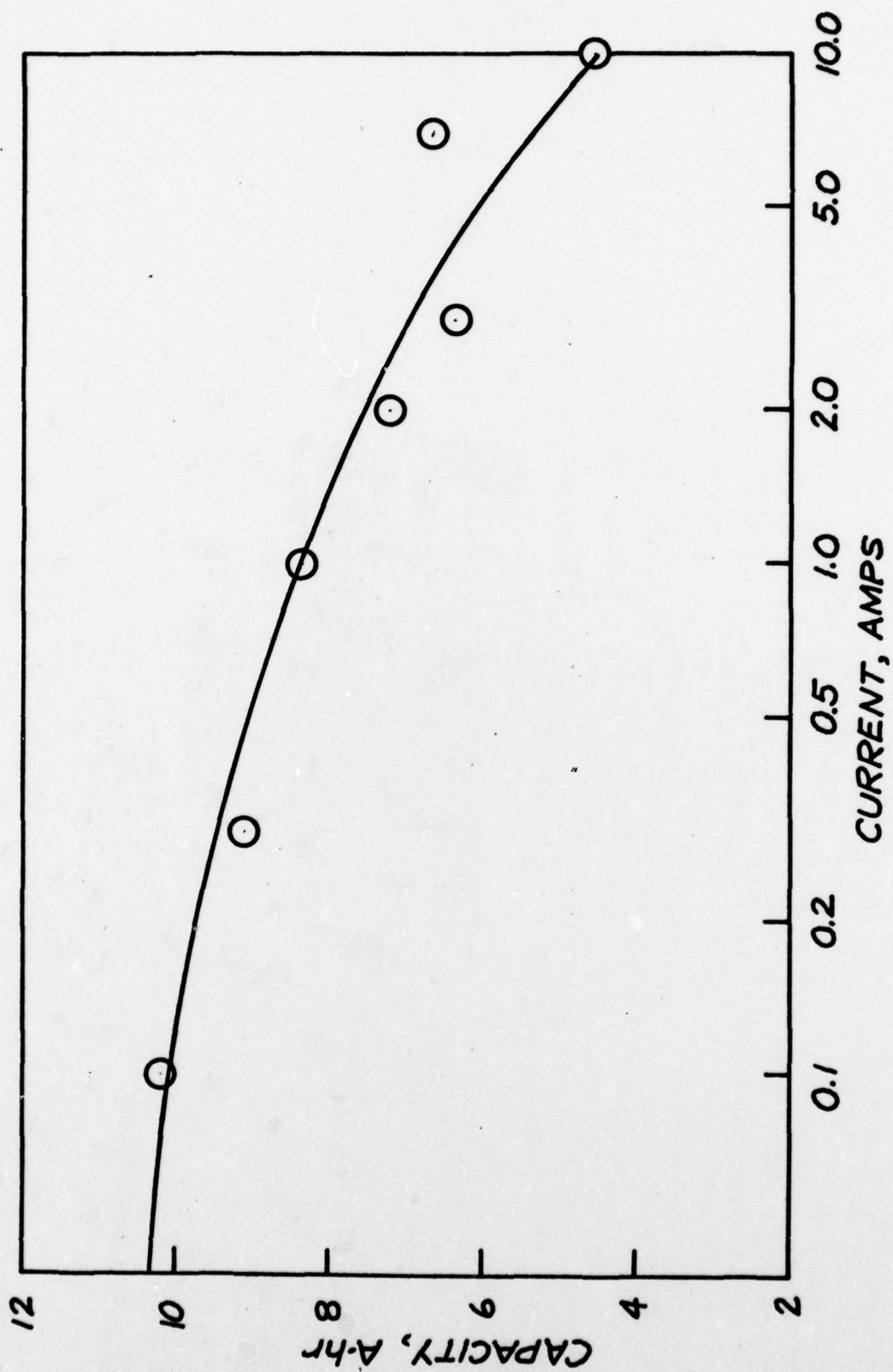


Fig. 5. Capacity-Rate Characteristics of LO26S Cells of Type 1b at 25°C

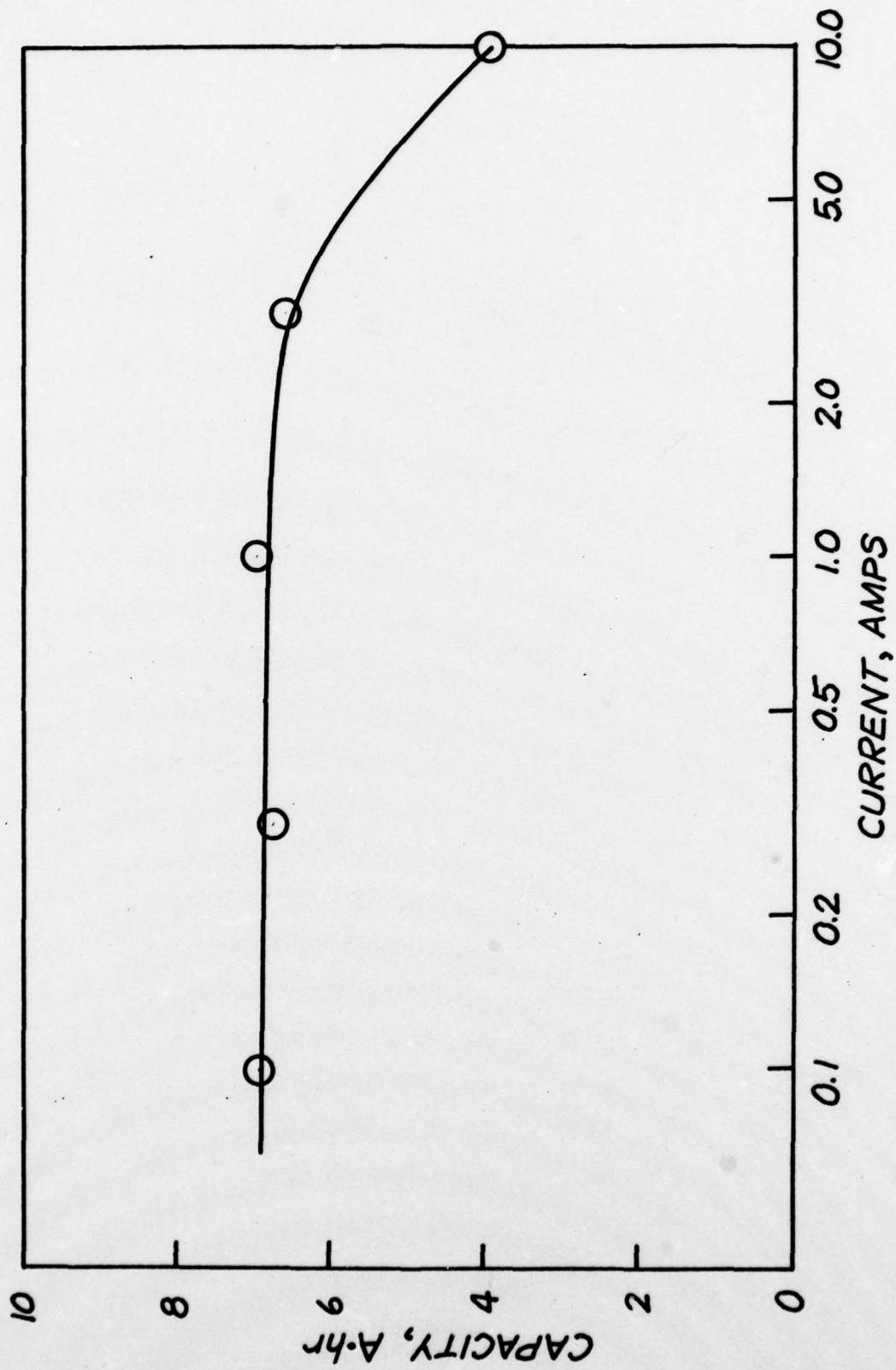


Fig. 6. Capacity-Rate Characteristics of