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☐1. General System Health

- ☐ **A. Inspect all thermal management subsystems for signs of wear or degradation.**
  - ☐ Surfaces exposed to thermal cycling, vacuum, or radiation show no signs of visible fatigue

    → If fatigue is observed, document affected zones, disassemble unit for close inspection, and test material strength before component replacement

    - ☐ No discoloration can be seen

      → If discoloration is present, analyze for UV/radiation exposure effects and thermal oxidation; replace affected parts

    - ☐ No cracking or surface fractures

      → If cracks are found, perform dye-penetrant or ultrasonic inspection; remove and replace component if crack depth exceeds safety threshold

    - ☐ No corrosion or oxidation is visible

      → If corrosion is detected, clean using approved solvent method, inspect surrounding materials for electrochemical damage, and replace if pitting or thinning is present
- ☐ **B. Inspect connectors for dust and security**
  - ☐ All mechanical and electronic connections are secure

    → If any connection is loose, torque to spec and verify retainer clips or fasteners are engaged

    - ☐ No loose connectors

→ If movement is detected, inspect mating hardware and re-secure with thread-lock or anti-vibration clips

- ☐ No bent or misaligned pins

  → If bent pins are detected, attempt careful realignment under scope; replace connector if alignment fails or damage is permanent

☐ All connections inspected and confirmed free of dust/debris

→ If contamination is found, clean connector with antistatic brush or dry nitrogen. Replace if pin-to-socket contact resistance remains elevated

- ☐ Double-checked electrical connectors

  → If mismatch or incorrect mating found, cross-check cable routing, confirm part numbers, and update harness diagram if necessary

- ☐ Harnesses are clean and undamaged

  → If abrasion or cuts are found, replace harness or apply aerospace-rated sleeve. Validate insulation resistance

- ☐ Mounting brackets and mechanical fixtures are debris-free

  → If debris is observed, remove using cleanroom vacuum and inspect for fastening looseness or material delamination

☐ Dust/debris inspection completed using at least one of the following tools:

- ☐ Optical Microscope
- ☐ Scanning Electron Microscope (SEM)
- ☐ Atomic Force Microscope (AFM)
- ☐ Confocal Scanning Microscope
- ☐ Particle Impact Sensor
- ☐ Surface Acoustic Wave Sensor (SAW)
- ☐ Electrostatic Dust Sensor

→ If any instrument detects localized dust >10 $\mu g/cm^2$, perform controlled wipe-down and re-scan. Consider ionizing bar if buildup recurs

- ☐ Particulate contamination confirmed below 10 μg/cm² threshold

  → If threshold exceeded, pause all thermal operations, log contamination event, and initiate cleaning protocol with documentation

☐ **C. Run diagnostics on printer operational temperature ranges**

- ☐ Diagnostic test run conducted on onboard printer system

  → If diagnostic fails to launch or crashes, validate firmware integrity and check sensor communications

  - ☐ Nozzle operating temperature recorded

    → If temperature reading exceeds spec or deviates >±3°C from model, recalibrate nozzle thermistor and inspect heater cartridge

  - ☐ Electronics and control board temperatures monitored

    → If board temperature exceeds margin, verify cooling fan or spreader operation and inspect thermal paste

  - ☐ Motor temperatures measured during full duty cycle

    → If motor temperature trends high, inspect for over-torque, driver board overcurrent, or insufficient ventilation

- ☐ All components remain within validated thermal margins

  → If any component nears thermal limit, reduce duty cycle, verify heatsink contact and airflow paths, and inspect for thermally degraded insulation

- ☐ Sensor data matches thermal model predictions within ±3°C

  → If sensor readings deviate from model, confirm thermal model boundary conditions and re-validate sensor calibration

- ☐ No component exceeds 80% of rated thermal limit

  → If limit is exceeded, shut down operation, perform post-cooldown inspection, and revise control thresholds to include earlier warnings

☐2. Passive Radiative Cooling Components

- ☐ **A. Verify emissivity of external radiators and coating integrity**
  - ☐ Measure surface emissivity

    → If emissivity < 0.85 over >5% of surface, clean surface, inspect coating degradation, and consider recoating with approved high-emissivity paint (e.g., Z-93, AZ-93)

