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Modeling and Analysis of Battery Thermal Control in a Geostationary Satellite

Murat BULUT*[1], Nedim SÖZBİR[2]

Abstract

Battery technology has been used for satellites since the first satellite sputnik-1 was launched in 1957. The majority of larger satellite's (geostationary or communication satellites) lives range from 7 to 15 years. During the lifetime of satellites, the batteries used must complete 1000 to 33000 cycles without any problems or likelihood of maintenance. There are three battery technologies, Li-ion, Ni-H_2 and Ni-Cd, that are well proven for Geostationary satellite applications. Energy density, lifetime, weight, ampere-hour capacity, depth of discharge, ruggedness and recharge-ability, battery management, thermal management, and self-discharge are main parameters that should be considered when comparing electrical and thermal performance of these three battery technologies. The purpose of this study is to compare the thermal control system for these three batteries for three-axis stabilized geostationary satellites. In particular, the thermal dissipation was compared, which is the temperature range required for battery operation. Thermal analysis was performed for Li-ion batteries using ThermXL software, and showed a temperature results variation ranging between 10.9 ^{o}C and 32.7 ^{o}C. The temperature during the battery module was not greater that its qualification temperature results.

Keywords: Battery, geostationary satellite, thermal control, Li-ion, Ni-H_2, Ni-Cd

1. INTRODUCTION

For the majority of satellites, whether for military, observation, scientific, communication or other purposes, in low Earth Orbit (LEO), Medium Earth Orbit (MEO), or Geostationary Orbit (GEO), continuous power and its supply is a matter of careful consideration [1].

GEO satellites are made up of several subsystems including the payload subsystem, telemetre and command subsystem, the propulsion subsystem, the structure and mechanical subsystem, the thermal control subsystem, the altitude orbit control subsystem (AOCS), and the power subsystem (EPS).

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The power subsystem comprises all components that deliver power. Energy is essential for supplying satellite load demand at all phases of each operation. Solar arrays and batteries are two devices that provide energy to satellites. When there is sunlight, solar arrays provide power as a primary power source. On the other hand, during an eclipse period, power is provided by batteries as a secondary power source. Normally a satellite in GEO orbit experiences two 45-day cycles per year of eclipses that last more than 72 min per day, resulting in 90 sequences of charging and discharging annually. For satellites in orbit for 15 years, this amounts to 90 eclipses per year and 1350 eclipses for 15 years.

The electrical power system (EPS) has the biggest mass ratio for spacecraft dry mass, approximately 30%, and the mass of batteries is the main contributor having about a 40% ratio of EPS mass [2, 3]. Therefore, it is critical to select an appropriate battery type and configuration.

Batteries convert chemical energy within its active material directly into electric energy via an electrochemical oxidation-reduction (redox) reaction [4], which is then stored energy in electrochemical form. Primary and rechargeable are the two main types of batteries. For primary batteries, the electrochemical reaction is irreversible; therefore, it cannot be used again after being fully discharged, and is therefore thrown away after use. Primary batteries are used for small periods of time during operations as the principal power source. For rechargeable batteries, the electrochemical reaction is reversible, meaning recharging can occur with direct current from an external location. Rechargeable batteries are utilized in longer operations in which a secondary source of power is accessible for recharging the battery. Rechargeable batteries have been used for satellite applications since early in the space age. Nickel cadmium (Ni-Cd), nickel hydrogen (Ni-H_2), and lithium-ion (Li-ion) are commonly used secondary batteries for spacecraft.

