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Performance of the SAC-C satellite electricity storage system

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ABSTRACT

The analysis of telemetry data of the Argentine electricity storage system SAC-C satellite is presented. Diagnostic indicators were established in order to evaluate the in-flight performance of the satellite nickel-hydrogen batteries. The state of charge of the batteries was related to the hydrogen pressure. A predictive analysis allowed us to detect early failure of the electricity storage system.

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1. Introduction

The Argentine SAC-C satellite (Satellite of Scientific Application) uses nickel-hydrogen batteries to store electric energy in its power system. The satellite orbits the earth at an altitude of 705 km, performing 14.7 orbits each day at a speed of 7 km/s. Each flight path lasts 98 min, from which 64 min are under sunlight and 34 min in the dark (eclipse). During the light period the sun energy is converted into electricity by the solar panels. During the eclipse the energy is provided only by the batteries.

The nickel-hydrogen battery is a hybrid system that combines advanced technologies of batteries and fuel cells [1–3]. The nickel hydroxide positive electrode is the same as that used in Ni-Cd and Ni-MH alkaline batteries, and the hydrogen negative electrode is a gas-diffusion porous electrode catalyzed with platinum similar to those used in alkaline fuel cells. This type of battery is widely used in space technology because of its high reliability, high specific energy (60 Wh/kg), long cycle life (30,000 cycles at 40% depth of discharge), high tolerance to overcharge and mostly for its ability to determine the actual state of charge via pressure measurement [4,5].

In this work, results of the processing and analysis of telemetry data from the SAC-C satellite Ni-H_2 batteries are presented. The investigations have allowed us to determine diagnostic indicators (DI) to daily check the performance of the electricity storage system of the satellite.

2. Experimental

The satellite electricity generation and storage system consists of two solar panels, with a peak generation of 712 W and average generation of 500 W at beginning-of-life, and two Ni-H_2 batteries connected in parallel. Each battery has eleven cells connected in series. These cells (Eagle Picher RNHC-12-3) are of the common pressure vessel (CPV) type, in which there are two unit cells connected in series that share the container. The cells have a nominal capacity of 12.8 Ah (at 10 °C) and a voltage of 2.5 V.

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The remote measurement of the working parameters of the battery (voltage, current, hydrogen pressure and temperature) involves telemetry. From each battery the current, total battery voltage, half battery voltage, two temperatures and two hydrogen pressures (in two single cells) are measured. The measure of each of these variables is stored every 8 s, therefore 13,000 points of each variable are generated every day. By analyzing and processing these variables, two DIs were determined. The DIs allow evaluating the performance of the electricity storage system.

3. Results and discussion

The overall reaction that takes place in the Ni-H_2 battery during a charge-discharge cycle is

$$Ni(OH)_2 \leftrightarrow NiOOH + \frac{1}{2}H_2 \quad (1)$$

The reaction that occurs at the positive electrode is

$$Ni(OH)_2 + OH^- \leftrightarrow NiOOH + H_2O + e^- \quad (2)$$

and at the negative electrode

$$H_2O + e^- \leftrightarrow \frac{1}{2}H_2 + OH^- \quad (3)$$

As can be seen from reaction (1), hydrogen is generated in the charge reaction and is consumed in the discharge reaction. Thus, the state of charge (SOC) can be followed by measuring the hydrogen pressure. To correlate the hydrogen pressure (P) with the SOC, the diagnose indicator $\Delta P/Q$ (psi/Ah) is used, which indicates the hydrogen pressure variation (ΔP) per unit of circulated charge (Q). The $\Delta P/Q$ is calculated from telemetry data by dividing the pressure change during discharge by the total charge delivered by the battery on each orbit and averaging the values for the day. At constant temperature, the DI should be constant for proper behavior.

As the inner cell temperature may vary within a few degrees as a result of several factors, which will be described below, a small variation of the DI as a function of temperature is accepted. Therefore, any departure from the expected values would indicate probable failures occurring in the battery. Fig. 1 shows the variation of the battery capacity on one telemetry day calculated from the $\Delta P/Q$. It can be seen that the capacity at full SOC is higher than the capacity established by the manufacturer [5]. The depth of discharge is ca. 15% and under this condition a lifetime of about 70,000 charge/discharge cycles is expected, while the SAC-C had performed only ca. 59,000 cycles to date. From Fig. 1 it can be seen that the capacity values go through a series of maxima and minima on each day corresponding to the orbits of the satellite. An average of the maximum and minimum values can then be used as an estimation of the values for the day.