    - ☐ Use calibrated IR thermography

      → If scan shows inconsistent readings, recalibrate IR sensor and verify emissivity input settings match material specs

    - ☐ Emissivity ≥ 0.85 across ≥ 95% of surface area
  - ☐ Scan surface for integrity

    → If micro-abrasions or delamination found, log area, compare to wear limits, and assess need for resurfacing or recoating

    - ☐ Use 3D profilometry or optical reflectometry
    - ☐ Confirm no micro-abrasion or coating delamination

      → If corrosion or discoloration appears, take spectroscopic sample and consider layer removal for deeper evaluation

  - ☐ Visual inspection under magnification (≥10x)
    - ☐ No corrosion, discoloration, or peeling observed
  - ☐ Tools Required

    → If any tool is nonfunctional or miscalibrated, halt inspection, notify metrology team, and swap for certified backup unit

- ☐ FLIR T1030sc or equivalent
- ☐ Keyence LJ-V7000 or equivalent

☐ **B. Check radiator orientation and deployment mechanisms (if adjustable)**

- ☐ Test deployment in TVAC chamber

  → If deployment time >30s or mechanism jams, inspect actuator geartrain, lubricate moving joints, and verify motor torque spec

  - ☐ Simulate thermal cycles: -100°C to +120°

    → If mechanical resistance increases at extremes, review thermal expansion tolerances and requalify mechanism materials

  - ☐ Full deployment achieved in < 30 seconds
- ☐ Verify orientation and alignment
  - ☐ Angular positioning accuracy within ±1.0°
  - ☐ Use optical encoders or LIDAR tracking

    → If deviation >±1.0°, recalibrate encoders or realign deployment arms. If persistent, inspect hinge or encoder backlash

- ☐ Cycle test actuators
  - ☐ Complete 100 deployment cycles without failure

    → If failure occurs before 100 cycles, isolate failed part, analyze fatigue/friction wear, and replace with high-cycle-rated component

- ☐ Tools Required
  - ☐ Thermal Vacuum Chamber
  - ☐ Leica Tracker / Encoder system

☐ **C. Inspect for micrometeoroid impact damage or surface contamination**

- ☐ Inspect for micrometeoroid impact or structural damage
  - ☐ No punctures, pitting, or cracks > 0.3 mm

    → If damage >0.3 mm is found, record impact coordinates, assess structural impact, and apply bonded patch or replace panel

- ☐ Dust/contamination test
  - ☐ Perform white-glove wipe and analyze particles per ISO 14644-1

- ☐ Dust level conforms to ISO Class 5

  → If results exceed ISO Class 5, perform full surface cleaning, inspect upstream dust control, and schedule re-inspection

- ☐ Color and surface reflectance test
  - ☐ Use spectrophotometer
  - ☐ $\Delta E < 2.0$ from original standard

  → If $\Delta E > 2.0$, log change, test reflectance over time, and verify if material degradation has begun. Replace if reflective loss exceeds thermal margin allowance

☐ **D. Confirm thermal contact between heat sources and radiative elements**

- ☐ Check heat transfer efficiency
  - ☐ Measure thermal contact resistance $< 0.1\ K\cdot cm^2/W$
  - ☐ Use differential thermocouples or heat flux sensors

  → If thermal contact resistance $> 0.1\ K\cdot cm^2/W$, reapply or replace TIM, increase mechanical clamping force, and repeat measurement

- ☐ Inspect thermal bonds
  - ☐ Use ultrasound or X-ray NDT
  - ☐ Confirm $\geq 95\%$ bond area coverage
  - ☐ No voids or delaminations > 2 mm

  → If bond area coverage $< 95\%$, disassemble and reapply adhesive per process spec. Voids >2 mm must be patched or fully re-bonded

- ☐ Confirm use and condition of TIM
  - ☐ Verify proper application and thickness
  - ☐ Check for uniformity under visual or infrared scan

  → If TIM layer is non-uniform or degraded, remove, clean mating surfaces, and reapply new TIM with verified thickness control (e.g., shim gauge or film uniformity sensor)

☐3. Pumped Fluid Loop (Low Boiling Point Fluids)

- ☐ **A. Inspect fluid integrity; check for discoloration, particulate contamination, or phase separation**
  - ☐ Visual inspection of fluid sample
    - ☐ No discoloration, clouding, or visible degradation
    - ☐ No particulate matter visible under 10x magnification

