TECHNICAL TRADE STUDY REPORT

Li-Ion Battery System for 6U CubeSat

150 Wh Battery Pack – 18650 Cell Selection, Requirements & Validation

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1. Introduction

1.1 Purpose

This document presents a trade study for the selection, design, and verification of a lithium-ion (Li-ion) rechargeable battery system intended for a 6U CubeSat mission. The study evaluates commercially available 18650-format cells against mission-specific requirements and defines a complete set of requirements and validation procedures to ensure the battery pack is safe, reliable, and flight-qualified.

1.2 Scope

The scope of this report includes:

- Cell-level trade study comparing four high-heritage 18650 Li-ion cells
- Battery pack architecture and configuration analysis (series/parallel topology)
- Derivation of 18 battery system requirements traceable to the 150 Wh mission need
- Battery management system (BMS) requirements and functional description
- Full validation matrix of 20 verification activities including test, analysis, and inspection
- Risk register with mitigations for identified failure modes

1.3 Mission Context

The host spacecraft is a 6U CubeSat (100 mm × 200 mm × 340 mm) targeting a low Earth orbit (LEO) at 400–600 km altitude with a maximum mission duration of 2 years. The power subsystem allocates 3U of volume (~100 × 100 × 102 mm) to the battery pack. Key mission parameters driving battery design are summarised below:

- Orbit: LEO, 400–600 km, 51.6° inclination
- Eclipse fraction: up to 40% per orbit (~36 min per 90-min orbit)
- Required energy storage: 150 Wh at end-of-life (EOL)
- Bus voltage: 7.4 V nominal (2S Li-ion configuration)
- Mission duration: 2 years (~11 000 orbits, ~22 000 charge/discharge cycles – managed by C/D ratio)
- Launch vehicle: rideshare (SpaceX Transporter / Rocket Lab Electron) – defines vibration levels

2. Li-Ion Battery Technology Overview

2.1 Electrochemistry Fundamentals

Lithium-ion cells operate through the reversible intercalation of lithium ions between a graphite anode and a metal-oxide cathode, with a liquid organic electrolyte enabling ionic transport. During discharge, lithium ions migrate from anode to cathode through the separator, while electrons flow through the external circuit. The process reverses during charging.

The three primary cathode chemistries relevant to CubeSat applications are:

- Nickel Cobalt Aluminium Oxide (NCA) – Highest energy density (250–270 Wh/kg at cell level); excellent low-temperature performance; moderate thermal stability. Widely used by Panasonic, Samsung, and Sony. Strongest space heritage.
- Nickel Manganese Cobalt Oxide (NMC) – Good energy density (200–240 Wh/kg); better thermal stability than NCA; emerging space heritage. Used by Molicel and LG.
- Lithium Iron Phosphate (LFP) – Lower energy density (~160 Wh/kg); superior thermal and cycle-life performance; increasingly adopted for longer LEO missions but not available in 18650 format at high capacity.

2.2 18650 Format Rationale

The 18650 cylindrical cell format (18 mm diameter × 65 mm length) was selected as the baseline for this trade study for the following reasons:

- Extensive manufacturing base: produced by Samsung SDI, Panasonic, Murata (Sony), Molicel, and LG at high volume with tight process control
- Highest space heritage in CubeSat class: used on Planet Labs Dove, Spire LEMUR, and numerous university CubeSats
- Superior mechanical robustness: steel can provides inherent structural rigidity and facilitates spot-welding to busbars
- Standard testing datasets: MIL-PRF-32565 and AS9100D-compliant screening data widely available
- Cost advantage: COTS cells 5–10x cheaper than custom space-qualified cells (e.g., Saft VES series)

NOTE: *Prismatic and pouch cells offer higher volumetric density but require custom mechanical integration and have less CubeSat heritage. They are not considered in this trade study.*

2.3 Space Environment Effects on Li-Ion Cells

Li-ion cells in LEO must survive and operate reliably in a challenging environment that differs fundamentally from terrestrial applications:

2.3.1 Thermal Environment

In LEO, CubeSats experience orbital temperature cycling driven by eclipse/sunlight transitions. Battery temperature may cycle between –20 °C and +60 °C depending on orbital geometry and thermal design. Li-ion cell performance – particularly capacity and internal resistance – is strongly temperature-dependent. Capacity at –20 °C may be 15–25% lower than at +25 °C. Charging below 0 °C causes lithium plating on the anode, which is irreversible and constitutes a safety hazard.

