CUBERG
A NORTHVOLT COMPANY

Cuberg aviation battery module

External testing report – May 2024

www.cuberg.net
press@cuberg.net

Industry-leading commercialization of advanced chemistries for aviation batteries

Product overview

Cuberg, based in California, designs and manufactures batteries for electric aviation and other high performance markets. This report will present key findings from an independent third-party validation testing conducted on Cuberg's aviation module.

Cuberg is committed to designing and manufacturing batteries with next-generation lithium-metal anodes. Cuberg cells are lightweight and high-performance and can enable electric mobility applications beyond the capabilities of traditional lithium-ion technology.

The battery module described in this report was built with Cuberg's 20 Ah lithium-metal cells. These 20 Ah cells have an externally validated specific energy of 395 Wh/kg.

Two world-firsts

- The first-ever third-party validation of a lithium-metal module
- The first-ever third-party validation of an advanced battery module built specifically for aviation

Testing

Cuberg contracted with TÜV SÜD, a German company with a new facility in Michigan, U.S.A., to conduct external validation. TÜV SÜD is widely regarded within the battery industry as a neutral and trustworthy third-party technical service provider.

Our product

An unprecedented engineering achievement

The Cuberg aviation module demonstrates that lithium-metal cells can be efficiently integrated into an engineered system ready for vehicle integration. Our team was able to simultaneously solve for complex mechanical and electrical integration challenges while also developing a consistent manufacturing process. The module technology is envisioned as a building block for a commercially available battery system.

Historically, many next-generation battery chemistries have failed to take the next step into consistent and performative module integration. Cuberg technology, as demonstrated by this third-party validation, is different. Lithium-metal batteries with our proprietary electrolyte are ready to power the future of mobility.

Module Design Specification		
Characteristic	**Value**	**Unit**
Cell count	60	# of cells
S&P configuration	10S6P (10 in series, 6 in parallel)	[]
Max ToC* - Min loaded voltage	42.8 - 25.0	Volts
Energy (C/20 at 45°C)	4.7	kWh
Capacity (C/20 at 45°C)	122.3	Ah
Specific energy (C/20 at 45°C)	284.8	Wh/kg
Module mass	16.4	kg

* Top of Charge

What is a module, and why does it matter?

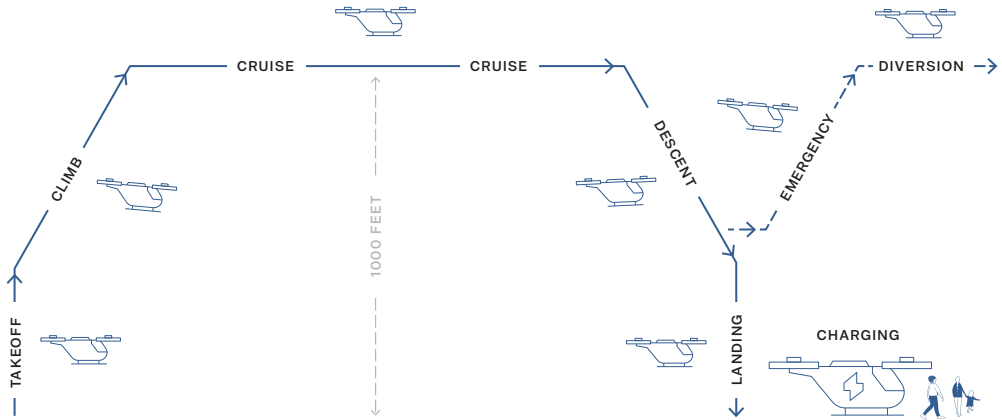
Battery modules are groups of battery cells mechanically integrated to provide higher voltage and capacity. They are the building blocks of battery packs and a key milestone on the path to commercialization.