      → If discoloration or particulates detected, filter sample and test full loop. If repeat contamination appears, flush and refill with certified fluid batch

  - ☐ Chemical stability check (e.g., GC-MS or FTIR analysis)
    - ☐ No unexpected molecular breakdown detected

      → If breakdown products detected, isolate affected loop section, verify compatibility of wetted materials, and replace degraded fluid

  - ☐ Phase uniformity
    - ☐ No visible phase separation after 24-hour storage at operational temperature extremes (0°C to 60°C)

      → If phase separation occurs at temperature extremes, remove sample for analysis, verify shelf life, and replace with reformulated blend if needed

- ☐ **B. Test pump functionality and verify stable flow rates**
  - ☐ Measure steady-state flow rate
    - ☐ Target: 10 mL/min ± 5% under 0.16 G
    - ☐ Tool: Inline ultrasonic flow meter or Coriolis flow sensor

      → If flow deviates >±5%, inspect pump inlet for blockage, check impeller or rotor condition, and recalibrate flow meter

  - ☐ Motor efficiency and noise check
    - ☐ Electrical draw within spec (e.g., <5W)

        - ☐ Acoustic/vibration signature within baseline range (recorded during ground testing)

          → If electrical draw exceeds spec or acoustic signature changes, inspect bearing wear, rotor balance, and pump alignment

    - ☐ Thermal test
        - ☐ Confirm pump maintains performance between -20°C to +60°C

          → If performance degrades at thermal extremes, review pump insulation, motor driver tuning, and inspect for thermal expansion interference

- ☐ **C. Check seals, valves, and joints for leakage or pressure loss**
    - ☐ Visual and dye-enhanced inspection of seals, joints, and valves
        - ☐ No visible leakage or moisture accumulation

          → If leakage is detected, mark location, remove component, and replace gasket or seal material. Log part number and incident time

    - ☐ Pressure test system
        - ☐ Hold pressure at 150% nominal operating pressure for 30 minutes
        - ☐ No pressure drop >2% during test

          → If pressure drops >2% in test, isolate leak zone using segmental valve closure, retighten joints, and repeat pressurization

    - ☐ Electronic leak detection (optional)
        - ☐ Use gas sniffer or sensor if integrated

          → If gas sensor triggers, trace concentration gradient, increase ventilation, and consider installing localized leak capture features

- ☐ **D. Microgravity readiness and cavitation monitoring**
    - ☐ Simulated reduced gravity testing
        - ☐ Run system on parabolic flight or validated ground-based lunar gravity simulator
    - ☐ Check for cavitation / vapor lock indicators
        - ☐ No air bubbles detected in return lines
        - ☐ No drop in pressure head or irregular pump RPM

- ☐ No spiking in acoustic/vibration signature

  → If cavitation occurs, review fluid line routing, increase backpressure valve settings, and consider gas purge protocol prior to ops

- ☐ **E. Redundancy and failover verification**
  - ☐ Backup pump test
    - ☐ Confirm backup unit activates within <2 seconds after primary pump shutdown
    - ☐ Flow continues within nominal range after switch

      → If backup activation exceeds 2s or flow is insufficient, test relay actuation and verify controller switching logic. Replace failed motor or switch

  - ☐ Passive failsafe function (if present)
    - ☐ Validate thermal siphon or gravity-assisted loop as fallback mode

      → If thermal siphon fails to activate, test for loop blockage or height differential shortfall. Adjust geometry or verify fluid properties under gravity level

  - ☐ Switch-over protocol test
    - ☐ Simulate fault event and log automatic recovery behavior
    - ☐ Control system logs and sensor feedback confirm successful handoff

      → If automatic recovery does not occur, inspect fault tree logic in control software, validate sensor inputs, and verify override pathways

☐4. Phase Change Materials (PCMs)

- ☐ **A. Verify PCM reservoir containment and structural integrity**
  - ☐ Inspect all PCM containers post-thermal cycling for cracks, bulging, seal deformation, or material fatigue

    → If deformation or cracks detected, log failure mode, cut open sample container, and test welds or seam joints. Replace faulty batch

  - ☐ Use high-sensitivity strain gauges and volumetric displacement sensors to detect micro-expansion due to repeated melt/freeze transitions

