HEAT DISSIPATION OF HIGH RATE Li-SOCl$_2$ PRIMARY CELLS

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INTRODUCTION

The present investigation is a part of a series of investigation being carried out at JPL and Drexel University to better understand the heat dissipation problem occurring in the lithium thionyl chloride cells discharged at relatively high rates under normal discharge conditions. The earlier work presented at the 168th Electrochemical Society Meeting at Las Vegas[1] identified four heat flow paths, and the thermal resistances of the relating cell components along each flow path were accordingly calculated. From the thermal resistance network analysis, it was demonstrated that about 90 percent of the total heat produced within the cell should be dissipated along the radial direction in a spirally wound cell.

In addition, the threshold value of the heat generation rate at which cell internal temperature could be maintained below 100°C, was calculated from total thermal resistance and found to be 2.8 W. However, these calculatons were made only at the cell components' level, and the transient nature of the heat accumulation and dissipation was not considered. In the present study, a simple transient model based on the lumped-heat-capacity concept has been developed to predict the time-dependent cell temperature at different discharge rates. The overall objectives of the study was to examine the influence of cell design variables from the heat removal point of view under normal discharge conditions and to make recommendations to build more efficient lithium cells.

TRANSIENT ANALYSIS OF HEAT DISSIPATION FROM THE CELL

In the present investigation, the co-called lumped-heat-capacity method has been used instead of solving the energy equation in the cylindrical coordinates system.   As demonstrated in our previous study[1], approximately 90 percent of thermal resistance particularly along the radial direction occurs from the outer wall of the case can to the environment, where heat is removed from the cell by natural convection. In other words, the thermal resistances of cell components along the radial as well as axial direction within the cell are so small that heat will be diffused out quickly throughout the cell, reaching the case can without much delay. This also implies that the internal temperature of the cell may be assumed uniform radially and axially and equal to the cell wall temperature as a first-order approximation.   Hence, it is an ideal problem to apply the lumped-heat-capacity concept to estimate the transient temperature of the cell. Of note is that a more complicated modelling work to take

into account radial and axial temperature variation is being developed and will be reported in the future.

The governing transient heat balance equation becomes

$$\dot{q} = \rho VC \frac{dT(t)}{dt} + hA [T(t) - T_\infty] \qquad (1)$$

where h is the heat transfer coefficient from the cell surface to the environment and ρVC is the so-called thermal mass of the cell. Physically, the first term in the right hand side represents the amount of heat stored within the cell and the second term that dissipated into the environment. Since the amount of heat to be dissipated out by natural convection depends on the temperature difference between the wall and the environment, the heat transfer coefficient h is a function of the cell temperature accordingly. However, in the present study, h is assumed to be constant for the mathematical simplicity.

Using the initial boundary condition, $T = T_\infty$ at $t = 0$, the solution of the above equation becomes

$$T(t) - T_\infty = \frac{\dot{q}}{hA} [1 - e^{\frac{hA}{\rho VC}t}] \qquad (2)$$

where $\dot{q}$ is the heat generation rate to be determined by the discharge rate of the cell. Since hA is the inverse of the thermal resistance R_{SV} between the case can and the environment, it becomes

$$hA = \frac{1}{R_{SV}} = 0.0352 \quad W/^\circ C \qquad (3)$$

Note that the heat transfer coefficient h for the present D-size cell becomes 4.4 $W/m^2 {}^\circ C$, which is a typical value[2] for the case of heat dissipation to the room temperature by natural convection. Also note that for the adiabatic boundary condition which occurs in many military applications of the lithium cells, the second term of the right hand side in Eq. (1) disappears and the corresponding solution becomes

$$T(t) - T_\infty = \frac{\dot{q}}{\rho VC}t \qquad (4)$$

As shown in Eqs. (2) and (4), the thermal mass of the cell PVC is an important parameter in the calculation of the transient cell temperature T. Therefore, the thermal mass of each cell component was calculated based on the JPL's first generation D-size cell specification and shown in Table 1. Values of mass of each cell component, ρV, are the data experimentally measured at JPL and the

specific heats of lithium, nickel and stainless steel were taken from Ref. (3). The specific heat of the electrolyte (i.e., 1.8 M $LiAlCl_4$ in $SOCl_2$, received from Lithium Corporation of America, Lithcoa) was estimated from the work by Venkatasetty[4] and founded to be 1215 J/KgK.