Meeting the unique demands of aviation flight

TÜV SÜD ran repetitions of a representative eVTOL mission profile on the Cuberg aviation module. These mission profiles were characterized by very high C-rates during takeoff and landing.

eVTOL aircraft fly mission profiles that are uniquely demanding on a battery system – requiring a lot of power to take off, relatively less power to coast, and a lot of power to land. Battery modules built for purpose enable this mission profile by providing high discharge rates at the beginning and end of the mission and a large reserve for cruising over distance.

Testing concluded several weeks later with the module successfully completing 692 cycles. Read on to see the results of these tests.



Designed for certification

Cuberg's batteries are designed to meet aviation safety standards. They will be produced under an FAA approved quality system with Technical Standard Order Authorization (TSOA), inclusive of design and production approval. Cuberg expects our batteries ultimately to be certified at the aircraft level, especially due to the unique installation aspects of each customer's application. TSOA will aid our customers in certifying their aircraft with a Cuberg Battery System.

Mission profile details

PULSE TIMES

Take-off pulse:	~4 minutes
Cruise pulse:	~20 minutes
Landing pulse:	~2 minutes

AVG. DEPTH OF DISCHARGE

55%

MAX DISCHARGE

5.4C

Key findings

Lifecycle

692 cycles

The Cuberg aviation module achieved 692 cycles under a demanding eVTOL mission profile.

Specific energy

284.8 Wh/kg

The Cuberg aviation module has achieved an industry-leading specific energy by integrating our next-generation lithium-metal cells.

Definitions

Cycle life

Each cycle of the Cuberg aviation module, beginning at 100% state of charge, represents a completed mission profile of a market-representative eVTOL flight. It is not a complete depth-of-discharge of the battery.

End of testing

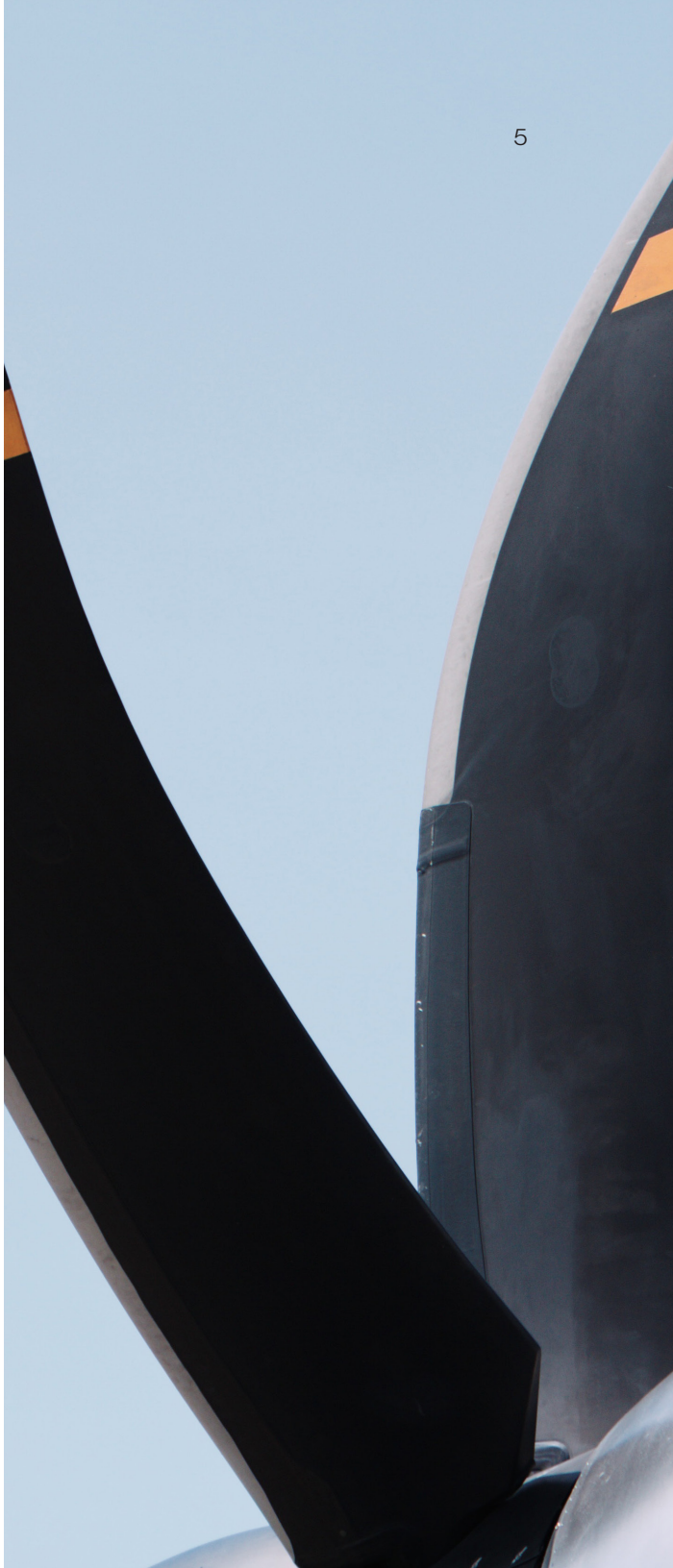
Cuberg's battery system team ended cycling when module capacity retention reached 90%, an end-of-life threshold for some aviation applications.

