# Internal impedance of nickel–cadmium batteries with applications to space

D. Lahav and J. Appelbaum
*Tel Aviv University, Faculty of Engineering, Tel Aviv 69978 (Israel)*

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## Abstract

A study of the internal impedance of a 7 A h, SAFT VO7S4, Ni–Cd battery cycled under low earth orbit conditions at high current rates and low temperatures is presented. The tested battery consist of three cells selected from a group of fifty well matched cells. The study presents a relationship between the battery internal impedance, the state of charge and the operating temperature. This relationship may be used as an indicator for the battery state of charge during missions in space.


## Introduction

The internal impedance of an electrical battery is an important parameter affecting the battery terminal voltage at charge and discharge states of the battery [1, 2]. Knowing the value of the internal impedance enables the power subsystem designer to determine the changes in the battery voltage. This is especially important in unregulated main bus voltage systems. When the charge method used for battery charging is of the 'end of charge voltage' type, the voltage drop owing to the internal impedance has to be compensated in order to charge the battery to a full state of charge.

The internal impedance of the battery is affected by several factors of which the most important are the battery state of charge [1, 3, 4], battery operating temperature [1, 2] and battery ageing. The interrelation between these factors can be used to formulate a relationship between the internal impedance and the battery state of charge to serve as a charge indicator.

The purpose of this article is to determine the internal impedance of a Ni–Cd battery based on battery tests for low earth orbit (LEO) applications. The relationship between the internal impedance, the battery state of charge and operating temperature are essential to predict the battery performance within the power system of LEO missions. The study was carried out on Ni–Cd 7 A h SAFT VO7S4 prismatic cells under LEO conditions at high currents and low temperatures. A complete study on the battery was performed which included, among others, the internal impedance.

## Experimental

### *Cycling test*

The cycling tests on each cell were divided into two groups with approximately 2500 cycles per group. In the first group the cycling tests were performed with 25%

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depth of discharge at a constant temperature of 7.5 °C. The charging method used was tapering current with 1.5 V per cell as the end of charge voltage. The maximum charge current was $C/2$ and the discharge current was kept constant at the level of $C/2$. In the second group (approximately between 2500 and 5000 cycles) the cycling tests were performed with 37% depth of discharge in the temperature range of 3 to 8 °C. The tapering current charge method was again used with a maximum charge current of 1 C and an end of charge voltage of 1.47 V per cell. The discharge current was kept constant at the value of 0.6 C. After each group of cycling tests, various measurements on the battery were performed at temperatures of 3, 7.5 and 13 °C. This include open-circuit voltage, capacity test and internal impedance test.

*Internal impedance measurements*

The tests for measuring the internal impedance of the battery were performed at different temperatures and different states of charge. A distinction was made between a battery in an operating system and a disconnected battery.

Measurement of the internal impedance may be done by either applying a d.c. current step [1, 2, 3–5] or a sinusoidal current wave [1, 6, 7]. In the present tests we used a sinusoidal current wave. The internal impedance was determined by dividing the r.m.s voltage across the terminals of each cell by the r.m.s applied current. A KEPCO BOP50M8 was used as a current source. The amplitude and frequency of the current was controlled by a function generator model HP 8111 A.

In order to obtain a relationship between the internal impedance and the state of charge, the internal impedance test was carried out at different states of charge. The battery was discharged in steps of 0.1 C charge down to 1 V. The test started with a fully charged battery obtained in three current steps of $C$, $C/2$, $C/5$ reaching an average cell voltage of 1.5 V.

*Disconnected battery*

Each test was performed at three different temperatures of 3, 7.5 and 13 °C after the following number of battery cycles: 0, 665, 1165, 1642 and 2168. The amplitude of the sinewave was set to 5 A r.m.s at a frequency of 190 Hz.

*Connected battery*

We have investigated the effect of the amplitude and frequency of the sinewave on the battery internal impedance. The tests were performed at temperatures of 3 and 13 °C after 5500 battery cycles. The amplitude of the sinewave was set to 1 and 2 A r.m.s, at frequencies of 90, 190 and 570 Hz, and battery charge current of 1 and 2 A.

## Results and discussion

*Disconnected battery*

Some of the test results are shown in Figs. 1 and 2. Figure 1 describes the relationship between the internal impedance and the state of charge of an average cell for a cell temperature of 7.5 °C and a different number of battery cycles. For other temperatures, the results are similar. Figure 2 shows the relationship between the internal impedance and the state of charge for an average cell after 665 battery cycles at different temperatures. For a different number of cycles, the results are similar.

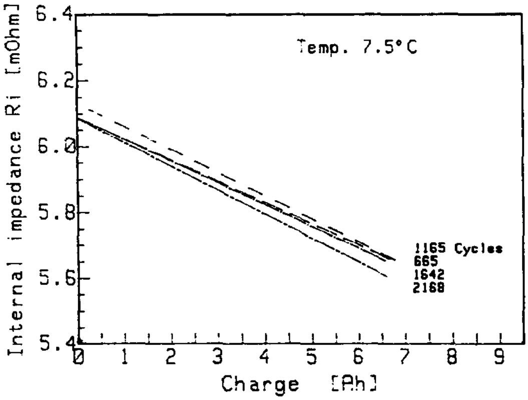


Fig. 1. Internal impedance of the battery, at temperature of 7.5 °C, as a function of the state of charge and number of cycles.