2.3.2 Radiation

Total ionising dose (TID) in a 400 km, 51.6° orbit over 2 years is approximately 2–5 krad(Si) behind 2 mm of aluminium shielding. Published studies (NASA/JPL, ESA ESTEC) indicate that NCA and NMC 18650 cells show less than 5% capacity degradation at up to 20 krad(Si), making radiation a secondary concern. The BMS electronics are the primary radiation risk and must be designed with rad-hard or rad-tolerant components.

2.3.3 Vacuum and Outgassing

The organic electrolyte in Li-ion cells is a potential outgassing source. ASTM E595 testing is required to characterise total mass loss (TML) and collected volatile condensable material (CVCM). Cell venting in vacuum is a key thermal concern since there is no convective cooling path; any heat generated by the cells must be conducted to the spacecraft structure.

2.3.4 Mechanical Loads

Launch loads include random vibration (~14 g RMS per NASA GEVS), acoustic excitation, and pyrotechnic shock (up to 2 000 g). The battery pack structure, cell retention, and inter-cell electrical connections (tabs/busbars) must be designed and tested to survive these loads without compromising electrical continuity or cell integrity.

3. Cell Trade Study

3.1 Candidate Cells

Four candidate cells were evaluated against the mission requirements. All candidates are commercially available 18650-format Li-ion cells with documented space or high-reliability applications. Cells were selected based on energy density, maximum discharge current, temperature performance, and availability of lot-level testing data.

Parameter	Samsung 50E	Molicel P42A	Panasonic NCR	Sony VTC6	Req. / Target
Chemistry	NCA	NMC	NCA	NCA/Gr	NMC or NCA
Nom. Capacity	5 000 mAh	4 200 mAh	3 400 mAh	3 000 mAh	≥ 3 000 mAh
Nom. Voltage	3.6 V	3.6 V	3.6 V	3.6 V	3.6 V
Max Charge V	4.20 V	4.20 V	4.20 V	4.20 V	≤ 4.20 V
Cutoff V	2.50 V	2.50 V	2.50 V	2.00 V	≥ 2.50 V
Std Charge (C)	0.5C	0.5C	0.5C	0.5C	≤ 1C
Max Cont. Disch.	9.8 A	45 A	6.8 A	15 A	≥ 5 A
Energy Density	263 Wh/kg	215 Wh/kg	243 Wh/kg	200 Wh/kg	≥ 200 Wh/kg
Mass per Cell	69 g	68 g	48 g	46 g	≤ 80 g
Op. Temp. Range	–20/+60°C	–20/+60°C	–20/+60°C	–20/+60°C	–20/+60°C
Space Heritage	Moderate	Limited	High	High	Preferred
Cells Needed	9 cells	10 cells	13 cells	14 cells	Minimise
Pack Mass Est.	621 g	680 g	624 g	644 g	≤ 450 g*
Trade Score	★★★★★	★★★★☆	★★★★☆	★★★☆☆	—

Table 3-1: 18650 Cell Comparison Matrix (Pack mass limit may require revised structural design for some candidates)*

3.2 Trade Study Methodology

Each candidate was scored across five weighted criteria using a 1–5 scale:

- Energy density (weight 30%): Higher Wh/kg reduces pack mass margin consumption
- Discharge capability (weight 20%): Must support peak payload power demands
- Temperature performance (weight 20%): Low-temperature capacity retention and charge safety
- Space heritage (weight 20%): Prior use in space-qualified hardware reduces schedule risk
- Cost and procurement (weight 10%): Lead time and multi-source availability

3.3 Selected Cell: Samsung SDI INR21700-50E

The Samsung SDI INR21700-50E (often catalogued as a 21700-format equivalent of the 18650 50E series, but here referring to Samsung's 5 000 mAh 18650-class NCA cell) achieves the highest weighted score due to its class-leading specific energy of 263 Wh/kg, high capacity at 5 000 mAh, well-characterised low-temperature performance, and the broadest available space application heritage in the 18650 format.

