This document outlines my initial engineering plan for Helogen's protein crystallization satellite test campaign. It's meant as a first-pass framework to drive further team discussion, highlight system trade-offs, and propose a feasible approach given mission constraints. Feedback is welcome

Mission Overview:

Helogen is developing a satellite platform to study protein crystallization in microgravity, supporting drug development. The mission will test 12 protein samples in a lab module (9x9x27 cm) within a 6U CubeSat, maintaining a stable 20°C and pressurized environment, and returning performance data after a two-week experiment.

Mission Requirements

- Temperature Control
  - The thermal control system shall maintain 20°C ±0.5°C for all samples.
  - Temperature fluctuations shall not exceed ±0.2°C/hour during crystallization.
- Pressure Integrity
  - The pressure vessel shall maintain 1 atm ±5% throughout the mission.
  - Leak rate shall not exceed 0.1% volume loss per day under simulated vacuum.
- Deployment
  - The payload shall comply with 6U CubeSat deployer mechanical and electrical interfaces.
- Data Return
  - All sensor data shall be stored locally and transmitted as a single packet at mission end.

Test Campaign:

Requirements	Verification Method	Test Name/Type	Success Criteria (Full/Partial/Minimal)
The system shall maintain 20°C ±0.5°C for all 12 samples for 14 days.	Test	Thermal Vacuum Cycling	Full: All samples in range for the entire duration. Partial: 10/12 samples in ±2°C for ≥75% duration. Minimal: 6/12 samples between 15–25°C for nucleation.
The pressure vessel shall maintain 1 atm ±5% throughout the mission.	Test	Pressure Leak Test	Full: ≤5% loss over 14 days. Partial: Pressure >0.8 atm. Minimal: Pressure >0.5 atm.

The payload shall comply with 6U CubeSat deployer interfaces.	Inspection/Test	Fit Check/Deployment Test	Full: Ejects within 30s of command. Partial: Deploys with manual reset. Minimal: Functional if not ejected.
All sensor data shall be stored and transmitted at mission end.	Test/Analysis	Data Integrity Test	Full: 100% data returned, <0.1% corruption. Partial: ≥80% data recovered. Minimal: Basic health/status data received.
The microcontroller shall sample temperature sensors every 60 seconds.	Test/Analysis	Data Logging Test	Full: All samples logged at 1 min intervals. Partial: Missed logs <10%. Minimal: At least one log per hour.

Test Campaign summary:

The test campaign for the protein crystallization satellite rigorously validates mission-critical systems to ensure reliable operation over the 14-day mission. Thermal Vacuum Cycling verifies the thermal control system maintains 20°C ±0.5°C across all 12 samples, with full success requiring continuous stability, partial allowing 10/12 samples within ±2°C for ≥75% of the mission, and minimal ensuring 6/12 samples stay between 15–25°C to enable crystal nucleation. Pressure Leak Tests confirm the vessel retains 1 atm ±5%, prioritizing ≤5% pressure loss for full compliance, while partial and minimal thresholds tolerate reduced pressures (≥0.8 atm and ≥0.5 atm, respectively) to preserve functionality. Deployment compatibility is validated via Fit Check/Deployment Tests, requiring ejection within 30 seconds for full success, with fallbacks for manual reset or non-ejection scenarios. Data Integrity Tests enforce 100% data return with <0.1% corruption for full success, while partial (≥80% recovery) and minimal (basic health data) criteria ensure critical telemetry survives transmission faults. Data Logging Tests mandate temperature sampling every 60 seconds, allowing <10% missed logs for partial success and hourly updates at minimum. This tiered approach balances stringent standards with pragmatic fallbacks, systematically mitigating risks to deliver actionable scientific data while accommodating real-world constraints.

Thermal Control System design:

To properly test the effects of thermal cycling, I first needed to design a suitable thermal control system. I began by researching various thermal management approaches, carefully weighing their advantages, limitations, and the specific challenges each would present in a microgravity, small-volume environment. After evaluating options such as passive insulation, resistive heating, and active thermoelectric cooling, I selected the hybrid TEC-MLI system for its precision, reliability, and proven performance in space applications. This paragraph outlines the reasoning behind my choice, emphasizing a methodical decision-making process grounded in both technical requirements and practical trade-offs.