Battery characteristics show linear and predictable trend lines

The Cuberg module continued to perform consistently, and in alignment with the requirements of eVTOL flight, throughout its tested lifespan of 692 missions. Testing demonstrated linear trend lines for the following performance and health metrics:

- Discharge capacity retention
- DCIR*
- Module voltage
- Minimum module voltage
- Maximum cell temperature

*Direct Current Internal Resistance. This is the resistance in charge and discharge to a direct current demand applied across the terminals.



Enabling aviation businesses

eVTOL operators need a battery with high discharge rates, low weight, and consistent performance over hundreds of missions. Cuberg battery systems can provide all three.

Specific energy

The Cuberg module has achieved specific energy of 284.8 Wh/kg, an industry-leading accomplishment for electric aviation. This significant improvement in specific energy translates to increased flight range which, in turn, enables new use cases for electric aviation.

High specific energy enables operators to choose between longer cruise times or heavier payloads – both of which massively expand the universe of profitable use cases for an eVTOL. Some operators could see their practical range more than double, depending on their aircraft and powertrain design.

Manageable heat

Airframers designing eVTOL aircraft will also take note of the Cuberg module's very low growth in direct current internal resistance (DCIR). Low resistance growth reduces demand on thermal management system engineering, thereby facilitating lightweight and low-volume battery systems.

Long service time

A module that does all of the above, while retaining 90% state of health at approximately 700 missions, is well-suited to underpin a profitable eVTOL operation.

What does 692 mission profiles buy?

Fly an eVTOL with a Cuberg battery 692 times, and you can:

- Fly 66,432 total miles with a fully loaded aircraft
- Serve 2,768 passengers on one-way trips
- Avoid 29.3 tons[1] of CO_2 compared to driving