Table 1 shows that about 54 percent of the total thermal mass can be attributed to the electrolyte at the beginning of the discharge. Of note is that near the end of normal discharge, i.e., 80 percent DOD, approximately half of the electrolyte is consumed, thus reducing the thermal mass of the cell correspondingly. In this regard, of note is that a flooded cell may be safer than a starved cell from the heat transfer point of view since the percentage loss of thermal mass in the flooded cell due to the electrolyte consumption is relatively small compared to the case of the starved cell. However, in the present study, the time-dependent effect of the electrolyte consumption was not considered. A complete model to take into account the transient nature of the thermal mass of the electrolyte as well as the heat transfer coefficient h will be developed and reported in the future.

The cell temperature was predicted from Eq. (2) in which the heat generation rate, $\dot{q}$, was calculated from the discharge characteristics curve experimentally obtained at C/2, i.e., see Fig. 1. The resulting cell temperature vs. time is shown in Fig. 2, which also gives the percentage depth of discharge along the abscissa. This figure clearly demonstrates that the cell temperature increases gradually to 100°C for the first 95 min and then suddenly jumps to about 200 250°C within the next 15 min. The horizontal dashed line indicates the maximum allowable cell temperature of 100°C, which is below the melting points of cell components such as sulfur (112°C) and lithium (179°C). The corresponding DOD to the cell temperature of 100°C was approximately 80 percent with the discharge rate of C/2. This indicates that the present cell may be discharged safely at C/2 rate up to 80 percent DOD. Although the time-dependent temperature prediction with the lumped-heat-capacity method was carried out with the constant values of the heat transfer coefficient h and the initial thermal mass ρVC, the resulting temperature showed the actual trend observed in the test of the lithium cell. An IBM-PC based computer code to calculate thermal resistance of cell components and to predict the transient cell temperature including the effect of electrolyte consumption and the temperature-dependent heat transfer coefficient h will be developed and reported accordingly with a detail comparison with experimental data.

FIN ANALYSIS

When the lithium cells are in contact with the environment during the normal discharge, one way to improve heat dissipation from the cell is to add fins around the cell. In so doing, it is important to recognize the conditions for which the finned surface has advantages over the unfinned surfaces. Particularly for aerospace applications, the weight

added, the space needed and the cost of adding fins are of the greatest importance. Also note that the installation of fins on a heat transfer surface will not necessarily increase the heat transfer rate. In general, if the value of 2k/ht is larger than 5, it is advantageous to use fins around the heat transfer surface. Here, k is the thermal conductivity of a fin material, h is the heat transfer coefficient between the fin surface and the environment, and t is the fin thickness. For the present application, h is relatively small, being approximately 4 7 W/m^2°C and k is large, being 16.3 W/m°C for stainless steel and 204 W/m°C for aluminum. Hence, it is clearly advantageous to install fins around the cell.

The proposed fin dimensions in the present study as shown in Fig. 3 are as follows; t(thickness) = 0.04 cm, L(length) = 0.44 cm and H(height) = 5.69 cm same as the height of the D-size cell. The proposed total number of fins is 32. Therefore, the value of 2k/ht for stainless steel fins becomes 18,500, which demonstrates the usefulness of installation of these types of fins. A valid method of evaluating fin performance is to compare heat transfer with the fin to that which would be obtained without the fin. The ratio of the two for a single fin becomes

$$\frac{<\dot{q}> \text{ with fin}}{<\dot{q}> \text{ without fin}} = \frac{\tanh mL}{\sqrt{hA/kP}} \tag{5}$$

where $< >$ indicates a value for a single fin and m is $\sqrt{hP/kA}$. Of note is that when the value of L/(t/2) is equal to or larger than unity, the fin is considered long, in which the heat loss from the fin end surface is negligibly small. In the present study, the value of L/(t/2) becomes 285, which is far beyond the threshold value of one. Hence, the simple solution, Eq. (5), which was derived for the case with an insulated fin end, is valid for the present analysis. Applying the proposed fin dimensions, the ratio in Eq. (5) for a single fin was calculated to be

$$\frac{<\dot{q}> \text{ with fin}}{<\dot{q}> \text{ without fin}} = 21.65 \text{ for a stainless steel fin} \tag{6}$$

Next, the total heat dissipated from the cell with 32 fins was calculated and compared with that without fins. The ratio of the two becomes

$$\frac{\text{total heat dissipated from the cell with 32 fins}}{\text{total heat dissipated without fins}} = 3.4 \tag{7}$$

This indicates that the heat transfer from the cell could be enhanced by a factor of 3.4 when compared with that without fins. This implies that the thermal resistance will be decreased to the one-third of the

present value of 28.4 °C/W. This is a considerable improvement in the heat dissipation from the lithium cell when heat is removed from the cell to the environment by natural convection.