Thermal Control System Design

Core Requirements: Maintain 20°C ±0.5°C for 12 protein samples in microgravity.
Approach:

- Active Thermal Management:
    - Thermoelectric Cooler (TEC): Miniature TEC paired with a PID controller to regulate temperature, as TECs offer precise control in small volumes.
    - Insulation: Multi-layer insulation (MLI) to minimize heat exchange with the space environment.
    - Heaters: Redundant electrical resistive heaters for backup heating during cold phases.

Trade-offs:

Component	Advantages	Challenges
TEC	High precision, compact	Higher power consumption
MLI	Passive efficiency	Adds mass/volume
Heaters	Low cost, simplicity	Limited cooling capability

Testing:

- Thermal Cycling: Simulate extreme orbital temperatures (e.g., -20°C to +40°C) to validate stability.
- Power Budget Analysis: Optimize TEC duty cycles to minimize energy use while maintaining 20°C

Final Recommendation

A hybrid TEC-MLI system balances precision, reliability, and power efficiency:

1. TEC Primary: Actively regulates temperature with PID control.
2. MLI Secondary: Reduces thermal load on the TEC, conserving power.

This approach aligns with NASA's SmallSat best practices (thermal-control) and precedents in protein crystallization experiments. Resistive heaters should only serve as a backup for TEC failures.

Key Features

1. Dual-Mode PID Control:
    - Negative PID output → TEC cools
    - Positive PID output → TEC heats

2. Fault Tolerance:

- 4 DS18B20 sensors (average readings, detect sensor failures)
- Resistive heaters activate if temperature drops critically

3. Power Management:
    - PWM limits max TEC current to 2A (66% duty cycle @ 3A max)
    - Deep sleep between cycles (disabled here for clarity)

Hardware Design

```
thermal_control/
├── include/
│   └── config.h      # PID params, pins
├── lib/
│   ├── PID/          # PID library
│   └── OneWire/      # DS18B20 library
├── src/
│   └── main.cpp      # Core logic
└── platformio.ini    # Build config
```

Code Explanation:

I built a simple code for how the mechanism would work in C++/ Arduino code as I imagined the microcontroller to be an arduino (would be different for the actual implementation). This PID controller maintains a precise 20°C setpoint for protein crystallization by dynamically adjusting power to the thermoelectric cooler (TEC). This code is in Appendix 1.

The system continuously reads temperature data from four redundant DS18B20 sensors, averages their values to mitigate sensor errors, and calculates a corrective output using three key components:

- Proportional: Responds immediately to the current error (difference between actual and target temps).
- Integral: Eliminates residual drift over time (e.g., gradual heat leaks).
- Derivative: Predicts and dampens overshoot from rapid changes (critical in orbital thermal swings).

The TEC is driven bidirectionally—cooling when the PID output is negative (reversing current via an H-bridge) or heating when positive. All temperature readings, PID outputs, and emergency heater activations are logged to an SD card in CSV format every 5 minutes, creating a time-stamped record of micro fluctuations (±0.1°C resolution). Scientists can later analyze this data to correlate temperature stability with crystal growth quality, validate experimental conditions, and refine future mission parameters.

Components

1. Microcontroller: arduino (Wi-Fi/Bluetooth, GPIO, ADC)
2. Thermoelectric Cooler (TEC): Laird Thermal Systems CP101242 (12V, 3A max)
3. TEC Driver: L298N H-Bridge Module (to reverse current for heating/cooling)
4. Temperature Sensors: 4x DS18B20 (One-wire digital sensors, ±0.5°C accuracy)
5. Heaters: 2x 5W Resistive Heaters (Backup)
6. MLI: 10-layer aluminized mylar insulation (externally wrapped)

Thermal Cycling test:

The thermal cycling test subjects the satellite's lab module to precisely controlled, extreme temperature fluctuations within a thermal vacuum chamber to rigorously validate its ability to maintain 20°C ±0.5°C for all 12 protein samples under orbital conditions. The chamber simulates the satellite's 90-minute orbital cycle by alternating between +50°C (sunlight phase) and -30°C (eclipse phase) at a rate of 5°C per minute, replicating the rapid heating and cooling experienced in LEO. During these transitions, the test actively monitors the hybrid thermoelectric cooler (TEC) and multi-layer insulation (MLI) system's performance, including:

- PID controller response times to temperature deviations (e.g., how quickly it adjusts TEC power to counteract a 1°C overshoot).
- Power consumption profiles of the TEC and backup heaters during peak heating/cooling loads.
- Temperature uniformity across the 12 sample chambers, measured by 36 strategically placed DS18B20 sensors (3 per chamber).
- Insulation efficiency by tracking heat flux through the MLI using calibrated thermocouples on the module's exterior.

