A Comprehensive Guide to Selecting and Testing Batteries for High-Altitude Balloon Missions

Josué Aldana
Micro-Macro Observatory (MMO)
Don Bosco University
San Salvador, El Salvador
jaldana.aguilar@ieee.org

Osmin Larreynaga
Micro-Macro Observatory (MMO)
Don Bosco University
San Salvador, El Salvador
osmin.larreynaga@ieee.org

***Abstract*—High-Altitude Balloon (HAB) missions require efficient energy systems to conquer the challenges of the stratosphere. This paper offers a comprehensive guide for selecting and testing batteries, integrating the International Standard Atmosphere (ISA) model with CUSF simulator using Python. It includes a detailed analysis of Commercial Off-The-Shelf (COTS) Li-ion battery options, identifying exceptional candidates for exposure to these environmental conditions. Additionally, a proposed functional diagram for battery testing circuits is presented. This guide significantly contributes to HAB missions, promoting more reliable energy systems for scientific exploration.**

***Index Terms*—HAB Missions, Li-ion Batteries, COTS, International Standard Atmosphere, Trajectory Simulation.**

I. Introduction

Making High-Altitude Balloon (HAB) missions successful in the stratosphere depends on operating energy systems effectively. This requires a deep understanding of the challenging atmospheric conditions these systems will face.

Using trajectory prediction software is essential for HAB missions. It helps estimate where the balloon will land, plan its flight path, and prepare for recovery. Some popular programs [1], [2] for this are the Cambridge University Spaceflight (CUSF) simulator [3], Balloon Trajectory Forecasts from the University of Wyoming [4], and Balloon Prediction [5]. All of these tools rely on the Global Forecast System (GFS) model from NOAA [6].

The Cambridge University Spaceflight simulator's standout feature is its ability to provide easily downloadable CSV data, including location details like latitude, longitude, and altitude [7]. Making it a valuable asset for mission planning (Fig. 1).

Fig. 1. CUSF trajectory simulation on Google Earth.

Additionally, the ISA [8] offers a standardized model for Earth's atmosphere, a key reference for aerospace system design, illustrating temperature, pressure, and air density variations with altitude. Integrating ISA with trajectory prediction software improves HAB mission planning, empowering researchers and maximizing exploration potential.

In this paper, we cover the integration of ISA and CUSF trajectory simulation with Python in Section II, selection criteria for Commercial Off-The-Shelf (COTS) batteries for HAB missions in Section III, a comprehensive testing procedure for 18650 Li-ion batteries in Section IV, and conclusions in Section V.

II. Integrating ISA and CUSF Trajectory Simulation with Python

A. Sectionated Functions for the ISA Model

The ISA analysis is based on the descriptive equations from [9]. For convenience, relevant information is summarized in Table I and Table II.

TABLE I
Constants of ISA

Layer	z_0 [m]	T_0 [K]	λ_0 [K/m]	P_0 [Pa]
1	0	288.15	-0.0065	101,325.00
2	11,019	216.65	–	22,632.10
3	20,063	216.65	0.0010	5,474.89
4	32,162	228.65	0.0028	868.02
5	47,359	270.65	–	110.91

TABLE II
Formulas of ISA

Layer	**Temperatura [K]**	**Presión [Pa]**
1	$T_0 + \lambda_0(z - z_0)$	$P_0 \left(\frac{T_0}{T}\right)^{g(z)\, M_{air}/(R\, \lambda_0)}$
2	T_0	$P_0\, e^{-g(z)\, M_{air}\cdot(z-z_0)/(R\, T)}$
3	$T_0 + \lambda_0(z - z_0)$	$P_0 \left(\frac{T_0}{T}\right)^{g(z)\, M_{air}/(R\, \lambda_0)}$
4	$T_0 + \lambda_0(z - z_0)$	$P_0 \left(\frac{T_0}{T}\right)^{g(z)\, M_{air}/(R\, \lambda_0)}$
5	T_0	$P_0\, e^{-g(z)\, M_{air}\cdot(z-z_0)/(R\, T)}$

B. CUSF Simulation parameters

As a test place to run the simulations, we selected an arbitrary location situated in Usulutan, a department of El Salvador. While specific coordinates are not disclosed here for practical reasons, the provided information and details in Table III allowed us to generate a comprehensive CSV file containing minute-by-minute data.