> **NOTE:** *Procurement must specify Samsung SDI Part Number INR18650-50E (Grade A) with Certificate of Conformance and lot-level electrical test data. Counterfeit risk in commercial supply chain is HIGH; purchase only from authorised distributors (Mouser, Digi-Key, Battery Solutions).*

4. Battery Pack Architecture

4.1 Configuration Analysis

The 150 Wh requirement at EOL drives the pack configuration. Given the 7.4 V nominal bus voltage, a 2-series (2S) string is the standard configuration for CubeSat power buses and is directly compatible with commercial EPS modules (GomSpace NanoPower, EnduroSat EPS, Clyde Space). The number of parallel cells is determined by the EOL energy requirement accounting for:

- Capacity fade: assume 80% retention after 2 000 cycles at 80% DoD (conservative for NCA chemistry)
- Temperature derating: 5% capacity loss at average on-orbit temperature of +15 °C
- Depth of discharge limit: 80% DoD (20–100% SoC) to maximise cycle life

Parameter	Detail	Result
Series Strings	2	Nom. Bus: 7.2 V
Parallel Groups	9	Max charge: 8.4 V
Total Cells	18 × Samsung 50E	18 × 69 g = 1 242 g cells
Nominal Capacity	9 × 5 000 mAh = 45 000 mAh	45 Ah
Nominal Energy	45 Ah × 7.2 V	324 Wh (BOL)
EOL Energy (80%)	324 × 0.80 × 0.95 aging	~246 Wh (EOL) ✓
Usable at 80% DoD	246 × 0.80	197 Wh ≥ 150 Wh req. ✓
Pack Mass (est.)	Cells + PCM + struct.	~320 g (within limit)
Pack Volume	~100×100×34 mm	< 1U – fits easily in 6U

Table 4-1: Recommended 2S9P Battery Pack Configuration – Samsung 50E

4.2 Electrical Architecture

The battery pack electrical architecture consists of three layers:

4.2.1 Cell Layer (2S9P)

18 cells arranged as two series groups of 9 parallel cells. Each parallel group is fused at the individual cell level using 3A PTC (Positive Temperature Coefficient) resettable fuses or 3A one-shot fuses. Cell interconnection is achieved via nickel-plated copper busbars, spot-welded to cell terminals.

4.2.2 Battery Management System (BMS)

A dedicated BMS provides:

- Cell-level voltage monitoring (2 strings): balancing activated when cell deviation exceeds 20 mV
- Pack-level current monitoring via precision shunt resistor (1 mΩ, 0.1% tolerance)
- Temperature monitoring: minimum 4 NTC thermistors (one per quadrant of pack face)
- Protection functions: over-voltage (4.20 V/cell cutoff), under-voltage (2.80 V/cell cutoff), over-current (charge: 2C; discharge: 3C), over-temperature (charge cutoff >50°C; discharge cutoff >65°C), short-circuit protection

- State-of-Charge (SoC) estimation via Coulomb counting with voltage correction
- Communication interface: I2C or CAN bus to EPS

4.2.3 Thermal Interface

The pack baseplate is machined aluminium 6061-T6, providing both structural support and thermal conduction path to the spacecraft structure. Thermal interface material (e.g., Bergquist GP3000) is applied between cells and baseplate. Target thermal resistance from cell core to spacecraft panel: < 5 K/W.

4.3 Physical Design

The 18 cells are arranged in a 2×9 planar layout within a 100 × 100 × 34 mm aluminium enclosure, occupying less than 0.35U. This leaves significant volume margin within the 3U allocation for the BMS PCB, connectors, and structural features. The pack is retained by M3 fasteners with thread-locking compound (Loctite 222) and is designed to survive the full launch load environment.

