

Development and Flight Validation of a 250 Wh/kg-Class, 8C-Rate Lithium-Ion Battery Module for Urban Air Mobility Applications

By Su-Ho YU,¹⁾ Yu-Jin JUNG,¹⁾ and Bum-Dong CHO¹⁾

¹⁾V-SPACE Co., Ltd, Incheon, Republic of Korea

Battery systems for electric vertical takeoff and landing aircraft must deliver both high energy density for cruise and high discharge rates during hover: a combination that existing pack designs rarely demonstrate above 230 Wh/kg. This paper presents the design, fabrication, and validation of a 14-series, 90 Ah lithium-ion battery module that achieves 253.8–257.5 Wh/kg at the pack level with sustained 8C (720 A) discharge, using an entirely passive thermal design. Performance was verified on four prototype units: 229.9–242.7 Wh/kg at -20°C after a 2 h cold soak, 4C pulse operation across -20°C to +43°C, and charge to 90% state of charge in 0.176 h. Environmental qualification adapted from RTCA DO-160G and UN 38.3 was passed without anomaly: six-axis shock (30 g, 11 ms), vibration, altitude (11.6 kPa), drop, humidity, and acceleration. In a module-level thermal runaway test, the heat-spreader–fire-barrier–cell laminate delayed cell-to-cell propagation by more than 12 minutes after trigger-cell ignition, over twice the 5-minute occupant-egress criterion of electric-vehicle regulation. The module powers the V-Speeder X UAM demonstrator, flown under Ministry of Land, Infrastructure and Transport oversight, and has been delivered to cargo eVTOL platforms in the 40 kg and 200 kg payload classes.

Key Words: eVTOL, Lithium-Ion Battery, Battery Packaging, Thermal Runaway Propagation, Safety and Reliability

Nomenclature

<i>C</i>	: C-rate, 1/h
<i>CFRP</i>	: Carbon Fiber Reinforced Polymer
<i>eVTOL</i>	: electric Vertical Take-off and Landing
<i>NCM</i>	: Nickel Cobalt Manganese
<i>POM</i>	: Polyoxymethylene
<i>SOC</i>	: State of Charge, %
<i>TR</i>	: Thermal Runaway
<i>UAM</i>	: Urban Air Mobility

1. Introduction

UAM and eVTOL aircraft place demands on battery systems that differ fundamentally from those of electric ground vehicles. During vertical takeoff, landing, and transition, the propulsion system draws power at rates several times the pack's rated capacity; during cruise, achievable range is directly limited by gravimetric energy density. Fredericks et al. quantified this dual requirement, estimating that practical eVTOL operation demands pack-level specific energy and specific power combinations that no automotive pack is designed to provide simultaneously.¹⁾ Yang et al. further identified fast charging between revenue flights and low-temperature operability as binding constraints on commercially viable eVTOL fleets, noting that turnaround time drives fleet utilization economics.²⁾ Bills et al. extended the analysis to larger electric aircraft, reinforcing that the pack, not the cell, is where the aviation electrification bottleneck lies.³⁾

At the cell level, high-nickel NCM chemistries now

routinely exceed 270 Wh/kg. The engineering gap is packaging efficiency: structural enclosures, thermal management hardware, busbars, and battery management circuitry typically consume 30–40% of pack mass in automotive designs, dropping pack-level energy density well below the eVTOL threshold. Active liquid cooling, standard in electric vehicles, adds pumps, cold plates, and coolant mass that aviation weight budgets cannot absorb, and introduces leak-related failure modes undesirable in airworthiness assessment. Safety adds a further axis: aviation authorities expect demonstrable behavior under cell thermal runaway, yet every gram of fire barrier competes directly with the energy density target.

This paper reports the development and validation of a battery module that addresses this three-way conflict among energy, power, and safety at the packaging level. The module achieves over 250 Wh/kg at the pack level while sustaining 8C discharge, passes a full aviation-adapted environmental qualification campaign, and delays thermal runaway propagation between cells by more than 12 minutes, all with standard commercial cells and no active cooling. Section 2 describes the module architecture and the design decisions behind the mass budget. Section 3 details test methods. Section 4 presents results measured on four prototype units, drawn from cyclor records sampled at 1 s intervals. Section 5 summarizes flight application on an operational UAM demonstrator, and Section 6 concludes.