TABLE III
HIGH-ALTITUDE BALLOON MISSION DETAILS

CUSF Simulator Parameter	Value
Launch altitude [masl]	495
Target Burst Altitude [masl]	30,000
Balloon model	Kaymont 1500
Payload Mass [kg]	2.207

C. Environmental Variables in Simulated Trajectory

The Python-based calculations in [10] and [11] yield critical insights into extreme stratospheric conditions, where temperatures can reach as low as 216.65 Kelvin, and the atmospheric pressure can be as low as 1.18% of standard atmospheric pressure. The simulation uncovers a maximum temperature decrease of 2.78 Kelvin per minute, along with a 4.74% atmospheric pressure decrease per minute, emphasizing the severity of environmental challenges faced during the trajectory.

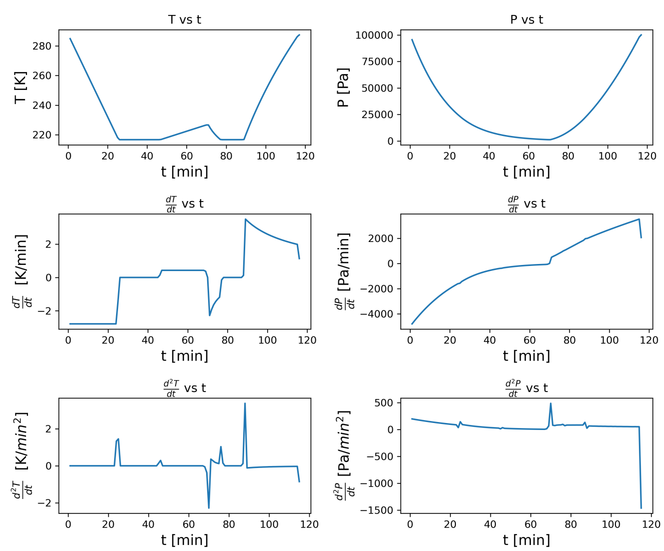

Fig. 2. Simulated Atmospheric Variables for a 30 km HAB Mission

As we can see in Fig. 2 and consistent with the findings in [12], a crucial region emerges during ascent, primarily driven by forced convection. This critical area, situated near the tropopause at approximately 11,000 meters above sea level, experiences the most significant thermal changes. These observations have significant implications for selecting electronic components and emphasizing the necessity of an effective thermal control system to ensure mission success.

III. SELECTING COMMERCIAL OFF-THE-SHELF (COTS) BATTERIES

The selection of appropriate Commercial Off-The-Shelf (COTS) Li-ion batteries for high-altitude balloon missions is a critical consideration. While COTS batteries offer cost-effectiveness, wide availability, and a proven track record in various applications, the unique challenges of operating at extreme altitudes must be carefully addressed. HAB missions demand reliable battery performance, even under harsh and unpredictable environmental conditions.

Low temperatures and pressures can significantly impact battery performance, potentially compromising mission safety. Operating batteries under such conditions leads to detrimental effects, including altered ionic conductivity, internal resistance, and charge-transfer kinetics [13], [14]. Given the importance of battery power for electronic systems during HAB missions, evaluating COTS Li-ion batteries is essential to ensure the success of the mission.

A. Chemistry and geometry of batteries

Lithium-ion rechargeable batteries are widely favored for various electronic applications, including CubeSat missions, due to their high energy density and extended shelf life. These batteries comprise interconnected cells with anodes, cathodes, and electrolytes, enabling efficient energy storage and release through oxidation-reduction reactions during charging and discharging. Despite their compact size, high energy density, and low self-discharge rate, lithium-ion batteries come with inherent risks, such as fire or explosions resulting from internal short circuits [15].