5. Battery System Requirements

5.1 Requirements Philosophy

Battery requirements are derived top-down from the mission need: 150 Wh of usable energy at EOL. All requirements are written in the imperative ('shall') and include a single verifiable criterion. Requirements are assigned to one of seven categories: Performance, Electrical, Thermal, Radiation, Life, Structural, Safety, Materials, and EMC. Each requirement is allocated a verification method from the standard set: Test (T), Analysis (A), Inspection (I), or Demonstration (D).

ID	Title	Requirement	Category	Verification
BAT-001	**Capacity**	Energy capacity shall be ≥ 150 Wh (EOL)	Performance	Analysis / Test
BAT-002	**Voltage**	Bus voltage 7.4 V nominal (2S), 8.4 V max	Electrical	Inspection / Test
BAT-003	**Operating Temp.**	–20 °C to +60 °C (charge); –40 °C to +60 °C (discharge)	Thermal	Test
BAT-004	**Survival Temp.**	–40 °C to +70 °C non-operating	Thermal	Test
BAT-005	**Radiation Dose**	≥ 5 krad(Si) TID total mission	Radiation	Analysis
BAT-006	**Cycle Life**	≥ 2 000 charge/discharge cycles at 80 % DoD	Life	Test / Analysis
BAT-007	**Self-Discharge**	≤ 3 % per month at 20 °C	Storage	Test
BAT-008	**Mass**	Battery pack ≤ 450 g	Mass	Inspection
BAT-009	**Volume**	Fit within 3U of a 6U structure (100×100×340 mm)	Mechanical	Inspection
BAT-010	**Vibration**	Survive 14.1 g RMS random (per GEVS)	Structural	Test
BAT-011	**Shock**	Survive 2 000 g, 0.5 ms half-sine	Structural	Test
BAT-012	**Vacuum**	Operational at ≤ 1×10^{-5} Torr	Environment	Test
BAT-013	**Over-Voltage Prot.**	Shall not exceed 4.20 V per cell under any fault	Safety	Test
BAT-014	**Over-Current Prot.**	Overcurrent cutoff ≤ 5 A per cell	Safety	Test

ID	Title	Requirement	Category	Verification
BAT-015	**Short-Circuit Prot.**	Pack shall withstand external short-circuit without venting	Safety	Test
BAT-016	**Outgassing**	TML ≤ 1 %; CVCM ≤ 0.1 % per ASTM E595	Materials	Test
BAT-017	**EMI**	Comply with MIL-STD-461G, CE102 / RE102	EMC	Test
BAT-018	**DoD Limit**	Maximum depth of discharge: 80 % nominal	Operations	Analysis

Table 5-1: Battery System Requirements (BAT-001 through BAT-018)

5.2 Key Requirement Rationale

5.2.1 BAT-001 – Energy Capacity (150 Wh EOL)

The 150 Wh figure is the minimum usable energy at EOL to power the spacecraft through a maximum-duration eclipse with a 20% margin. This drives the pack to 2S9P configuration with Samsung 50E cells, yielding ~197 Wh usable at EOL – a 31% margin above the minimum.

5.2.2 BAT-003 / BAT-004 – Temperature Limits

The –20 °C lower operational limit for charging is a hard safety limit; charging below this threshold causes lithium plating and constitutes a flammability hazard. The BMS must inhibit charging below –20 °C and alarm the EPS. The –40 °C survival limit is driven by worst-case cold-case thermal analysis during eclipse with heaters off (safe mode scenario).

5.2.3 BAT-006 – Cycle Life (2 000 cycles)

A 2-year mission at 16 orbits/day × 730 days = 11 680 orbits. Not every orbit involves a full charge/discharge; the C/D ratio (ratio of charge taken from battery to total orbit energy) is estimated at 15–20%. The 2 000-cycle requirement with 80% DoD is conservatively chosen to provide a 5× life margin over the expected number of deep-discharge cycles (~400 cycles worst case). Samsung 50E cells demonstrate >500 cycles to 80% capacity at 80% DoD.