    → If excessive displacement detected, analyze expansion pattern, revise fill volume margin, and apply expansion-tolerant container design

  - ☐ Use ultrasonic thickness gauges to verify wall uniformity; acceptable deviation: <5% of nominal thickness

    → If deviation >5%, perform targeted wall scan and correlate with thermal cycles. Reinforce or replace affected reservoirs

  - ☐ Scan outer surfaces with optical profilometers for delamination or wear-induced surface anomalies
  - ☐ Confirm no leakage through dye-penetrant or helium mass spectrometry leak test

    → If dye/helium leak is detected, evacuate chamber, mark leakage point, and destructively examine seal quality. Do not reuse failed units

- ☐ **B. Validate phase change behavior**
  - ☐ Compare actual thermal transition points to manufacturer specs using differential scanning calorimetry (DSC)

    → If deviation >±5%, identify batch code and compare to reference PCM database. Re-test with fresh sample and flag batch for disqualification

  - ☐ Run controlled heating/cooling cycles in a thermal vacuum chamber replicating lunar day/night extremes (100 K to 380 K)

→ If enthalpy curve deviates or fails to stabilize, remove PCM for chemical reanalysis and confirm latent heat capacity via calorimeter

- ☐ Record temperature-time curves and ensure latent heat absorption/release aligns with predicted enthalpy values (±5% deviation allowed)
- ☐ Perform 10-cycle endurance test; phase transition point must not drift more than 2°C over test duration

→ If drift >2°C observed, flag material for fatigue, compare against prior test results, and select alternate formulation for longer-duration missions

- ☐ **C. Check thermal interfaces**
  - ☐ Inspect TIM (thermal interface materials) between PCM and adjacent hardware

    → If full contact not achieved, remove PCM module, clean surfaces, and reapply TIM per layer thickness spec. Ensure uniformity with pressure mapping film

  - ☐ Confirm full contact area coverage using pressure-sensitive film or IR thermal mapping
  - ☐ Use ultrasound or X-ray NDT to detect voids, inclusions, or dry spots in TIM layer

    → If voids/inclusions found, assess if critical to thermal path. If so, rebuild interface or reapply compliant TIM with improved spread control

  - ☐ Verify compressibility, thermal conductivity, and reusability of TIM per ASTM D5470
- ☐ **D. Monitor operational performance (as needed)**
  - ☐ Install Type-K or RTD sensors at PCM input/output junctions
  - ☐ Log temperature differentials across each cycle to confirm proper heat exchange

    → If dT falls outside expected range, inspect for thermal blockage, check sensor drift, and confirm heat flow directionality via heat flux mapping

  - ☐ Cross-reference heat flux data with expected latent energy values (e.g. 200–300 J/g for paraffin-based PCMs)

    → If lag or phase delay is detected, run in-situ DSC validation or replace PCM brick with tested alternate

- ☐ If anomalous thermal lag or phase delay occurs, schedule PCM material replacement or requalification

☐5. Environmental Insulation and Radiation Shielding

- ☐ **A. Test system insulation under lunar temperature swings**
  - ☐ Simulate full lunar day/night cycles in thermal vacuum environment (≥12-hour duration each)

    → If cycle fails to complete due to system error, pause test, log anomaly code, inspect vacuum pump, heaters, and chamber seals. Rerun after confirming environmental control stability

  - ☐ Use internal array of thermocouples to track core-to-surface gradients

    → If sensors report irregular or missing data, verify sensor placement and calibration. Replace faulty thermocouples, reinitialize data logging software, and repeat measurement run

  - ☐ Insulation must hold internal ΔT within ±5°C of thermal baseline over full cycle

    → If ΔT exceeds threshold, evaluate insulation material interfaces, inspect for voids or compression, and re-model thermal conduction paths

  - ☐ Conduct cyclic thermal fatigue test (50+ day/night simulations) to verify long-term resilience

    → If failure occurs before 50 cycles, identify mode (e.g., delamination, brittleness, thermal short). Disassemble insulation stack, analyze failed layer, and test alternate materials or bonding techniques

- ☐ **B. Inspect radiation shielding**
  - ☐ Use onboard dosimeters or TLDs to measure cumulative particle flux (target: <100 mSv/year exposure)