Although battery technology is a widely studied subject with a large corpus of published work [1, 3-30], there is a persistent lack of established literature on thermal control systems for batteries. In their paper [3-30], a study on batteries technologies from nanosatellite to deep-space exploration missions was presented. Bulut et al. [31] studied thermal design and thermal analysis of a Turkish satellite. Thermal analysis was performed using ESATAN software. The satellite performed within a temperature range between 0 and 40 ^{o}C. Bulut et al. [32] discussed electrical and thermal properties and performance comparison of li-Ion, NiH_2 and NiCD batteries for geostationary satellite applications. They presented a thermal analysis of Li-ion batteries, and they found that the temperatures varied within the qualification temperatures. Sundu and Döner [33] studied the detailed thermal design and control of an observation satellite in low earth orbit and included a battery thermal analysis. They concluded that the design temperature of the battery was achieved by utilizing a thermistor to control the heaters automatically [34]. Boushan [35] studied thermal modeling of Li-ion battery boxes using Thermal Desktop 6.0, with SINDA/FLUINT 5.8 for MR SAT, and included five model revisions. Both steady state and transient analyses were performed. For steady state analysis of model revision D, the temperatures were 4.32 ^{o}C for the hot case and -21.47 ^{o}C for the cold case. For transient analysis of model revision D, the temperatures were 7.35 ^{o}C for the hot case and -24.58 ^{o}C for the cold case. For transient analysis of model revision E, the temperatures were 42.87 ^{o}C for the hot case and 5.42 ^{o}C for the cold case. The modeling and design of the passive thermal control system for the European Student Orbiter (ESEO) satellite was also studied [36, 37]. Thermal analysis was performed using Thermal Desktop (TD) software. Temperature results obtained from the simulation were presented and compared with ESEO published results using ESATAN software. The battery temperatures were between 5.3 ^{o}C and 10.3 ^{o}C for the operative phase. Bailing et al. [38] studied influence analysis of Li-ion battery configuration outside the east/west panel on GEO satellite platform. Thermal analysis results showed that the new configuration of Li-ion battery has more advantages compared to its configuration inside the north/south panel. The heating power and heat rejection area was decreased by 70%. Ya et al. [39] studied thermal behavior of Li-ion battery for the large power synthetic aperture radar (SAR) satellites. The charge and discharge process were tested. The temperature rise during 2C, 3C and 5C discharge process under the adiabatic state increased to 18 ^{o}C, 21.7 ^{o}C and 33 ^{o}C, respectively.

Batteries are designed and qualified to withstand extreme temperature ranges, high vibration/shock levels, high specific energy, very high reliability, etc. Because the cost often limits satellite and space programs, it is essential to decrease the weight and size of rechargeable batteries to gain the largest return on investment.

Batteries need to be designed to support all equipment power loads from beginning of life (BOL) to end of life (EOL). This paper provides a summary of the thermal control system (TCS) for batteries in three-axis stabilized GEO satellites. This paper also discusses the thermal design and the results of a thermal analysis for the batteries using ThermXL software.

2. SATELLITE BATTERY TECHNOLOGY EVALUATION

There is a wide range of battery systems available for spacecraft applications. Ni-Cd was the first satellite battery that was produced in the 1960s. It was the most common battery until the mid-1980s. Unfortunately, series problems such as degradation of the electrodes and hydrolysis of the separator limited the lifetime and performance of Ni-Cd batteries [5]. The Ni-Cd battery consists of a cadmium negative electrode, a nickel positive electrode, an aqueous 35 % potassium hydroxide (KOH) electrolyte, and a nylon cloth separator [6]. During discharge, the cadmium negative electrode provides electrons to the external circuit during the oxidizing phase [31], after which these electrons are accepted by the nickel positive electrode. The 35 percent potassium hydroxide (KOH) electrolyte completes the circuit internally [32], which is held in place by a nylon cloth that separates the positive and negative plates [32].

Ni-H_2 technology batteries, a successor to Ni-Cd, came into use in the 1980s. These batteries are hybrid battery-fuel cell devices. The battery has a positive electrode like a standard battery and a fuel cell negative electrode [37]. Ni-H_2 batteries have a rechargeable electrochemical power source formed from nickel and hydrogen. Even though hydrogen exits as either a liquid or gas, nickel is considered a ferrite [37]. Hydrogen gas is diffused onto a catalyst, usually platinum, at the negative electrode where the reaction occurs [37]. High pressure vessels are required to contain the gas [37]. For an electrolyte, Ni-H_2 cells use 26% potassium hydroxide (KOH). Ni-H_2 rechargeable batteries have notable electrical attributes making them a good candidate for storing electrical energy in satellites.

The earliest on-orbit use of Li-ion battery technology was by the European Space Agency (ESA) funded PROBA-1 LEO technology development satellite launched in October, 2001 [7]. Li-ion batteries provide high energy density and are therefore very attractive candidates as secondary energy sources for telecommunication satellites. After seeing the success of the Li-ion battery technology, many are hopeful that it has potential to accept a large number of cycles with future and further development of rechargeable Li-ion technology using it on future missions [6].