2. Module Design

2.1. Requirements

The module was specified against the mission profile of a two-seat class UAM vehicle: vertical flight segments drawing up to 8C from the pack for tens of seconds, cruise at 1-2C, a -20 to +43°C ambient operating envelope covering four-season operation, and a between-flight recharge to 90% state of charge within 30 minutes. The quantitative targets were ≥ 250 Wh/kg gravimetric energy density at module level, 8C (720 A) discharge sustained for 60 s, ≥ 220 Wh/kg delivered at -20°C, and full compliance with an environmental test program adapted from RTCA DO-160G⁴⁾ and UN 38.3.⁵⁾

2.2. Architecture

The module integrates fourteen 90 Ah high-nickel NCM pouch cells in series (14S1P), yielding a nominal voltage of 53.2 V and nominal capacity of 90 Ah (~4.8 kWh). The complete module (enclosure, busbars, interconnects, and slave battery-management electronics) weighs approximately 18.3 kg, placing packaging overhead below 20% of total mass. Cells are stacked with fire-propagation-delay pads interleaved between aluminum heat-spreader plates and cells, forming the repeating heat-spreader-barrier-cell laminate shown in Fig. 1. The stacking order serves two purposes simultaneously: the spreader plates conduct heat laterally to the module's finned exterior surfaces during high-rate discharge, and the interleaved barrier pads impede cell-to-cell heat transfer in a thermal runaway event.

Thermal management is entirely passive. Aluminum heat sinks are applied to three surfaces of the module, coupled to the cell stack through thermal-interface silicone, with finned exterior cooling surfaces sized for the airflow available in flight. Eliminating pumps, cold plates, and coolant loops saves mass and removes an entire class of leak- and pump-failure modes from the airworthiness case. For aircraft installation, two modules are connected in series to form a 28S1P pack; all results in this paper are reported at the single-module level.

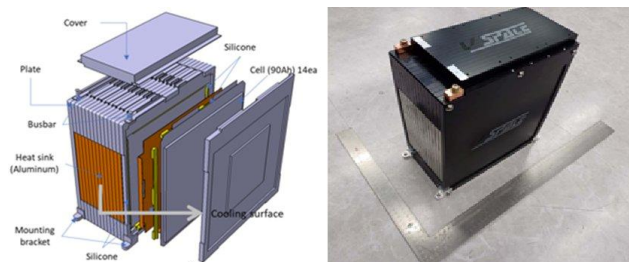


Fig. 1. Module architecture in exploded view (left) and fabricated prototype (right; 14S1P, 90 Ah, ~18.3 kg).

2.3. Design evolution

The module reported here is the fourth design iteration. Relative to the third iteration, total volume was reduced by 6.9% to raise both gravimetric and volumetric density, achieved by tightening the cell pitch and integrating the busbar plane into the cover assembly. The enclosure material was changed from CFRP to POM after insulation evaluation revealed micro-current conduction through machined CFRP cross-sections, where exposed carbon

fibers form conductive paths; a dielectric coating over the complete case was judged impractical for series production, and POM provided the required dielectric strength at acceptable structural margins. Silicone compliance elements were added at the cell-stack boundary to improve mechanical shock tolerance, and mounting brackets were reinforced for airframe integration. Table 1 summarizes the resulting module specifications.

Table 1. Module specifications.

Items	Values
Configuration	14S1P (90 Ah high-nickel NCM pouch)
Nominal voltage / capacity	53.2 V / 90 Ah (~4.8 kWh)
Module mass	~ 18.3 kg
Energy density (measured)	253.8 - 257.5 Wh/kg
Max discharge	8C (720 A), 60 s
Operating envelope	-20 to +43 °C
Thermal management	Passive, 3-surface Aluminum heat sink

3. Test Methods

All performance tests were run on a regenerative pack cyclor recording total voltage, current, and multi-channel temperatures at 1 s intervals; every measurement figure in Section 4 is plotted directly from these records. Procedures were adapted from RTCA DO-160G environmental categories and UN 38.3 transport requirements, with pass criteria fixed in a dedicated test standard developed during the program. Figure 2 shows the module mass measured on a calibrated platform scale before testing, and electrical health was verified before and after each environmental item: open-circuit voltage, insulation resistance (1,000 V, 60 s), AC internal resistance, and weld resistance at cell junctions.