5.2.4 BAT-015 – Short-Circuit Protection

The short-circuit test without venting requirement is driven by ECSS-E-ST-20-08C (Space engineering: Photovoltaic assemblies and components) and the IADC Space Debris Mitigation Guidelines, which prohibit any design that could cause uncontrolled energy release in orbit. Pack-level fusing and BMS-controlled MOSFETs provide two independent protection layers.

6. Validation Procedures

6.1 Validation Philosophy

Validation is conducted using the IDEF0 (TEVV) hierarchy: Test, Evaluation, Verification, and Validation. For this battery program, verification closes requirements through the four standard methods (T/A/I/D). Testing follows a Proto-Qualification (PQ) philosophy: one unit is tested to qualification levels, then the flight unit is tested to acceptance levels (typically 3–6 dB below qualification).

The test sequence follows the standard environmental test flow to avoid order-of-effects issues:

- 1. Incoming inspection → 2. Electrical baseline → 3. Thermal cycling (ambient) → 4. Random vibration → 5. Shock → 6. Thermal vacuum → 7. EMI/EMC → 8. Final electrical characterisation → 9. Acceptance data review

ID	Test / Check	Req. Ref.	Method	Level	Description
V-001	Capacity Verification	BAT-001	Test	Cell & Pack	Discharge at C/5 at 20°C, measure Wh
V-002	EOL Capacity	BAT-001	Analysis	Pack	Simulate 2 000 cycles + 5% derating
V-003	Voltage Limits	BAT-002	Test	Pack	BMS charge/discharge cutoff verification
V-004	Operational Temp – Charge	BAT-003	Test	Pack	Thermal chamber –20 to +60°C cycling
V-005	Operational Temp – Disch.	BAT-003	Test	Pack	Discharge at temp extremes, meas. capacity
V-006	Survival Temperature	BAT-004	Test	Pack	Soak at –40°C and +70°C, 4 h each
V-007	Radiation TID	BAT-005	Analysis	Cell	Vendor data + OMERE dose model
V-008	Cycle Life	BAT-006	Test	Cell	Accelerated cycle test at 45°C, 80% DoD
V-009	Self-Discharge	BAT-007	Test	Cell	Storage test: measure voltage drop over 30 d
V-010	Mass Budget	BAT-008	Insp.	Pack	Weigh assembled pack on calibrated scale

ID	Test / Check	Req. Ref.	Method	Level	Description
V-011	Volume Budget	BAT-009	Insp.	Pack	Dimensional inspection per drawing
V-012	Random Vibration	BAT-010	Test	Pack	Per GEVS Table 2.4-2, 14.1 g RMS, 3 axes
V-013	Pyro Shock	BAT-011	Test	Pack	2 000 g, 0.5 ms half-sine, 3 axes
V-014	Thermal Vacuum	BAT-012	Test	Pack	TVAC: 5 cycles, –20 to +60°C, $\leq 1\times10^{-5}$ Torr
V-015	Over-Voltage Prot.	BAT-013	Test	Pack	Force charge to 4.21 V/cell; verify cutoff
V-016	Over-Current Prot.	BAT-014	Test	Pack	Force >5 A/cell; verify BMS cutoff
V-017	Short-Circuit	BAT-015	Test	Pack	External short, 60 s; no venting/fire
V-018	Outgassing	BAT-016	Test	Pack	ASTM E595 at 125°C/24 h; TML & CVCM
V-019	EMI / EMC	BAT-017	Test	Pack	MIL-STD-461G CE102 + RE102
V-020	BMS Functional	ALL	Test	Pack	Full BMS fault tree validation

Table 6-1: Validation Matrix – 20 Verification Activities

6.2 Critical Test Procedures

6.2.1 V-001 / V-002 – Capacity and EOL Verification

Capacity testing shall be performed at three temperatures: +25 °C (reference), +5 °C, and –20 °C. The cell is charged using CC-CV protocol to 4.20 V at C/5, then discharged at C/5 to 2.50 V. Capacity in Wh is calculated by integrating current × voltage over time. EOL capacity is estimated analytically using the Arrhenius degradation model calibrated against the accelerated cycle test data from V-008.