The test also intentionally induced failures, such as disabling primary temperature sensors or cutting power to the TEC mid-cycle, to verify redundancy mechanisms like backup heaters and secondary sensors activate seamlessly. To prevent condensation—a critical risk in vacuum conditions—the chamber is purged with dry nitrogen (5 L/min flow rate) throughout testing. After 10+ cycles, the pressure vessel undergoes helium mass spectrometry leak testing to detect micro-leaks caused by thermal expansion/contraction of seals.
Compliance with [NASA ECSS-E-ST-31C] is validated by ensuring:

- Temperature stability (±0.5°C) is maintained for ≥95% of the test duration.
- Cold starts from -30°C reach 19°C within 5 minutes using only backup heaters.
- No single-point failures compromise the 14-day mission.

This test directly correlates to mission success: even a 30-minute excursion beyond ±0.5°C could denature proteins or disrupt crystal growth, invalidating the experiment. By quantifying the system's response to orbital thermal stresses, the test ensures both hardware survivability and scientific data integrity.

Pressurization testing:
The pressurization test subjects the lab module to 1.5 atm (150% operating pressure) for 24 hours in a thermal vacuum chamber while cycling temperatures between -40°C and +50°C to simulate orbital thermal stresses. Using helium mass spectrometry, the test bombards seals and welds with helium tracer gas at 2 atm, detecting leaks as small as 1×10^{-6} cc/sec—equivalent to losing just 0.0003% of internal pressure per day, critical for maintaining the 1 atm ±5% requirement. The module is mounted in a Thermal Vacuum (TVAC) testing chamber with a residual gas analyzer (RGA) to quantify helium leakage rates, while strain gauges monitor for material fatigue at weld joints.
Test Phases:

1. Component-Level: Test individual O-rings/gaskets at 2 atm helium, rejecting any with leaks $>1\times10^{-7}$ cc/sec.
2. Subsystem: Pressurize the assembled module to 1.5 atm with nitrogen, monitoring decay over 48 hours in a thermally stabilized (±1°C) environment.
3. Full Environmental: Repeat at 1.1 atm in thermal vacuum while replicating orbital cycles (90 mins hot/cold) and applying 14.1 Grms vibration (NASA 6U profile). Full-level TVAC is at 1.1 atm to replicate worst-case 1.05 atm + 5% manufacturing tolerance.

Pass Criteria:

- Post-test leak rate $\leq1\times10^{-6}$ cc/sec (validated via RGA).
- Zero visible deformation or micro-cracks (CT-scanned post-test).
- Pressure stability within ±1% during 14-day mission simulation.

Why Helium?
While costly (~$50k/test), helium spectrometry is non-negotiable for space hardware—it detects leaks 1000x smaller than pressure decay methods, ensuring proteins aren't denatured by pressure shifts

equivalent to ascending 100m underwater. Cheaper alternatives (e.g., soap-bubble tests) lack the precision to meet NASA/ESA standards for crew-equivalent payloads.
Failure Impact: A leak rate of just 1×10^{-5} cc/sec would drop pressure by ~5% over 14 days, having significant consequences for protein growth. This test directly answers whether the lab's mechanical design can survive launch vibrations and orbital thermal flexing without compromising the experiment.

Fit Check/Deployment Test
This test rigorously validates the 6U CubeSat's mechanical compatibility with industry-standard deployers (e.g., Tyvak Nano-Satellite Systems) and ensures reliable ejection in microgravity. The process begins with precision measurement using a coordinate-measuring machine (CMM) to verify the module's dimensions (90.0×90.0×270.0 mm ±0.1 mm) and mass (≤6.0 kg), adhering strictly to the CubeSat Design Specification (CDS). Any protrusions exceeding 0.2 mm (e.g., misaligned connectors) are flagged for rework. The CubeSat is then mounted into a flight-representative deployer equipped with load cells to measure spring force (20–30 N) and high-speed cameras to capture ejection dynamics. During deployment trials, the module must release within 30 seconds of command without binding, jamming, or requiring manual intervention. To simulate worst-case scenarios, three consecutive tests are conducted:

1. Nominal Conditions: 25°C, 1 atm.
2. Cold Soak: -30°C for 4 hours (mimics launch vehicle ascent).
3. Post-Vibration: After 14.1 Grams of random vibration (NASA GEVS 6U profile).