LO26S Cells of Type 1g at 25°C

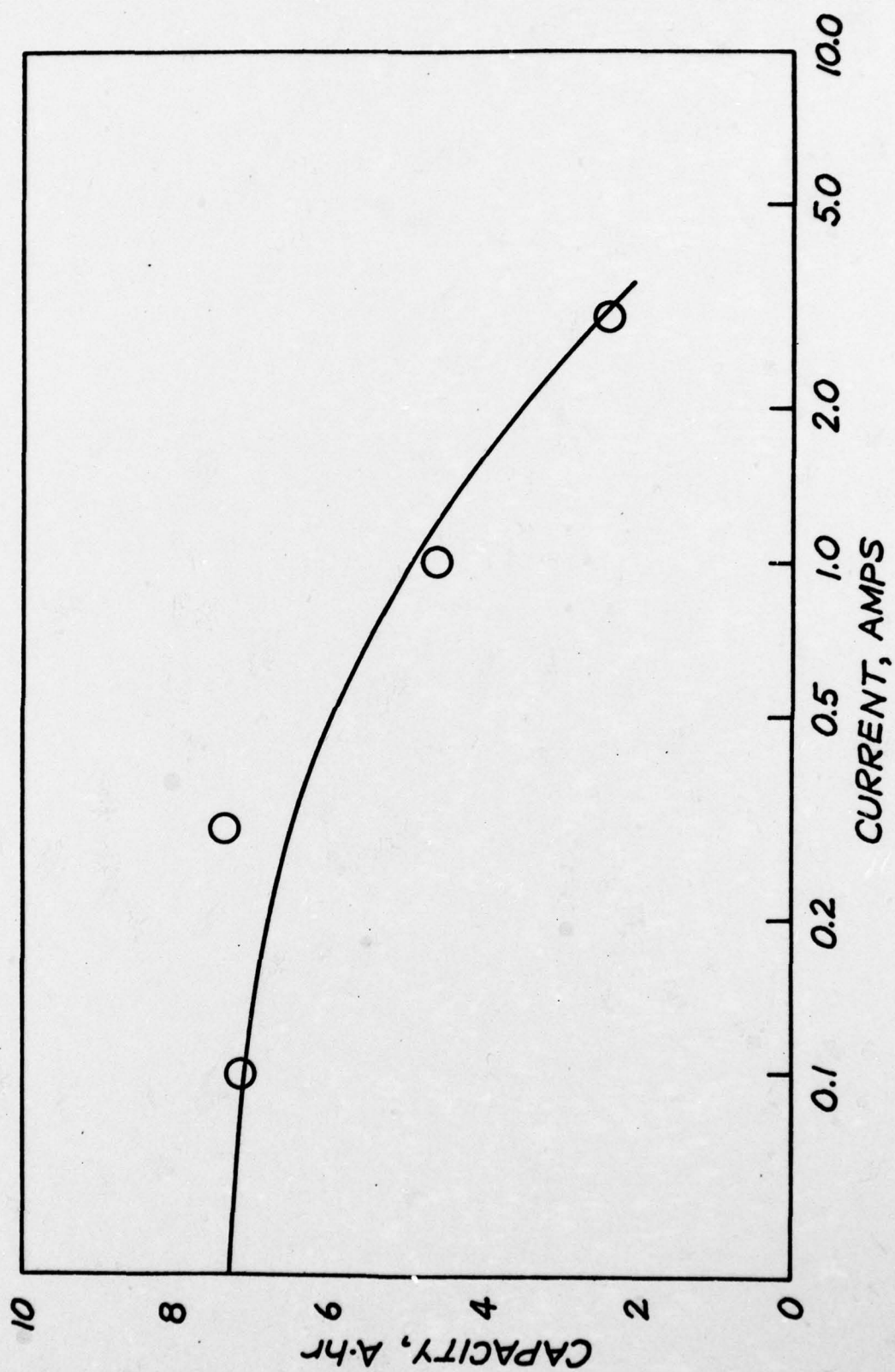


Fig. 7. Capacity-Rate Characteristics of LO26S Cells of Type 2g at 25°C

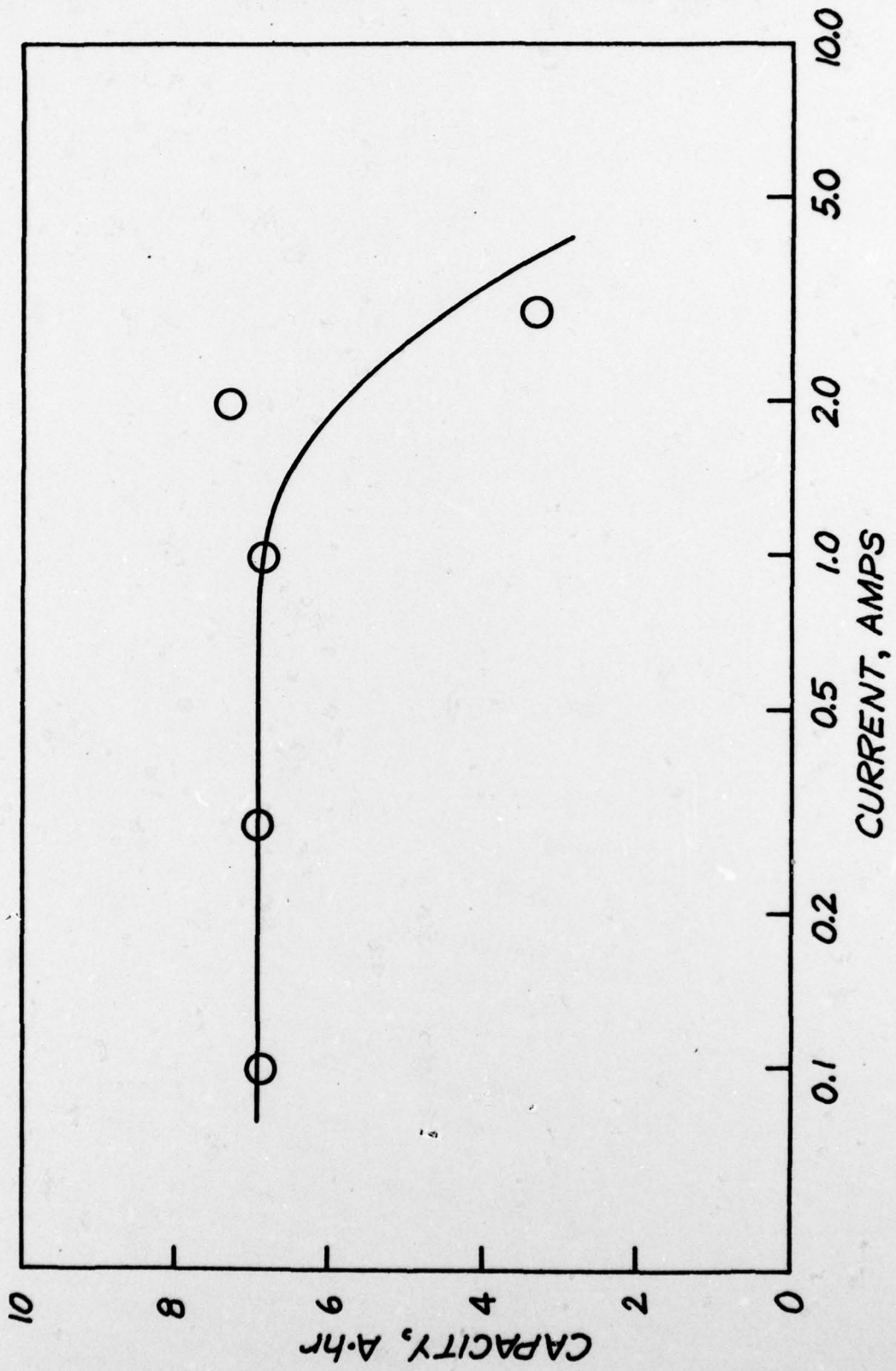