Fig. 2. Module mass measurement prior to energy density testing (Prototype #1, 18.295 kg): scale readout (left) and module on the platform scale (right).

The principal test items were: (1) Energy density: full discharge at 9.0 A to a 35 V cut-off, 30 min rest, full charge to 60.2 V at 9.0 A with 4.5 A taper cut-off, 30 min rest, then a metered 9.0 A discharge to cut-off; delivered energy is integrated over the final discharge and divided by measured module mass. (2) High-rate discharge: 720 A (8C) constant current sustained for 60 s from full charge; pass requires no cell under-voltage and no protective cut-off. (3) Low-temperature capacity: 2 h soak at -20°C, then 9.0 A

discharge to a 25 V cut-off inside the chamber with the integrated heater active. (4) Operating envelope: 4C (360 A, 30 s) pulse discharges at -20°C and $+43^{\circ}\text{C}$ on both test units, plus a 2C (180 A) continuous reference discharge at $+18^{\circ}\text{C}$. (5) Fast charge: constant current up to 270 A (3C) with taper; elapsed time to 90% SOC is recorded. (6) Mechanical shock: half-sine 30 g, 11 ms pulses in all six directions ($\pm X$, $\pm Y$, $\pm Z$), followed by inspection and electrical verification. (7) Thermal runaway propagation: a film heater on a trigger cell energized at 50 Vdc / 20 A and increased until ignition; heating then stops and neighboring-cell temperatures and voltages are monitored. (8) Additional environmental items: sinusoidal vibration sweep (7–200 Hz), altitude exposure at 11.6 kPa for 6 h, 1,000 mm free drop, humidity, and acceleration.

4. Results and Discussion

4.1. Energy density

Figure 3 shows the complete top-up-charge and metered-discharge profile of the energy density measurement for both units; the metered discharge alone spans 9.7 h per unit at a chamber temperature of 20°C . Prototype #1 delivered 87.29 Ah from a measured mass of 18.295 kg, corresponding to 253.8 Wh/kg at the 53.2 V nominal voltage; Prototype #2 delivered 88.67 Ah at 18.320 kg, corresponding to 257.5 Wh/kg. Both exceed the 250 Wh/kg target with margin.

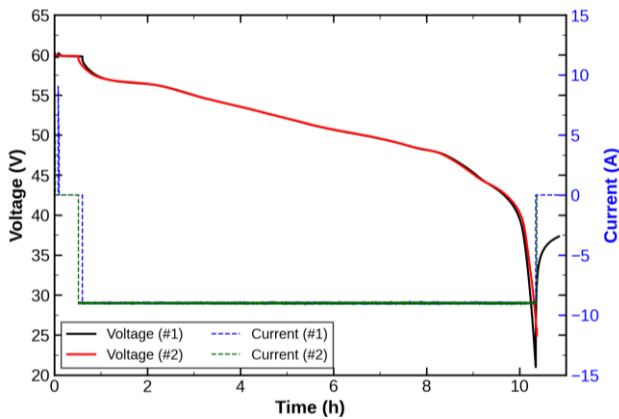


Fig. 3. Energy density protocol at 9.0 A, Prototypes #1 and #2 (voltage, left axis; current, right axis).

Figure 4 replots the metered discharge as voltage versus discharged capacity: the two units track each other within measurement scatter over the full 88 Ah window, indicating consistent cell lot quality and assembly process control between builds. The flat mid-plateau around 51–47 V and the steep knee beyond 80 Ah are characteristic of the high-nickel NCM chemistry and confirm that the full cell capacity is accessible through the module's busbar and interconnect design without premature cut-off.