Li-ion batteries have exclusive properties that markedly affect charge/discharge cycles. Over charging or discharging Li-ion cells will cause irreversible damage, which is different from Ni-Cd and Ni-H_2 cells [40]. Therefore, Li-ion batteries are sensitive to overcharge and over-discharge conditions. Figure 1 shows mass and volume comparison of Li-ion against heritage battery technologies [8]. Values given are for a 10 kWh battery with a maximum DoD of 75% and shows that a Li-ion battery would cause a noteworthy decrease in mass and volume versus Ni-Cd and Ni-H_2 technologies [41].

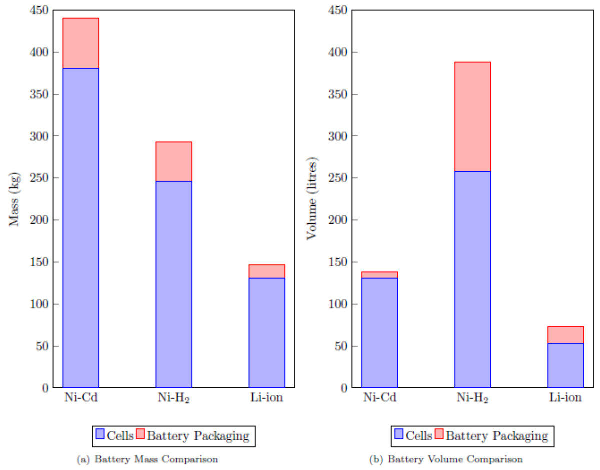

Figure 1 Mass and volume comparison of battery technologies [8].

Li-ion batteries will likely become more commonly used within the satellite structure because they have both a high energy density and working voltage as compared to Ni-Cd and Ni-H2 batteries. In addition, Li-ion energy densities are approximately 125 Wh/kg, about two times the densities of Ni-Cd and Ni-H2 batteries. As the weight and low heat dissipation become a key driving parameter for satellites, Li-ion is the likely technology of choice to meet this criterion.

3. ELECTRICAL PERFORMANCE COMPARISON OF BATTERIES

Comparison of Li-ion, Ni-H_2, and Ni-Cd is shown in Table 1. Useful energy density, battery management complexity, thermal management, self-discharge, and flight heritage are chosen in order to compare the batteries. Table 1 shows that the Li-ion battery has less hazardous problems and higher energy density versus the Ni-Cd or Ni-H_2 technology batteries. In addition, a greater amount of available energy can be used by Li-ion batteries, because they can accept deep discharge [6]. Li-ion provides considerable wider operating temperature ranges than either Ni-Cd or Ni-H_2 batteries.

The high specific energy contained in the Li-ion battery system gives it an advantage over the other batteries because of the added weight reduction. In fact, the specific energy of Li-ion is greater than 125 Wh/kg, much higher that of the Ni-H_2, which can achieve no higher than 60 Wh/kg. The higher specific energy achieved by the Li-ion results in at least a 40 percent battery weight reduction, and more than 350 kg weight reduction (a factor of 2) on a 20 kW satellite is anticipated.

The Li-ion battery can discharge itself at a rate of 0.03% of capacity loss per day, which is quite low compared with the Ni-H2 system, which is 10%. Managing the state of charge (SOC) for a Li-ion battery on a satellite during the integration, launch pad and solstice phases is not as difficult compared with Ni-H2 because recharge is given to the battery until the final countdown.

Table 2 Comparison of batteries [1, 13].

	Ni-Cd	**Ni-H_2**	**Li-ion**
Energy Density (Wh/kg)	25	60	125
Battery Management	Is tolerant to overcharge mechanism	Is tolerant to overcharge mechanism	No overcharge allowed: rigid constraints on charge management, dedicated balancing electronics, bypass and protection are required
	Reconditioning needed	Reconditioning needed	No reconditioning
Thermal Management (oC)	0 to 25	0 to 20 . Need to be cold charged for food charge efficiency	0 to 40. Optimum condition 20
	at lower temperatures and at high temperatures degraded	High heat generation in discharge	Between 3 and 4 times less dissipations in discharge
Self discharge	High self discharge according to nominal capacity	High self discharge	Low discharge
			AIT operations simplified
Flight Heritage	Many tests/in flight data available	Many tests/in flight data available	Many tests/in flight data available

Furthermore, Li-ion does not have a memory effect which influences battery cycling performance. On the other hand, Ni-Cd and Ni-H_2 systems do have a memory affect. If the battery has been repeatedly discharges slightly (10-20%) and then recharged again, it will gradually developed a memory effect and lose some of its capacity after a period of time [9].