When considering the battery shape, prismatic designs optimize space utilization but may require improvements in thermal efficiency. Pouch-type batteries offer flexibility, albeit necessitating proper support. On the other hand, cylindrical batteries, like the 18650-type, exhibit mechanical stability and feature built-in safety systems, making them well-suited for high-altitude Balloon applications [16].

B. COTS 18650 Li-ion Batteries

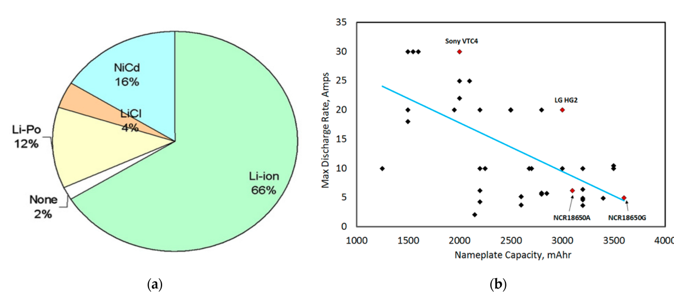

Fig. 3. (a) Battery types used in pico- and nano-satellites [17]. (b) Summary of maximum discharge rate capabilities versus nameplate capacity of some representative COTS 18650 Li-ion cells [18]

Based on the comprehensive study conducted in [19] and shown in Fig. 3, the performance of lithium-ion cells can be effectively constrained by three specific models: Sony VTC4, LG HG2, and Panasonic NCR18650G. However, the practical implementation of these models may pose challenges in certain regions, such as El Salvador, where access to these alternatives might be limited or unavailable in local stores.

Given the significance of evaluating local alternatives and considering the availability of options in the international market, we recognized the need to explore viable substitutes for the aforementioned models. To address this issue, a thorough assessment was conducted [20]–[23], and the results are summarized in Table IV.

TABLE IV
SELECTION OF 18650 BATTERIES BASED ON DATASHEETS INFORMATION

Model	T1 [°C]	T2 [°C]	I [A]	Q [mAh]	V [v]	Min. V [v]
Steren	0	50	—	2200	3.7	—
NCR18650GA	-20	60	10	3450	3.6	2.5
LG MJ1	-20	60	10	3500	3.6	2.5
Samsung 35E	-10	60	8	3500	3.6	2.65
Sony VTC5D	-20	60	30	2800	3.6	2.5

TABLE V
RULES OF SELECTION

Detail	Points
$\geq 25\%$ Better than the mean	1.0
$\geq 10\%$ Better than the mean $< 25\%$	0.50
$< 10\%$ variation	0.0
$\geq 10\%$ and $< 25\%$ worse than the mean	-0.50
$\geq 25\%$ worse than the mean (including "No" or "Unknown")	-1.0

To evaluate and compare the various cell options, we have established specific rules in Table V to determine their suitability. These rules assign positive or negative scores based on advantageous characteristics. Additionally, we consider two crucial factors not listed in the table, the cell's track record in aerospace applications and the availability of documentation, including discharge curves in various temperatures.

By applying these rules and considering these factors, we can effectively assess and rank the different cell options, enabling us to make an informed and reliable choice tailored to our specific requirements. The resulting scores can be found in Table VI.

TABLE VI
BATTERY COMPARISON RESULTS

Battery Model	Score
Steren	-5.50
NCR18650GA	+0.50
LG MJ1	+0.50
Samsung 35E	-2.50
Sony VTC5D	+1.50

After a thorough evaluation, we have identified three exceptional battery cells with similar pricing and a proven track record in aerospace applications [16], [19], [24], [25]: Panasonic NCR18650GA, LG MJ1, and SONY VTC5D. The availability of detailed datasheets with discharge curve information further enhances their suitability for our research. These selected cells are highly promising candidates for high-altitude balloons. However, the final decision will be made based on the specific design of the missions.

IV. TESTING PROCEDURE FOR 18650 LI-ION BATTERIES

Thorough ground testing of 18650 Li-ion batteries for high-altitude balloon missions is essential before flight. A valuable tool for replicating stratospheric flight conditions is the thermal-vacuum chamber. In developing countries like El Salvador, obtaining high-quality chambers can be challenging. Cost-effective alternatives are explored in [15].