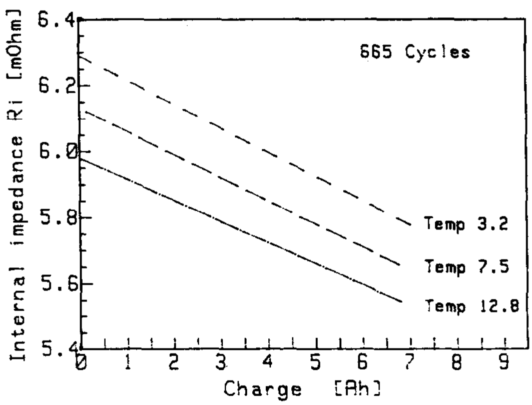


Fig. 2. Internal impedance of the battery after 665 battery cycles as a function of the state of charge and temperature.

All test results that were performed on a disconnected battery are summarized in Fig. 3. These results show the relationship between the battery internal impedance as a function of the state of charge for temperatures of 3, 7.5 and 13 °C. The points are scattered due to variations in temperature and state of charge measurements during the tests.

The tests results were fitted to an empirical equation describing the internal impedance as a function of the temperature and the state of charge.
The fitted equation is of the form:

$$R_i = K_0 + K_1 T + (K_2 + K_3 T) \cdot SOC \tag{1}$$

where $R_i$ = calculated internal impedance (mΩ), $K_i$ = fitting coefficients, $T$ = temperature, $SOC$ = state of charge.

The numerical values of the fitting coefficients applied to the results of Fig. 3 are : $K_0 = 6.34280595572$, $K_1 = -0.0301009723097$, $K_2 = -0.0818870983468$, $K_3 = 0.00166432204812$. The full lines describe the fitted equation for temperatures of 3, 7.5 and 13 °C. A good correlation of 0.986 was obtained with a confidence level

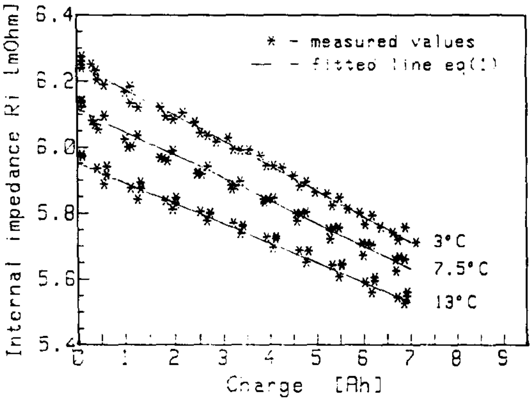


Fig. 3. Comparison of measured and calculated internal impedance. Dependence of the internal impedance on the state of charge of a battery.

of 95%. The maximum and average confidence interval are 1.31% and 0.56%, respectively. The maximum and average error are 1.29% and 0.41%, respectively. The dependence of the internal impedance on the number of cycles (see Fig. 1) may be expressed by adding the term $K_4 \times$cycles to eqn. (1). The numerical value for $K_4$ is $K_4 = 5.2707$ E–6. The contribution of this term, however, to the internal impedance is negligible.

For known coefficients $K_0$–$K_3$, state of charge and battery operating temperature during the mission in space, the internal impedance may be determined by eqn. (1). The internal impedance may then be used in the battery end of charge voltage equation [1, 8] given by:

$$E_{ocv} = E_{oc} + \alpha_{vt} T + I_c R_i \tag{2}$$

where $E_{ocv}$ = calculated end of charge voltage at temperature $T$ and charging current $I_c$, $E_{oc}$ = end of charge voltage at zero temperature and zero charging current, $\alpha_{vt}$ = cell voltage change with temperature coefficient.

By rearranging eqn. (1) we obtain the battery state of charge:

$$SOC = \frac{R_i - K_0 + K_1 T}{K_2 + K_3 T} \tag{3}$$

Equation (3) can be used as an indicator for the battery state of charge during the mission in space. For this purpose the internal impedance must be measured during the mission. This may be accomplished by an additional electronic circuit. A sinusoidal $I_s$ current at a given frequency may be accomplished in the same electronic circuit by modulating the control voltage of the charge current shunt regulator. The state of charge is determined for the measured operating temperature and the internal impedance of the battery in space. The coefficients $K_0$–$K_3$ are determined by the battery tests on the ground.

The results of many tests show the following characteristics:

(i) the internal impedance decreases linearly with increasing the state of charge [1];

(ii) the internal impedance decreases with increasing the battery temperature [1];

(iii) the dependence of the internal impedance on the number of battery cycles is very small for the depth-of-discharge used in the experiments.