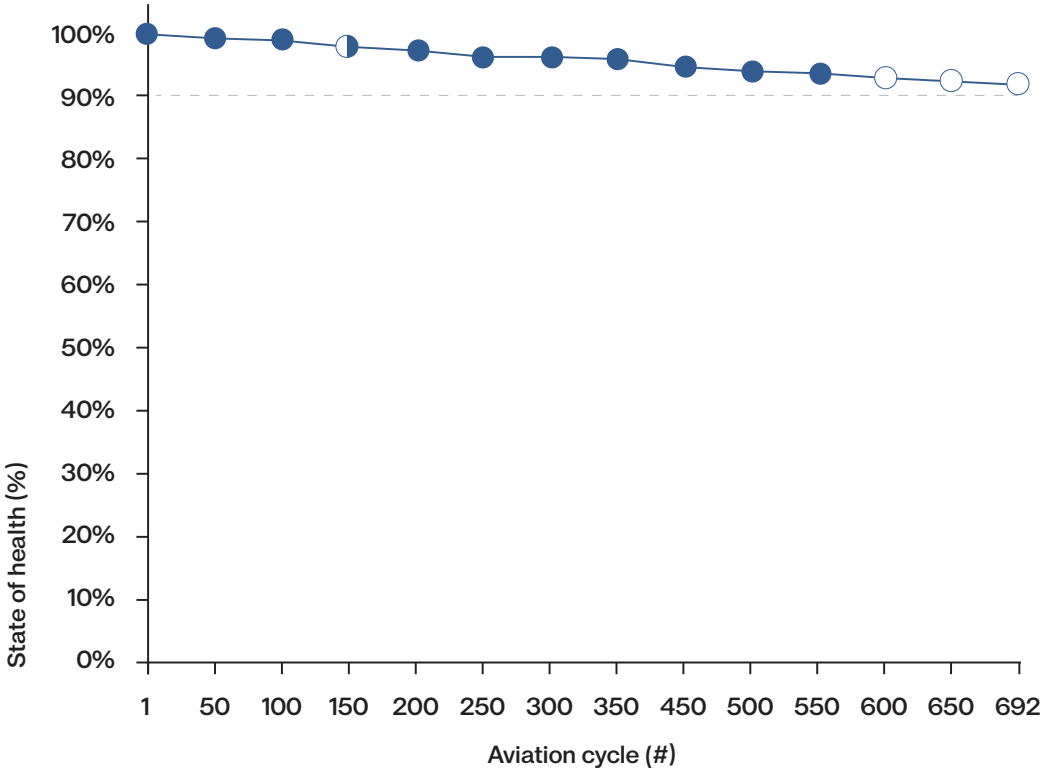
[1] Based on typical passenger car CO_2 emissions calculated by the EPA

Reserve requirements impact range

Aviation regulators are likely to require that eVTOL batteries have significant amounts of flight time set in reserve. Does your battery system have the specific energy that your missions requires?

Fig. 1

Discharge capacity retention



Legend

- Interpolated values
- Extrapolated values
- 1D capacity retention (%)

Groundbreaking advanced chemistry lifespan

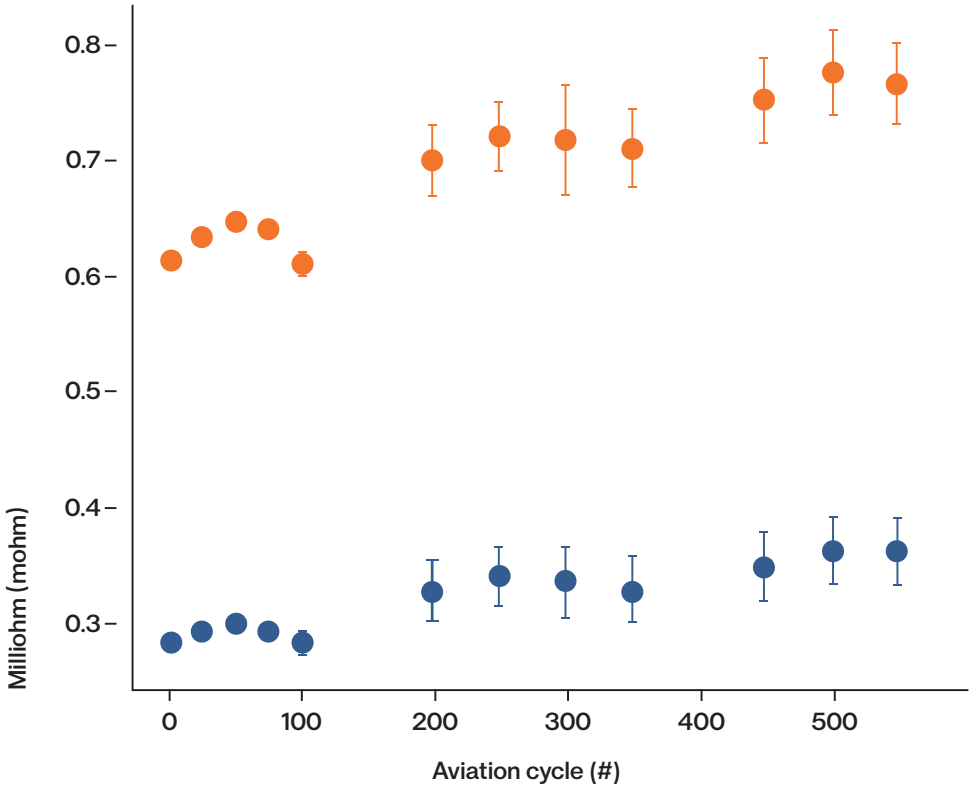
The Cuberg aviation module performed 692 mission profiles before reaching capacity retention of 90%. This has never before been achieved with a module built on lithium metal cell technology.