Our paper presents a testing procedure to simulate actual balloon flights. We propose incorporating a throttling mechanism into the vacuum system to mimic pressure and temperature changes realistically. Results are shown in Fig. 5, and we use Celsius degrees for better understanding.

A. Proposed Functional Diagram for Battery Test

For COTS 18650 Li-ion batteries performance assessment and fundamental electrical parameter determination, we designed a functional diagram inspired by prior works [26], [27]. See Fig. 4.

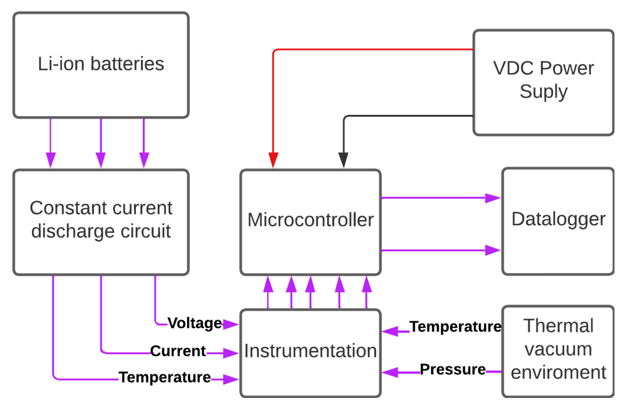

Fig. 4. Functional Diagram for thermal vacuum battery tests. Purple wires represent data, black is ground, and red is +VCC.

V. ANALYSIS OF RESULTS

The integration of the International Standard Atmosphere (ISA) model with the Cambridge University Spaceflight (CUSF) simulator using Python enhances the accuracy of trajectory predictions for High-Altitude Balloon (HAB) missions. By incorporating ISA, the atmospheric conditions are more realistically modeled, providing researchers with a valuable tool for optimizing mission planning.

The analysis of Commercial Off-The-Shelf (COTS) Li-ion batteries revealed several exceptional candidates suitable for exposure to the challenging environmental conditions of the stratosphere. The selection criteria considered factors such as