Use of aluminum (k = 204 W/m°C) or copper (k = 385 W/m°C) as a fin material was also examined to see if those materials may further increase the heat dissipation from the cell. However, the fins considered in the present study are too short to show any improvement over the fins made with stainless steel (k = 16.3 W/m°C). For reference, the ratio in Eq. (6) for copper fins was found to be 21.96. Also, when the thickness of fins is doubled to 0.08 cm, the corresponding ratio in Eq. (7) was calculated to be 3.35. Therefore, the heat transfer enhancement with thicker fins (i.e., t = 0.08 cm) is essentially the same that with thinner fins (i.e., t = 0.04 cm).

SUMMARY AND CONCLUSIONS

A simple transient model to predict the time-dependent cell temperature was developed based on the lumped-heat-capacity method. The transient cell temperature predicted from the model for the case of C/2 discharge rate with the JPL's D-size cell indicated a gradual increase of the cell temperature for the first 95 min. Then, for the next 15 min, there was a sharp increase of the cell temperature to about 200~250°C, as was observed in many of experimental test results. This suggests that the present cell may be discharged safely at C/2 discharge rate up to 80 percent DOD while the cell temperature remains below 100°C.

As a practical way of the heat transfer enhancement, the feasibility of installing fins was considered. With the proposed fins in the present study, it was demonstrated that about three times more heat could be removed from the cell. Additionally, the use of aluminum or copper fins, and thicker fins than the present ones was also discussed.

As a final remark, the present analysis is based on the assumption that the cell is in contact with air. Therefore, in some of aerospace applictions of these cells where there is no air, the heat dissipation analysis based on the radiation heat transfer should be carried out.

REFERENCES

1. Y. Cho, S. Subbarao, J.J. Rowlette and G. Halpert, Thermal assessment of high rate Li-SOCl$_2$ primary cells, presented at the 168th Electrochemical Society Meeting, Las Vegas, Oct. 1985. (Extended Abstracts, ,Vol. 85-2, pp. 169-170).