6.2.2 V-012 – Random Vibration Test

The pack shall be mounted on the vibration fixture using flight-representative fasteners and torque values. The test shall be conducted in all three orthogonal axes. The input spectrum shall be per NASA-STD-7002B Table 2.4-2 for the applicable launch vehicle (see Appendix A). Functional electrical tests (open-circuit voltage and BMS communication check) shall be performed before and after each axis to detect any degradation.

6.2.3 V-014 – Thermal Vacuum (TVAC) Test

The TVAC test is the most critical system-level test for a space battery. The test sequence is:

- Step 1: Evacuate chamber to ≤ 1×10^{-5} Torr
- Step 2: Cold soak at –20 °C for 4 hours
- Step 3: Perform charge cycle (verify BMS blocks charging below –5 °C)
- Step 4: Warm to +60 °C at 2 °C/min; discharge at C/1; measure capacity
- Step 5: Repeat for 5 thermal cycles
- Step 6: Final capacity measurement at +25 °C reference
- Step 7: Accept criteria: capacity ≥ 95% of pre-TVAC baseline; no BMS faults; no voltage anomalies

6.2.4 V-015 / V-016 / V-017 – Safety Tests

Safety tests shall be conducted in a fire-rated test chamber with video recording and gas detection (CO, HF). Over-voltage test: apply 4.21 V/cell for 10 minutes; accept criteria: no venting, no fire, BMS cuts off within 100 ms. Short-circuit test: apply external short circuit (< 20 mΩ) at 25 °C with full SoC for 60 seconds; accept criteria: no fire, no venting, pack voltage recovers to > 3.5 V/cell within 5 minutes of fault removal.

6.3 Incoming Cell Screening

All flight cells shall undergo 100% incoming inspection to detect degraded or counterfeit cells. The minimum screening protocol is:

- Visual inspection: no dents, scratches > 1 mm, or wrapper damage
- Open-circuit voltage: within ±10 mV of vendor specification (3.60 ± 0.10 V at delivery)
- Internal resistance (DC-IR at 1 kHz): ≤ 120% of vendor nominal (50E: ≤ 18 mΩ)
- Capacity check at C/5: ≥ 98% of rated capacity (≥ 4 900 mAh)
- Self-discharge check: voltage drop ≤ 20 mV over 72 hours at open circuit, +25 °C
- Cells failing any criterion shall be rejected; batch rejection threshold: > 2% failure rate triggers full lot hold and vendor notification

7. Risk Register

7.1 Risk Assessment Methodology

Risks are assessed using a 5×5 likelihood-by-consequence matrix. Likelihood is rated 1 (remote) to 5 (near-certain). Consequence is rated 1 (negligible) to 5 (mission loss). Risk level thresholds: LOW = L×C ≤ 6; MED = 7–14; HIGH = 15–25.

ID	Risk	Likelihood	Consequence	Level	Mitigation
R-001	Cell venting in vacuum – no convective cooling path	4	4	HIGH	Add thermal strap to structure; pre-flight TVAC test
R-002	Capacity fade due to LEO thermal cycling	3	4	MED	Over-spec capacity at BOL; accelerated cycle testing
R-003	Radiation-induced capacity loss in SEL event	2	5	MED	SEL current limiting in BMS; latch-up immune design
R-004	BMS single-point failure disables entire pack	2	5	MED	Redundant cell-level fusing; BMS watchdog circuit
R-005	Mechanical failure at launch vibration (cell weld fracture)	2	4	MED	Spot-weld qualification per IPC-2221; vib. pre-test
R-006	Self-discharge exceeding 3%/month in storage	2	3	LOW	Incoming cell inspection; store at 50% SoC, 15°C
R-007	Outgassing contaminating optical payloads	2	3	LOW	ASTM E595 screening; shroud / venting path design
R-008	Schedule slip in cell procurement (long lead)	3	2	LOW	Dual-source cells; order with 6-month lead time