Fig. 8. Capacity-Rate Characteristics of LO26S Cells of Type 3g at 25°C

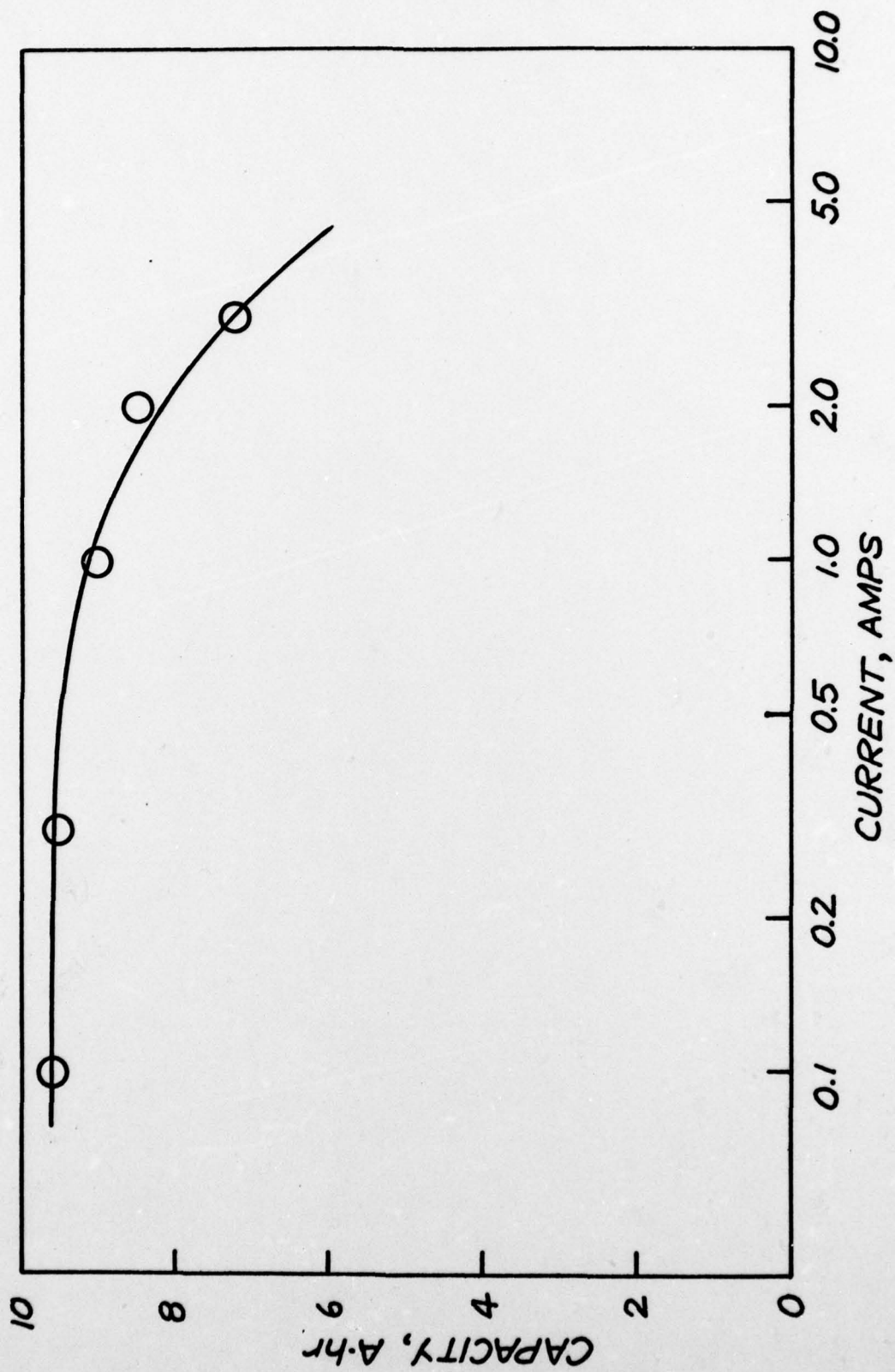


Fig. 9. V & T Profiles on 2A Reversal at  $-30^{\circ}\text{C}$  of LO26S Cells of Type 1a