2. J.P Holman, "Heat Transfer," McGraw-Hill, New York (1981).

3. Handbook of Tables for Applied Engineering Science, R.E Bolz and G.L. Tuve, Editors, CRC, Cleveland (1970).

4. H.V. Venkatasetty, Final Report to Naval Ocean Systems Center, E47992, Dec. (1982).

Table 1. THERMAL MASS OF CELL COMPONENTS

	ρVC (W·S/°C)	%
Lithium	19.5	20
Nickel	6.7	6.8
Stainless Steel	19.2	20
Electrolyte	53.0	54
Others	0	0
Total	98.4	100%
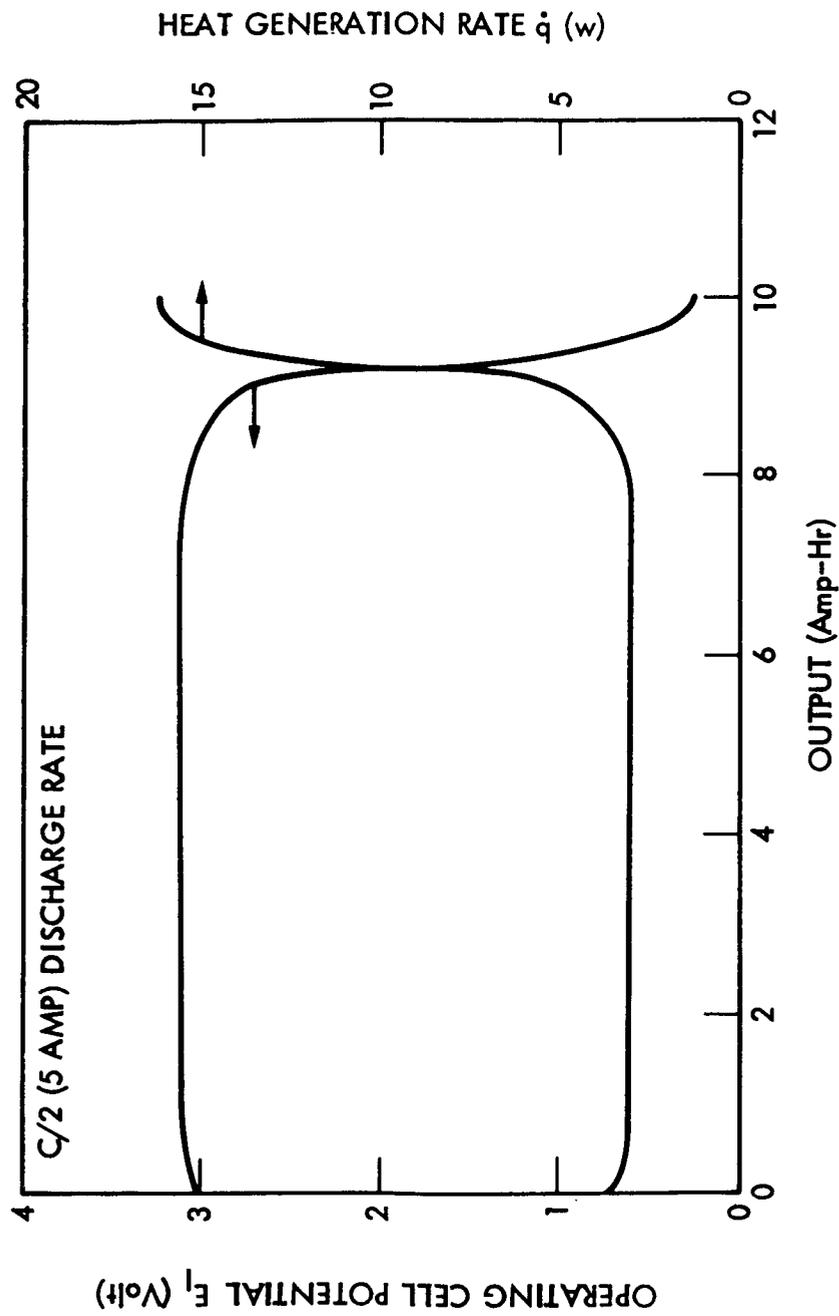
Figure 1. DISCHARGE CHARACTERISTICS OF JPL'S D-SIZE CELL AT C/2 RATE AND THE CORRESPONDING HEAT GENERATION RATE CALCULATED BASED ON $q = I(E_H - E_I)$, WHERE E_H IS THE THERMONEUTRAL POTENTIAL, 3.72 VOLT
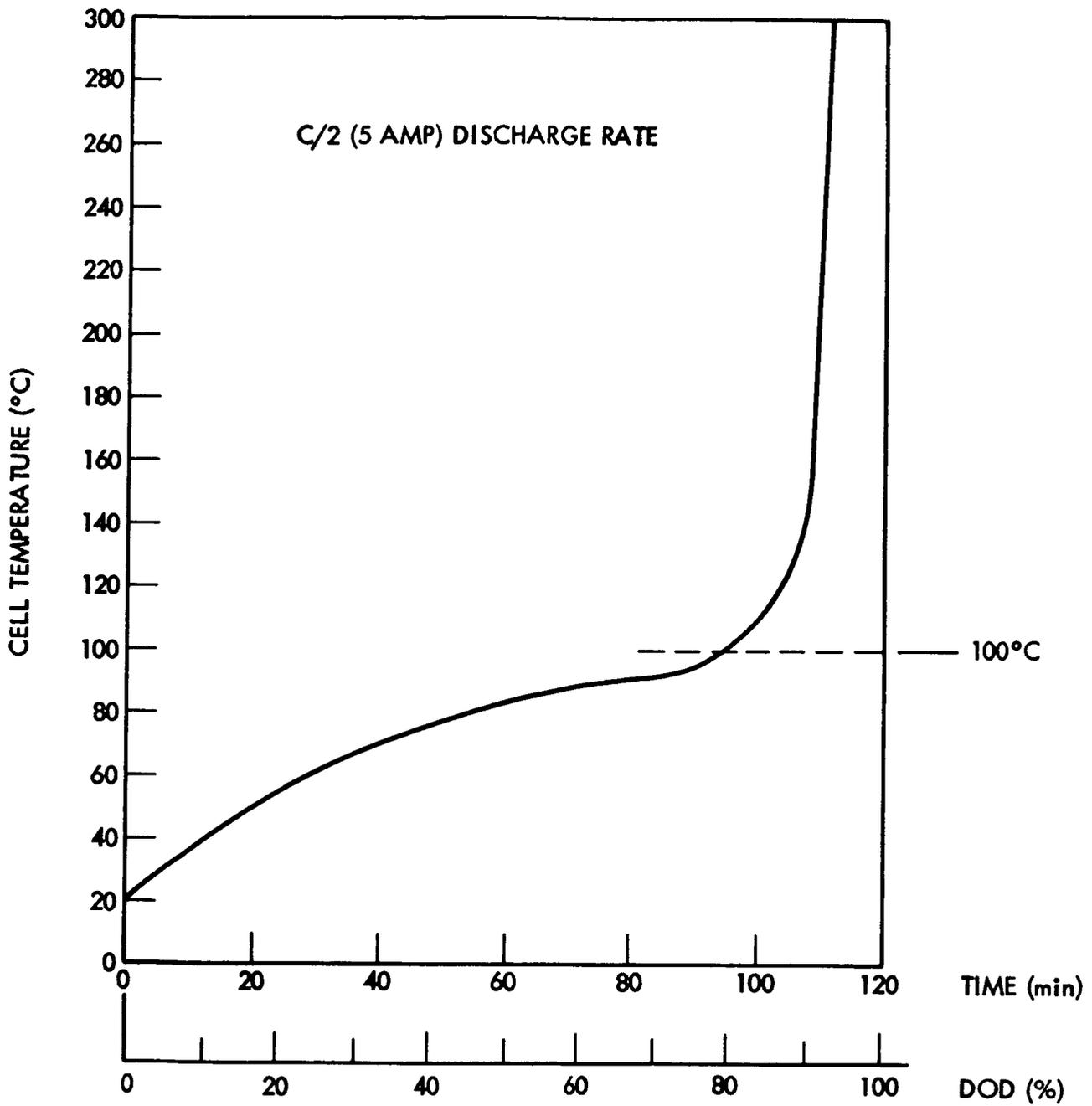
Figure 2. CELL TEMPERATURE PREDICTION FROM THE TRANSIENT MODEL, EQ. (1)