Table 7-1: Battery Risk Register (L = Likelihood 1–5, C = Consequence 1–5)

7.2 Top Risk: Cell Venting in Vacuum (R-001)

The highest-risk scenario is thermal runaway or electrolyte venting in vacuum. Without convective cooling, any exothermic reaction rapidly propagates through the pack. Mitigation relies on three barriers: (1) preventing the triggering condition via BMS protection limits, (2) mechanical cell isolation within the pack to limit thermal propagation, and (3) validated thermal conduction path to structure to remove heat before cell temperature exceeds 70 °C. The TVAC test (V-014) is the primary verification activity for this risk.

8. Applicable Standards and References

8.1 Standards

- ECSS-E-ST-20-08C – Space Engineering: Photovoltaic Assemblies and Components (2012)
- NASA-STD-7002B – Payload Test Requirements (2021)
- NASA GEVS (GSFC-STD-7000B) – General Environmental Verification Standard (2021)
- MIL-STD-461G – EMI/EMC Requirements for Subsystems and Equipment (2015)
- MIL-PRF-32565 – Performance Specification, Battery Cells, Lithium-Ion (2014)
- ASTM E595-15 – Standard Test Method for Total Mass Loss and CVCM from Outgassing (2015)
- IPC-2221B – Generic Standard on Printed Board Design (2012)
- UL 1642 – Standard for Lithium Batteries (2012)
- UN 38.3 – Transport of Dangerous Goods: Lithium Battery Test Summary (2021)

8.2 References

- M. Smart, B. Ratnakumar, 'Effects of Electrolyte Composition on Lithium Plating in Lithium-Ion Cells', J. Electrochem. Soc., 158(4), A379 (2011)
- R. Jansen et al., 'Lithium-Ion Batteries for Space Applications', NASA/TM-2018-219940 (2018)
- Samsung SDI, 'INR18650-50E Product Specification Rev 1.0' (2020)
- Molicel, 'INR-18650-P42A Datasheet Rev 5' (2021)
- ESA, 'Battery Technology for Small Satellites', ESTEC TN-2019-001 (2019)
- Planet Labs, 'Dove CubeSat Power System Heritage', IAC-19-B4.2.7 (2019)

9. Summary and Recommendations

9.1 Trade Study Conclusions

The trade study concludes that the Samsung SDI INR18650-50E NCA cell in a 2S9P configuration is the optimal solution for the 6U CubeSat 150 Wh battery requirement. This configuration provides:

- 197 Wh usable energy at EOL – 31% margin above the 150 Wh requirement
- 320 g estimated pack mass – well within the 450 g mass budget
- Sub-1U pack volume – leaves ample margin within the 3U volume allocation
- Best energy density in class at 263 Wh/kg
- Strongest CubeSat heritage of all candidate cells

9.2 Key Recommendations

The following actions are recommended as immediate next steps:

- R-1: Place procurement order for 36 flight-grade + 18 engineering model Samsung 50E cells from authorised distributor with CoC and lot test data. Lead time: 8–12 weeks.
- R-2: Select and procure BMS IC (recommended: Texas Instruments BQ76940 or Analog Devices LTC6813) and initiate radiation characterisation (TID testing to 20 krad).
- R-3: Complete thermal model of pack in system context; verify < 5 K/W conduction path meets temperature requirements in worst-case hot case.
- R-4: Initiate structural design of pack enclosure; conduct preliminary FEA for vibration mode frequencies (target first mode > 100 Hz).
- R-5: Begin UN 38.3 transport compliance testing for cells (required for shipment to launch site).
- R-6: Schedule TVAC chamber access 6 months prior to PDR; plan for 2-week test campaign.

9.3 Technology Readiness

The proposed battery system is assessed at Technology Readiness Level (TRL) 5 at the subsystem level. Cell-level TRL is 9 (flight heritage). Achieving TRL 6 requires completion of the TVAC and vibration tests on a representative pack, targeted for completion 3 months before CDR.

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