The charge efficiency (CEF) DI indicates the difference between the total charges delivered (discharge) and received (charge) by the battery during the day. Fig. 2 shows the daily average charges delivered and received by the battery. The CEF allows one to diagnose deficiencies in the charge system

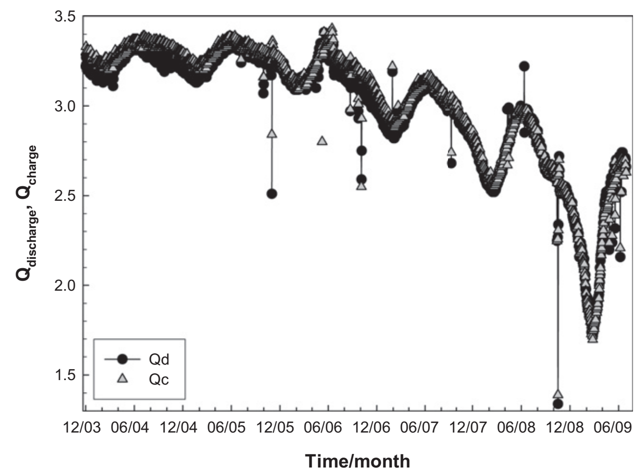

Fig. 2 – Time evolution of the daily average charge delivered and received by the battery starting on 12/03.

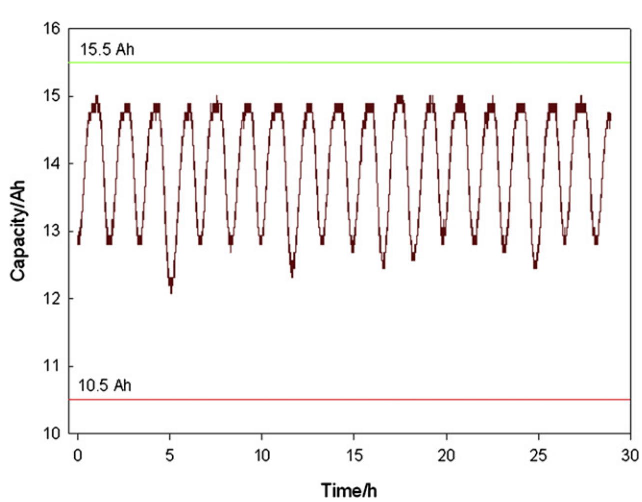

Fig. 1 – Battery capacity corresponding to 09/01/09 calculated from the DI $\Delta P/Q$.

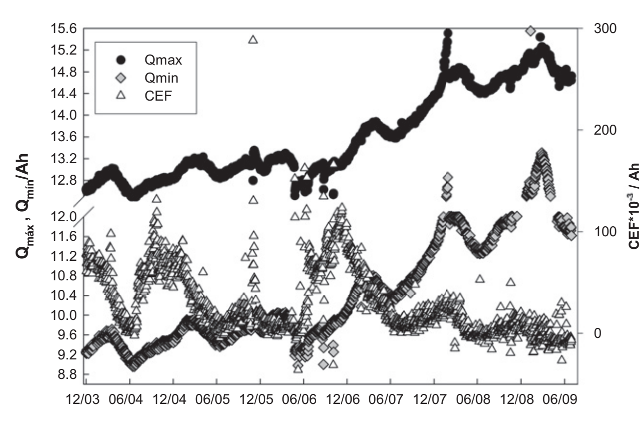

Fig. 3 – Variation of daily average values of CEF and maximal and minimal capacities with time starting on 12/03.

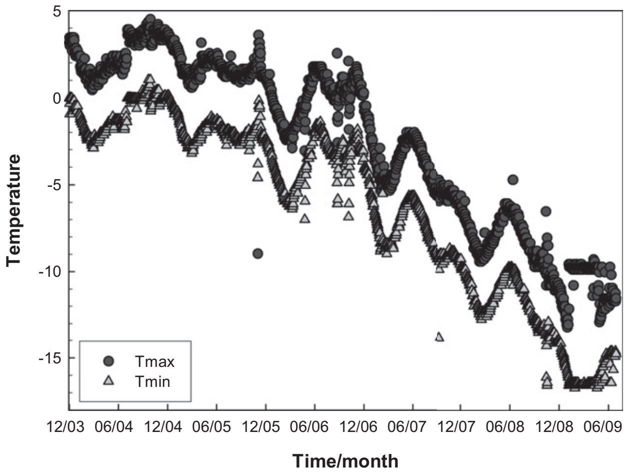

Fig. 4 – Daily variation of maximal and minimal temperature values with time starting on 12/03.

of the battery and then to take corrective actions in order to maintain the capacity in a safe range of operational values.

Fig. 3 shows the change of both daily average values of maximal and minimal capacities and CEF as a function of time. As the relationship between the capacities and the CEF depends upon the SOC and temperature, a clear correlation cannot be derived. Since November 2002 the SAC-C satellite has been operating with only one battery, so the operating conditions have become more demanding. The charge and discharge currents were doubled and then, the control of the temperature became difficult since the heat generated in the battery cannot be removed. Under these conditions the variations in temperature can be attributed to several factors, such as a chemical reaction associated with the overcharge reaction (alkaline water electrolysis) and the Joule effect, both being the most important sources of heat release. During the charge process and before the 100% SOC is reached, a parallel reaction called overcharge starts, by which oxygen is produced at the positive electrode. This reaction is very harmful to the battery because the oxygen gas bubbles trapped in the electrolyte can react chemically with hydrogen gas at the catalytic negative electrode to produce micro-explosions, creating small burn holes [6,7]. The overcharge

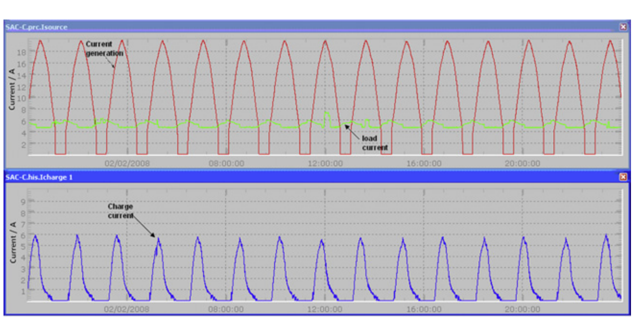

Fig. 5 – Daily variation of current generation by solar panels, current loads and current delivered by the battery before satellite repositioning.