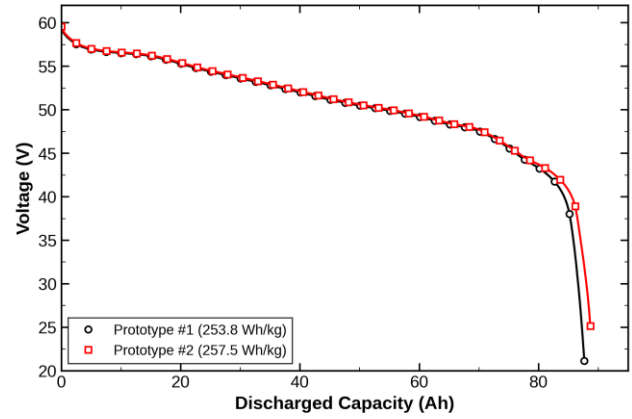


Fig. 4. Metered discharge: voltage versus discharged capacity over the full 88 Ah window.

4.2. 8C sustained discharge

Figure 5 shows the modules connected to the high-current cyclor for the 8C test, and Fig. 6 presents the measured response of Prototypes #3 and #4. Both units sustained 720 A for the full 60 s window. Prototype #3 fell from 58.51 V to 48.14 V over the pulse; Prototype #4 from 58.74 V to 49.00 V.

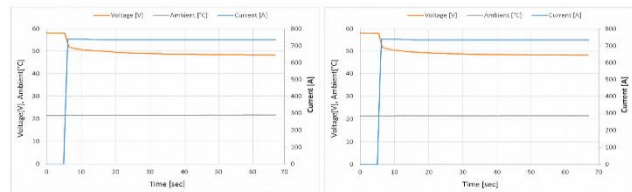


Fig. 5. 8C test configuration: Prototypes #3 (left) and #4 (right) connected to the 720 A cyclor.

The instantaneous IR drop at current application is approximately 6.5 V ($\approx 9 \text{ m}\Omega$ at module level, $\approx 0.65 \text{ m}\Omega$ per cell including interconnects), with the remaining sag accumulating from polarization and state-of-charge depletion; the pulse alone removes 12 Ah, or 13% of capacity. No cell reached the under-voltage limit and no thermal protection tripped. Module surface temperatures recorded during and after the pulse rose by less than 5°C , confirming that the heat-spreader plates and three-surface heat sink absorb the transient heat load of a hover-power draw without active cooling.

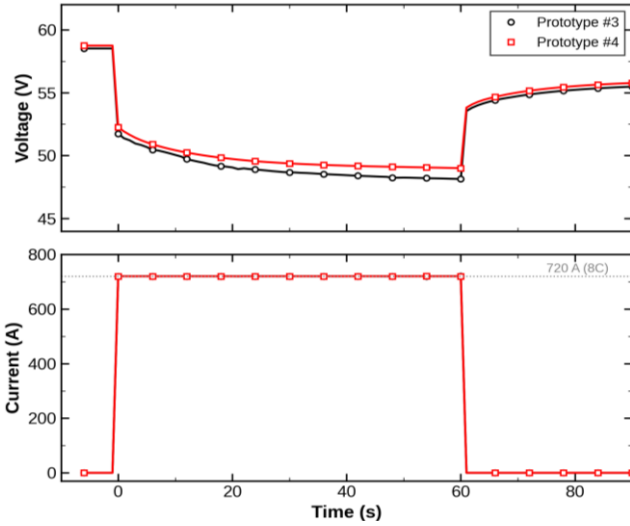


Fig. 6. Sustained 8C (720 A, 60 s) discharge, Prototypes #3 and #4.

4.3. Low-temperature capacity

Figure 7 shows the -20°C discharge after a 2 h cold soak, with chamber temperature overlaid. With the integrated heater active, Prototype #3 delivered 86.67 Ah (242.7 Wh/kg at 19.0 kg including heater mass) and Prototype #4 delivered 81.71 Ah (229.9 Wh/kg at 18.9 kg). Both units exceed the 220 Wh/kg requirement, delivering 229.9–242.7 Wh/kg. The voltage recovery visible in the early discharge phase reflects internal self-heating raising cell temperature out of the high-impedance region, a behavior that benefits sustained low-temperature operation once the mission has begun.