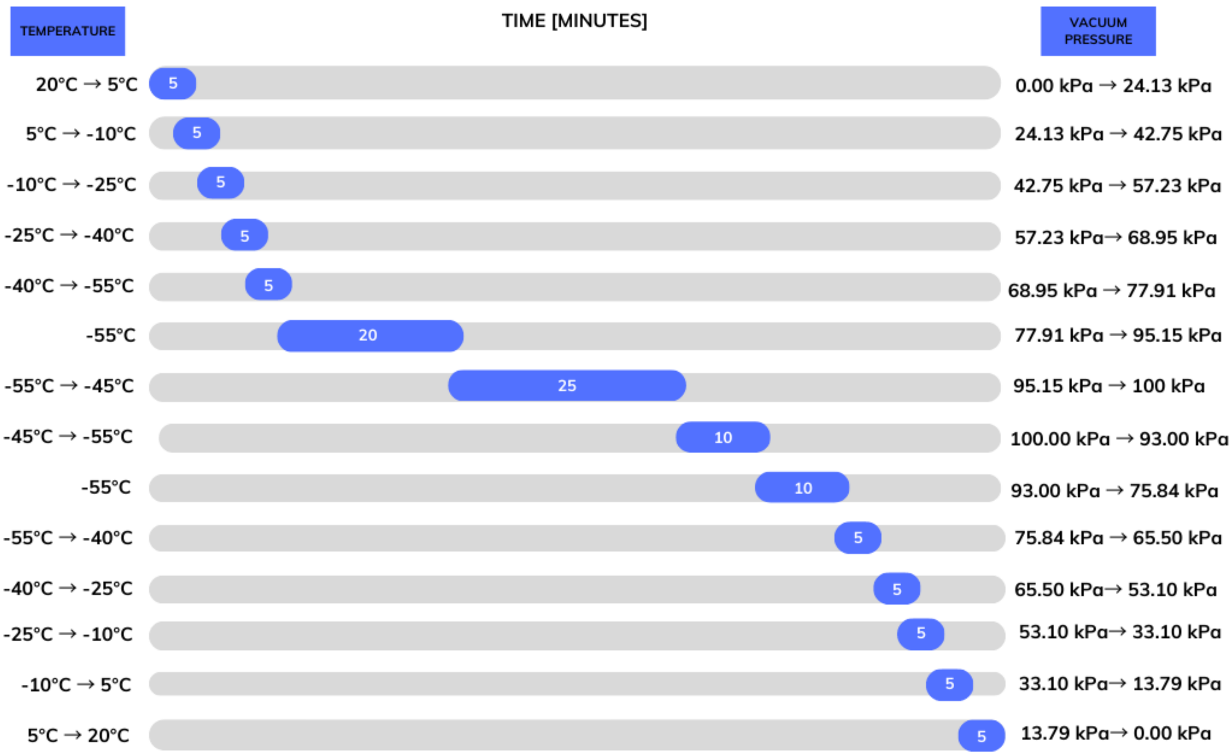

Fig. 5. Timeline diagram for temperature and pressure transitions

capacity retention, temperature sensitivity, and overall performance. The chosen batteries exhibit robustness in extreme temperatures and low-pressure conditions, ensuring reliable energy supply during HAB missions.

The proposed functional diagram for battery testing circuits offers a structured approach to assess the performance of batteries under simulated mission conditions. This framework facilitates systematic testing and comparison of different battery models, contributing to the development of more reliable energy systems for scientific exploration in the stratosphere.

VI. Conclusions

The integration of the ISA model and CUSF trajectory simulation with Python enhances HAB mission planning accuracy. Exceptional COTS Li-ion batteries were identified through a comprehensive testing procedure, showcasing resilience to stratospheric environmental conditions. The proposed battery testing circuit diagram provides a solid foundation for future instrumentation circuit designs, contributing to the development of reliable energy systems for scientific exploration.

Acknowledgment

The authors would like to express their sincere gratitude to the Micro-Macro Observatory (MMO) for their invaluable support and collaboration throughout the development of the StratoBalloon project, a HAB mission. MMO's assistance has been instrumental in the successful execution of this research, making this paper an integral part of the overall research process.

References

[1] G. Gyuk, J. G. Garcia, C. Tarr, and K. Walczak/, "Light pollution mapping from a stratospheric high-altitude balloon platform," pp. 20–32, 2021. [Online]. Available: https://www.arcgis.com/apps/Viewer/index.html?appid=81204cec708945dba62b257121375c05

[2] A. Shaqeer and M. Thaheer, "Mission design and analysis of c high-altitude balloon mysat-1u cubesat for electron density measurement view project," 2017. [Online]. Available: https://www.researchgate.net/publication/322930091

[3] Project Horus. (2023) Leaflet predictor wiki. [Online]. Available: https://github.com/projecthorus/leaflet_predictor/wiki

[4] (2023, Julio) Upper air balloon trajectory. University of Wyoming. Accedido el 14 de julio de 2023. [Online]. Available: https://weather.uwyo.edu/upperair/balloon_traj.html

[5] (2023, Julio) Balloon prediction - noaa global monitoring laboratory. NOAA Global Monitoring Laboratory. Accedido el 14 de julio de 2023. [Online]. Available: https://gml.noaa.gov/ozwv/wvap/sw.html#:~:text=Balloon%20Prediction,accurate%20results%20are%20not%20guaranteed)

[6] NOAA. (2023) Gfs. [Online]. Available: https://www.emc.ncep.noaa.gov/emc/pages/numerical_forecast_systems/gfs.php

[7] C. University. (2013) Cambridge university spaceflight landing predictor. [Online]. Available: https://predict.sondehub.org/

[8] NOAA, NASA y USAF, "U.S. Standard Atmosphere, 1976," Washington, D.C, Technical Report, Oct 1976. [Online]. Available: https://www.ngdc.noaa.gov/stp/space-weather/online-publications/miscellaneous/us-standard-atmosphere-1976/us-standard-atmosphere_st76-1562_noaa.pdf

[9] J. L. P. da Fonseca *et al.*, "Trajectory generation for non-powered lift-enabled vehicles in planetary atmospheres," Technological Physics Engineering Examination Committee, Technical Report, 2012, inf. téc.

