# Sensor Package for Internal Detection In Extraterrestrial Regions (SPIDER)

*June 23rd, 2026*

Shawna Dodge, Riley Morris, Thomas Pierson

Advised by Dr. Mostafa Hassanalian

# Current systems do not incorporate many sensing modalities

Nasa uses The Fiber Optic Sensing System (FOSS) to take continuous measurements of a structure.
*Source: NASA.gov*

The Stanford Multi-Actuator Receiver Transduction (SMART) Layer, uses a network of piezoelectric sensors and actuators mounted on structures to detect structural damage.
*Source: NASA.gov*

# Sensor Reduction in Hardware Health Monitoring Systems

## Current Space Systems

**Baseline**

- ⊕ Reliable and effective monitoring
- ⊖ Few modalities included
- ⊖ High power consumption

Many dedicated sensors provide confidence, but add mass, power draw, and integration burden.

**Reduce sensors**

→

**Preserve function**

## Proposed SPIDER Approach

**Solution**

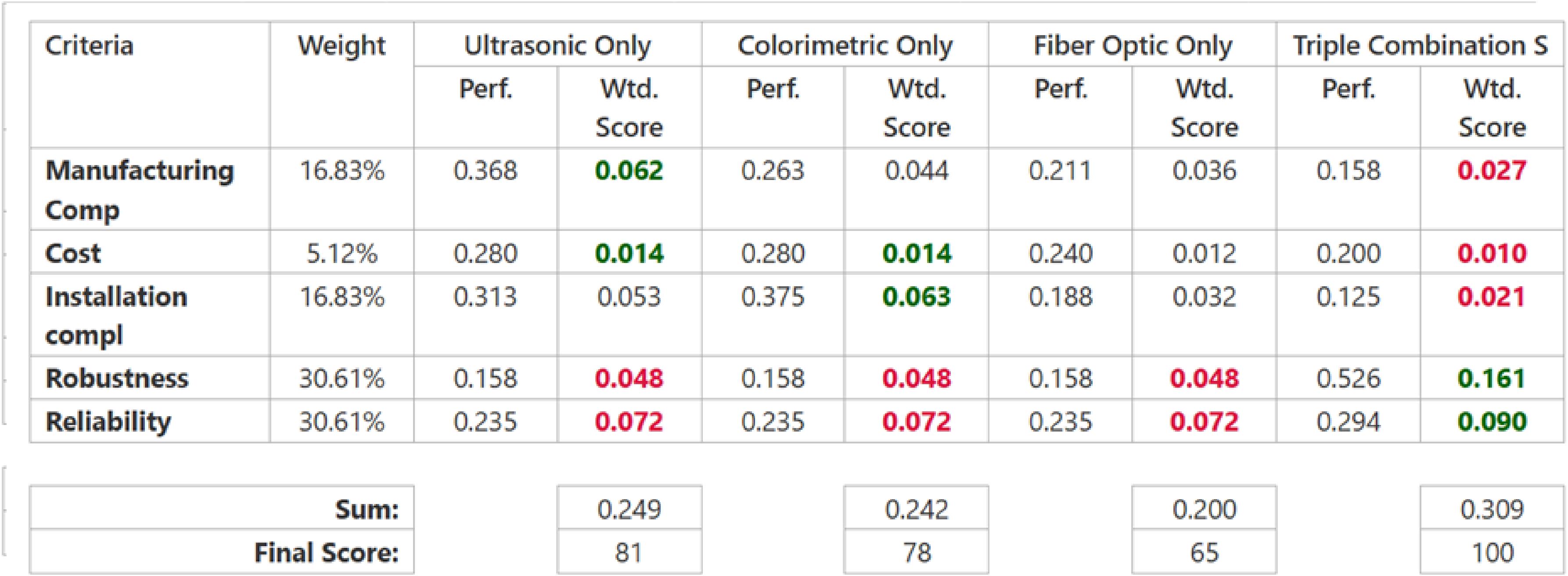
- ⊕ Many integrated sensors
- ⊕ Lower mass through distributed capability
- ⊕ Lower power demand
- ⊕ Maintains reliability and effectiveness

A reduced-sensor architecture targets equal monitoring value with lower system overhead.

# Three goals influenced SPIDERs design

*Low power consumption* + *Robust structural monitoring* + *Health hazard monitoring*

# A decision matrix was used to select a combination of three sensor modalities for each node



| Criteria | Weight | Ultrasonic Only | | Colorimetric Only | | Fiber Optic Only | | Triple Combination S | |
|---|---|---|---|---|---|---|---|---|---|
| | | Perf. | Wtd. Score | Perf. | Wtd. Score | Perf. | Wtd. Score | Perf. | Wtd. Score |
| **Manufacturing Comp** | 16.83% | 0.368 | 0.062 | 0.263 | 0.044 | 0.211 | 0.036 | 0.158 | 0.027 |
| **Cost** | 5.12% | 0.280 | 0.014 | 0.280 | 0.014 | 0.240 | 0.012 | 0.200 | 0.010 |
| **Installation compl** | 16.83% | 0.313 | 0.053 | 0.375 | 0.063 | 0.188 | 0.032 | 0.125 | 0.021 |
| **Robustness** | 30.61% | 0.158 | 0.048 | 0.158 | 0.048 | 0.158 | 0.048 | 0.526 | 0.161 |
| **Reliability** | 30.61% | 0.235 | 0.072 | 0.235 | 0.072 | 0.235 | 0.072 | 0.294 | 0.090 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Sum:** | | | 0.249 | | 0.242 | | 0.200 | | 0.309 |
| **Final Score:** | | | 81 | | 78 | | 65 | | 100 |

# Challenge: Combine sensors into a single package

*Low power consumption:*

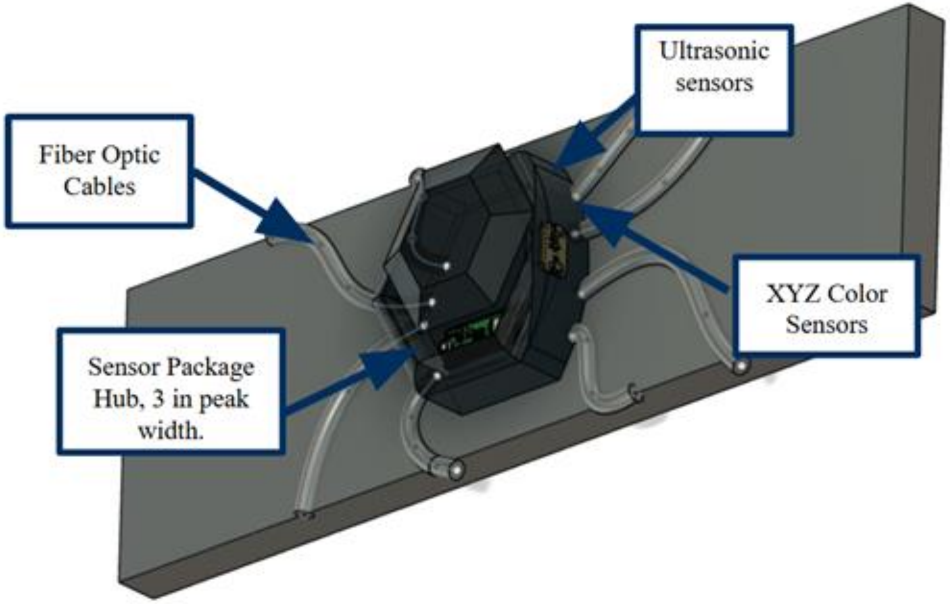
- Photovoltaic Cells
- Thermoelectric generator

*Structural Monitoring:*

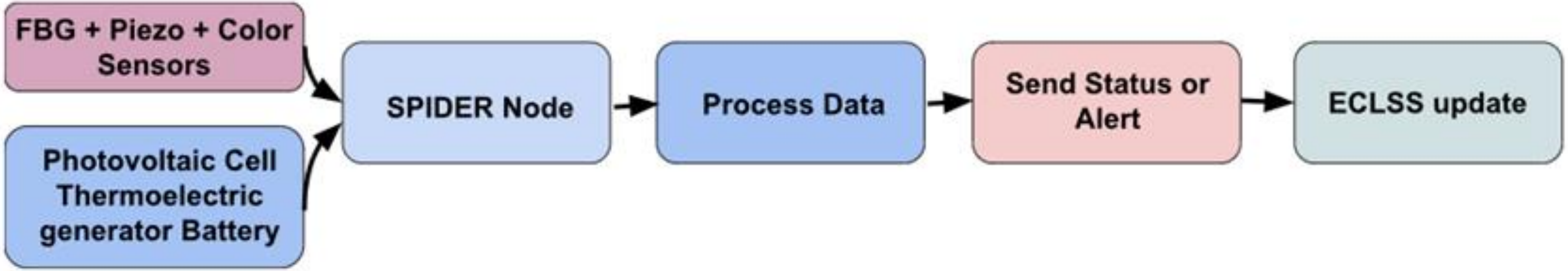
- FBG cables
- Ultrasonic sensors
- Piezoelectric wafers