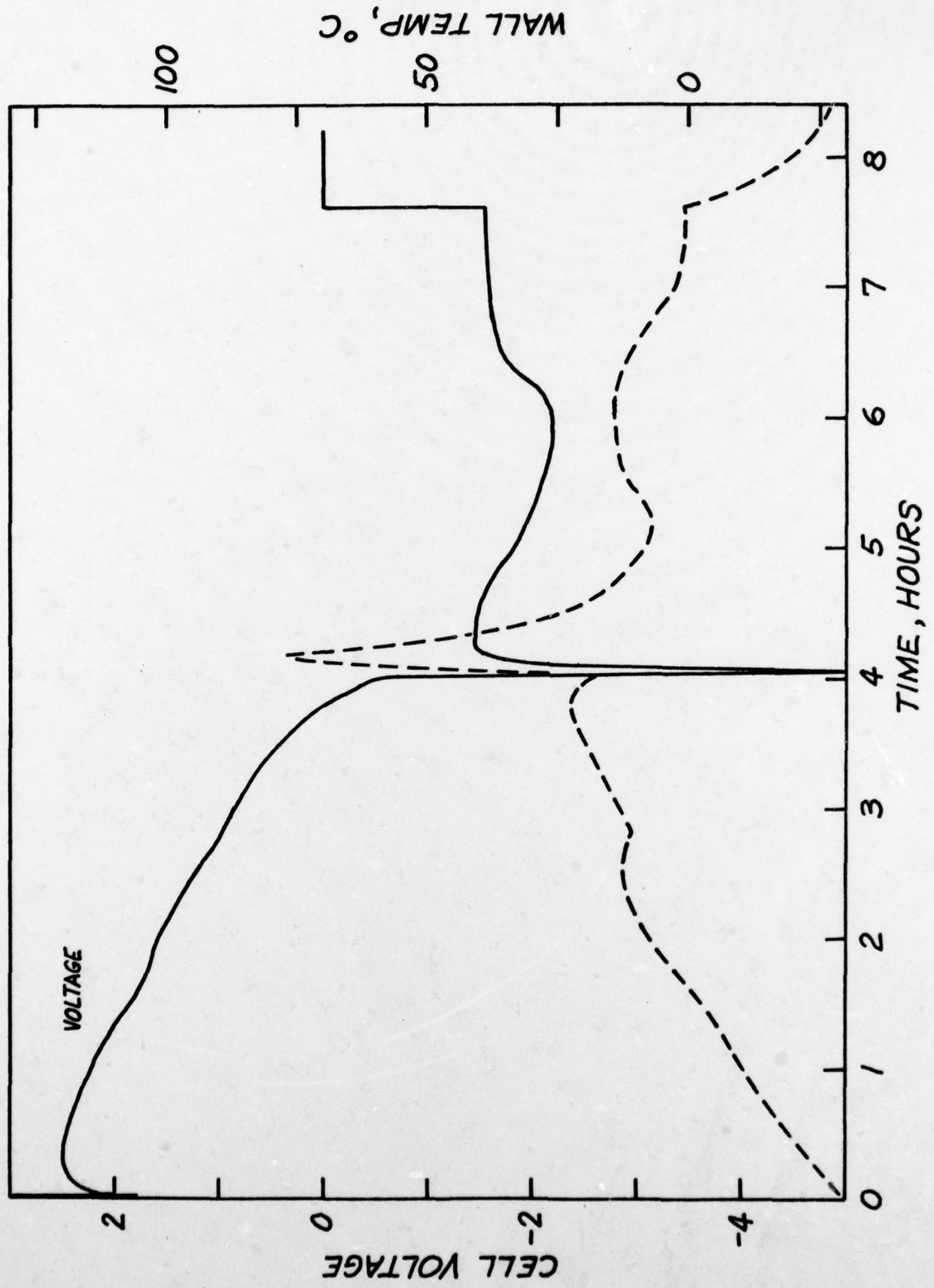


Fig. 10. V&T Profiles on 2A Reversal at  $-30^{\circ}\text{C}$  of LO26S Cells of Type 2a

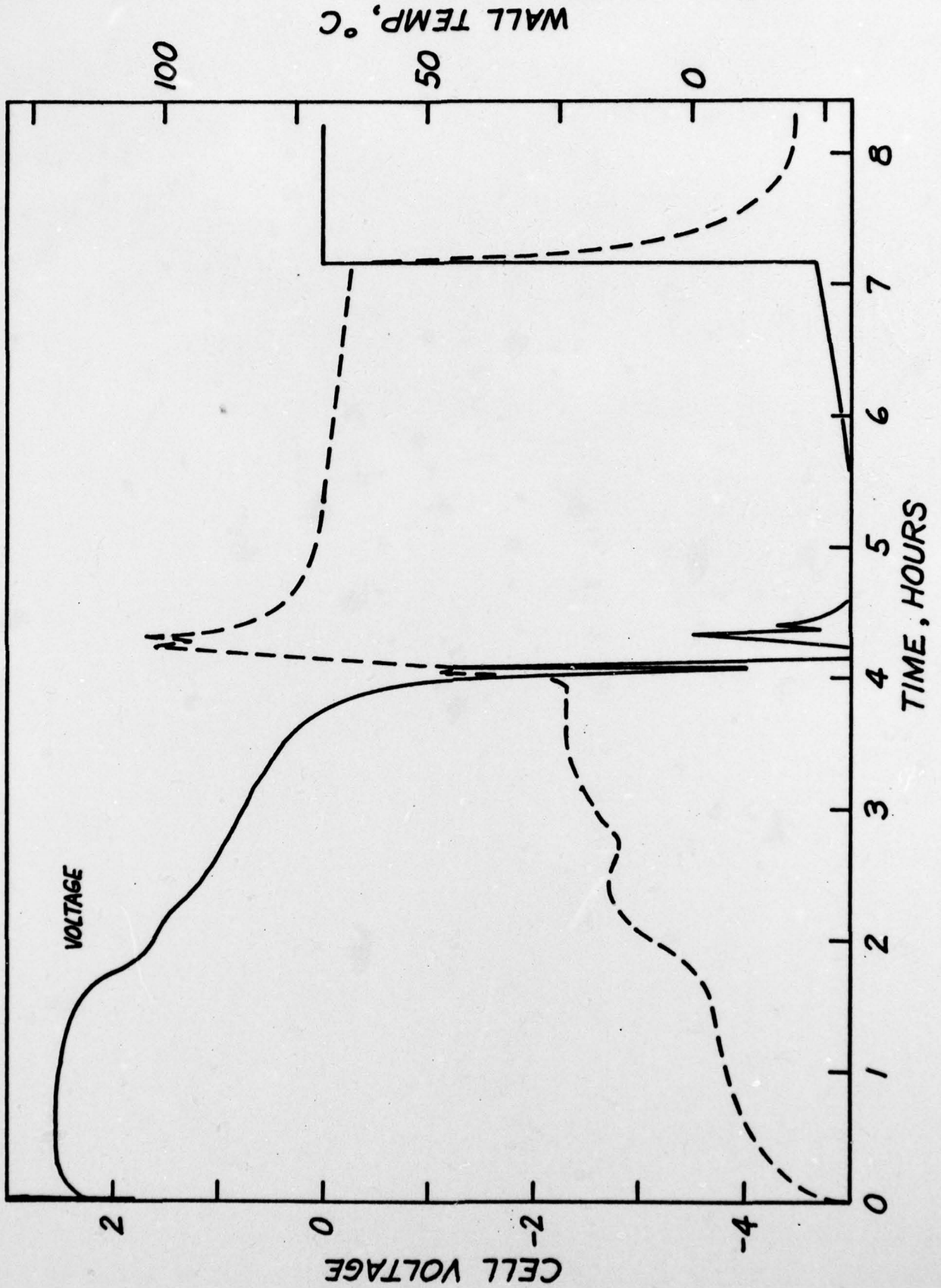


Fig. 11. V&T Profiles on 2A Reversal at  $-30^{\circ}\text{C}$  of LO26S Cells of Type 3a