The Li-ion system is also advantageous because there is a direct relationship between SOC and the open-circuit voltage (OCV). The SOC of Li-ion batteries is always known during missions because the voltage can indicate an absolute energy gauge. On the other hand, for Ni-H_2 batteries, strain gauges on the pressure vessel are employed, and show just a rough estimate of SOC.

4. THERMAL PERFORMANCE COMPARISON OF BATTERIES

Studying battery performance based on experimental work is costly and not available for designers during preliminary design phases [9]. Mathematical modelling and simulation help the designer to study and analyze the performance of the battery stack during the design phases [35].

Three different types of batteries, Ni-Cd, Ni-H_2, and Li-ion, are normally used on satellites. There is a slight difference between thermal control requirements and thermal design [42-44].

Battery thermal control is critical because it the largest sources of heat dissipation and the smallest allowable temperature range of the operation. Temperature significantly impacts the performance of batteries and also limits the application of batteries. The capacity and voltage characteristics of a battery is largely controlled by the temperature at which the battery is charged and discharged [10], because chemical activity decreases and internal resistance increases at lower temperatures. The ideal temperature depends on the specific chemistry and design of every battery and can be custom designed [10].

Ni-Cd batteries are utilized in older spacecraft power systems. The life of these batteries is maximized when the temperature of the batteries is maintained between 0 and 10 ^{o}C. The maximum beneficial life decreases markedly as the battery temperature rises above this range, and also, when the temperature falls below this range, because the electrolyte can freeze, damaging the battery [11]. One of the important thermal control requirements is to keep all the batteries on the spacecraft and cells within the same temperature range, above or below a specific value (for example, +/- 5 ^{o}C), ensuring that all cells charge and discharge simultaneously [11].

Li-ion batteries are best operated at room temperature around, 20-25 ^{o}C, and suffers degradation at low temperature. Battery thermal control would be more manageable if the temperature range of operation for Li-ion batteries was wider than for Ni-Cd and Ni-H_2 (typically -5 to +25 ^{o}C) [11]. An example photograph of a Li-ion battery assembly is shown in Fig. 2.

Figure 2 Photography of battery assembly [40]

Compared with the Ni-H_2 battery, the Li-ion is at an advantage because there is 5-10 % weight savings with its lower thermal dissipation and higher Faradic efficiency. These features impact the solar panel and radiator sizes. The Li-ion also needs less radiator area according to thermal dissipation which is shown in Fig. 3.

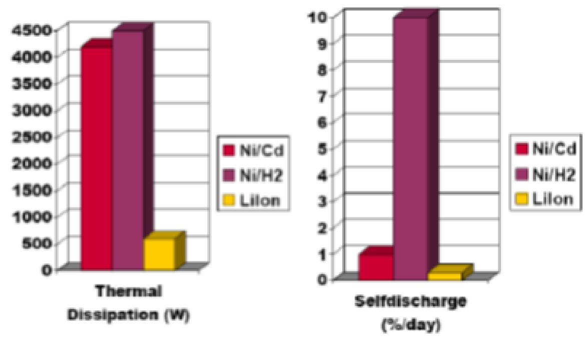

Figure 3 Thermal dissipation and self-discharge comparison of batteries (for 8kW satellite) [12, 13].

5. BATTERY THERMAL DESIGN CONCEPT

The overall cost, the thermal behavior including heat dissipation and optimal temperature ranges, and the weight and dimensions of a satellite, are the main drivers which are considered at the beginning of a satellite project.

The key part of battery design is ensuring that all cells are at similar temperatures. Consequently, designing thermal control of batteries is critical on spacecraft because of the narrow working temperature ranges of batteries. Therefore, most spacecraft manufacturers design thermal control of batteries individually. Figure 4 shows the location of the batteries on a three-axis stabilized GEO satellite. The location of the batteries is on the North and South service. Figure 5 shows the battery location on a GEO satellite.