*Health Hazard Monitoring:*

- Colorimetric sensors
- Colorimetric paint



# Diagram showing the system overview of SPIDER nodes



FBG + Piezo + Color Sensors

Photovoltaic Cell Thermoelectric generator Battery

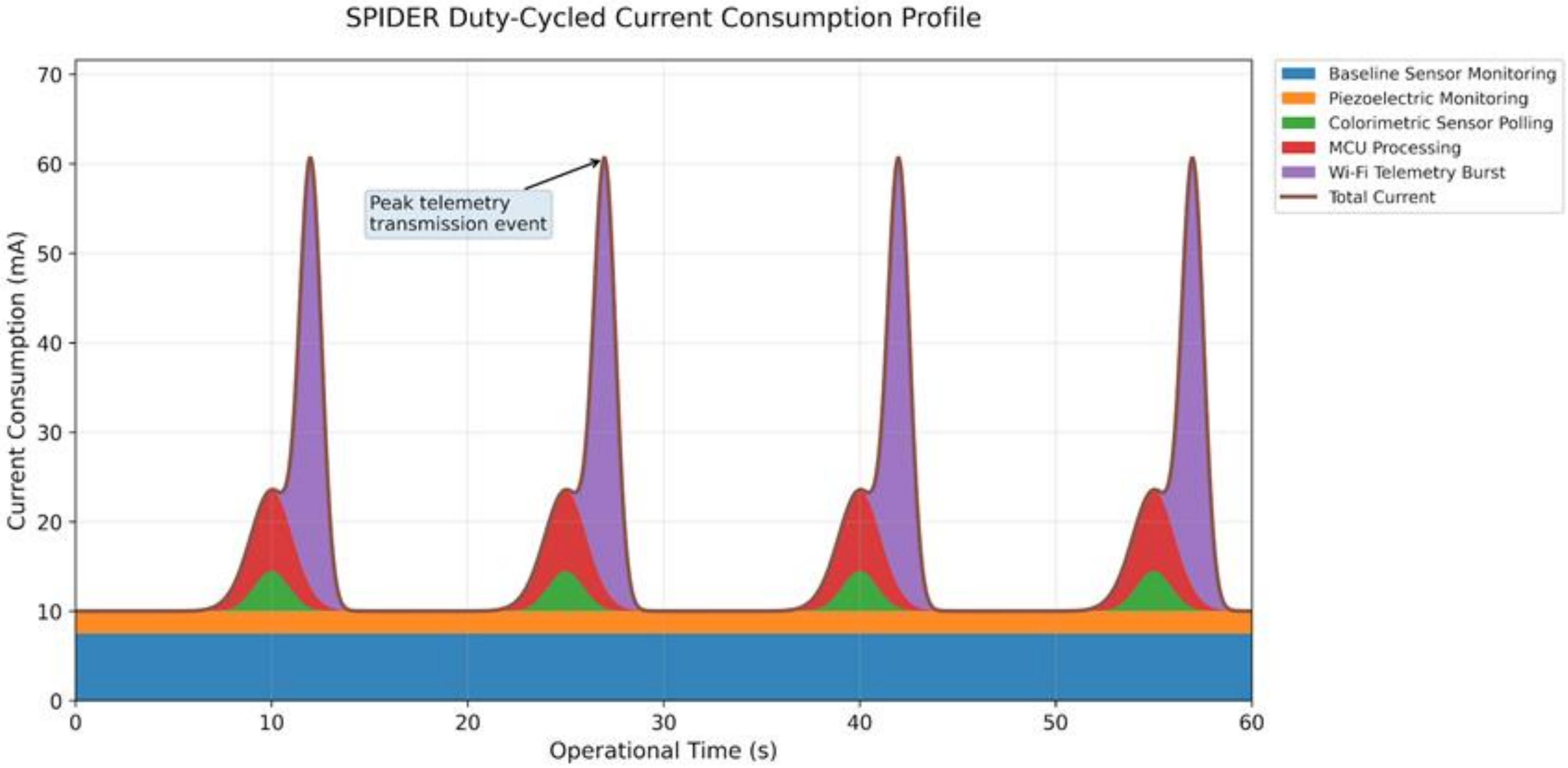
SPIDER Node

Process Data

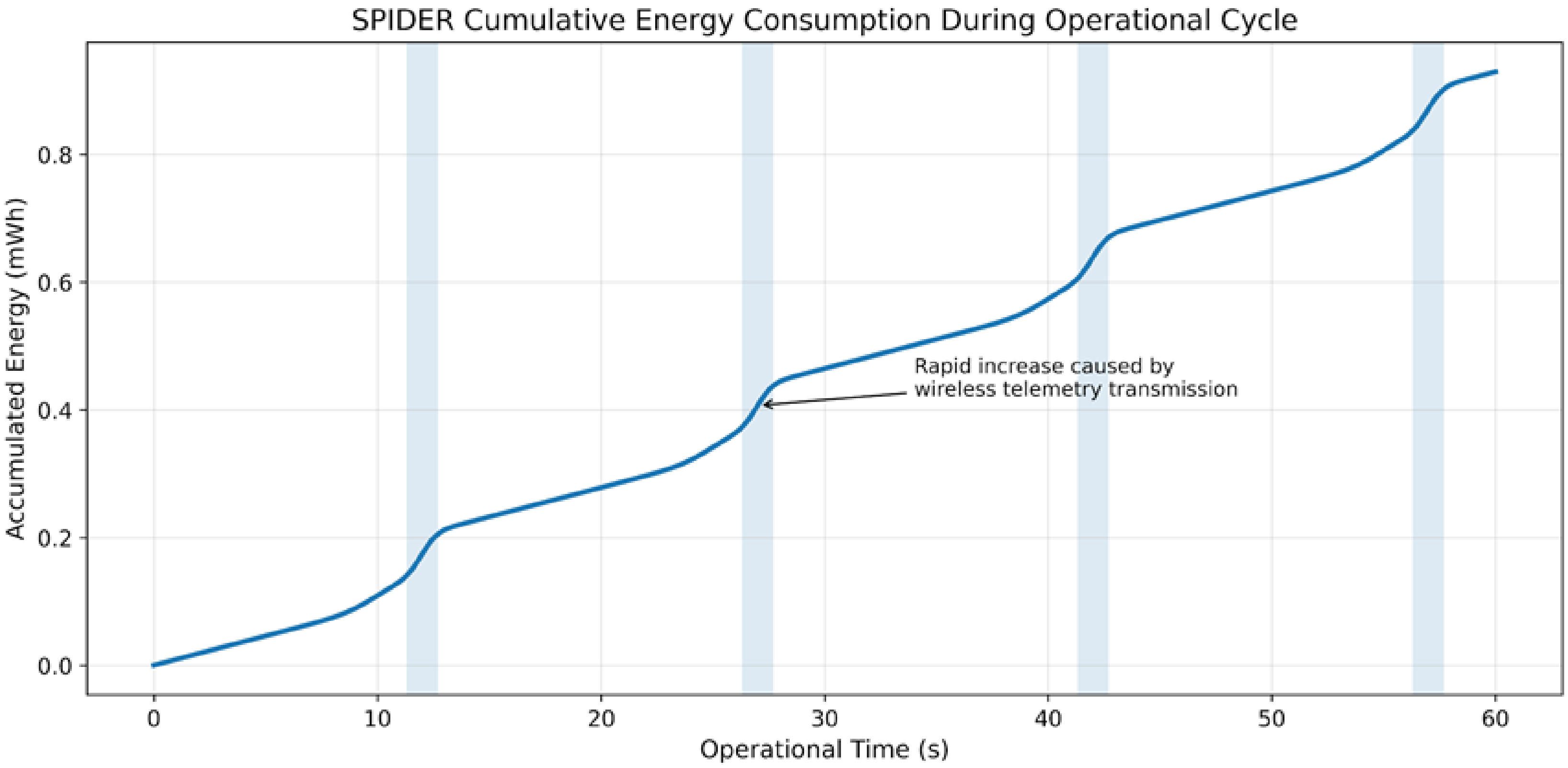
Send Status or Alert

ECLSS update

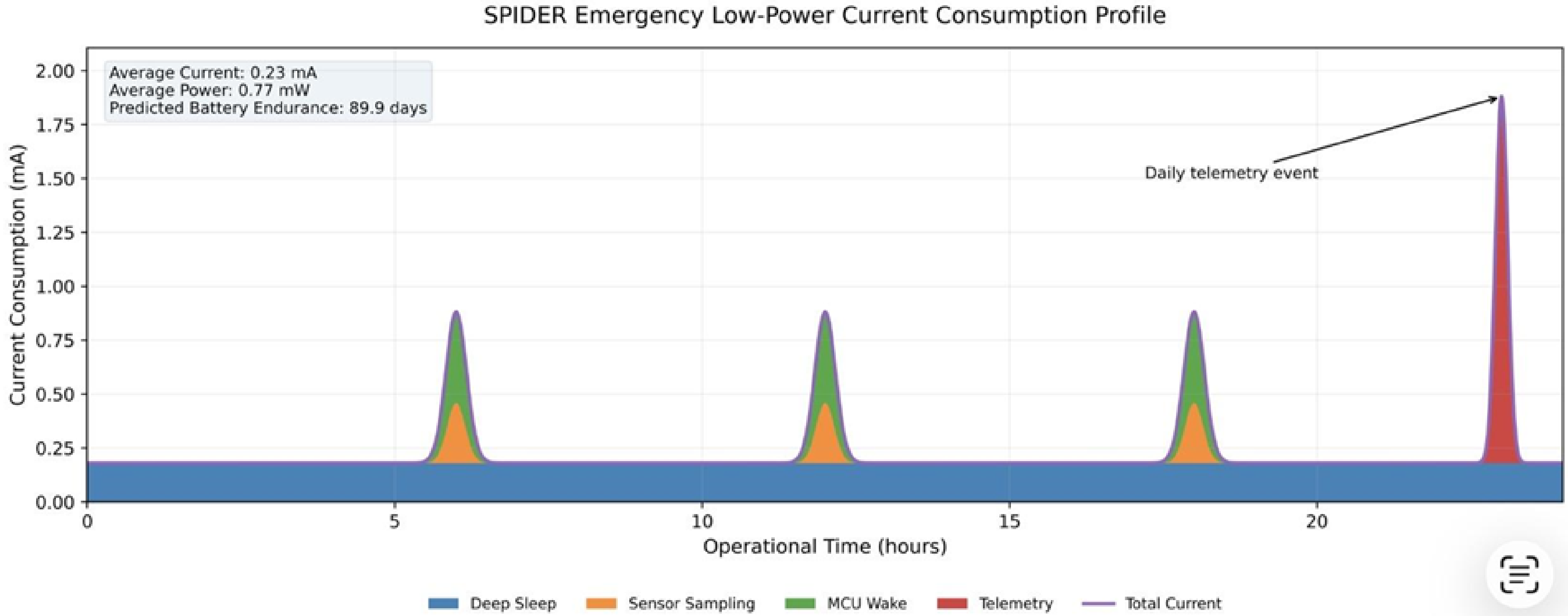
# Normal operation current consumption averages to 45mW



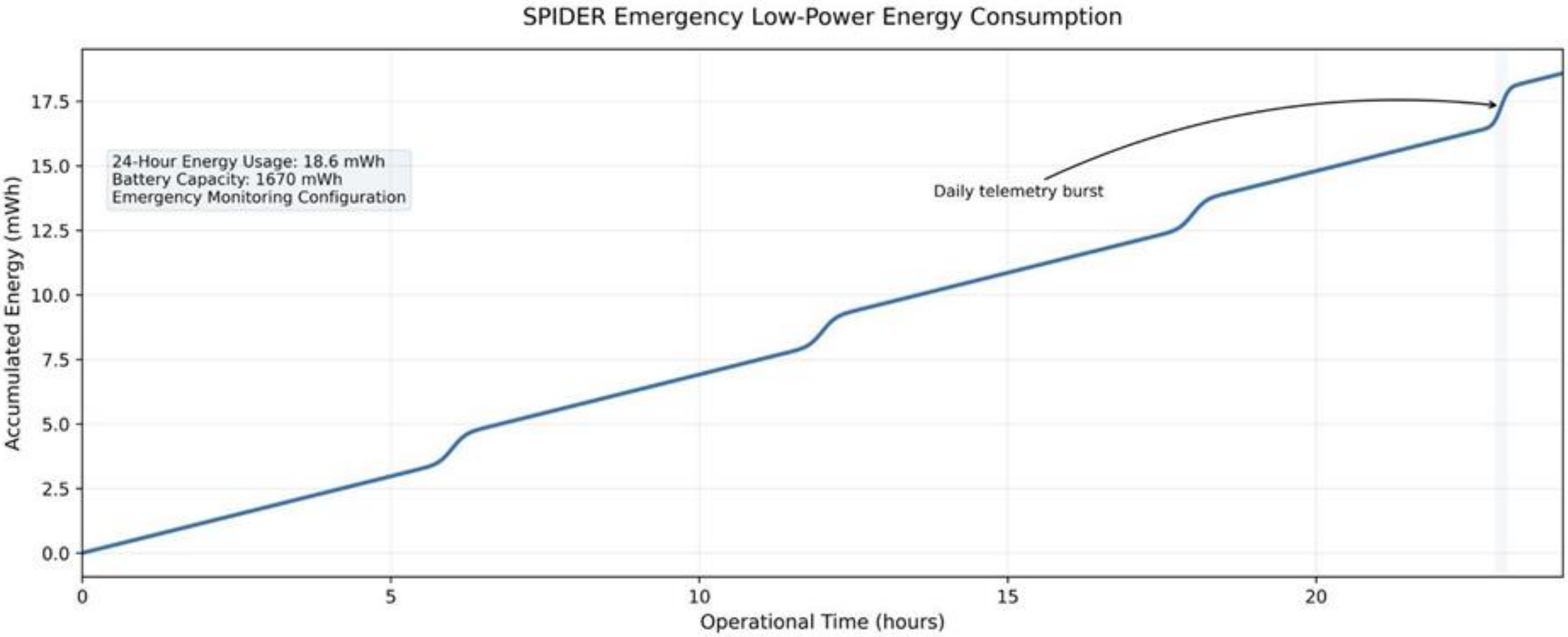
# Accumulated energy consumption over a 1 minute period



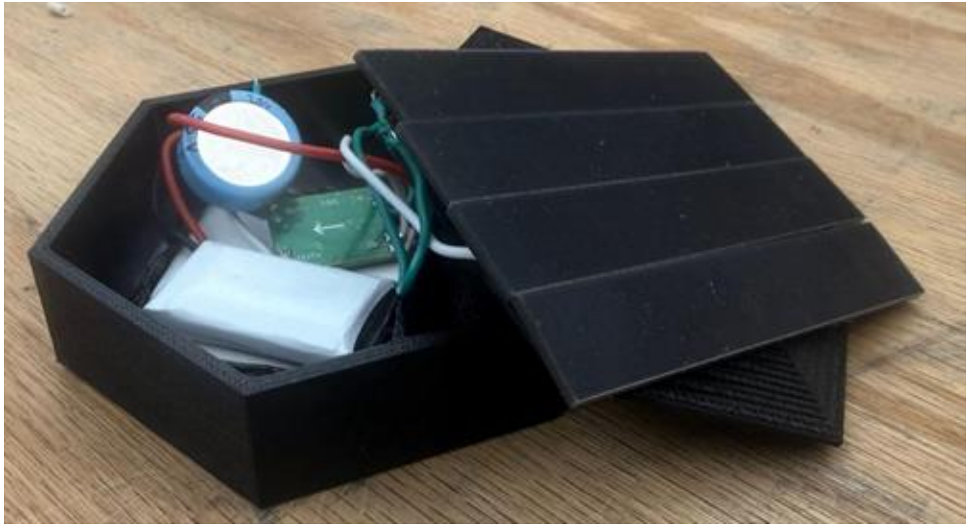
# Low power mode was simulated for data acquisition