THICKNESS = 0.04 cm

THICKNESS = 0.04 cm

H = 5.69 cm

LENGTH = 0.44 cm
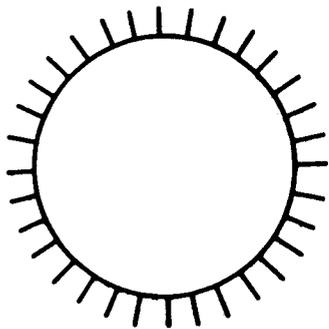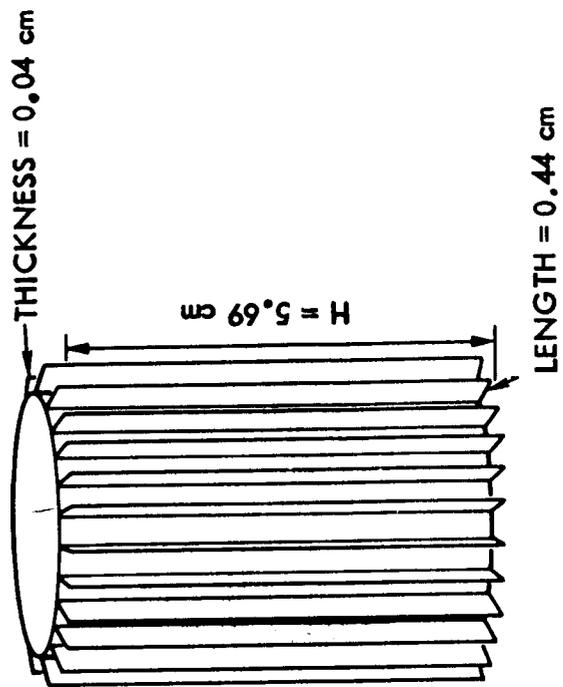
TOP VIEW (32 fins)

Figure 3. TOP VIEW AND SKETCH OF 32 FIN ARRANGEMENTS