Data integrity test:
Ensuring complete and accurate data return is instrumental in creating the product that Helogen is delivering to its customers. That means our data integrity test is extremely important; it's how we prove that what happened in orbit actually matches what we report on the ground. The goal is to guarantee that every single data point—temperature, pressure, system status, etc,—not only gets collected and stored without loss, but also arrives back on Earth uncorrupted, on time, and ready for analysis.
To pull this off, we're testing for completeness (no missing logs or gaps), accuracy (sensors have to stay within ±0.5°C for temperature and ±1% for pressure), and tamper resistance (so radiation, electromagnetic interference, or random software glitches can't mess things up). We're also making sure the whole dataset is delivered within an hour after the mission wraps up, because scientists want their data quickly. To cover our bases, we'll disable the main SD card mid-test and check that our backup memory picks up the slack—so even if hardware fails, the data survives.
On top of that, we're stress-testing the system by shaking it with 14.1 Grams of vibration (similar to the vibration during launch) and by blasting the memory with radiation to simulate space conditions, then checking file hashes to make sure nothing got corrupted.

Data logging testing

Data logging testing is important as it proves that the satellite's onboard systems can reliably record, store, and organize every critical measurement throughout the mission, regardless of the conditions in space. For this test, we set up the microcontroller to sample temperature and pressure sensors every 60 seconds, writing each log entry to both primary and backup storage such as an SD card to guard against hardware failures. During testing, we simulate mission conditions by running the payload inside a thermal vacuum chamber, exposing it to the same temperature swings and vibrations it will face in orbit. We then check that the data logger captures every reading at the right intervals, with no missed logs or time sync errors, and that the files can be read out and transmitted back to the ground without corruption. In appendix b there is some code that logs time + temp to the SD card every 60 seconds.

If we purposely disconnect a sensor or power-cycle the logger mid-test, we expect the system to recover gracefully and keep logging without losing more than a few minutes of data. This approach not only verifies that our hardware and software work under real-world stress, but also gives us the confidence that, once in space, we'll have a complete, trustworthy record of the experiment—essential for troubleshooting, scientific analysis, and meeting NASA's flight qualification standards

Risk Mitigation

Risk	Mitigation Strategy	Test Strategy
SD card corruption	Dual storage (SD + FRAM) with CRC32 checksums	Power-cycle during write ops
Radiation-induced bit flips	ECC memory, triple modular redundancy for critical data	Proton irradiation test
Transmission packet loss	CFDP protocol with automatic retransmission	Attenuate signal to -120 dBm

Test campaign timeline:
Month 1-2: Component Tests (TEC, sensors, seals)
Month 3-4: Subsystem Tests (thermal/pressure chambers)
Month 5-6: Environmental Tests (TVAC + vibration)
Month 7-8: Mission Simulation (14-day end-to-end)
Month 9:   Final Review & Launch Prep

Areas requiring further testing

While this campaign covers the most critical systems for the protein crystallization mission, there are several important areas that require further testing and deeper investigation to ensure full mission reliability. For example, I was not able to fully explore electromagnetic compatibility (EMC) testing, which is essential to guarantee that the microcontroller and sensor electronics are immune to interference from both the satellite's own subsystems and the space environment. Similarly, long-term outgassing tests for materials inside the pressure vessel should be performed, as volatile compounds released in microgravity could contaminate protein samples or degrade sensor performance. Another area needing more attention is software fault tolerance—specifically, how the flight code handles unexpected resets, memory overflows, or corrupted sensor data over the two-week mission. Additionally, while the data downlink is tested for integrity, the robustness of ground station operations and the ability to recover data after partial transmission failures should be validated under real-world conditions, including varying antenna alignments and weather disruptions. Finally, I would recommend further testing on the mechanical reliability of connectors and harnesses during repeated thermal and vibration cycles, since a single loose connection could jeopardize the entire experiment. These areas, though not fully addressed here due to time constraints, are critical for a flight-ready system and should be prioritized in the next phase of development and testing.

Summary:

This test campaign provides a framework to validate Helogen's protein crystallization satellite, focusing on thermal stability, pressurization, deployment reliability, and data integrity. By combining a hybrid TEC-MLI thermal system, helium leak detection, and code-driven redundancy, the plan ensures mission-critical performance under orbital stress. Tiered success criteria balance scientific goals with real-world constraints, while remaining aligned with NASA/ESA standards. Though some areas require further testing and exploration, the campaign effectively mitigates the highest risks—supporting confident delivery of meaningful results for space-based drug development.