# SPIDER would have a 90 day life on with onboard battery in low power mode

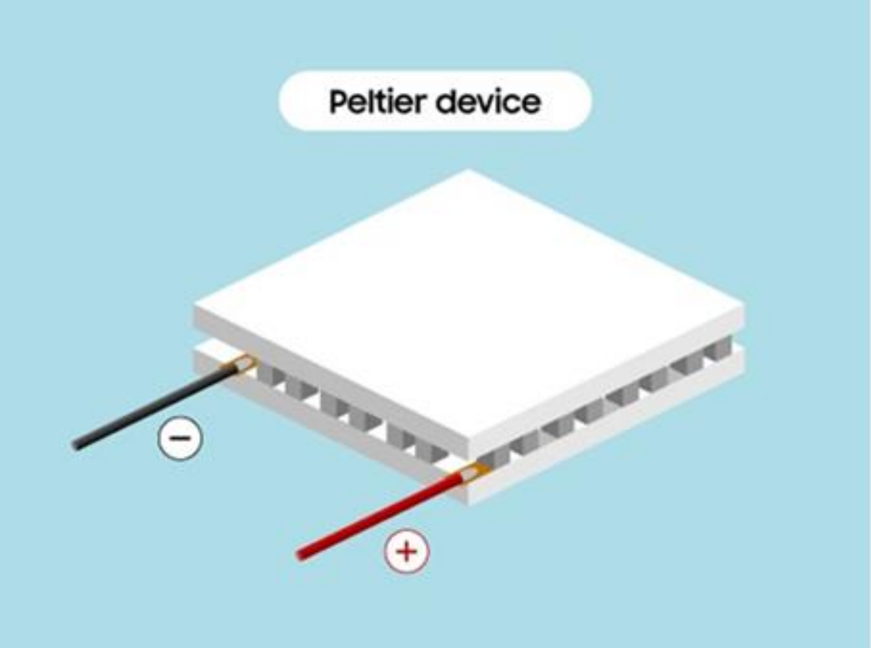


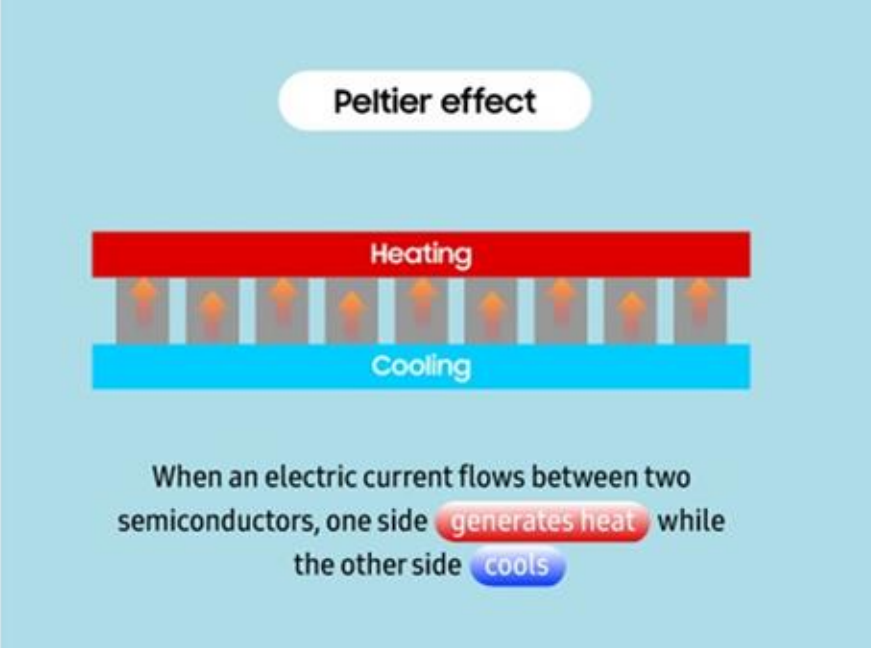
# Power is passively harvested with photovoltaic cells and a thermoelectric generator



*Power hub testing setup*

# Power generation using thermoelectric generator (TEG)


Peltier device


Peltier effect

When an electric current flows between two semiconductors, one side generates heat while the other side cools

*Source: samsung.com*

# Results show promise for the photovoltaic cells

| Power Generator | Voltage | Current | Key Takeaways |
|---|---|---|---|
| Photovoltaic cell (at a light level of 300 lux) | 8.41v | 51.6mA | Produced the strongest power contribution. |
| Thermoelectric Generator | 0.45v | 0.51mA | Very small power contribution |

Results of the experiment, where photovoltaic cells have a stronger power contribution than the thermoelectric generator.

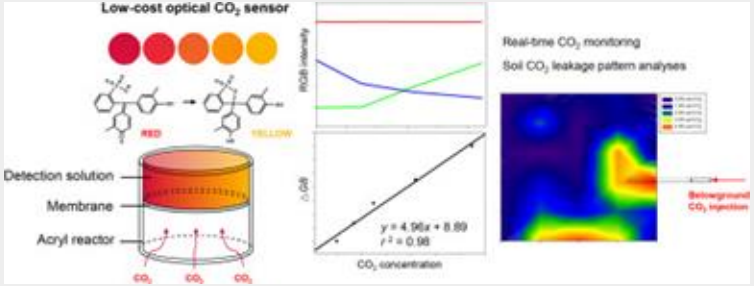
# Subsystem 2: Colorimetric sensing

Spacefaring humans can be exposed to many health hazards

Sensor Reduction: create a system that accounts for many health hazards at once

Draws upon existing research

## CO2 sensing:

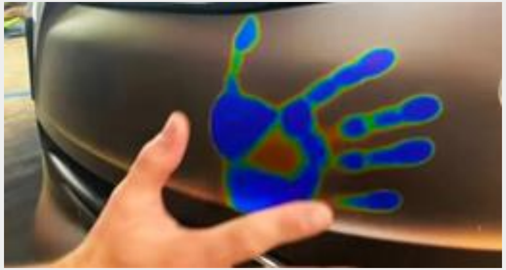


Source: Ko et. al. “Highly efficient colorimetric CO2 sensors for monitoring CO2 leakage from carbon capture and storage sites”

## Emission Phosphors:

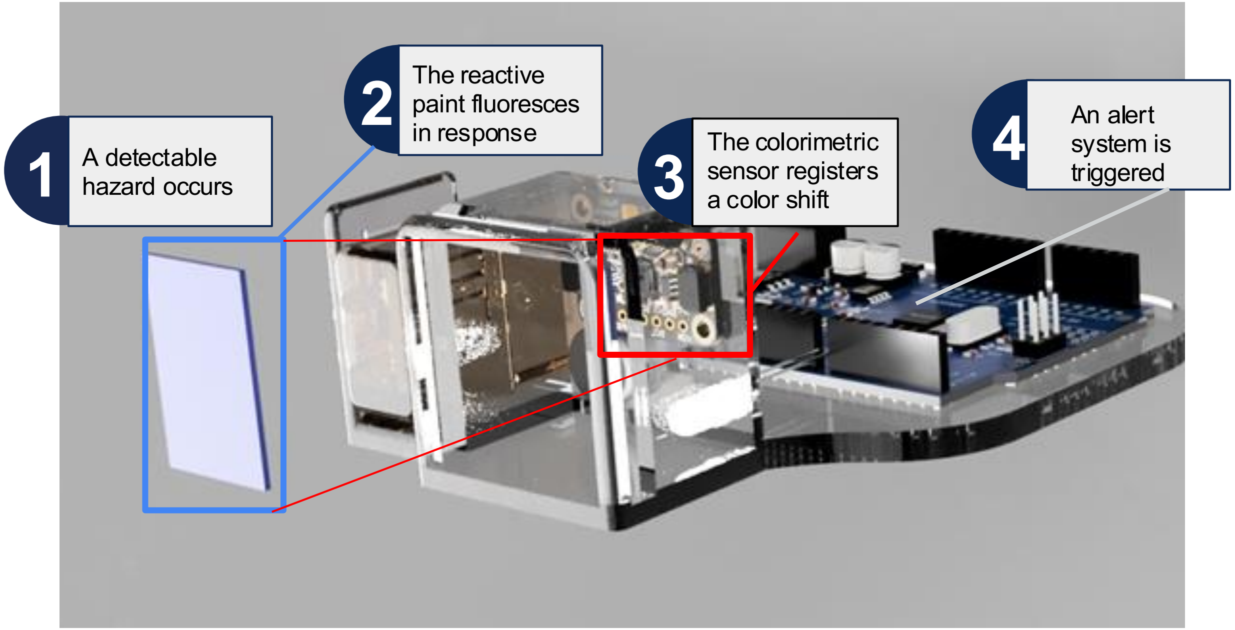
Source: PhosphorTech Corporation

## Thermochromic paint:



Source: motor1.com

# Colorimetric sensing is used to detect health hazards

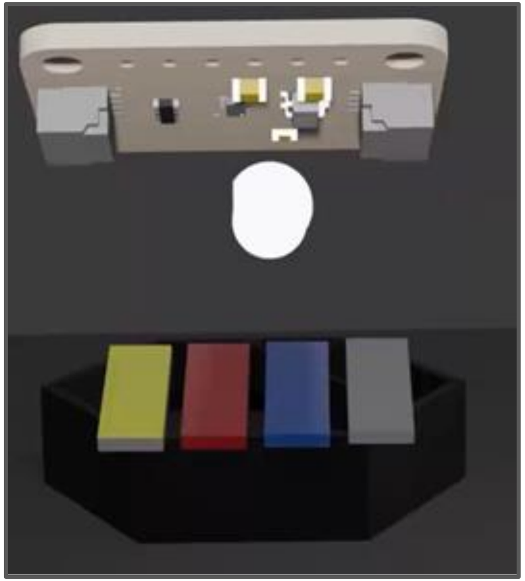


1 A detectable hazard occurs

2 The reactive paint fluoresces in response

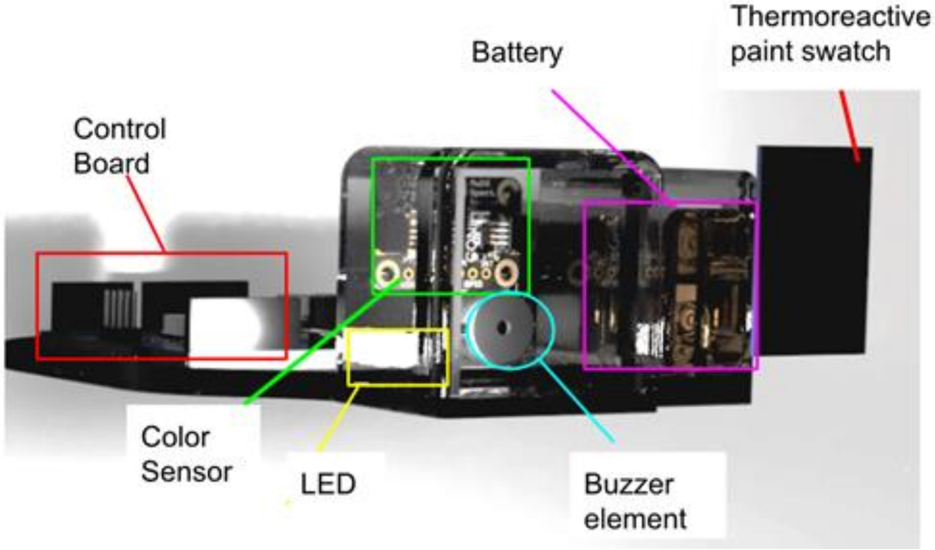
3 The colorimetric sensor registers a color shift