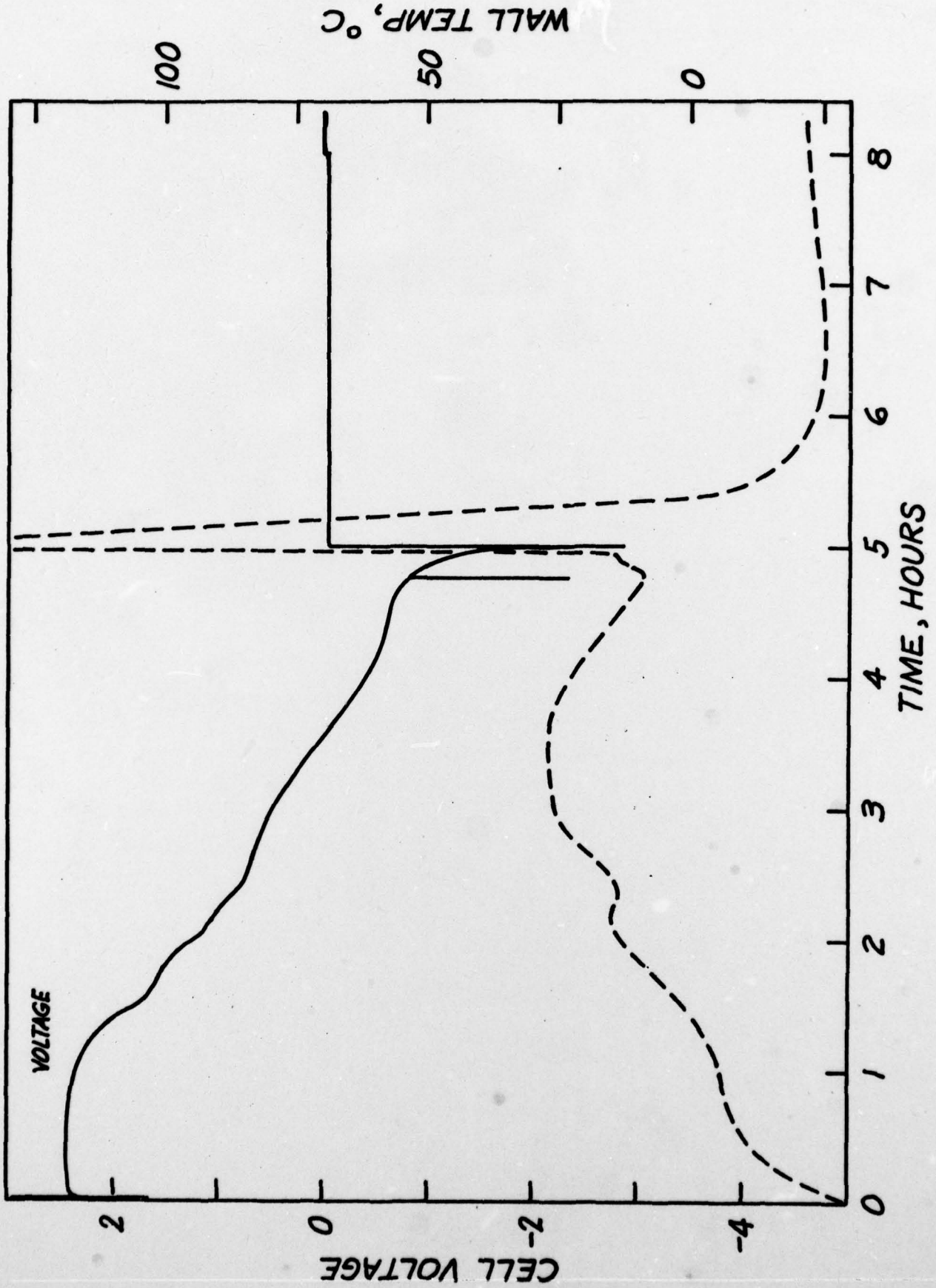


Fig. 12. V&T Profiles on 2A Reversal at  $-30^{\circ}\text{C}$  of LO26S Cells of Type 1b

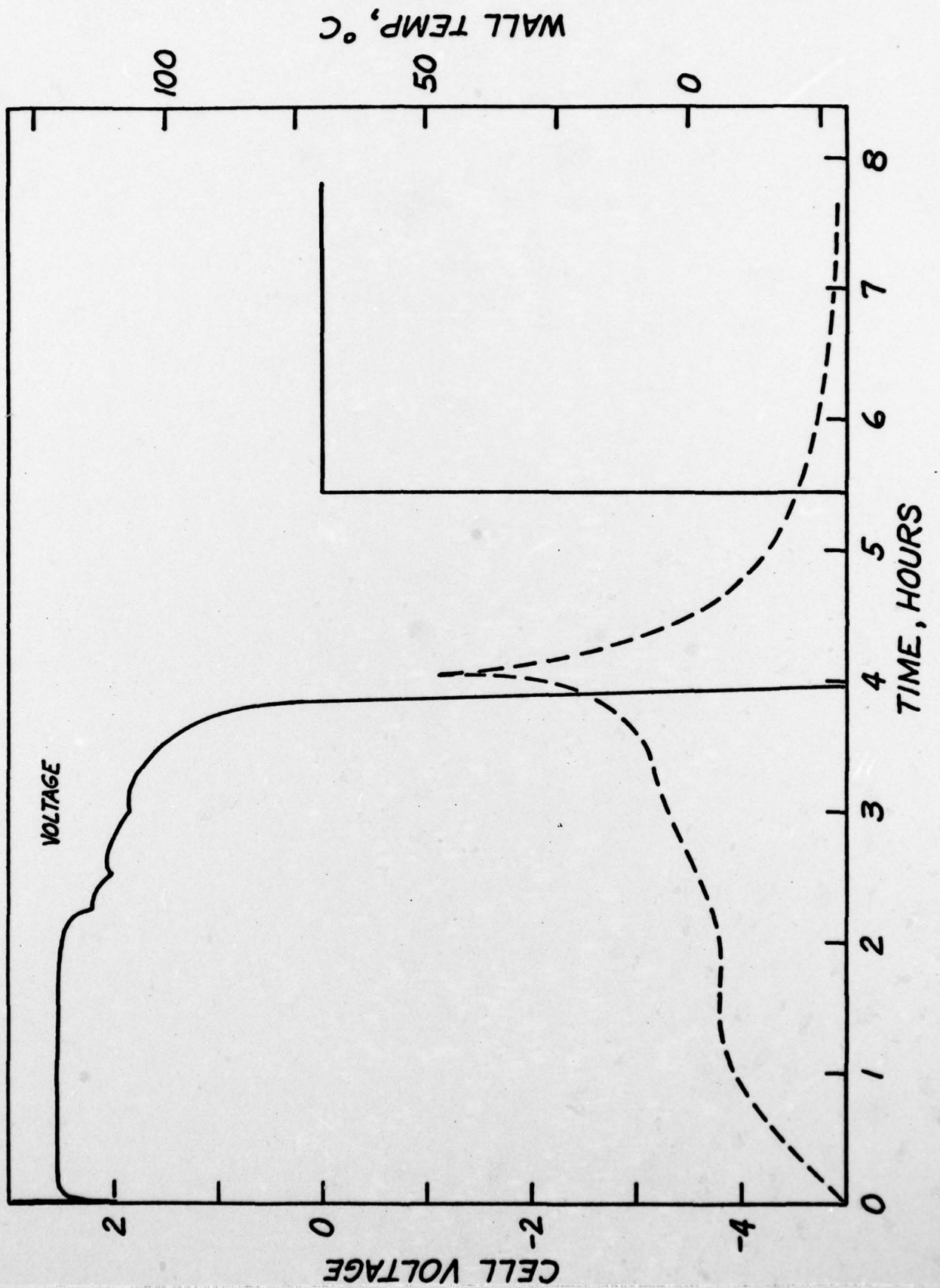


Fig. 13. V&T Profiles on 2A Reversal at  $-30^{\circ}\text{C}$  of LO26S Cells of Type 1g