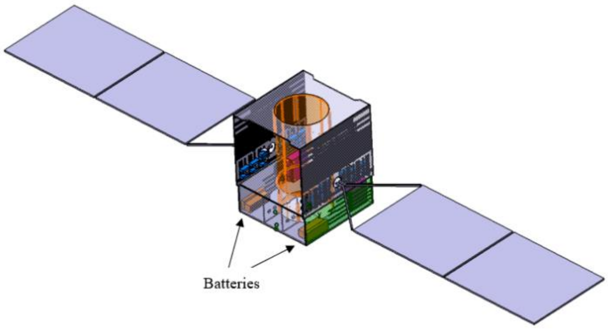

Figure 4 Location of the batteries at three-axis stabilized GEO satellite

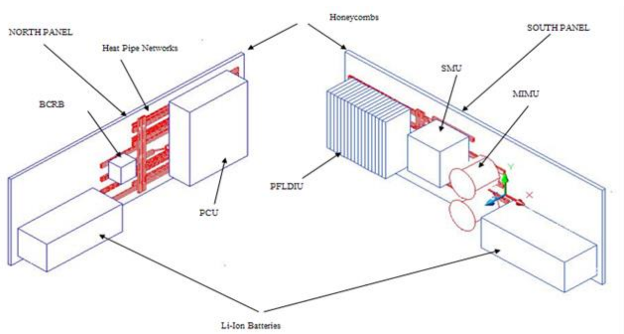

Figure 5 Schematic of the battery location [13].

Figure 6 shows the thermal design concept in which batteries' thermal status is self-contained because they are thermally insulated from the interior of the satellite. For thermal design, there is a multi-layer insulation (MLI) blanket cover, that keeps the batteries from being exposed to the interior of the satellite, and optical solar reflector (OSR) radiators located on a honeycomb panel containing heat pipes that radiate heat away from the batteries [45]. Heat dissipation also affects radiative areas. The size of the radiator is constructed to ensure the battery temperature is no more than the maximum allowable temperature for worst hot-case scenarios while controlled heaters are utilized to sustain lowest allowable temperatures for cold-case scenarios.

A thermal inter-filler provides good and removable thermal contact for the radiator. RTV 566 and CV-2942 are widely used between the batteries and honeycomb panel. MLI is used to decouple batteries from the internal thermal environment of the satellite. To control the temperature range, OSR radiators are installed under batteries [31]. To maintain batteries at lowest possible temperatures, nominal and redundant heaters are used [46].

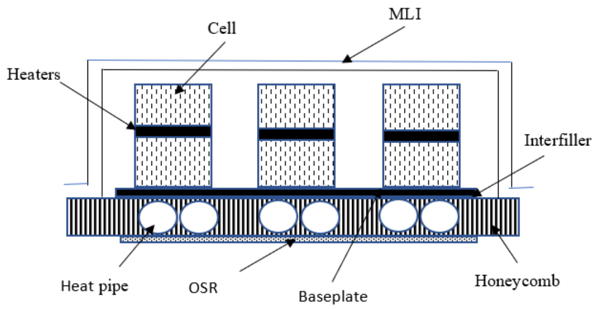

Figure 6 Battery thermal design concept

6. THERMAL MODELLING AND ANALYSIS

To extend the cycle and life of batteries and ensure safe use, heat dissipation during charge, discharge and self-discharge of batteries is an important part of the satellite system [14]. Many components of a satellite will only work within a specific temperature range. The thermal satellite design has three components: identifying the heat sources, designing appropriate heat transfer among all satellite components, and emitting heat to ensure all constituents operate within operating temperature ranges [47, 48].

Each component of the satellite is affected by external heat fluxes which are influenced by the position of the satellite in orbit, satellite attitude in its current position, relative positions of the sun and earth (equinox (EQ), winter solstice (WS), summer solstice (SS)), eclipse time, and satellite geometry [11].

By knowing the external heat fluxes and the dissipation of the elements, the temperature distribution variations can be calculated as a function of thermal couplings, area, solar absorptivity, and emissivity. These parameters can then be controlled, and various groups of parameters can be used to create the optimum temperature for a given dissipation.