4 An alert system is triggered



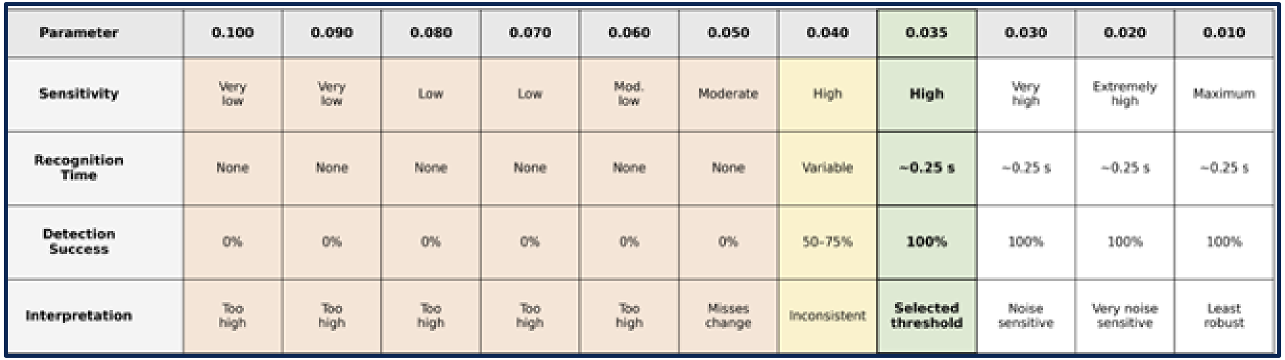
Different paints are used to identify different hazards

# Testing was done with thermochromic paint

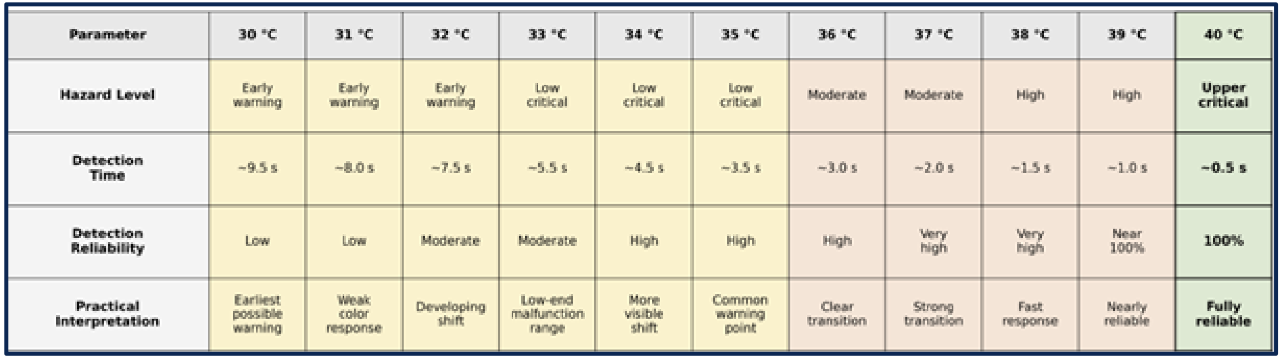


Test setup validated the ability of the sensor to report on a potential hazard: the color shift of the paint in response to temperature change

# Testing showed promising results for implementation



| Parameter | 0.100 | 0.090 | 0.080 | 0.070 | 0.060 | 0.050 | 0.040 | 0.035 | 0.030 | 0.020 | 0.010 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sensitivity** | Very low | Very low | Low | Low | Mod. low | Moderate | High | **High** | Very high | Extremely high | Maximum |
| **Recognition Time** | None | None | None | None | None | None | Variable | **~0.25 s** | ~0.25 s | ~0.25 s | ~0.25 s |
| **Detection Success** | 0% | 0% | 0% | 0% | 0% | 0% | 50-75% | **100%** | 100% | 100% | 100% |
| **Interpretation** | Too high | Too high | Too high | Too high | Too high | Misses change | Inconsistent | **Selected threshold** | Noise sensitive | Very noise sensitive | Least robust |



| Parameter | 30 °C | 31 °C | 32 °C | 33 °C | 34 °C | 35 °C | 36 °C | 37 °C | 38 °C | 39 °C | 40 °C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Hazard Level** | Early warning | Early warning | Early warning | Low critical | Low critical | Low critical | Moderate | Moderate | High | High | **Upper critical** |
| **Detection Time** | ~9.5 s | ~8.0 s | ~7.5 s | ~5.5 s | ~4.5 s | ~3.5 s | ~3.0 s | ~2.0 s | ~1.5 s | ~1.0 s | **~0.5 s** |
| **Detection Reliability** | Low | Low | Moderate | Moderate | High | High | High | Very high | Very high | Near 100% | **100%** |
| **Practical Interpretation** | Earliest possible warning | Weak color response | Developing shift | Low-end malfunction range | More visible shift | Common warning point | Clear transition | Strong transition | Fast response | Nearly reliable | **Fully reliable** |

## Key Results

- A threshold sensing level of 0.035 is ideal

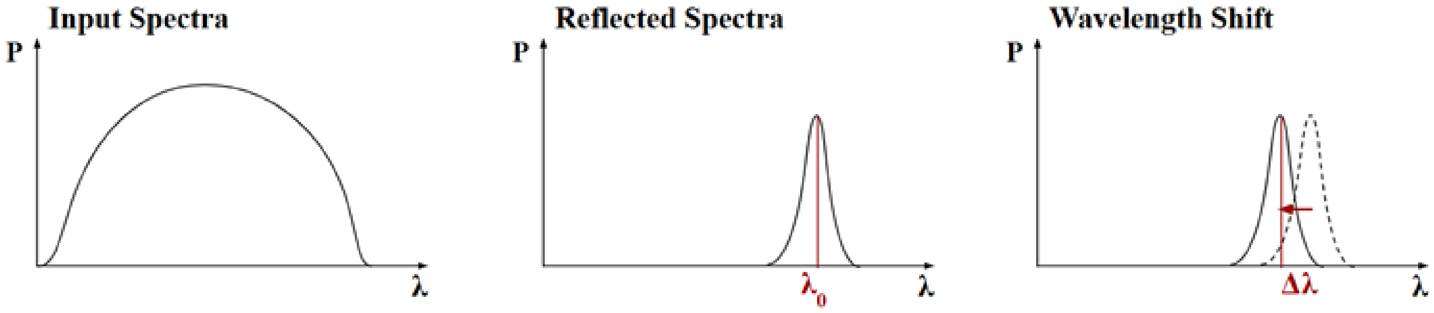
-Alert time is 0.5s-9.5s between 40-30°C

# Subsystem 3: FBG Optical Sensors

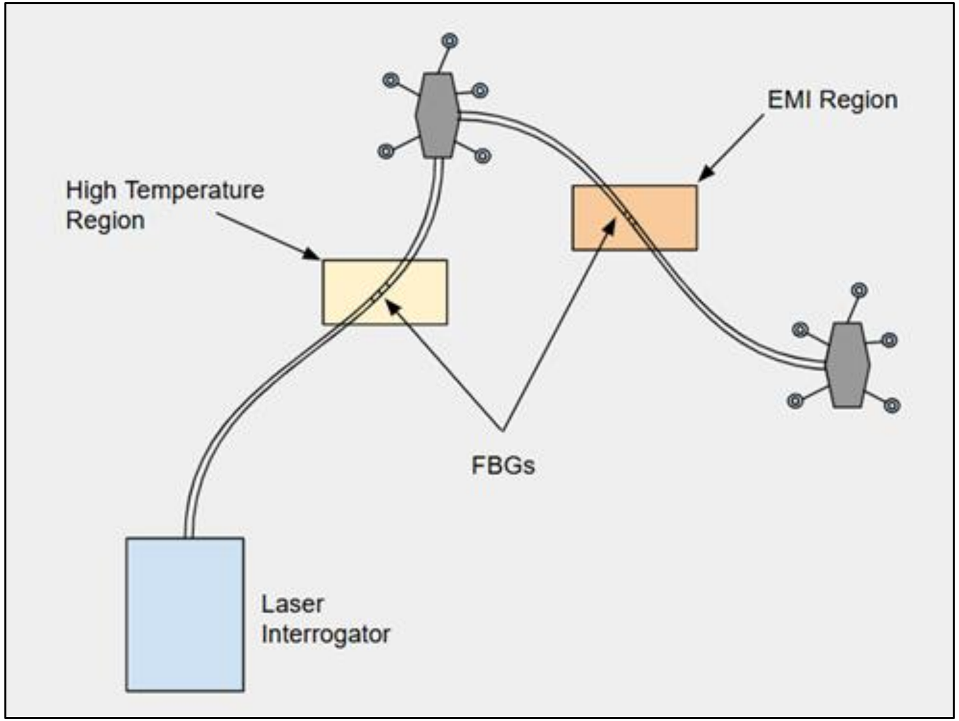
Calibrate strain readings

Adjust for heating effects

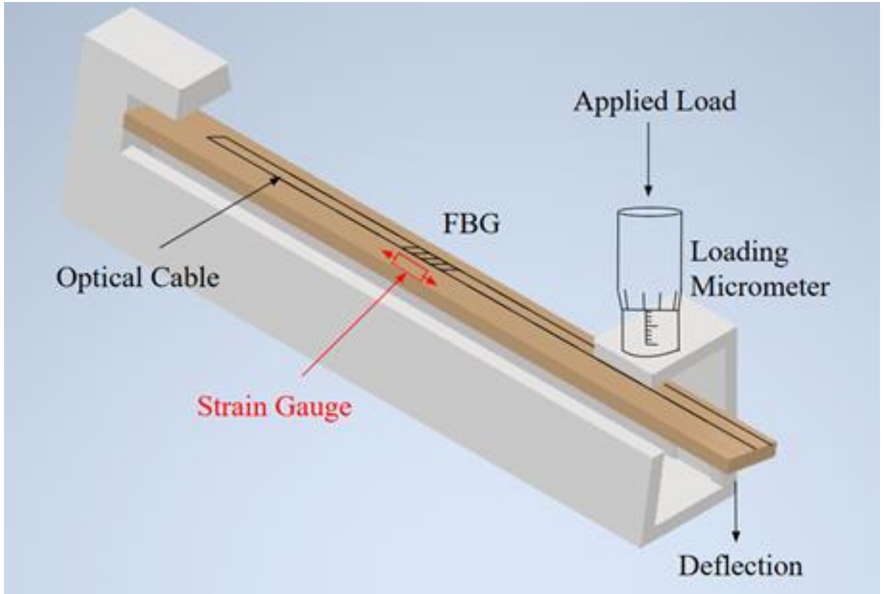
Localize damage in ECLSS

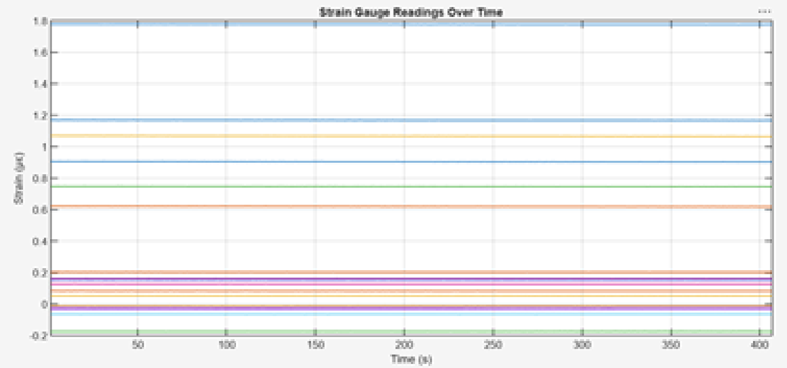


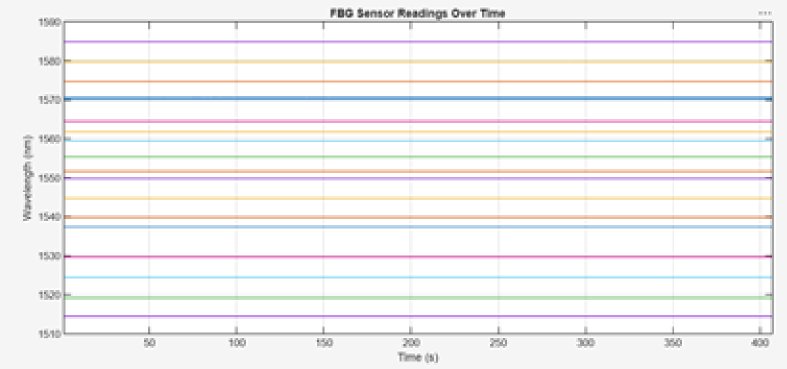
# FBG Sensors are powered non-locally, and can be used in high-temperature environments and electromagnetic fields



