

HEAT DISSIPATION OF HIGH RATE Li-SOCl₂ PRIMARY CELLS

YOUNG I CHO

Drexel University, Philadelphia, PA 19104 (U S A)

GERALD HALPERT

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109 (U S A)

Summary

A simple transient heat dissipation model based on the lumped-heat-capacity concept was developed to predict the time-dependent cell temperature at different discharge rates and compared with experimental results. This model predicts that at the C/2 rate a "D" cell temperature will remain below catastrophic levels (<100 °C) only to 80% DOD. Calculations show that the installation of fins improves the heat dissipation rate by a factor of at least 3.

Introduction

The present investigation is a part of a series of investigations being carried out at JPL and Drexel University to understand better the heat dissipation problem occurring in lithium-thionyl chloride cells discharged at relatively high rates under normal discharge conditions. Earlier work [1] identified four heat flow paths; the thermal resistances of the relevant 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. These calculations were made only at the cell component level, however, 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 were to examine the influence of cell design variables from the heat removal point of view under normal discharge conditions and to make recommendations for more efficient lithium cell designs.

Transient analysis of heat dissipation from the cell

In the present investigation, the so-called lumped-heat-capacity method has been used instead of solving the energy equation in the cylindrical coordinate system. As demonstrated in our previous study [1], approximately 90% of thermal resistance, particularly along the radial direction, occurs from the outer wall of the can to the environment, where heat is removed from the cell by natural convection and radiation. In other words, the thermal resistances of cell components along the radial as well as the axial direction within the cell are so small that heat will be diffused out quickly throughout the cell, reaching the 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 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

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

where \dot{q} is the heat generation rate, 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 depends on the temperature difference between the wall and the environment, the heat transfer coefficient, h , is a function of the cell temperature. In the present study, however, h is assumed to be constant for mathematical simplicity.

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

$$T(t) - T_{\infty} = \frac{\dot{q}}{hA} \left[1 - \exp\left(-\frac{hAt}{\rho VC}\right) \right] \quad (2)$$

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 can and the environment, it is

$$hA = \frac{1}{R_{sv}} = 0.0352 \text{ W } ^\circ\text{C}^{-1} \quad (3)$$

Note that the heat transfer coefficient, h , for the present D-size cell is $4.4 \text{ W/m}^2 \text{ } ^\circ\text{C}$, which is a typical value [2] for the case of heat dissipation to room temperature by natural convection and radiation. 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 eqn. (1) disappears and the corresponding solution is

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

As shown in eqns. (2) and (4), the thermal mass of the cell, ρVC , 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 JPL's first generation D-size cell specification and is shown in Table 1. Values of the mass of each cell component, ρV , were experimentally measured and handbook [3] values of the specific heats of lithium, nickel and stainless steel used. 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 Venkatesetty [4] and found to be 1215 J/kg K.

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

Table 1 shows that about 54% 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% DOD, approximately half of the electrolyte is consumed, thus reducing the thermal mass of the cell correspondingly. In this regard, note 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 with the case of the starved cell. In the present study, however, the time-dependent effect of the electrolyte consumption was not considered.

The cell temperature was predicted from eqn. (2) in which the heat generation rate, \dot{q} , was calculated from the discharge characteristics experimentally obtained at $C/2$, see Fig. 1. The resulting cell temperature *versus* time is shown in Fig. 2, which also gives the percent. 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

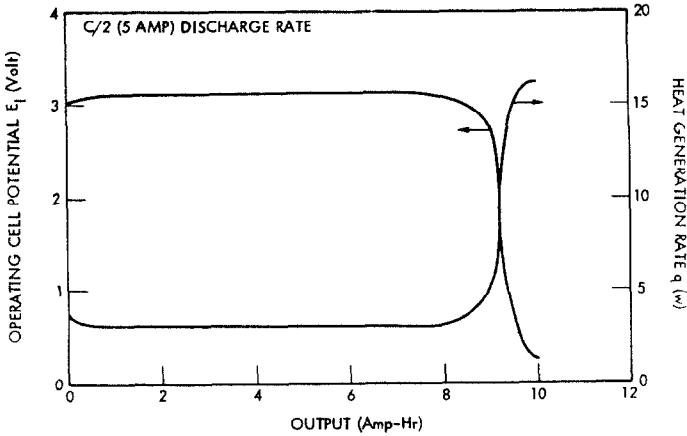


Fig 1 Discharge characteristics of JPLs D-size cell at $C/2$ rate and the corresponding heat generation rate calculated, based on $\dot{q} = I(E_H - E_I)$, where E_H is the thermoneutral potential, 3.72 V