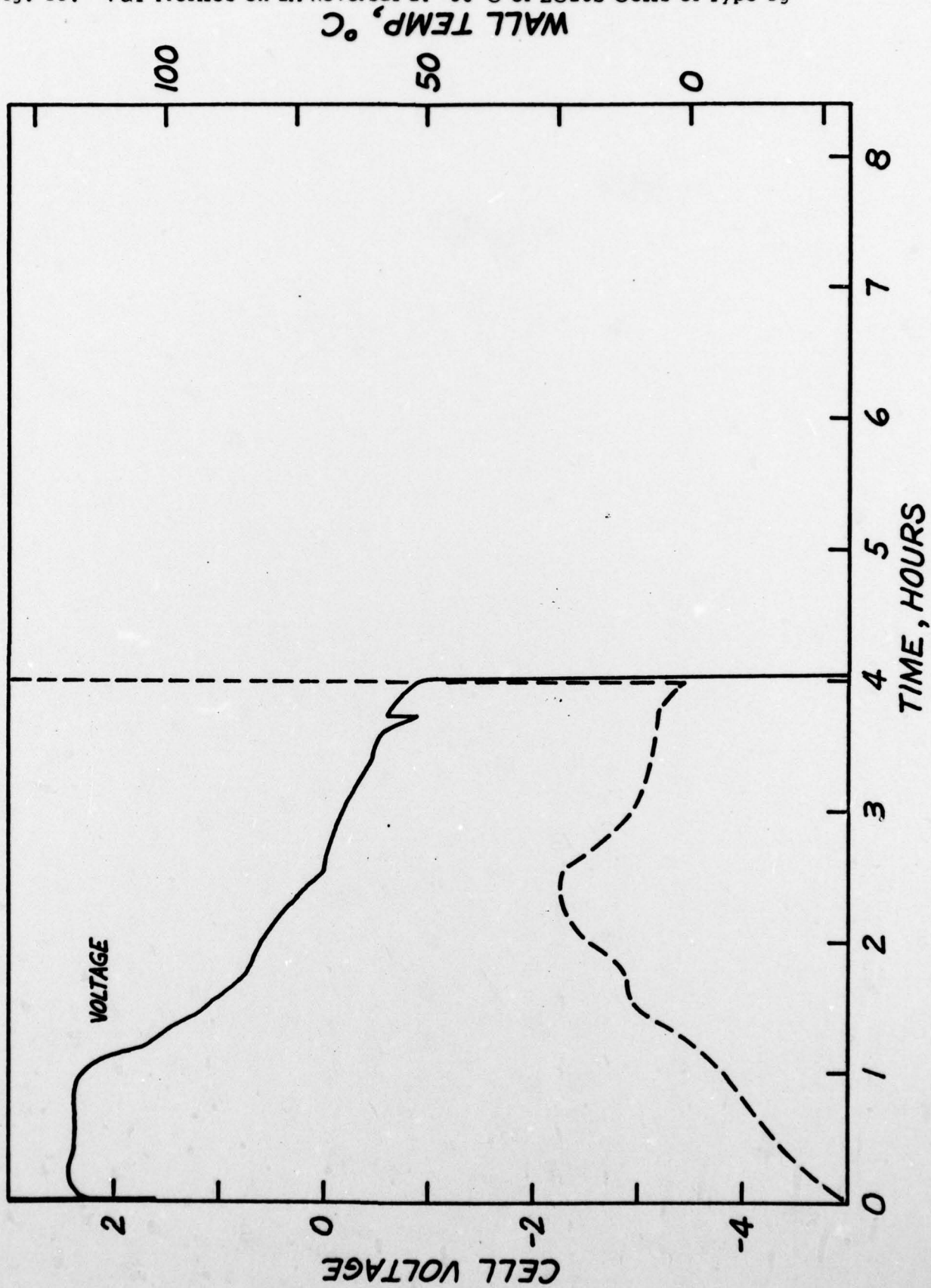


Fig. 14. V&T Profiles on 2A Reversal at  $-30^{\circ}\text{C}$  of LO26S Cells of Type 2g

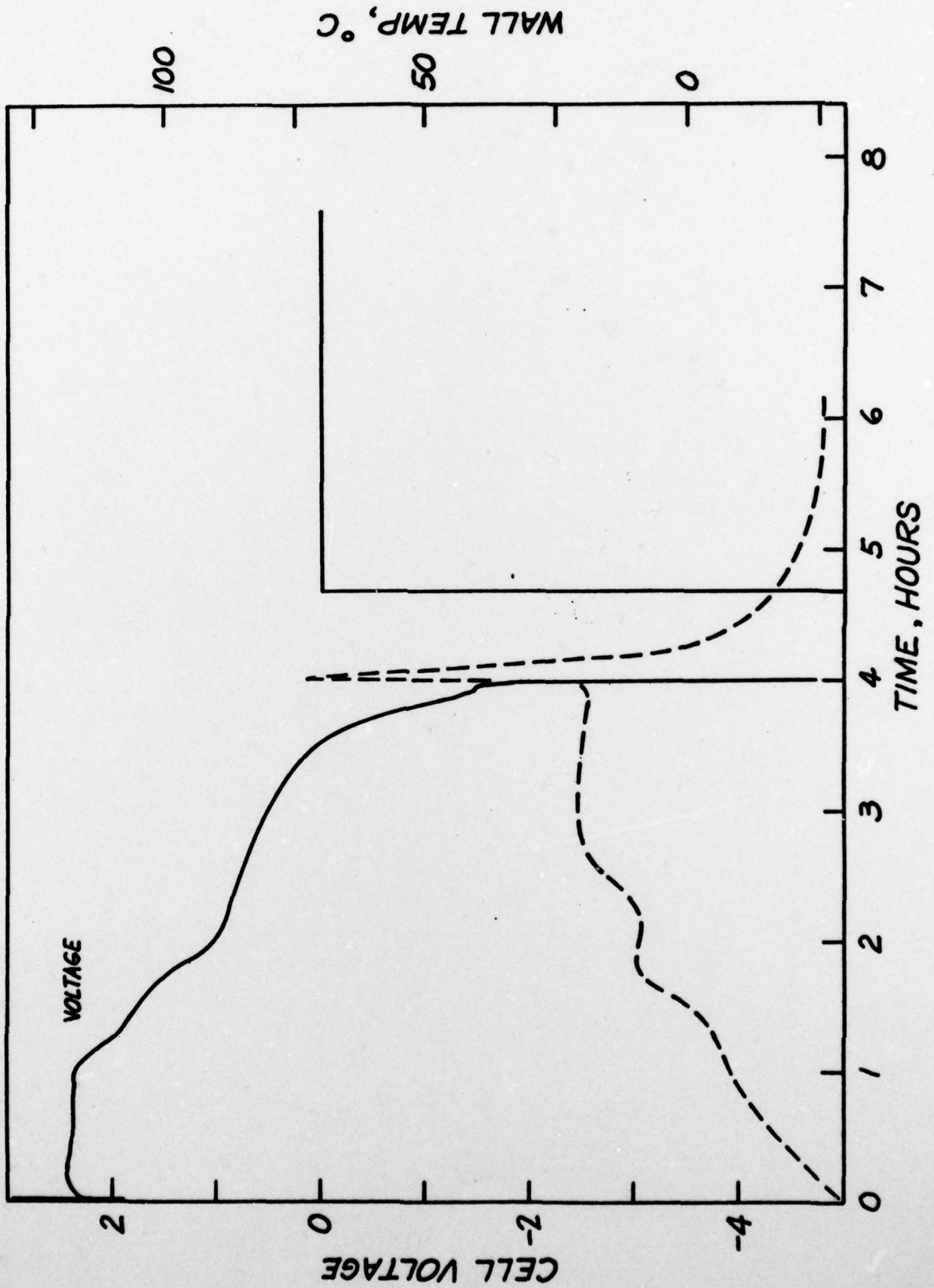


Fig. 15. V&T Profiles on 2A Reversal at  $-30^{\circ}\text{C}$  of LO26S Cells of Type 3g

