a **Methodological Ground Simulation Standards (3-Chamber Parity)**

T: ±0.3°C | RH: ±2% | CO_2: ±50 ppm | PAR: ±5 μmol m^{-2} s^{-1} | Airflow: ±0.05 m/s

Environmental Parity Verification Tolerances (6-Point Acceptance)

Experimental Purpose: Equal current, zero coil vector; isolates ohmic Joule heat (ΔT), vibration & ripple

Magnetic Regime: Opposing windings; net coil field B_coil≈ 0; ambient GMF (45–50 μT) retained

Chamber 3: Matched Bifilar Sham Control (Artifact Isolation)

Experimental Purpose: Lunar surface magnetic simulation (<0.82 nT ambient crustal void)

Magnetic Regime: <10 nT active cancellation or <1 nT shielded core (residual |B| < 1 nT)

Chamber 2: Near-Null Field Simulation (NNMF Active)

Experimental Purpose: Terrestrial environmental reference; unshielded Helmholtz/growth chamber

Magnetic Regime: 45–50 μT Ambient Terrestrial Field (calibrated local vector)

Chamber 1: Geomagnetic Baseline (GMF Control)

b **Payload Self-Magnetic Calibration & Transfer Deconvolution**

Subsystem Current Deconvolution & Uncertainty Budget

Subsystem 1: LED PAR Lighting Array (0–400 μmol/m²/s)

Power: 0–25 W (DC current 0.1–1.8 A) | Coupling: S_LED ≈ 8.3 μT/A

Induced Field: ΔB_LED ≈ 2–15 μT DC offset; PWM ripple ~20 nT_RMS at 1 kHz; twisted harness

Subsystem 2: Fluidic & Nutrient Delivery Pumps / Valves

Power: 0–8 W (pulsed current 0.5–1.5 A peak) | Coupling: S_pump ≈ 23.3 μT/A

Induced Field: ΔB_pump ≈ 8–35 μT transient DC pulses during scheduled 10-s root irrigation cycles

Subsystem 3: Thermal Control (Heaters & Thermoelectric Coolers)

Power: 0–30 W (resistive/TEC 1.0–2.5 A continuous) | Coupling: S_thermal ≈ 19.2 μT/A

Induced Field: ΔB_thermal ≈ 12–48 μT continuous DC; dominant during lunar night; bifilar traces mandatory

Subsystem 4: Avionics, Telemetry & Sensor Power Bus

Power: 3–12 W (quiescent flight bus 0.2–0.8 A) | Coupling: S_bus ≈ 5.0 μT/A

Induced Field: ΔB_bus ≈ 0.5–4 μT static DC baseline shift + high-frequency RF telemetry EMI

$\mathbf{B}_{ambient}(t) = \mathbf{B}_{sensor}(t) - \sum_k \mathbf{S}_k \cdot I_k(t)$ | **Uncertainty Budget: ±2 – 5 nT RMS**

Resolves sub-nT lunar signal against 2–48 μT DC spacecraft baseline via calibrated transfer matrices $\mathbf{S}_k$

c **Post-Flight Phenotypic Risk Disambiguation Matrix (Operational Decision Framework)**

Operational Multi-Stressor Disambiguation Matrix (Evidence Tiers & Validation Endpoints)

Near-Null Magnetic Field (<1 nT)

Primary Biophysical Target:

Cryptochrome flavin radical pairs (FAD/TrpH•+);
mitochondrial [4Fe-4S] cluster electron transfer.

Diagnostic Phenotypic Markers:

- Emergence lag (Δt50 = +12 to 36 h); capacity -10 to -30%
- Repressed chlorophyll (HEMA1, POR) & anthocyanin (CHS)
- Mitochondrial ROS leak; induction of AOX1D & CAT3
- Normal nuclear DNA integrity (zero γ-H2AX foci)

Operational Strategy & Validation:

- Evidence Tier: Tier 1 (Germination/Greening) & Tier 2
- Time Window: Phase I (0–72 h) & Phase II (72–120 h)
- Flight Modality: Active vector coil or Permalloy shield
- Rescue Validation: Fully rescued by 45 μT; 1g-insensitive

[Diagnostic: Rescued by 45 μT | Insensitive to 1g]

Lunar Partial Gravity (0.166 g)

Primary Biophysical Target:

Columella statolith sedimentation kinetics;
mechanosensitive ion channels (MSL); PIN polar auxin.

Diagnostic Phenotypic Markers:

- Germination capacity & greening rate are normal
- Directional root skewing, waving, & loss of g-angle
- Cell wall remodeling (pectin demethylesterification)
- Normal CRY signaling; localized apoplastic ROS (RBOH)

Operational Strategy & Validation:

- Evidence Tier: Tier 1 (Root Plagiotropism / Cytoskeleton)
- Time Window: Continuous 0–120 h post-radicle emergence
- Flight Modality: On-board 1g centrifuge control rotor
- Rescue Validation: Fully rescued by 1g rotor; B-insensitive

[Diagnostic: Rescued by 1g | Insensitive to B-field]

Deep-Space Radiation (GCR / SPE)

Primary Biophysical Target:

Nuclear & organellar DNA double-strand breaks;
radiolytic hydroxyl free radical (OH•) overflow.

Diagnostic Phenotypic Markers:

- Severe DNA double-strand breaks & γ-H2AX foci
- ATM/ATR activation; chromosome aberrations & G2/M arrest
- Widespread systemic oxidative stress & lipid peroxidation
- Low-dose GCR (60–100 mGy/yr): negligible 5-day penalty
- Acute SPE (>0.5 Gy): catastrophic cell cycle arrest

Operational Strategy & Validation:

- Evidence Tier: Tier 1 (Dosimetry / γ-H2AX) & Tier 2
- Time Window: Chronic GCR accumulation vs SPE event
- Flight Modality: Silicon dosimeter / radioprotectant
- Rescue Validation: Independent of B-field and 1g centrifuge

[Diagnostic: Correlates with Dosimeter | DNA Breaks]