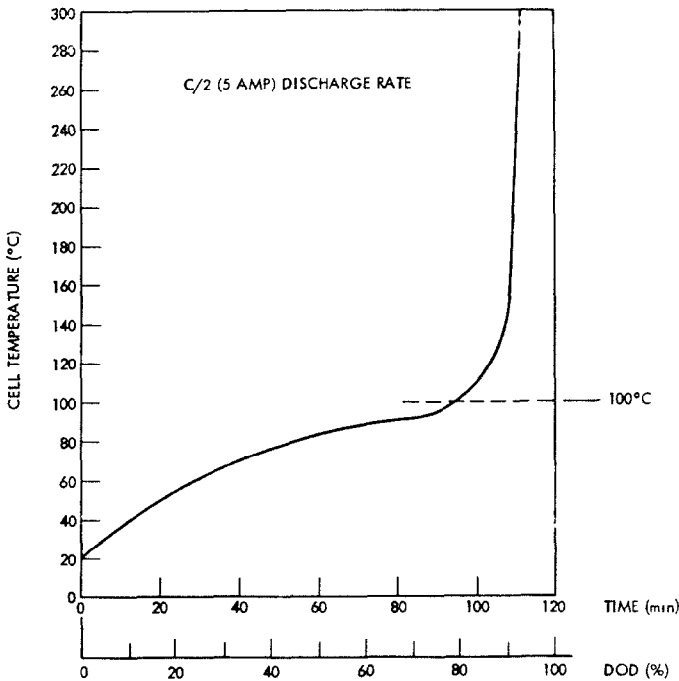


Fig 2 Cell temperature prediction from the transient model, eqn (1)

the melting points of cell components such as sulfur (112 °C) and lithium (179 °C) The DOD corresponding to the cell temperature of 100 °C was approximately 80% with the discharge rate of $C/2$. This indicates that the present cell may be discharged safely at the $C/2$ rate up to 80% 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. A complete computer based model to calculate the thermal resistance of the 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 in the future along with a detailed 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 $4.4 \text{ W/m}^2 \text{ }^\circ\text{C}$ and k is large, being $16.3 \text{ W/m }^\circ\text{C}$ for stainless steel and $204 \text{ W/m }^\circ\text{C}$ 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 , the same as the height of the D-size cell. The proposed total

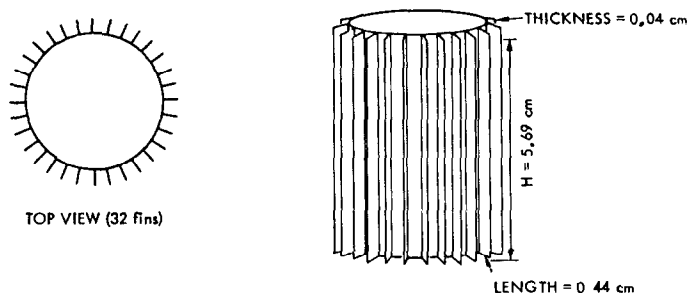


Fig 3 Top view and sketch of 32 fin arrangements

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 with that which would be obtained without the fin. The ratio of the two for a single fin becomes

$$\frac{\langle \dot{q} \rangle \text{ with fin}}{\langle \dot{q} \rangle \text{ without fin}} = \frac{\tanh mL}{(hA/kP)^{1/2}} \quad (5)$$

where $\langle \rangle$ indicates a value for a single fin and m is $(hP/kA)^{1/2}$. 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, eqn. (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 eqn. (5) for a single fin was calculated to be

$$\frac{\langle \dot{q} \rangle \text{ with fin}}{\langle \dot{q} \rangle \text{ without fin}} = 21.65 \text{ for a stainless steel fin} \quad (6)$$

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

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

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 one-third of the present value of $28.4 \text{ }^\circ\text{C W}^{-1}$. 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.

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

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 JPLs 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 cell temperature to about $200 - 250 \text{ }^\circ\text{C}$, as was observed in many experimental test results. This suggests that the present cell may be dis-

charged safely at the $C/2$ discharge rate up to 80% DOD while the cell temperature remains below $100\text{ }^{\circ}\text{C}$.

As a practical way of 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 examined and found to offer no advantage.

Finally, the present analysis is based on the assumption that the cell is in contact with air. Therefore, in some aerospace applications of these cells where air is absent, heat dissipation analysis based on the radiation heat transfer only should be carried out.

Acknowledgement

The first author acknowledges the support from the Jet Propulsion Laboratory, California Institute of Technology.

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 R E Bolz and G L Tuve (eds), *Handbook of Tables for Applied Engineering Science*, CRC, Cleveland, OH, 1970
- 4 H V Venkatesetty, *Final Report to US Naval Ocean Systems Center, E47992*, Dec, 1982