[10] AJ23A, "A comprehensive guide to selecting and testing batteries for high-altitude balloon missions," https://github.com/AJ23A/CONESCAPANXL, Julio 2023, accedido el 12 de julio de 2023.

[11] O. Lab, "Osmin lab github repository," https://github.com/osmin-lab/Proyec_Gda_Simula-PCB_Nav, Año actual, accedido el día de acceso.

[12] D. González-Bárcena, L. Peinado-Pérez, A. Fernández-Soler, Ángel Grover Pérez-Muñoz, J. M. Álvarez Romero, F. Ayape, J. Martín, J. Bermejo-Ballesteros, and Ángel Luis Porras-Hermoso, "Tasec-lab: A cots-based cubesat-like university experiment for characterizing the convective heat transfer in stratospheric balloon missions," *Acta Astronautica*, vol. 196, pp. 244–258, 7 2022.

[13] S. Ma, M. Jiang, P. Tao, C. Song, J. Wu, J. Wang, T. Deng, and W. Shang, "Temperature effect and thermal impact in lithium-ion batteries: A review," pp. 653–666, 12 2018.

[14] N. Navarathinam, R. Lee, and H. Chesser, "Characterization of lithium-polymer batteries for cubesat applications," *Acta Astronautica*, vol. 68, pp. 1752–1760, 6 2011.

[15] J. Meyer, B. Straub, and J. Flaten, "Improving a low-cost thermal-vac chamber for testing stratospheric ballooning payloads," 2020.

[16] A. Eleazar, P. Ramos, E. M. Aragón, and S. V. Reyes, "Baterías que dan vida a un nanosatélite," 2020. [Online]. Available: www.nanosats.eu

[17] J. Bouwmeester and J. Guo, "Survey of worldwide pico- and nanosatellite missions, distributions and subsystem technology," *Acta Astronautica*, vol. 67, pp. 854–862, 2010.

[18] K. Chin *et al.*, "Energy storage technologies for small satellite applications," *Proceedings of the IEEE*, vol. 106, pp. 419–428, 2018.

[19] V. Knap, L. K. Vestergaard, and D. I. Stroe, "A review of battery technology in cubesats and small satellite solutions," 8 2020.

[20] "Panasonic NCR18650GA Battery Datasheet," https://www.orbtronic.com/content/Datasheet-specs-Sanyo-Panasonic-NCR18650GA-3500mah.pdf, 07/17/2023.

[21] "LG MJ1 Battery Datasheet," https://www.nkon.nl/sk/k/Specification%20INR18650MJ1%2022.08.2014.pdf, 07/17/2023.

[22] "Samsung INR18650 35E Battery Datasheet," https://www.orbtronic.com/content/samsung-35e-datasheet-inr18650-35e.pdf, 07/17/2023.

[23] "Murata VTC5D Battery Datasheet," https://www.imrbatteries.com/content/murata_vtc5d-2.pdf, 07/17/2023.

[24] A. R. M. Holliday, T. T. C. Settle, and Z. M. D. Senesky. (2018) Pycubed. [Online]. Available: https://pycubed.org/

[25] B. V. H. Kumar, N. H., N. Worrakul, and P. Meemak, "Design of flexible battery pack and battery management system for nanosatellite," 2022.

[26] R. Dubey, "Performance evaluation of a lithium-ion pouch battery cell in simulated space environment for a pico-satellite concept (picosat)," 2022.

[27] M. Angel and B. Saucedo, "Generación de curvas de descarga de una batería de li-ion utilizando una plataforma de hardware libre," 2006. [Online]. Available: https://www.researchgate.net/publication/338435753