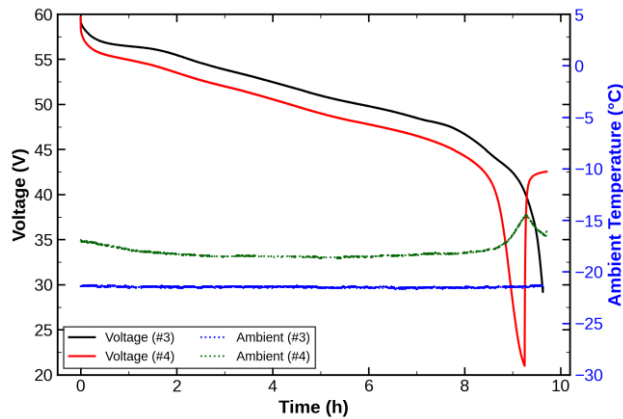


Fig. 7. Discharge at -20°C after 2 h soak (9.0 A), with ambient temperature overlaid (dotted, right axis).

4.4. Operating temperature envelope

Figure 8 overlays the 4C (360 A, 30 s) pulse discharges at both envelope extremes for both test units. At -20°C the modules exhibit the expected larger voltage sag from elevated internal resistance yet complete the pulse without protection events; at $+43^{\circ}\text{C}$ the sag is smaller and no over-temperature condition occurs. Unit-to-unit agreement at each temperature is within 0.5 V throughout the pulse. Together with the 2C continuous reference discharge at $+18^{\circ}\text{C}$, these results verify power capability across the full

-20 to $+43^{\circ}\text{C}$ operating envelope.

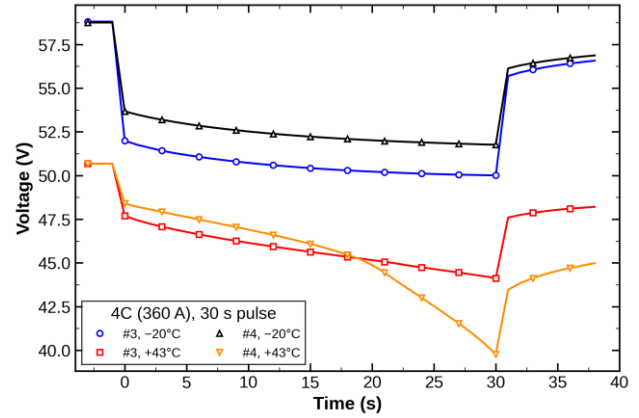


Fig. 8. 4C (360 A, 30 s) pulse discharge at -20°C and $+43^{\circ}\text{C}$, Prototypes #3 and #4.

4.5. Fast charge

Figure 9 shows the fast-charge profile up to 270 A (3C) with taper. Time to 90% SOC was 0.176 h (10.6 min) on the best unit per the certified measurement, well inside the 0.5 h requirement. At this charge rate a UAM operator can restore a mission-ready state of charge within a typical passenger boarding turnaround, directly supporting the fleet-utilization requirement identified by Yang et al.²⁾

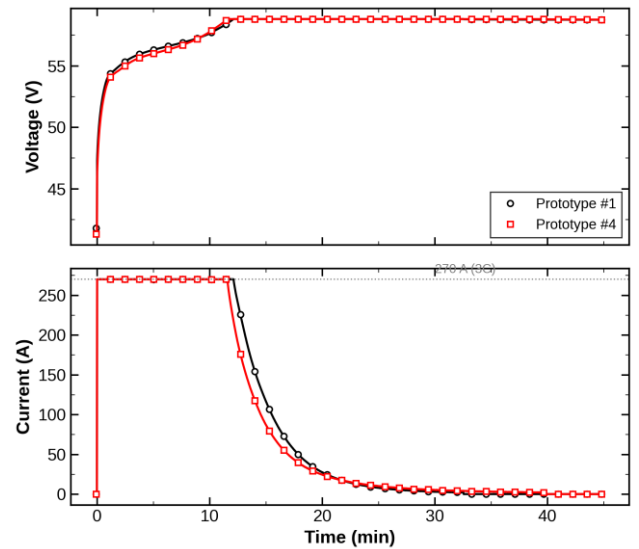


Fig. 9. Fast charge toward 90% SOC at up to 270 A (3C), Prototypes #1 and #4.

4.6. Mechanical shock

Half-sine 30 g/11 ms shock pulses were applied in all six directions with the module rigidly fixtured to the shock table in each orientation, as shown in Fig. 10.