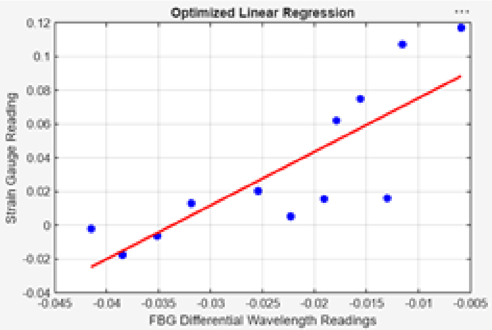
# A cantilever beam was used to calibrate strain readings from the FBG

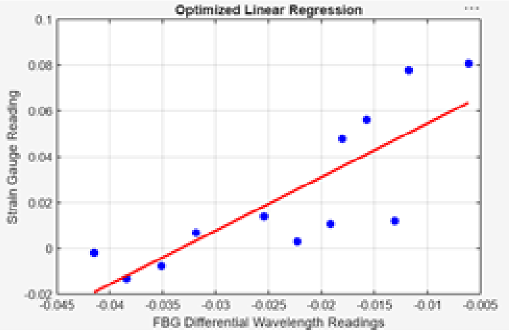






# Linear correlation fitting calibrated wavelength to strain readings





$$\varepsilon_{FBG} = S \cdot \frac{\Delta\lambda}{\lambda_0} + b$$

| Trial Number | 1 | 2 | 3 | Average |
|---|---|---|---|---|
| Mean Squared Error | 0.0003 | 0.0001 | 0.0006 | 0.0004 |
| Theta0 (Strain) | 0.0780 | 0.0491 | 0.1072 | 0.0781 |
| Theta1 (k) | 2.3418 | 1.5410 | 3.1805 | 2.3544 |

$$\mathrm{MSE}(m,b) = \frac{1}{n}\sum_{i=1}^{n}\left(y_i - (mx_i + b)\right)^2$$

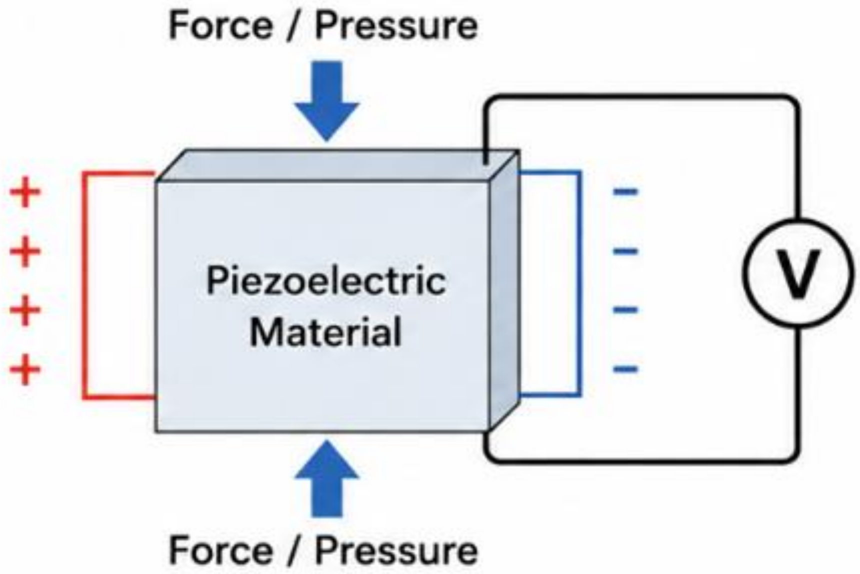
$$\hat{y} = \theta_0 + \theta_1 x$$

$$J(\theta_0,\theta_1) = \frac{1}{2m}\sum_{i=1}^{m}(\theta_0 + \theta_1 x_i - y_i)^2$$

$$\theta_0 := \theta_0 - \alpha\frac{1}{m}\sum_{i=1}^{m}(\hat{y}_i - y_i)$$

$$\theta_1 := \theta_1 - \alpha\frac{1}{m}\sum_{i=1}^{m}(\hat{y}_i - y_i)x_i$$

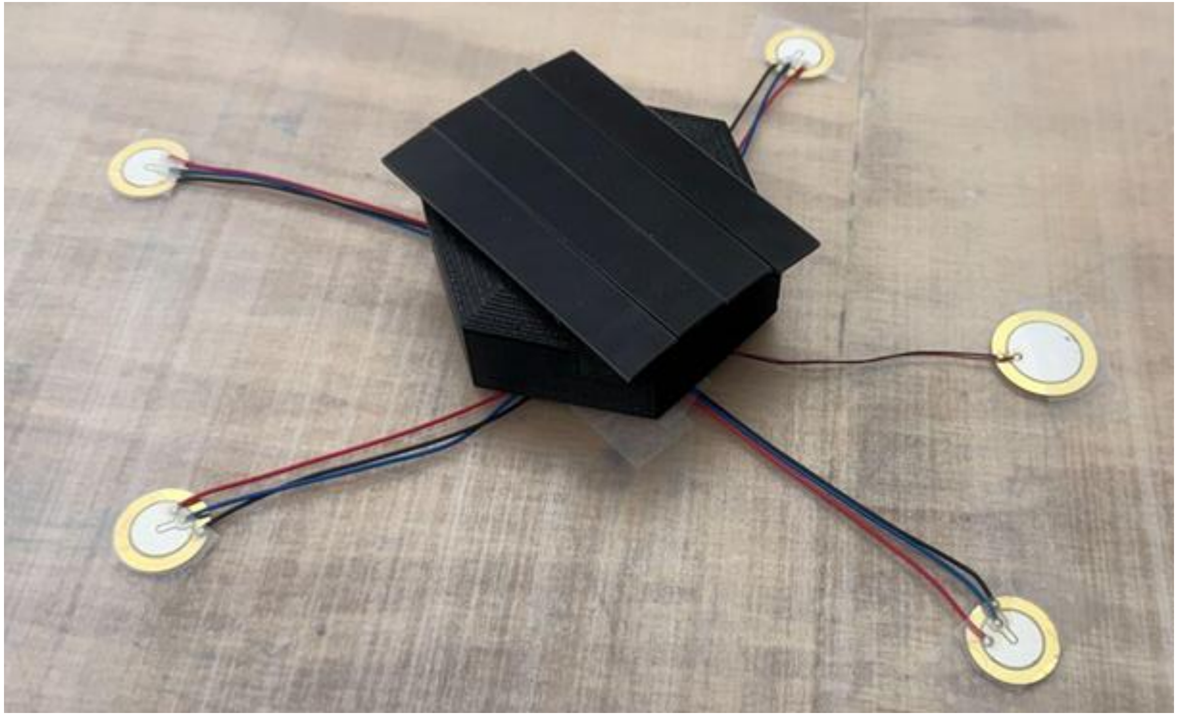
# Piezoelectrics can be used to detect sounds by converting sound waves into voltage spikes



Force / Pressure

Force / Pressure

# Piezoelectrics were set up with redundancy in mind



# Strong impacts show less localization error than smaller impacts

| Test Case | Impact Energy / Input | Nearest Sensor Distance | Farthest Sensor Distance | Detection Rate | Avg. Localization Error | Max Error | Key Takeaway |
|---|---|---|---|---|---|---|---|
| **Low energy impact** | 0.05 J | 75 mm | 425 mm | 90% | 24 mm | 34 mm | Low-energy events were detectable but had the highest error |
| **Medium energy impact** | 0.15 J | 75 mm | 425 mm | 100% | 17 mm | 26 mm | Best balance of clear signal and repeatable localization |
| **High energy impact** | 0.30 J | 75 mm | 425 mm | 100% | 13 mm | 21 mm | Strong signals improved timing accuracy and localization |

Data error averages were found using: $e = \sqrt{(x_{\text{est}} - x_{\text{true}})^2 + (y_{\text{est}} - y_{\text{true}})^2}$

# Localization was simulated using time of flight methods

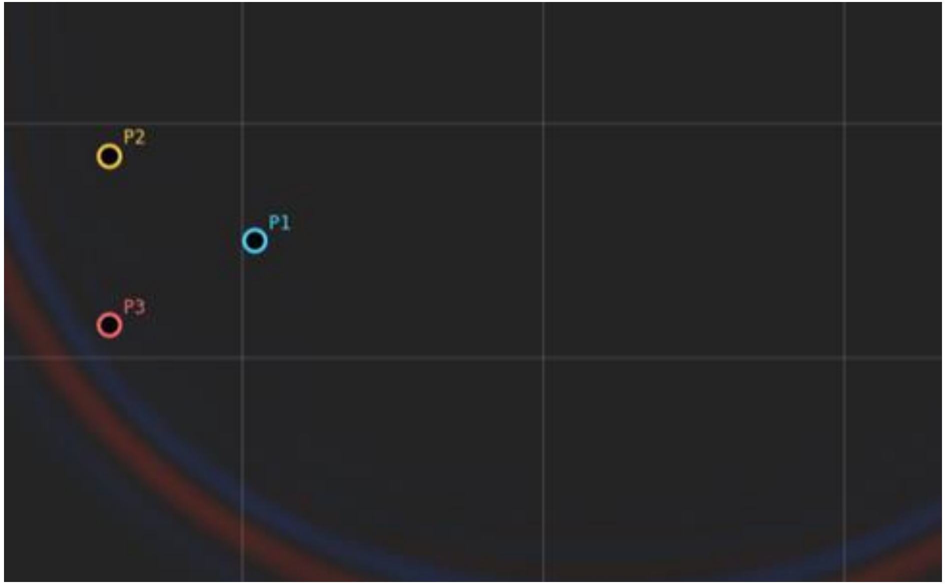
For a disturbance at an unknown location (x,y), the distance to sensor iii, located at ($x_i$, $y_i$), was modeled as

$$d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$$

The arrival-time difference between sensors i and j was then estimated using

$$\Delta t_{ij} = t_i - t_j = \frac{d_i - d_j}{c}$$

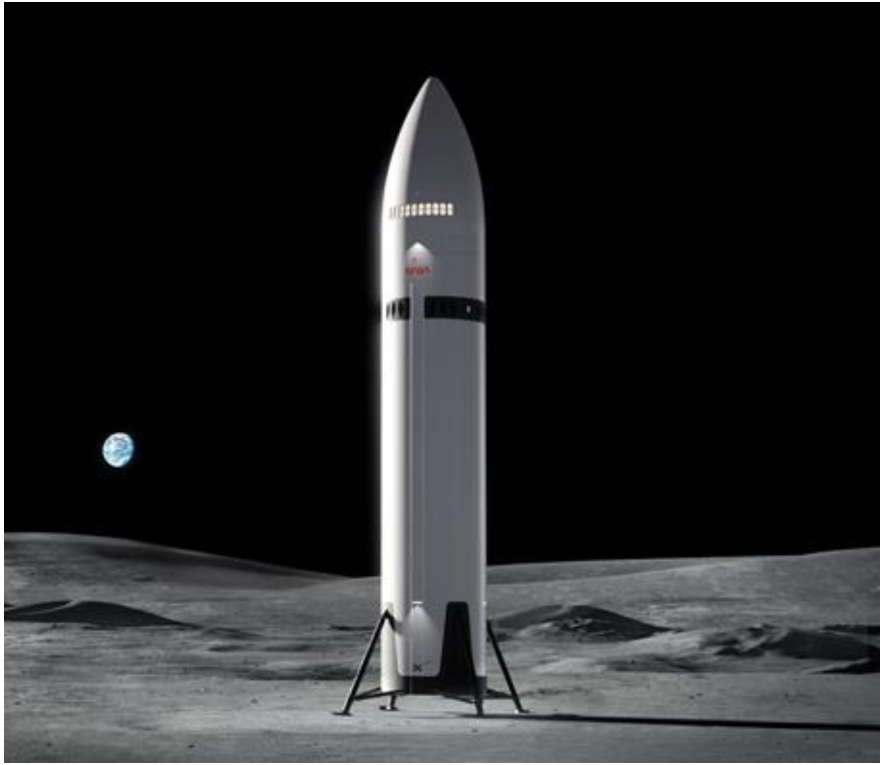
where c is the wave speed through the test panel. This approach allowed the system to estimate the source location without requiring the exact start time of the impact.