The energy equation is used for calculating temperature distribution and is made up of transient, conduction, and radiation terms and a source term that defines the boundary conditions (solar, albedo, earth radiation), and is given as [49-52]

$$M_i C_{pi} \frac{dT_i}{dt} = Q_{in} - Q_{out} \tag{1}$$

where M_i is mass, C_{pi} is specific heat, dT_i/d_t is the temperature derivative with respect to time, and Q_{in} is the sum of all heat flows into the element. Electronic equipment is represented by the node i and the heat generated in the equipment after it is switched on is represented by the thermal load Q_i. The thermal radiation absorbed by an external panel from an external source is also Q_i and is the sum of the following: $Q_{Sun} + Q_{albedo} + Q_{EarthIR}$. Q_{out} is the sum of all heat flows leaving the component and the subscript i is used as an index of the element number.

$$\left(MC_{pi}\right)\frac{dT_i}{dt} = Q_i + \sum_{j=1}^{N} C_{ji}\left(T_j - T_i\right) + \sum_{j=1}^{N} R_{ji}(T_j^4 - T_i^4)\,, \quad i = 1 \ldots\ldots N \tag{2}$$

The conductive couplings C_{ji} are calculated with knowledge of the unidirectional fluxes, while T_i and T_j are the temperatures of nodes i and j, respectively. The radiative couplings R_{ji} are determined using the Gebhart method [53].

The battery is investigated by running a mathematical model that determines radiator area and heater use. The battery thermal analyses are performed based on the most extreme condition which is obtained by a combination of cell dissipation (cell failure, discharge/charge, and shunt), solar illumination (seasons and solar array heat fluxes), thermo-optical properties (BOL and EOL), and external environment (webs/reflectors).

Table 2 shows an example of optical properties and thermophysical properties of the material, [32].

Table 2 Thermophysical and optical properties of several components [32].

Components	Solar absorptivity (BOL)	Solar absorptivity (EOL)	Emissivity	Thermal Conductance (W/m^2K)	Conductivity (W/mK)
Baseplate-honeycomb				3200	
Lateral					3.5
Transversal					1.35
External MLI	0.35	0.5	0.61		
External Black MLI	0.93	0.93	0.84		
Internal MLI	N/A	N/A	0.05		
OSR	0.11	0.27	0.84		

7. THERMAL ANALYSIS RESULTS

Thermal analysis of predicts the temperature of batteries in a given or expected heating realm, and is required to test and improve thermal design [51]. In this study, a thermal analysis was performed using ThermXL software. ThermxL provides an environment for constructing a lumped-parameter thermal analysis network, as well as built-in routines for solving the analysis in both transient and steady state (using the well-known finite difference method) [54]. Temperature results are indicated in Table 3. The qualification temperatures range of the batteries was from 0°C to 54 °C. As expected, the highest temperature was 32. 7 °C during EQ EOL with 2 stacks failing at the north panel. The lowest temperature was 10.9 °C during SS EOL at the north panel. As indicated in Table 3, there was a large variation in the calculated temperatures because of the parameters, shown in Table 2.

Table 3 also illustrates that all the temperatures were within the range of the allowable maximum values.

Table 3 The calculated cell temperatures of the batteries

		North Panel		South Panel	
		Cell		Cell	
Cases	Condition	Min	Max	Min	Max
WS BOL		18.8	25.4	18.3	24.3
SS BOL		17.1	21.7	18.8	25.8
WS EOL		18.5	26.1	15.1	21.2
SS EOL		11.2	19.3	19.6	24.7
WS EOL	shunt	18.1	25.9	14.8	21.8
SS EOL	shunt	10.9	18.8	19.1	26.1
EQ EOL		18.8	30.3	18.8	29.5
EQ EOL	1 stack failed	18.4	31.2	18.9	29.5
EQ EOL	2 stacks failed	18.9	32.7	18.9	31.4

8. CONCLUSION

An overview of TCS for batteries in three-axis stabilized GEO satellite were briefly reviewed and detailed information of electrical performance, thermal performance, thermal design, thermal modelling and analysis were presented for Ni-Cd, Ni-H_2 and Li-ion batteries.

In addition, the thermal model is developed and thermal analysis of Li-ion batteries was performed using ThermXL software. The thermal analysis results showed that the passive thermal control system is designed to withstand the hot and cold cases within the required operational temperature range. It has been seen that the analysis results are in line with the recommendations of the battery manufacturer and in the desired temperature range. The temperature of batteries did not exceed its qualification temperature results.

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The Declaration of Conflict of Interest/ Common Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contribution

The authors contributed equally to the study.

The Declaration of Ethics Committee Approval

The authors declare that this document does not require ethics committee approval or any special permission.

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