Fig. 10. Mechanical shock fixturing for X- (left), Y- (center), and Z-axis (right) orientations (30 g, 11 ms, both polarities each axis).

Post-test inspection found no structural damage, no cell displacement, no open-circuit-voltage shift, and no insulation degradation, as shown in Fig. 11; mass and voltage measured before and after the series agreed within instrument resolution. The sinusoidal vibration sweep (7-200 Hz), altitude exposure (11.6 kPa, 6 h), 1,000 mm drop, humidity, and acceleration items were likewise passed without anomaly, with electrical verification repeated after each item.

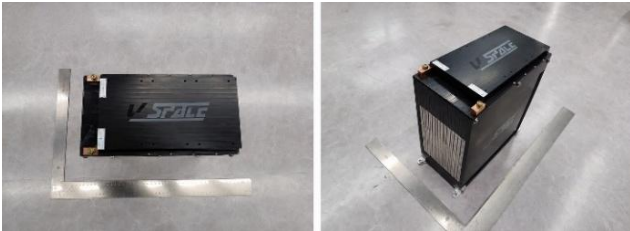


Fig. 11. Module condition before (left) and after (right) the six-axis shock series.

4.7. Thermal runaway propagation delay

Figure 12 presents the module-level thermal runaway propagation test. The film heater on the trigger cell was energized at 50 V DC and 20 A; the trigger cell ignited 3 min 05 s after heating began. Cell body temperatures and voltages of the adjacent instrumented cells show that propagation to the first neighboring cell occurred at 15 min 28 s, corresponding to a delay of more than 12 min after trigger-cell ignition. The peak cell body temperature at the trigger location reached approximately 1,000 °C. The sharp negative excursion in the trigger-cell temperature trace is a nonphysical measurement artifact caused by a temporary interruption of the thermocouple signal during cell rupture. The raw data are presented without correction in Fig. 12.

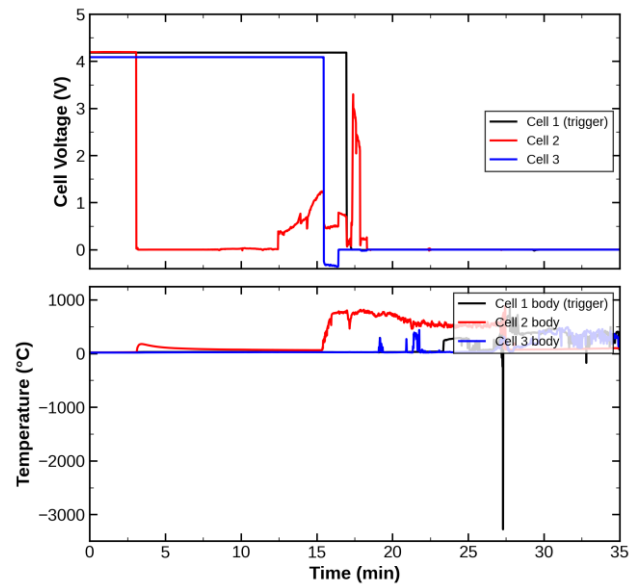


Fig. 12. Thermal runaway propagation test: cell voltages (top) and cell body temperatures (bottom). Trigger-cell ignition at 3 min 05 s; first neighbor propagation at 15 min 28 s.

The post-test module condition is shown in Fig. 13. Complete prevention of propagation, the program's original target, was not achieved; the interleaved barrier stack cannot indefinitely absorb the ~4.8 kWh released in cascade within the packaging mass budget available. The result is better assessed against the regulatory direction for battery systems: GB 38031 requires a 5-minute interval between thermal runaway warning and hazard to occupants,⁶⁾ while the corresponding thermal propagation provisions of UN GTR No. 20 remain under development.⁷⁾ Emerging aviation practice similarly frames propagation delay, rather than absolute prevention, as the certifiable criterion. The measured 12-minute delay exceeds the 5-minute reference by more than a factor of two, providing a substantial time window for descent and emergency landing. Table 2 summarizes the complete validation results. Extending this margin, and coupling it with system-level suppression, is the subject of ongoing work.



Fig. 13. Module condition after the thermal runaway propagation test: module exterior (left) and cell stack (right).