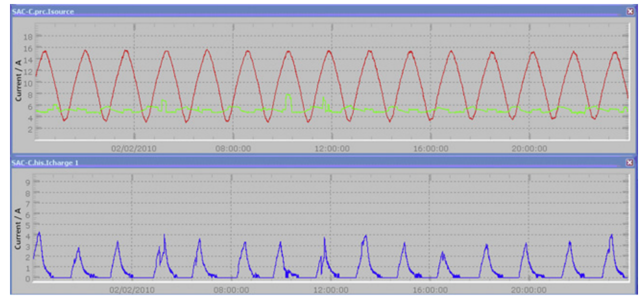

Fig. 6 – Daily variation of current generation by solar panels, current loads and current delivered by the battery after satellite repositioning.

reaction is favored when energy consumption is low and the SOC is near 100%, which corresponds to high CEF values. However, the main contribution to the temperature profile is given by the Joule effect ($Q = I^2R$).

Fig. 4 shows the daily variation of the maximal and minimal values of the battery temperature. From this figure and Figs. 2 and 3 the influence of charge consumption and CEF on the battery temperature is clearly indicated. High values of consumption mean high levels of current, and then temperature rise by the Joule effect takes place. The influence of CEF on temperature rise can only be observed at very high values where the overcharge reaction occurs.

Since June 2006, power delivery from the battery has been lower due to repositioning of the satellite in an orbit with a longer illumination period. This situation reduces current requirement from the electricity storage system and it impacts directly on the battery cycle life and temperature. It has been well recognized that the capacity of nickel-hydrogen batteries improves if the batteries are operated at relatively cool temperatures (−15 °C–10 °C) [8,9]. In fact, an increase in capacity was observed (Fig. 3), which was assigned to the decrease in temperature because of lower heat release from the battery due to lower current drain.

Furthermore, we can distinguish the stage in which the change in satellite repositioning occurred and its effect on battery health by using Acrux Hist View Software, CRUX S.I., La Plata, Argentina.

Fig. 5 shows current generation by solar panels, current loads and current delivered by the battery during the period before satellite repositioning. The maximum peaks of delivered current were near 6 A in the eclipse zone.

It can be seen (Fig. 6) that current generation by solar panels after satellite repositioning attains minimum values of

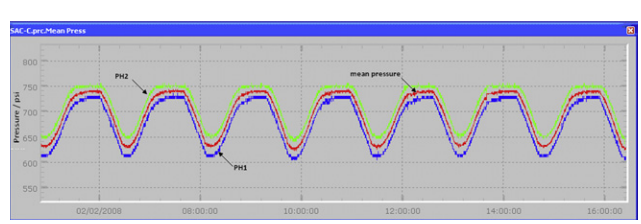

Fig. 7 – Daily variation of pressure by two sensors and average pressure before repositioning.

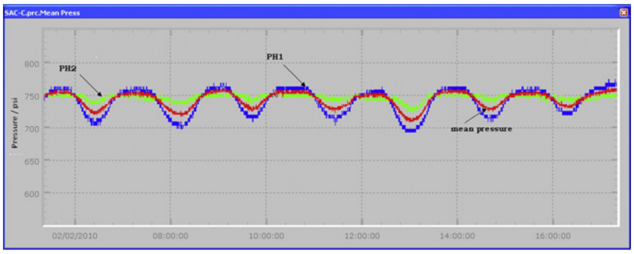

Fig. 8 – Daily variation of pressure by two sensors and average pressure after repositioning.

ca. 2 A. Therefore, for the same load consumption profile, battery current peaks reach maximum values of ca. 4 A, decreasing the depth of discharge.

The battery behavior can also be compared by measuring hydrogen pressure in two single cells (PH_1 and PH_2) and determining the average battery pressure before and after satellite repositioning. In the first case the pressure profile follows a typical trend of charge-discharge current (Fig. 7). On the other hand, in the second case the pressure profile appears flat due to sensor saturation (Fig. 8).

4. Conclusions

Diagnostic indicators (DI) were established by correlating hydrogen pressure with battery capacity ($\Delta P/Q$ DI) and thus monitoring the state of charge of the battery. The (CEF) DI allows the control of the battery state of charge and the temperature and the detection of early failures in the electricity storage system. Predictive analysis from telemetry data allowed the SAC-C mission control engineers to take corrective actions in order to maintain the operating parameters of the energy storage system at an optimum level.

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