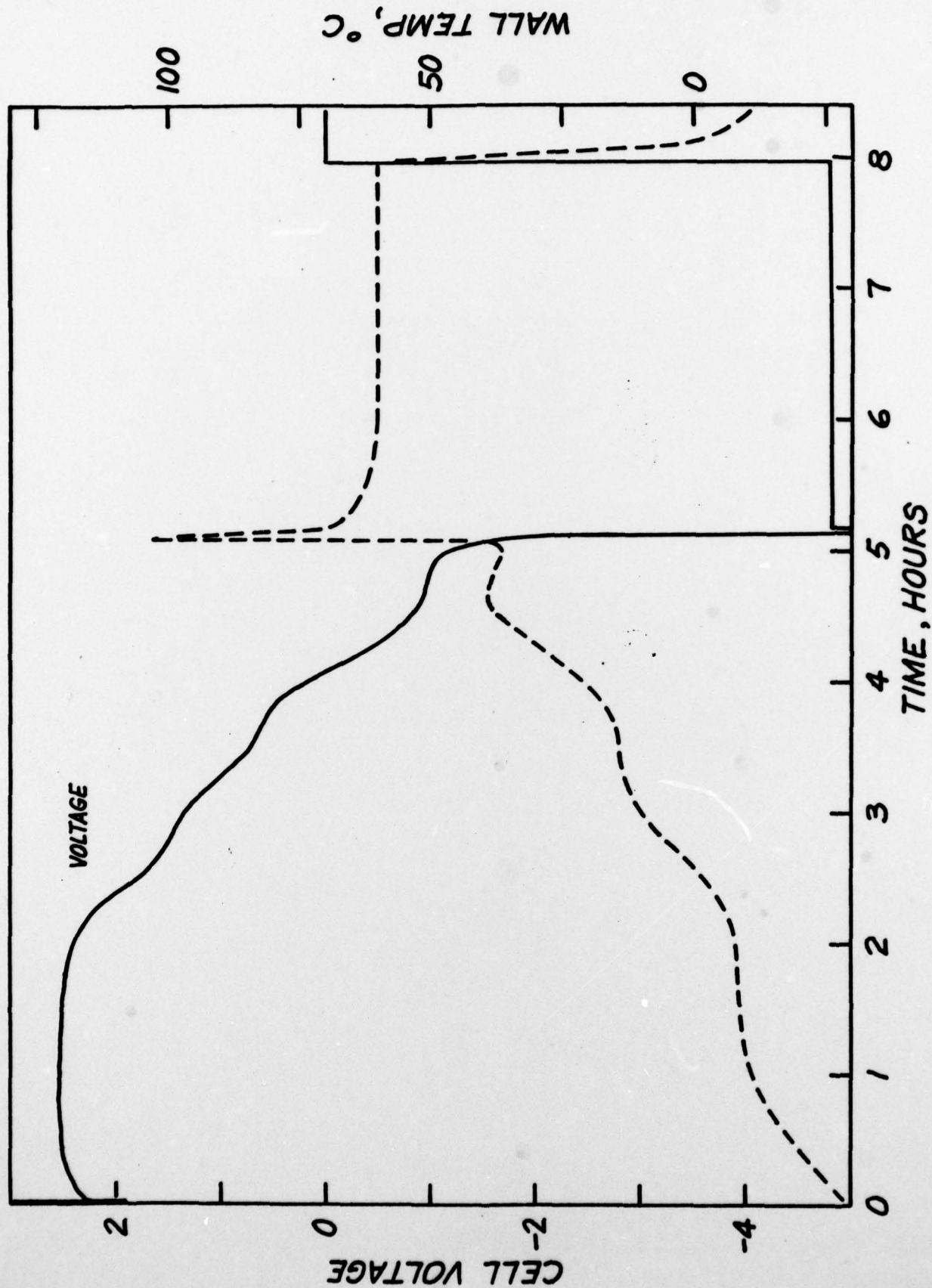


Fig. 16. Classification of Voltage Profiles of LO26S Cells of Various Types on 2A Reversal at  $-30^{\circ}\text{C}$