    → If exposure exceeds threshold, re-evaluate shielding thickness, composition, and configuration. Consider augmenting mass shielding or rerouting critical systems to lower-radiation zones

  - ☐ Perform borescope inspection of interior-facing shield surfaces for bubbling, cracking, or ablation

    → If anomalies are detected, record damage size and location, classify damage type, and assess if local repair is feasible or if full shield replacement is needed

  - ☐ Inspect MLI blankets and embedded radiation deflectors for fiber degradation, separation, or conductivity loss

    → If defects are found, replace damaged MLI sections, re-crimp or stitch fiber interfaces, and verify continuity of conductive layers using multimeter tester

  - ☐ Record radiation exposure profile and compare to maximum material dose ratings per NASA-STD-6016

    → If material dose limit is approached or exceeded, flag for accelerated life review and replace component or increase shielding before next exposure campaign

- ☐ **C. Simulate extended exposure cycles**
  - ☐ Run chamber simulations up to 672 hours continuous operation (28 lunar days)

    → If chamber operation halts or system fails, log shutdown timestamp and condition, inspect thermal control software for watchdog or thermal runaway errors

  - ☐ Observe for time-lagged temperature drift, material creep, or degradation of insulation layer reflectivity (via hemispherical reflectance meter)

→ If reflectivity drops >15% or temperature drift exceeds threshold, remove insulation sample and conduct surface analysis (SEM, spectrometry). Replace layer or apply recoating

- ☐ Use IR thermography to detect loss of thermal homogeneity (>±7°C is considered failure)

  → If nonuniformity is observed, localize hotspots or cold spots, examine thermal interfaces, and enhance thermal spreaders or insulation continuity in affected areas

☐ **D. Validate shielding response to particle events**

- ☐ Utilize active particle counters to capture transient solar or GCR events

  → If particle count spikes above expected levels, log event timestamp, correlate with solar data, and run real-time shielding stress mode

- ☐ Verify that critical systems maintain function without thermal breach

  → If system behavior degrades, switch to backup thermal path (if available), initiate safe mode, and diagnose control loop integrity. Log temperatures and review logs for command execution errors

- ☐ Examine for increased local surface temperatures or structural discoloration near shielding faults

  → If discoloration or hotspots are found, halt test, photograph affected regions, and sample material if possible. Assess for radiation-induced chemical changes or burn-through

- ☐ Ensure cumulative shielding thickness >10 g/cm^2 for SPE (Solar Particle Event) compliance

  → If thickness is insufficient, reinforce shield stack-up with additional material or layered laminates. Recalculate shielding effectiveness using GEANT4 or NASA's OLTARIS tool

☐6. Software and Monitoring

- ☐ **A. Sensor Calibration and Verification**
  - ☐ Verify all thermal sensors are within calibration date per manufacturer specs

    → If calibration is expired, remove from service, send for recalibration, or replace with a certified unit

  - ☐ Use precision temperature source (e.g., dry block or fluid bath) to test each sensor at multiple setpoints (e.g., -50°C, 0°C, +50°C)

    → If test cannot be completed, check for equipment malfunction or improper sensor contact. Re-seat sensor, confirm bath/stirring uniformity, and repeat test

  - ☐ Compare readings to NIST-traceable reference sensor; record deviations

    → If deviation exceeds ±0.5°C or specified tolerance, log sensor ID, flag as failed, and remove it from the system. Investigate for drift or physical damage

  - ☐ Flag and recalibrate/replace any sensors with deviations > ±0.5°C or outside specified tolerance

    → If recalibration fails or is not possible, dispose of the sensor per electronics waste protocols. Install new unit and re-run verification test

- ☐ **B. Sensor Failure and Dropout Simulation**
  - ☐ Disconnect each sensor manually to simulate dropout; verify system logs fault and triggers fallback mode

    → If fault not logged or fallback mode fails, inspect firmware error handling routines. Add diagnostics to detect loss of signal and ensure graceful degradation of control logi

- ☐ Inject false data or out-of-range values (e.g., -200°C or +200°C) and verify software response

  → If system accepts bad data without flag, update software to include input validation and hard-coded physical limits

- ☐ Test for sensor lag or slow response using controlled temperature ramps

  → If lag exceeds spec, verify sensor thermal contact and firmware filter settings. Replace sensor or increase sampling rate