# Piezoelectrics simulation with sound wave propagation

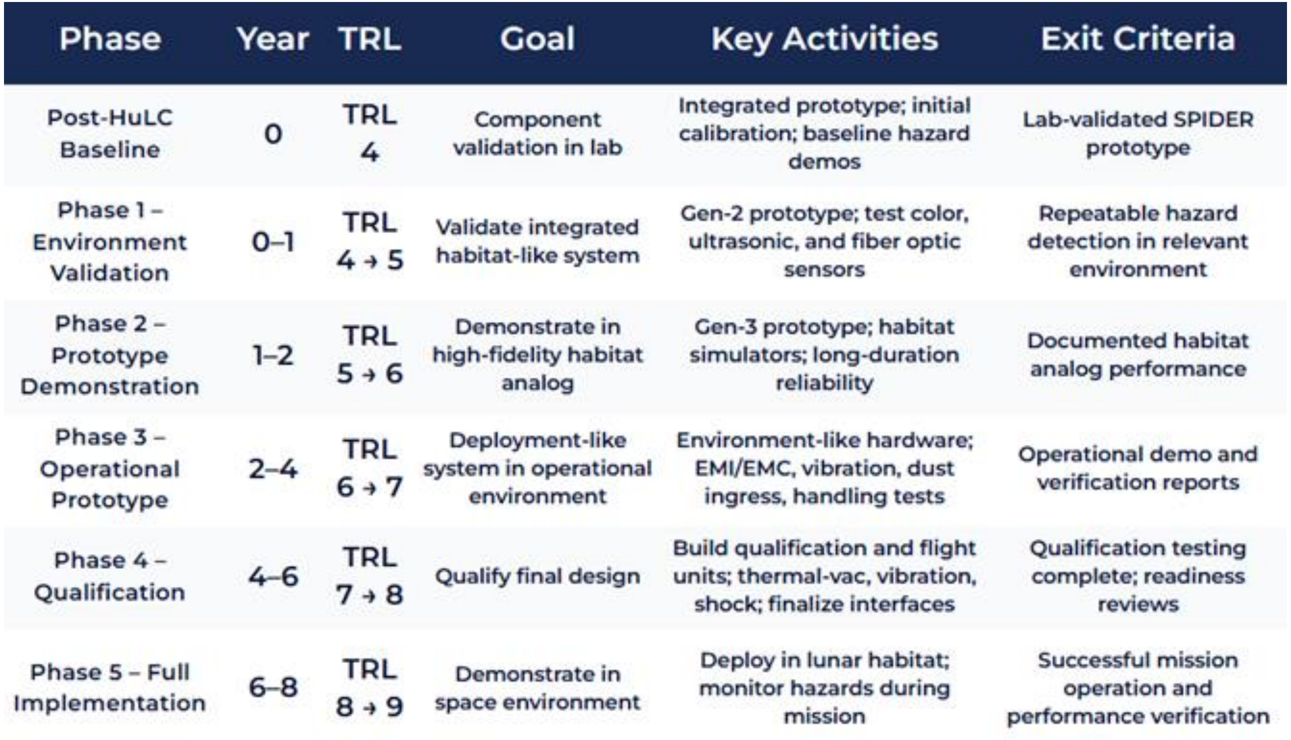
# Full implementation considerations

- Cost to implement **$4081000**
- Cost per node after TRL of 8-9 is reached is projected at $350,
- Total coverage of habitable areas of a proposed StarShip lunar base requires **11 nodes** assuming 1 node per 50m$^2$.



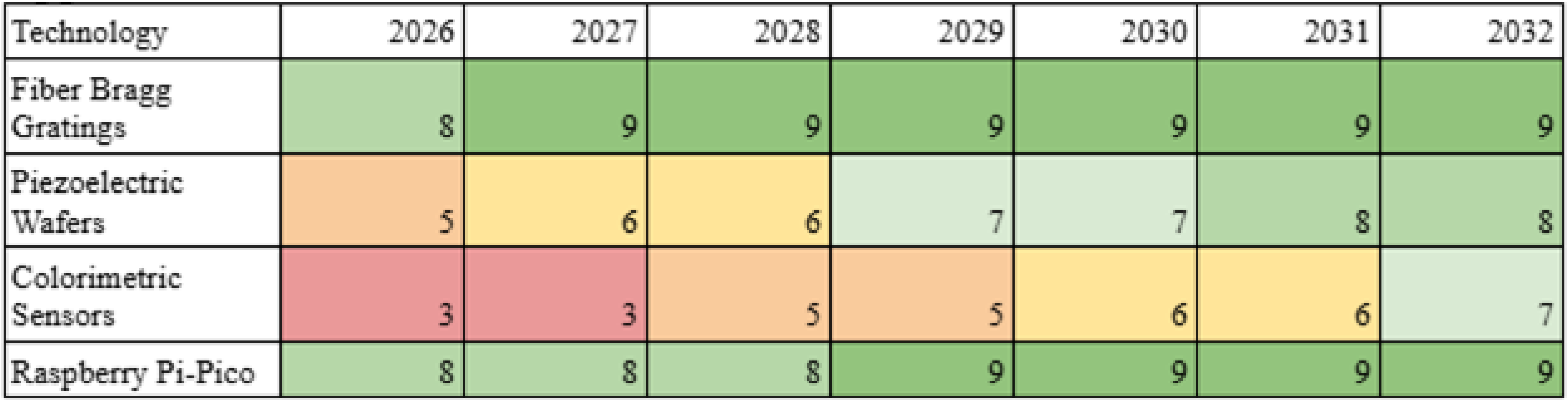
https://www.nasa.gov/reference/human-landing-systems/

# SPIDER will be ready for implementation at TRL 9



| Phase | Year | TRL | Goal | Key Activities | Exit Criteria |
|---|---|---|---|---|---|
| Post-HuLC Baseline | 0 | TRL 4 | Component validation in lab | Integrated prototype; initial calibration; baseline hazard demos | Lab-validated SPIDER prototype |
| Phase 1 – Environment Validation | 0–1 | TRL 4 → 5 | Validate integrated habitat-like system | Gen-2 prototype; test color, ultrasonic, and fiber optic sensors | Repeatable hazard detection in relevant environment |
| Phase 2 – Prototype Demonstration | 1–2 | TRL 5 → 6 | Demonstrate in high-fidelity habitat analog | Gen-3 prototype; habitat simulators; long-duration reliability | Documented habitat analog performance |
| Phase 3 – Operational Prototype | 2–4 | TRL 6 → 7 | Deployment-like system in operational environment | Environment-like hardware; EMI/EMC, vibration, dust ingress, handling tests | Operational demo and verification reports |
| Phase 4 – Qualification | 4–6 | TRL 7 → 8 | Qualify final design | Build qualification and flight units; thermal-vac, vibration, shock; finalize interfaces | Qualification testing complete; readiness reviews |
| Phase 5 – Full Implementation | 6–8 | TRL 8 → 9 | Demonstrate in space environment | Deploy in lunar habitat; monitor hazards during mission | Successful mission operation and performance verification |

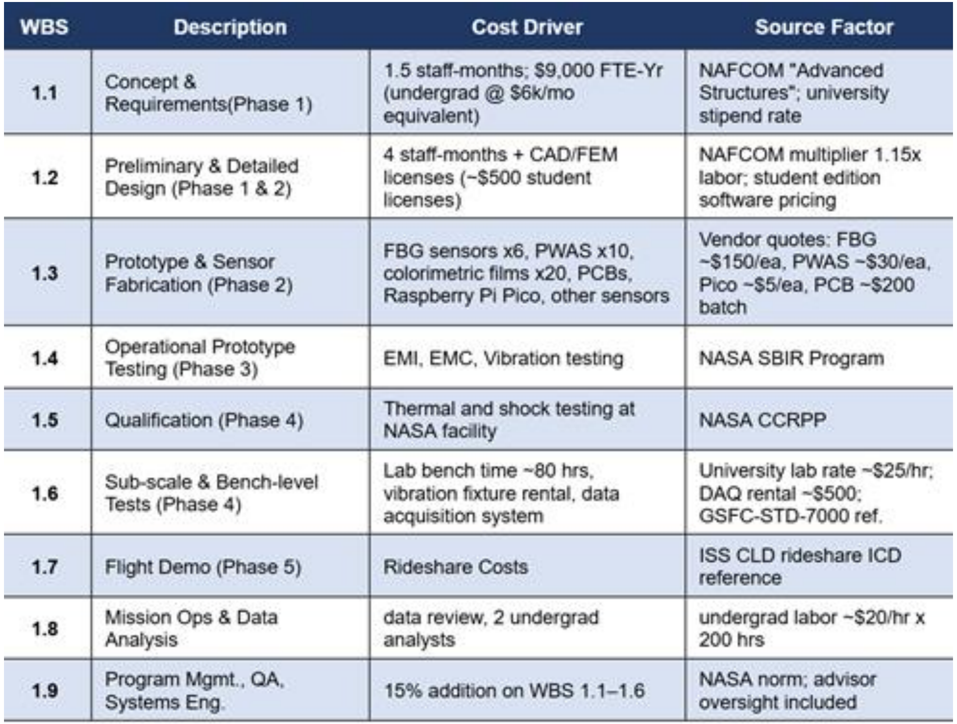
# SPIDER components should all be TRL 7+ by 2032



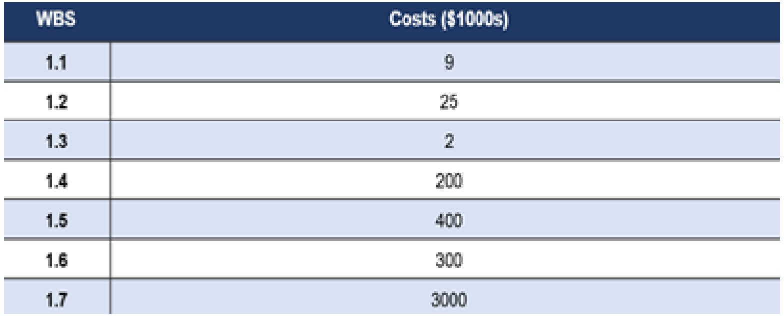
| Technology | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 |
|---|---|---|---|---|---|---|---|
| Fiber Bragg Gratings | 8 | 9 | 9 | 9 | 9 | 9 | 9 |
| Piezoelectric Wafers | 5 | 6 | 6 | 7 | 7 | 8 | 8 |
| Colorimetric Sensors | 3 | 3 | 5 | 5 | 6 | 6 | 7 |
| Raspberry Pi-Pico | 8 | 8 | 8 | 9 | 9 | 9 | 9 |

*TLR Chart 1: Predicted readiness of each utilized technology for in-space application*