*Connected battery*

Some of the test results are shown in Figs. 4–6. The Figures describe the relationship between the internal impedance and the state of charge for an average cell. The frequency, charge current $I_c$ and the amplitude of the sinusoidal current $I_s$ are shown in the respective figures. The asterisks represent the measured values and the full line represents the fitted equation of the form eqn. (1) with a correlation of 0.995. The results of many tests show again, as in the previous section, that the internal impedance decreases linearly (i) with increasing the state of charge and (ii) with increasing temperature of the battery.

The effect of the frequency of the sinusoidal test current on the internal impedance is shown in Fig. 7 for $I_c = 2$ A, $I_s = 2$ A and $T = 3$ °C. Results of many tests with different $I_c$, $I_s$ and $T$ show that the internal impedance decreases with increasing frequency. The reactance is capacitive [1, 2, 4] and increases with increasing depth of discharge [1, 2, 7]; the maximum change in the phase shift is about 2°. The phase shift for 570 Hz is about −10°. The effect of the frequency of the sinusoidal test current on the internal impedance is rather small both in magnitude and in phase

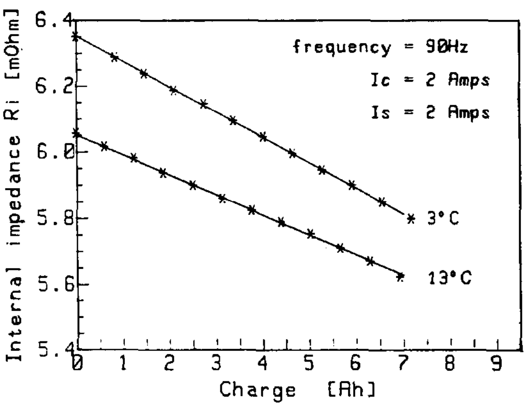


Fig. 4. Internal impedance as a function of the state of charge at charge current $I_c$ of 2 A and frequency of 90 Hz.

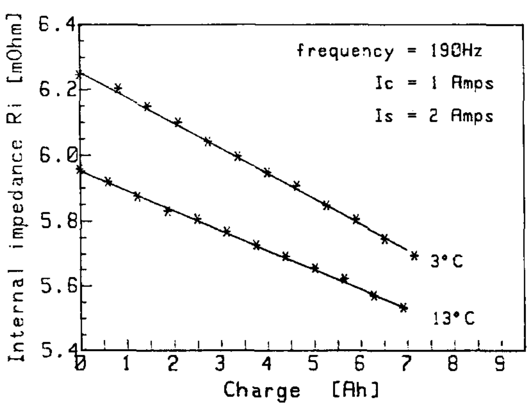


Fig. 5. Internal impedance as a function of the state of charge at charge current $I_c$ of 1 A and frequency of 190 Hz.

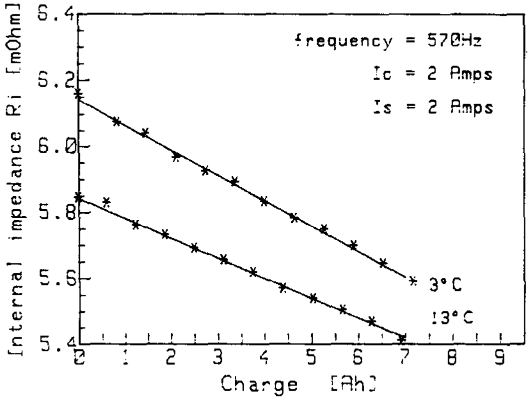


Fig. 6. Internal impedance as a function of the state of charge at charge current $I_c$ of 2 A and frequency of 570 Hz.

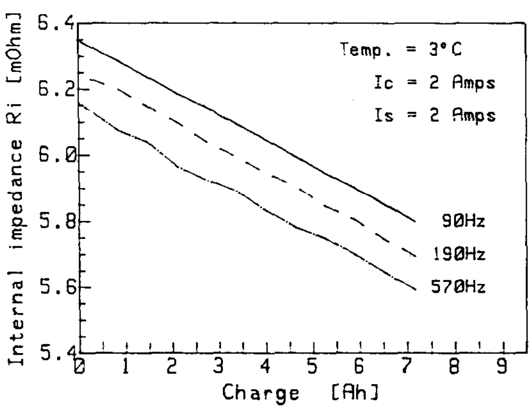


Fig. 7. Internal impedance as a function of the state of charge and the frequency.

shift in the range of frequencies under study. The internal impedance of the battery is mostly resistive. The internal impedance increases slightly with increasing of the amplitude of the sinusoidal test current, and the magnitude of the battery charge current has a minor effect on the internal impedance.

## Conclusions

The internal impedance tests results were fitted to an empirical equation describing the impedance as a function of state of charge and temperature. A good correlation of 0.98 was obtained with a confidence level of 95%. The maximum confidence interval was 1.31%. This empirical equation enables the battery state of charge to be calculated, after measuring the internal impedance and the temperature during the battery charging. The constants in eqn. (3) are obtained after a few tests of the internal impedance as a function of the state of charge and temperature. It was confirmed that the internal impedance of the cells decreases with increasing state of charge and temperature of the battery.

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