☐ **C. Control Algorithm Validation**

- ☐ Test PID or custom control logic in simulated environment with thermal hardware model

  → If test fails or system becomes unstable, tune PID gains or refine model fidelity. Add bounds checking, rate limiting, or anti-windup logic to prevent runaway control

- ☐ Run edge-case scenarios:
  - ☐ Rapid external temperature shift (simulate sun/shade transition)

    → If overshoot or instability occurs, adjust response time constants, add feedforward terms, or thermal rate-of-change caps

  - ☐ Sensor dropout or conflicting inputs

    → If software crashes or misbehaves, implement redundancy logic, sensor voting, or fallback default control profile

  - ☐ Coolant pump failure

    → If thermal system exceeds limits, test emergency heat dump or shutdown routine. Verify alerts and ensure thermal margins are adequate under no-flow conditions

- ☐ Verify system maintains safe thermal range without overshoot or oscillation

→ If not, revise control loop parameters, consider additional damping, or implement hierarchical control structure with safety overrides

- ☐ **D. Telemetry & Data Logging Accuracy**
  - ☐ Verify all sensor outputs and system states (valves, pumps, heater status) are logged at required intervals (e.g., 1 Hz or mission-specific)

    → If logging interval is inconsistent or missing data, check for CPU load issues, logger memory overflows, or incorrect task prioritization

  - ☐ Cross-check raw logs vs real-time display in control software

    → If mismatch found, inspect data pipeline from sensor to GUI, validate that buffers and converters (e.g., ADC to engineering units) are synchronized

  - ☐ Ensure logs include timestamps with synchronized time (e.g., GPS time or mission clock)

    → If timestamp drift or loss occurs, inspect time sync protocol (e.g., NTP/GPS), reset system clock, or add watchdog for time integrity

  - ☐ Induce network latency or dropout; verify data buffering and loss recovery

    → If data is lost or corrupted, improve buffer size, implement local storage fallback, and validate retransmission logic on reconnection

  - ☐ Simulate full mission scenario and ensure complete, lossless logging for full duration

    → If logging fails partway, diagnose storage write errors, thermal throttling of SSD, or file system faults. Implement log segmentation with redundancy and backup mechanism

- ☐ **E. Data Transmission and Integrity**
  - ☐ Check uplink/downlink packet integrity: Run CRC or checksum validation per packet

→ If checksum fails, isolate affected subsystem, increase error correction redundancy, and ensure consistent byte framing

- ☐ Simulate transmission interruptions (RF blackout, loss of signal)

  → If data is lost or not resumed correctly, verify transmission state machine, increase retransmit buffer size, and add re-acknowledgment logic

- ☐ Verify data retransmission and catch-up logic on re-establishment of connection

  → If gaps persist, ensure log pointer synchronization and verify start-of-message indicators are not lost. Add persistent queueing and session resumption

- ☐ Confirm secure, redundant storage of logs (e.g., onboard SSD + cloud/mirror storage)

  → If redundancy fails, test hardware RAID or replication scripts, verify regular sync schedule, and restore from backup to confirm recoverability

- ☐ Compare transmitted vs received data sets: Ensure byte-for-byte integrity

  → If mismatch found, trace packet loss locations, compare CRC results, and verify encoding schemes match on sender and receiver

☐7. Emergency Protocols

- ☐ **A. Contingency Plan: Passive-Only Operation**
  - ☐ Review and update thermal models to predict system performance under passive-only cooling (no pump operation)

→ If model predictions are inaccurate or non-converging, re-validate boundary conditions, heat load assumptions, and mesh fidelity. Cross-check with empirical thermal test data to recalibrate

- ☐ Run simulation of passive cooling under various mission thermal loads (e.g., internal heat sources + external fluxes)

  → If system overheats in simulation, identify critical nodes and determine if heat paths can be improved. Add insulation, adjust radiator orientation, or redistribute heat-generating components

- ☐ Determine and document survivability duration at each thermal load level (e.g., "maintain <50°C for 6 hours @ 80W load")

  → If survivability duration is insufficient, flag mission timeline or operating mode for restriction. Modify passive element design (larger radiator, more PCM mass) and re-simulate

- ☐ Validate backup passive elements (radiators, heat sinks, phase change materials) for integrity and capacity