Table 2. Summary of module validation results.

Items	Targets	Measured
Energy density (20°C)	≥ 250 Wh/kg	253.8 / 257.5 Wh/kg
8C discharge (720 A)	60 s sustained	60 s, no cut-off
Low-temp energy (-20°C)	≥ 220 Wh/kg	229.9 / 242.7 Wh/kg
Operating envelope	-20 to +43°C	Verified (4C pulses)

Charge to 90% SOC	≤ 0.5 h	0.176 h
Mechanical shock	No damage	No anomaly
Vibration / altitude / drop	Per procedure	No anomaly
TR propagation	No propagation	Delayed > 12 min
Module mass	-	18.3 kg

5. Flight Application

Two series-connected modules (28S1P) power the V-Speeder X, a Korean-developed UAM demonstrator. The aircraft has completed public flight demonstrations conducted under the oversight of the Korean Ministry of Land, Infrastructure and Transport, providing flight-level confirmation of the module's discharge capability under real hover and transition loads, its passive thermal behavior in flight airflow, and its structural integration under airframe vibration. Modules of the same architecture have additionally been delivered to unmanned cargo eVTOL platforms in the 40 kg and 200 kg payload classes under a multi-batch supply arrangement extending toward production, and a type-certification program for a follow-on certified aircraft is in progress with the national aviation authority. Figure 14 shows the aircraft in hovering flight and on the vertiport pad.



Fig. 14. V-Speeder X demonstrator powered by two series-connected modules (28S1P): hovering flight in an urban environment (left) and the aircraft at a vertiport (right).

6. Conclusion

A 14S1P, 90 Ah lithium-ion battery module for UAM applications was developed and validated on four prototype units. Measured pack-level energy density reached 253.8–257.5 Wh/kg with sustained 8C (720 A) discharge; low-temperature delivery reached 229.9–242.7 Wh/kg at -20°C ; and charge to 90% SOC required 0.176 h. A full aviation-adapted environmental campaign (six-axis 30 g shock, vibration, altitude, drop, humidity, acceleration) was passed without anomaly. In the module-level thermal runaway test, the heat-spreader–fire-barrier–cell laminate delayed cell-to-cell propagation by more than 12 minutes, over twice the 5-minute egress criterion of electric-vehicle regulation, although complete propagation prevention within the packaging mass budget was not achieved. All results were obtained with standard high-nickel NCM cells and an entirely passive thermal design, demonstrating that the energy-power-safety conflict of UAM battery systems is substantially addressable at the packaging level. Flight operation on the V-Speeder X demonstrator confirms real-world applicability. Ongoing work targets extended

propagation delay, system-level suppression integration, and certification-oriented test standardization.

Acknowledgments

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References

- 1) Fredericks, W. L., Sripad, S., Bower, G. C., and Viswanathan, V.: Performance Metrics Required of Next-Generation Batteries to Electrify Vertical Takeoff and Landing (VTOL) Aircraft, *ACS Energy Lett.*, 3 (2018), pp. 2989–2994.
- 2) Yang, X.-G., Liu, T., Ge, S., Rountree, E., and Wang, C.-Y.: Challenges and Key Requirements of Batteries for Electric Vertical Takeoff and Landing Aircraft, *Joule*, 5 (2021), pp. 1644–1659.
- 3) Bills, A., Sripad, S., Fredericks, W. L., Singh, M., and Viswanathan, V.: Performance Metrics Required of Next-Generation Batteries to Electrify Commercial Aircraft, *ACS Energy Lett.*, 5 (2020), pp. 663–668.
- 4) RTCA Inc.: DO-160G Environmental Conditions and Test Procedures for Airborne Equipment, RTCA DO-160G, Washington D.C., 2010.
- 5) United Nations: Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, Section 38.3: Lithium Metal and Lithium-ion Batteries, 7th revised edition, UN, New York and Geneva, 2019.
- 6) Standardization Administration of China: Electric Vehicles Traction Battery Safety Requirements, GB 38031-2020, Beijing, 2020.
- 7) United Nations Economic Commission for Europe: Global Technical Regulation on the Electric Vehicle Safety (EVS), UN GTR No. 20, ECE/TRANS/180/Add.20, Geneva, 2018.