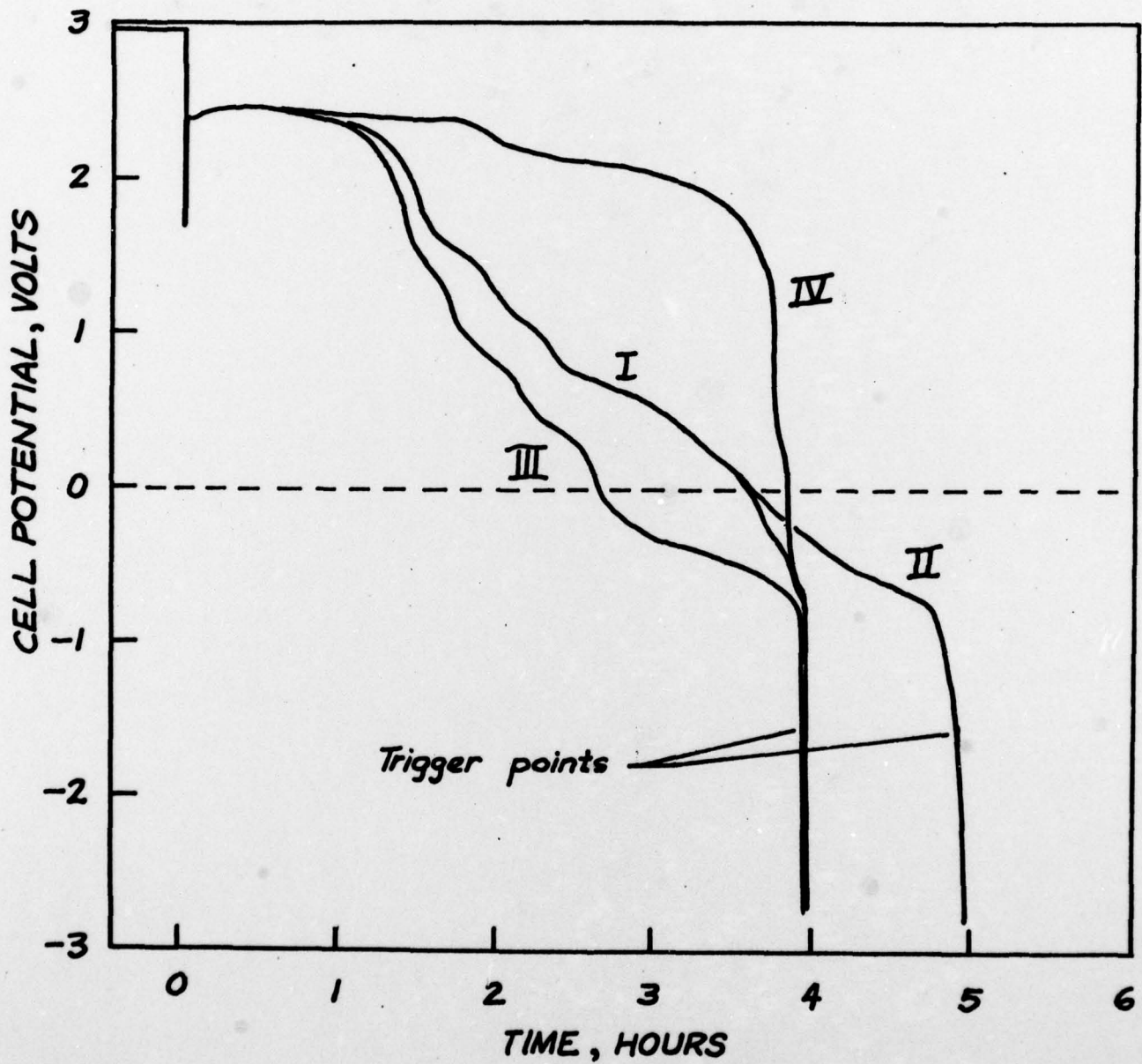


Fig. 17. V&T Profiles on 2A Charging at 25°C of LO26S Cells of Type 3a

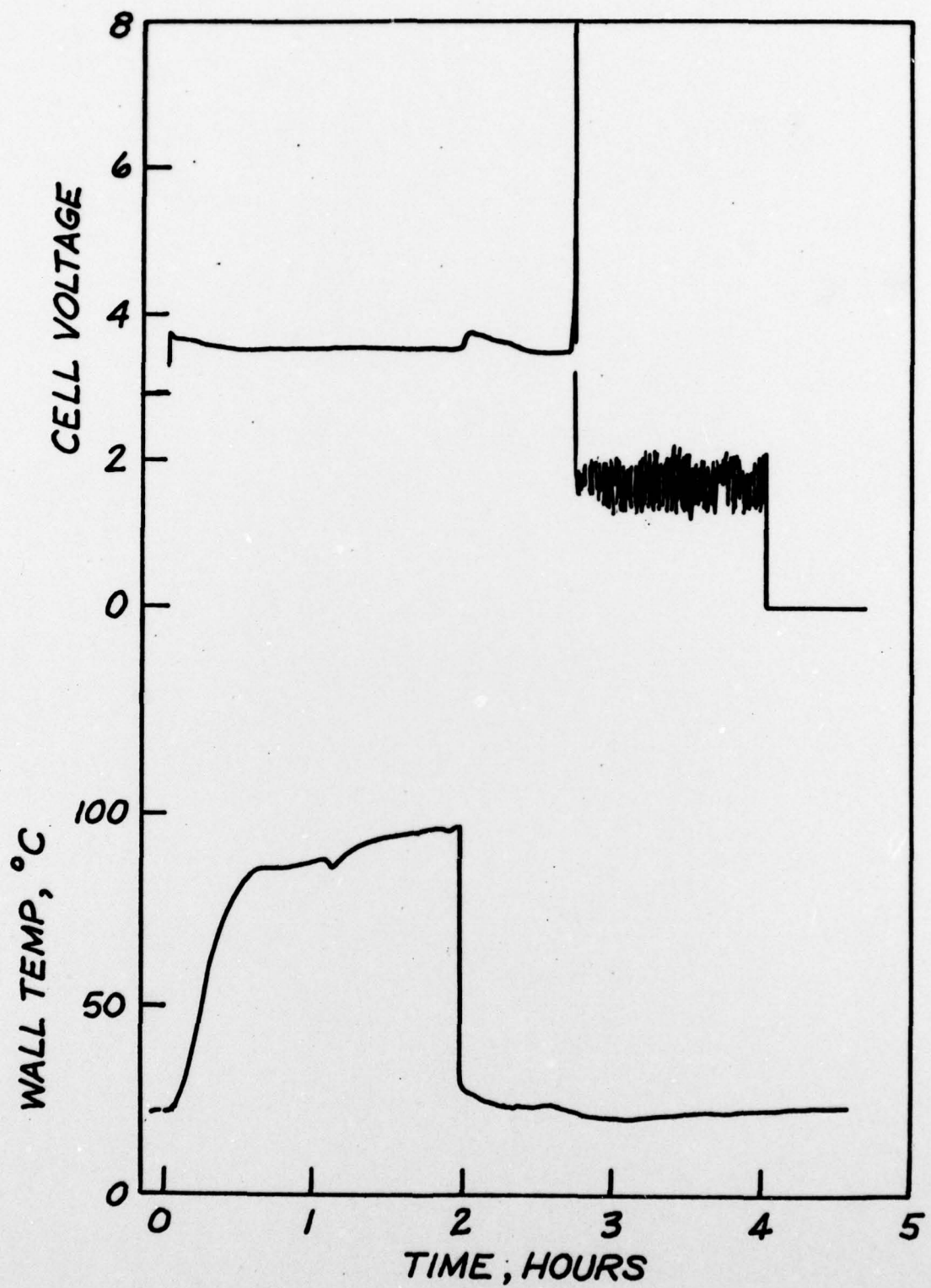
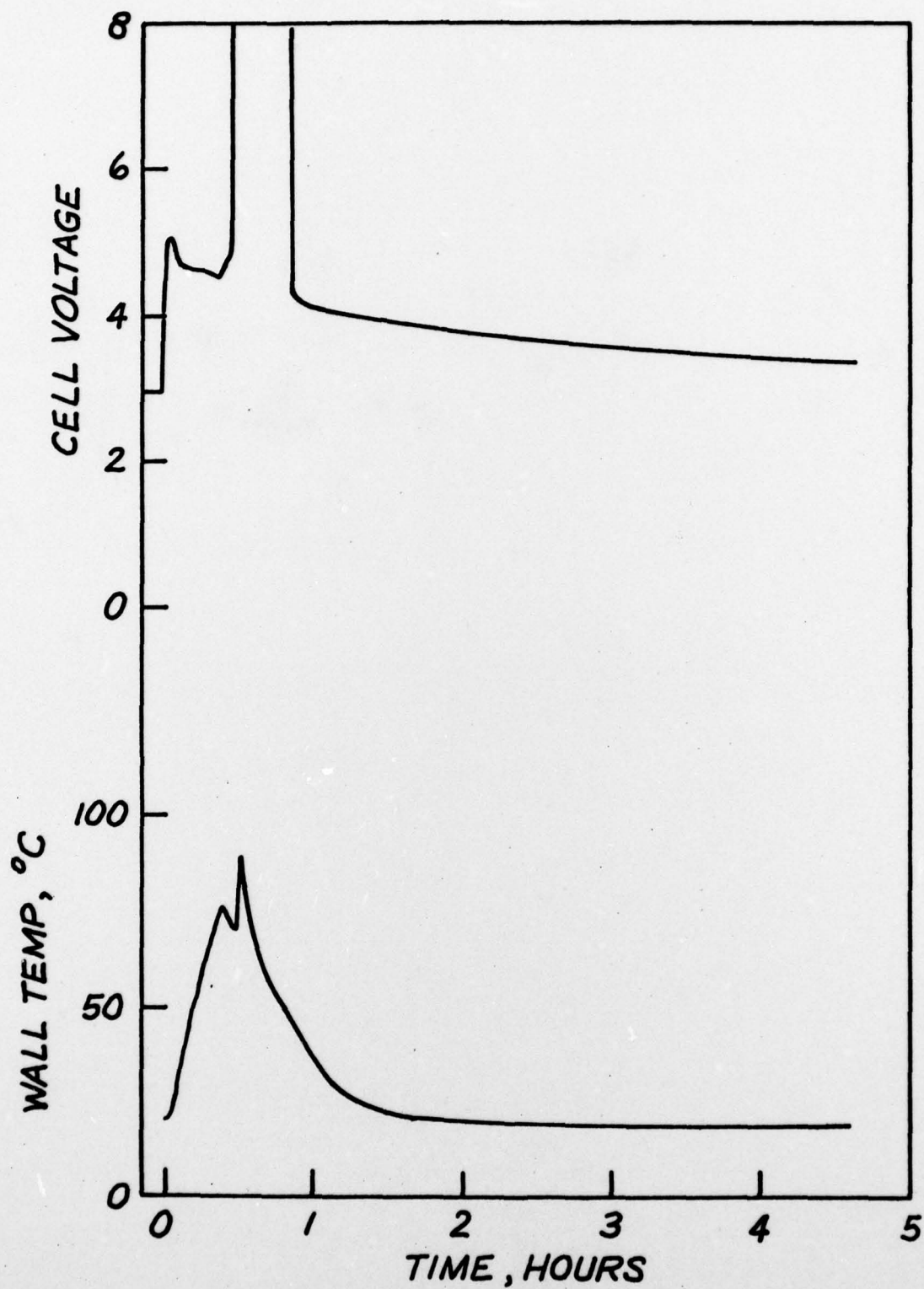


Fig. 18. V&T Profiles on 2A Charging at 25°C of LO26S Cells of Type 1b



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