Enabling eVTOL operators

An eVTOL battery with a useful lifespan of ~700 extremely consistent mission profiles changes the calculus for advanced air mobility business models.

Fig. 2

Direct current internal resistance (DCIR)



Legend

Vertical bars represent +/- 1 standard deviation across 10 bricks (parallelized cells)

DCIR 25s DCIR 1s

Negligible and linear resistance growth

The Cuberg aviation module shows minimal resistance growth through 692 cycles, as monitored through reference 1C discharge pulses.

DCIR pulses at 1-second and 25-second durations (illustrated at Top of Charge and at room temperature) exhibit negligible and linear resistance growth throughout the cycling campaign.

Resistance growth does not escalate in a non-linear manner, allowing for effective thermal management, prolonged cycle life, and stable module voltage performance as depicted in *Figure 3*.

Fig. 3

Module voltage during mission profile

3A: Take-off

eVTOL power profile demands high discharge rates at take-off (up to 5.4C).

Cuberg's aviation module does not drop significant voltage levels and bounces back at cruise, showing limited strain on the system during high-rate discharges.

3B: Cruise

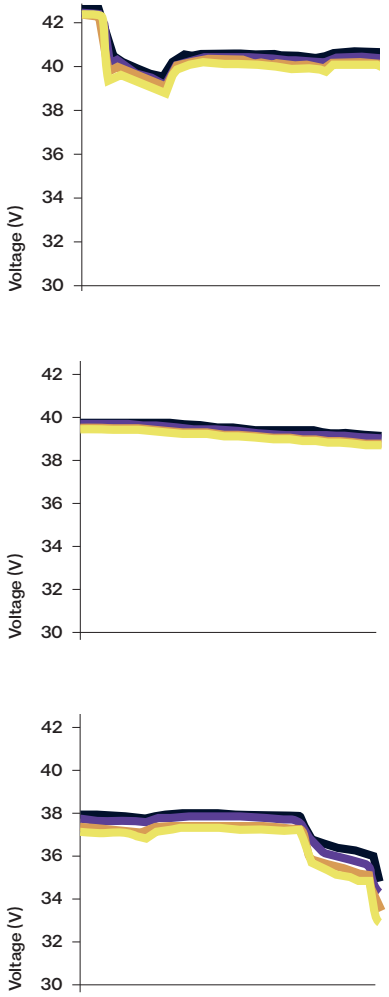
Once in air, optimized aerodynamics allow an eVTOL aircraft to fly with limited strain on the battery.

Cuberg's aviation module consistently delivers power during cruise, proving voltage stability on a next-generation battery system.

3C: Landing

At destination, an eVTOL must slow to landing speed then discharge power at high rates to safely land.

At the end of a demanding flight cycle, when required to discharge at high rates, Cuberg's aviation module again delivers demanding landing power across cycles.



Consistent performance over hundreds of missions

The Cuberg aviation module shows consistent performance over 692 mission profiles at discharge rates up to 5.4C.