# Long-term development cost was budgeted to be $4 million



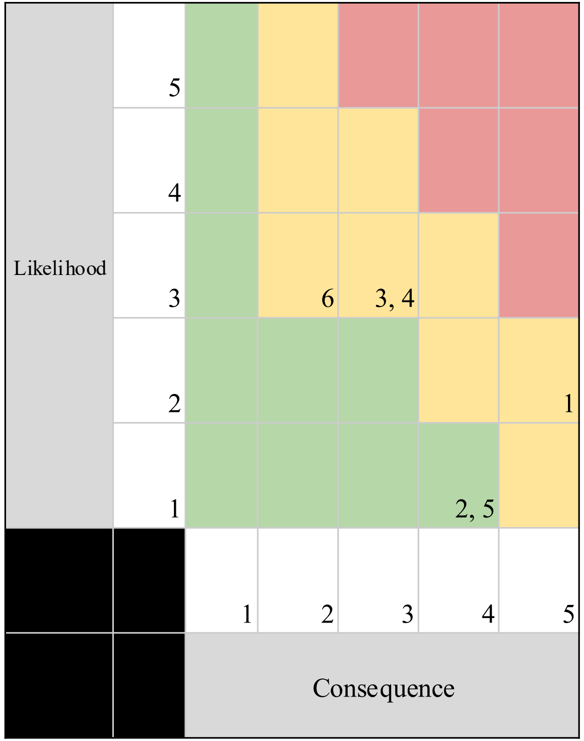
| WBS | Description | Cost Driver | Source Factor |
|---|---|---|---|
| 1.1 | Concept & Requirements(Phase 1) | 1.5 staff-months; $9,000 FTE-Yr (undergrad @ $6k/mo equivalent) | NAFCOM "Advanced Structures"; university stipend rate |
| 1.2 | Preliminary & Detailed Design (Phase 1 & 2) | 4 staff-months + CAD/FEM licenses (~$500 student licenses) | NAFCOM multiplier 1.15x labor; student edition software pricing |
| 1.3 | Prototype & Sensor Fabrication (Phase 2) | FBG sensors x6, PWAS x10, colorimetric films x20, PCBs, Raspberry Pi Pico, other sensors | Vendor quotes: FBG ~$150/ea, PWAS ~$30/ea, Pico ~$5/ea, PCB ~$200 batch |
| 1.4 | Operational Prototype Testing (Phase 3) | EMI, EMC, Vibration testing | NASA SBIR Program |
| 1.5 | Qualification (Phase 4) | Thermal and shock testing at NASA facility | NASA CCRPP |
| 1.6 | Sub-scale & Bench-level Tests (Phase 4) | Lab bench time ~80 hrs, vibration fixture rental, data acquisition system | University lab rate ~$25/hr; DAQ rental ~$500; GSFC-STD-7000 ref. |
| 1.7 | Flight Demo (Phase 5) | Rideshare Costs | ISS CLD rideshare ICD reference |
| 1.8 | Mission Ops & Data Analysis | data review, 2 undergrad analysts | undergrad labor ~$20/hr x 200 hrs |
| 1.9 | Program Mgmt., QA, Systems Eng. | 15% addition on WBS 1.1–1.6 | NASA norm; advisor oversight included |



| WBS | Costs ($1000s) |
|---|---|
| 1.1 | 9 |
| 1.2 | 25 |
| 1.3 | 2 |
| 1.4 | 200 |
| 1.5 | 400 |
| 1.6 | 300 |
| 1.7 | 3000 |

# A risk assessment matrix was used to consider failure modes

| No. | Risk | Description | Mitigation |
|---|---|---|---|
| 1 | Sensor failure during deployment | Sensors may be damaged or improperly installed, preventing them from providing health monitoring data and potentially allowing damage to go undetected. | Prioritize ease of packaging and installation to reduce the chance of deployment errors. |
| 2 | Detection sensitivity limits | The sensor network may be installed successfully but still fail to detect critical health indicators within the system. | Use three complementary sensor modalities and perform testing in relevant environments to validate detection capability. |
| 3 | Design is too heavy | The sensor system may exceed mass limits, reducing the benefit of replacing existing methods. | Continuously optimize the design to minimize weight throughout development. |
| 4 | Design uses too much power | Excessive power consumption may be impractical for lunar habitat operations. | Select low-power components and prioritize energy efficiency in design decisions. |
| 5 | Sensor degradation in lunar environment | Radiation exposure and thermal cycling in lunar habitats may degrade sensor performance and reduce signal fidelity. | Ensure electronics and components are rated for lunar environmental conditions. |
| 6 | Noisy readings during mission | Differences between lunar habitat and lab conditions could produce unstable or noisy sensor signals. | Conduct thorough laboratory testing and calibration to stabilize signal interpretation. |



| Likelihood |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  | 5 | 🟩 | 🟨 | 🟥 | 🟥 | 🟥 |
|  | 4 | 🟩 | 🟨 | 🟨 | 🟥 | 🟥 |
|  | 3 | 🟩 | 🟨 6 | 🟨 3, 4 | 🟨 | 🟥 |
|  | 2 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 1 |
|  | 1 | 🟩 | 🟩 | 🟩 | 🟩 2, 5 | 🟨 |
|  |  | 1 | 2 | 3 | 4 | 5 |
|  |  | Consequence |  |  |  |  |

# Current testing was successful, future work is promising

## Completed work

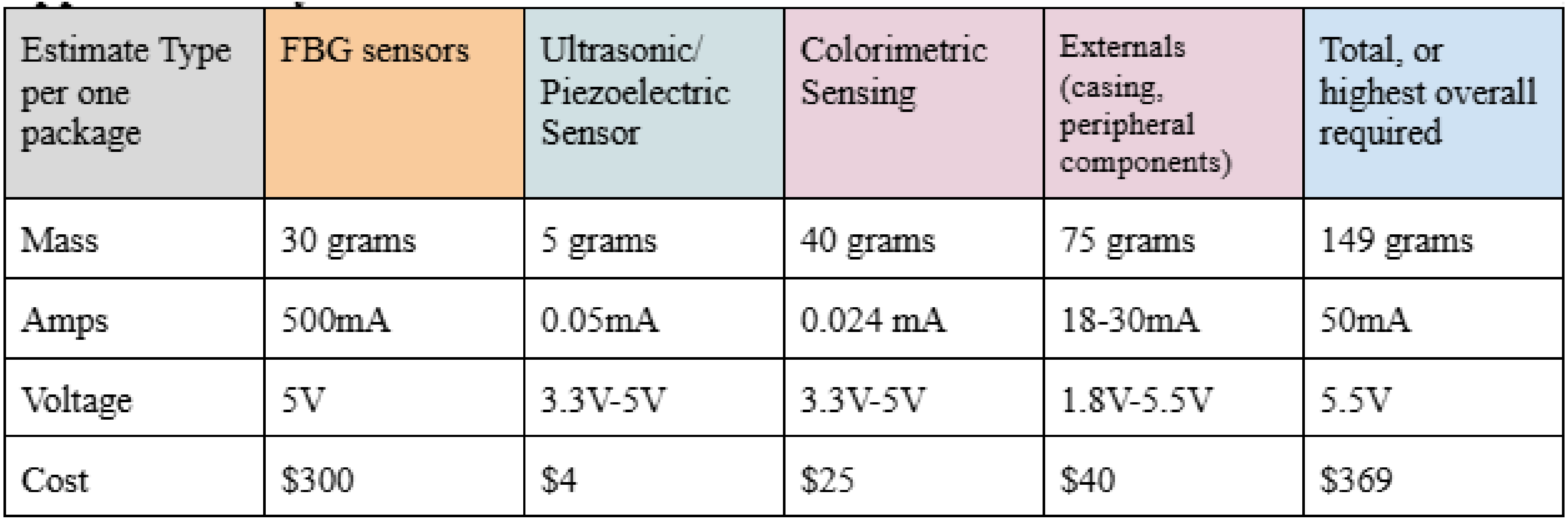
- Successful power harvesting
- Successful sensor validation
- Conference paper manuscript submitted for AIAA Scitech 2027

## Future work

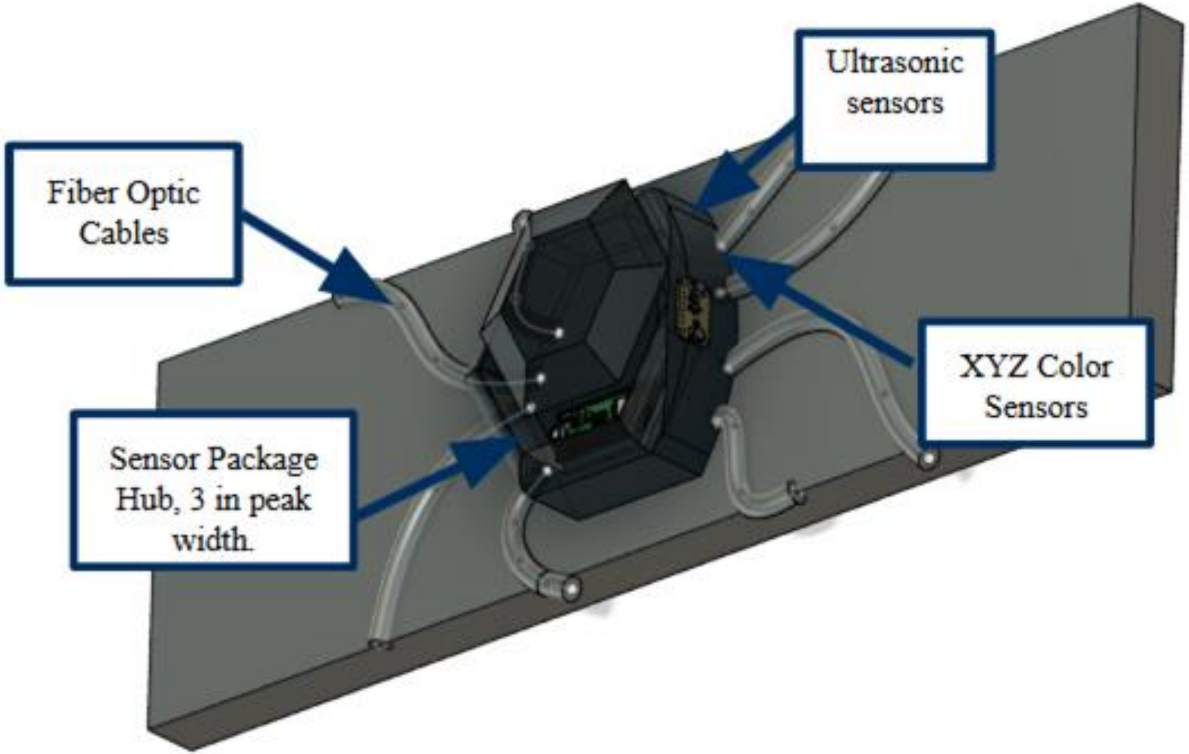
- Triple- integrated testing
- Refinement of integrated hub
- Creation of a lunar habitat-like testbed
- Testing and validation in a lunar habitat-like testbed

# Questions?

# Questions?



| Estimate Type per one package | FBG sensors | Ultrasonic/ Piezoelectric Sensor | Colorimetric Sensing | Externals (casing, peripheral components) | Total, or highest overall required |
|---|---|---|---|---|---|
| Mass | 30 grams | 5 grams | 40 grams | 75 grams | 149 grams |
| Amps | 500mA | 0.05mA | 0.024 mA | 18-30mA | 50mA |
| Voltage | 5V | 3.3V-5V | 3.3V-5V | 1.8V-5.5V | 5.5V |
| Cost | $300 | $4 | $25 | $40 | $369 |

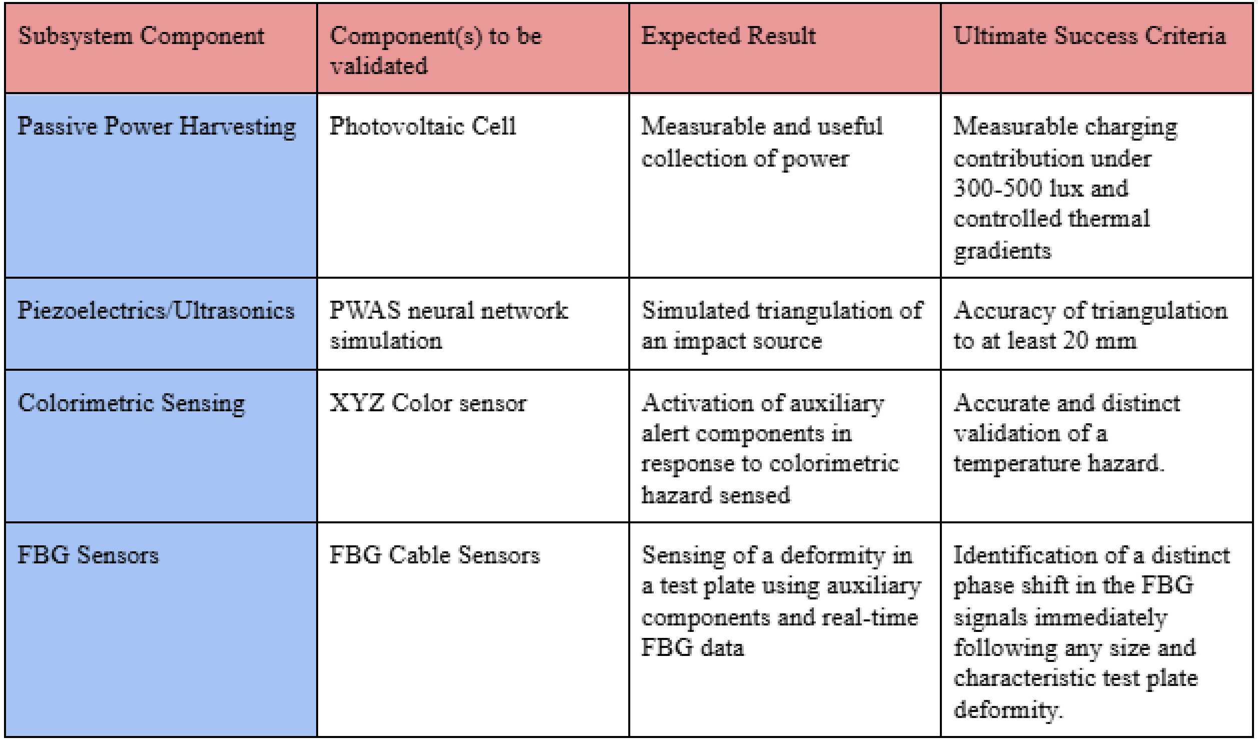


Fiber Optic Cables

Ultrasonic sensors

XYZ Color Sensors

Sensor Package Hub, 3 in peak width.