  → If physical degradation is found (e.g., cracked fins, PCM leaks), document failure type, remove component, and replace with verified spare. Re-run passive system validation after repair

☐ **B. Low-Power / Pump-Out Survival Readiness**

- ☐ Simulate low-power state (<10% nominal system power) and verify essential thermal protection functions remain operational

  → If thermal protection fails, identify which subsystem lost function. Evaluate battery reserve allocation and check autonomous transition logic. Reprioritize thermal protection in low-power hierarchy

- ☐ CCheck for autonomous switch to low-power cooling mode (e.g., PCM use, radiator exposure adjustment)

  → If switch does not occur, debug system state logic and sensor inputs. Update firmware to ensure fallback logic initiates at correct thresholds

- ☐ Set and confirm thermal load thresholds above which system cannot passively regulate

  → If thresholds are too low for mission success, explore hardware upgrades (e.g., deployable radiators) or limit thermal output of secondary systems

- ☐ Document shutdown time estimates once thresholds are exceeded

  → If estimates are inconsistent with test data, refine thermal capacity models, validate initial conditions, and rerun failure cascade simulations

☐ **C. Automated Thermal Shutdown & Alerts**

- ☐ Verify real-time temperature monitoring triggers shutdown protocols at predefined thresholds (e.g., >75°C on CPU, >50°C on battery pack)

  → If shutdown does not initiate, check sensor mapping, software logic, and relay actuation path. Confirm firmware threshold constants are correctly defined and tested

- ☐ Test full chain of action: → Sensor → Software → Shutdown Signal → Component Shutdown

  → If any link fails, isolate component and perform subsystem diagnostics. Log fault, repair or reflash affected module, and re-run validation

- ☐ Inject overheating scenario in test bench or software simulation and confirm:
  - ☐ Proper shutdown of non-critical systems

    → If critical systems are affected or non-essentials remain online, revise shutdown prioritization matrix in control logic

  - ☐ Emergency alert transmitted to mission control

    → If alert is missed or delayed, check communication buffer, telemetry bandwidth limits, and packet priority

- ☐ Telemetry log includes thermal event details

  → If event is not logged, verify telemetry schema and ensure logging service is not overloaded or improperly formatted

- ☐ Confirm reset logic: system only resumes when safe conditions are re-established or manual override is issued

  → If reset occurs prematurely, update state machine with stricter condition checks. Implement hysteresis or manual review before restart

☐ **D. Failure Mode and Effects Analysis (FMEA)**

- ☐ Review current FMEA every 3 months, focusing on components with observed degradation or failures

  → If review is overdue or incomplete, escalate to systems lead, reschedule immediately, and add overdue reviews to audit logs

- ☐ Add new failure cases from testing, field data, or mission events

  → If data is missing or incomplete, retrieve anomaly logs from test sessions or mission reports. Assign responsible engineers to retroactively analyze and add to database

- ☐ Re-score risk levels (Severity × Occurrence × Detection) for all failure modes

  → If risk scoring is inconsistent or outdated, use cross-functional team to validate inputs. Re-assess based on most recent test statistics and mission criticality

- ☐ Identify high-priority risks and assign mitigation strategies

  → If no strategy exists, flag issue with risk owner and engineering management. Assign temporary mitigation while permanent solution is developed

- ☐ Verify backup or redundant components for each critical failure mode

→ If backup system is unverified or inoperable, schedule test or perform manual failover check. Log readiness status in FMEA tracking tool

- ☐ **E. Documentation & Mitigation Updates**
  - ☐ Update thermal operations manual with new test results, edge cases, and any revised procedures

    → If documentation is out of date, assign responsible author, set deadline for update, and send release notes to relevant teams

  - ☐ Log all failure test outcomes (simulated or real) into anomaly database

    → If test results are missing from database, backfill data from test reports and ensure future tests use standardized logging format

  - ☐ Document all new mitigation strategies, including firmware updates, hardware redundancies, or procedural changes

    → If not documented, require engineering signoff before mission integration. Review all undocumented fixes during readiness review

  - ☐ Ensure engineering and operations teams are briefed on changes and mitigation timelines

    → If briefing was missed, organize immediate catch-up meeting or training session. Record attendance and upload briefing slides to central repository