Each mission profile began at 42V at 100% state of charge and ended at approximately 33V. The module can safely discharge under load to 25V.

Cycle (#)

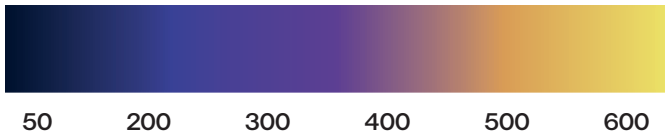
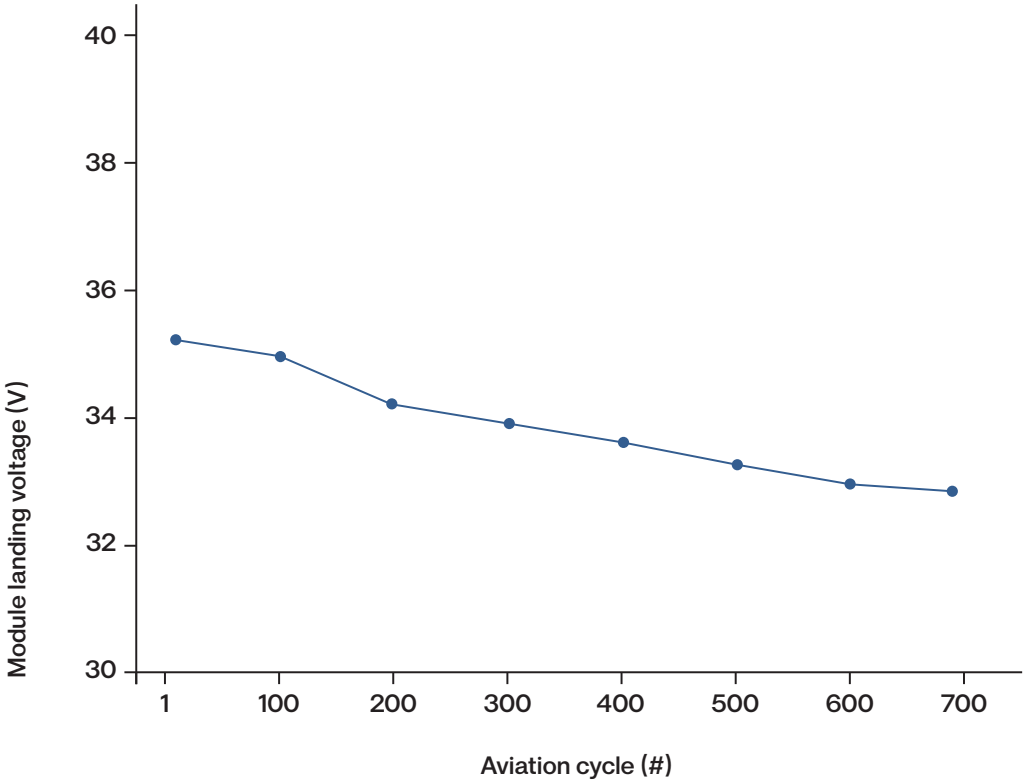


Fig 4

Minimum voltage under load (landing voltage)



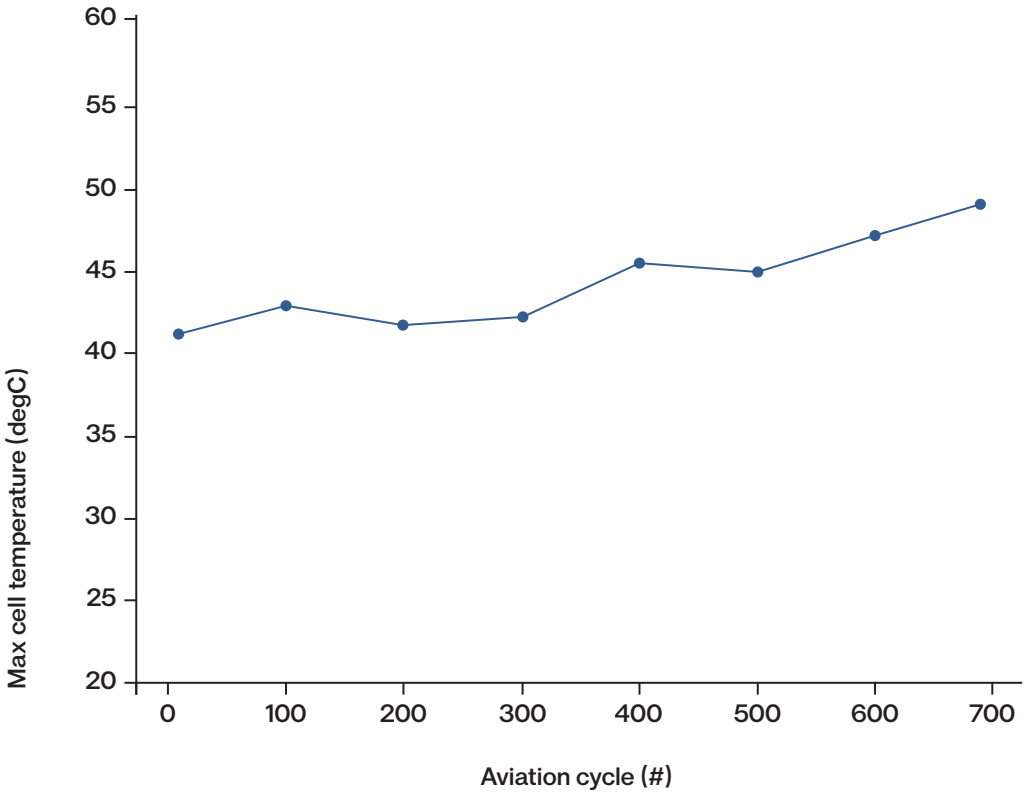
Manageable reduction in landing voltage

The Cuberg aviation module demonstrated slow and linear reduction in landing voltage across 692 cycles, with a last recorded landing voltage of 32.95V.

The lower landing voltage is attributed to the reduction in cell capacity over time. This causes the cell to use up proportionally more energy in the cell to meet the same demanding profile (as high as 5.4C).

FIGURE 5

Maximum cell temperature during discharge



Manageable and linear temperature growth

The Cuberg aviation module maintained acceptable maximum cell temperature across 692 missions. Maximum temperature increased in predictable proportion to resistance growth.

Testing occurred within a temperature-controlled environment with ambient temperature of 25°C. Temperatures were managed with modest active air cooling. Direct exchange of heat from the module's external surfaces was achieved via ambient air flow imparted on the module from an electric fan. Overall heat transfer coefficient ranged from 12 to 15 W/m^2-C at the interface between the module side panel and ambient air.

Cuberg lithium-metal cells are rated for standard operating temperature up to 60°C.

Lithium-metal leads the way for aviation

How does the Cuberg aviation module compare to other aviation batteries?

Product

Other advanced chemistries that can maintain high discharge rates, such as cells with silicon anodes, have not yet demonstrated performance at the module level, nor have they shown ability to achieve the combined power, energy, and cycle life performance demonstrated here.

Specific energy

Lithium-ion batteries cannot match the specific energy of lithium metal technology. eVTOL operators who want maximum flexibility in their mission profiles should rely on Cuberg batteries.

Temperature

Lithium-ion batteries generate more heat than Cuberg batteries due to higher internal resistance, while also having higher sensitivity to degradation at high temperatures.

Power

Mainstream lithium-ion technologies may struggle with the power requirements of an eVTOL flight profile. Under a comparable mission profile, it is likely that lithium-ion cells would not be able to achieve the same level of performance and cyclability. High power requirements of eVTOL missions are likely to rapidly increase resistance and shorten the life of the battery.