| Subsystem Component | Component(s) to be validated | Expected Result | Ultimate Success Criteria |
|---|---|---|---|
| Passive Power Harvesting | Photovoltaic Cell | Measurable and useful collection of power | Measurable charging contribution under 300-500 lux and controlled thermal gradients |
| Piezoelectrics/Ultrasonics | PWAS neural network simulation | Simulated triangulation of an impact source | Accuracy of triangulation to at least 20 mm |
| Colorimetric Sensing | XYZ Color sensor | Activation of auxiliary alert components in response to colorimetric hazard sensed | Accurate and distinct validation of a temperature hazard. |
| FBG Sensors | FBG Cable Sensors | Sensing of a deformity in a test plate using auxiliary components and real-time FBG data | Identification of a distinct phase shift in the FBG signals immediately following any size and characteristic test plate deformity. |

# Sensor Package for Internal Detection In Extraterrestrial Regions (SPIDER)

*New Mexico Institute of Mining and Technology*

## OBJECTIVE

Develop a wall-mounted sensor package to reduce weight and improve sensitivity of lunar base structural health monitoring systems

## Technical Approach

- Design a prototype sensor housing node containing multiple sensing modalities
- Develop signal processing hardware and algorithms to identify critical structural or environmental damage
- Validate health monitoring capabilities through simulation and experimentation

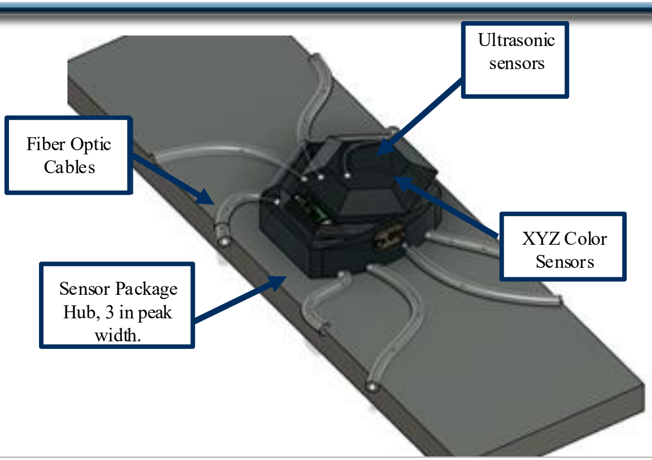


**Fig 2:** Prototype SPIDER Hub

## Key Design Details & Innovations of the Concept

Innovation: reduced-size wall sensing nodes, cross-validated through 3 modalities to detect radiation, temperature, and structural damage

### Bio-inspired design

Sensing design inspired by spider in a web

### Ultrasonic

Sensing vibrations on thin wires across lunar wall substrate

### Colorimetric paint

Radiochromic/thermochromic color sensing

### FBGs

Web of dispersed optical cables

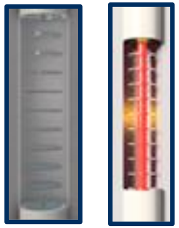
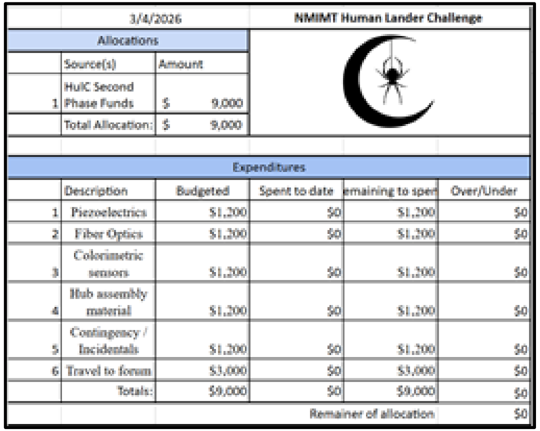


**Fig 1: Fiber-Bragg Grating Sensor**



| | 3/4/2026 | | NMIMT Human Lander Challenge |
|---|---|---|---|
| | Allocations | | |
| | Source(s) | Amount | |
| 1 | HuIC Second Phase Funds | $ 9,000 | |
| | Total Allocation: | $ 9,000 | |

| | Expenditures | | | | |
|---|---|---|---|---|---|
| | Description | Budgeted | Spent to date | emaining to sper | Over/Under |
| 1 | Piezoelectrics | $1,200 | $0 | $1,200 | $0 |
| 2 | Fiber Optics | $1,200 | $0 | $1,200 | $0 |
| 3 | Colorimetric sensors | $1,200 | $0 | $1,200 | $0 |
| 4 | Hub assembly material | $1,200 | $0 | $1,200 | $0 |
| 5 | Contingency / Incidentals | $1,200 | $0 | $1,200 | $0 |
| 6 | Travel to forum | $3,000 | $0 | $3,000 | $0 |
| | Totals: | $9,000 | $0 | $9,000 | $0 |
| | | | | Remainer of allocation | $0 |

**Fig 3: Budget Calculations**

Summer 2026, TRL 4:
Conclusion of HuLC

Year 0 of adoption, TRL 4-5:
Lab environment system validation

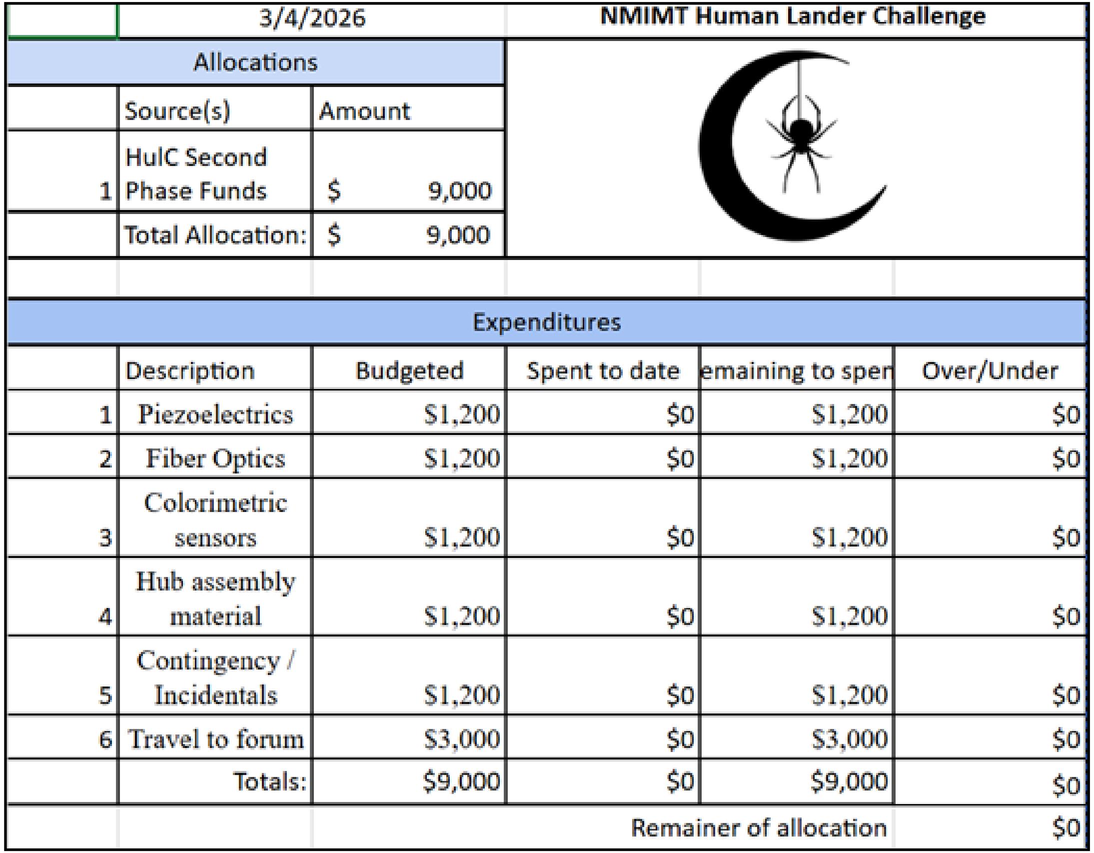
Year 1-2 of adoption, TRL 5-6:
High-fidelity habitat analog testing

Year 2-4 of adoption TRL 6-7:
Operational environment demonstration

Year 4-6 of adoption TRL 7-8:
Qualification of final design

Year 6-8 of adoption TRL 8-9:
Success in lunar environment

# Appendices



3/4/2026

**NMIMT Human Lander Challenge**

| Allocations | | |
|---|---|---|
| | Source(s) | Amount |
| 1 | HulC Second Phase Funds | $ 9,000 |
| | Total Allocation: | $ 9,000 |

| Expenditures | | | | | |
|---|---|---|---|---|---|
| | Description | Budgeted | Spent to date | emaining to spen | Over/Under |
| 1 | Piezoelectrics | $1,200 | $0 | $1,200 | $0 |
| 2 | Fiber Optics | $1,200 | $0 | $1,200 | $0 |
| 3 | Colorimetric sensors | $1,200 | $0 | $1,200 | $0 |
| 4 | Hub assembly material | $1,200 | $0 | $1,200 | $0 |
| 5 | Contingency / Incidentals | $1,200 | $0 | $1,200 | $0 |
| 6 | Travel to forum | $3,000 | $0 | $3,000 | $0 |
| | Totals: | $9,000 | $0 | $9,000 | $0 |
| | | Remainer of allocation | | | $0 |

# References

National Space Policy Council. "A Sustained Lunar Presence." NASA, April 2020. https://www.nasa.gov/wp-content/uploads/2020/08/a_sustained_lunar_presence_nspc_report4220final.pdf

Rojdev, K., et al. "Structural Material Options for a Lunar Habitat." NASA Technical Reports Server, 2009. https://ntrs.nasa.gov/api/citations/20090029953/downloads/20090029953.pdf

Xiao, F., Hulsey, J.L., Balasubramanian, R. "Fiber optic health monitoring and temperature behavior of bridge in cold region." *Structural Control and Health Monitoring*, 24(11), e2020, 2017. https://doi.org/10.1002/stc.2020

Juwet, M., et al. "Fiber Bragg Grating sensors in space environments." *npj Microgravity*, 2024. https://link.springer.com/article/10.1007/s44461-025-00003-6

"Recent Advances in Colorimetric Sensors for Environmental Monitoring." *ACS Nano*, American Chemical Society, 2020. https://pubs.acs.org/doi/10.1021/acsnano.0c05916

"Recent Developments in Colorimetric Detection of Environmental Contaminants." *New Journal of Chemistry*, Royal Society of Chemistry, 2016. https://pubs.rsc.org/en/content/articlelanding/2016/nj/c6nj02092e

"Advances in Fiber Optic Sensor Systems for Environmental Monitoring." *Sensors and Actuators A: Physical*, ScienceDirect, 2025. https://www.sciencedirect.com/science/article/pii/S1350448725001799

"Nanopigment Sensor Tracks pH Changes in Ten Seconds." *Phys.org*, February 2026. https://phys.org/news/2026-02-nanopigment-sensor-tracks-ph-ten.html

# References

Texas Instruments. "Op Amp Precision Design Guide." Application Report SBOA567.
https://www.ti.com/lit/ab/sboa567/sboa567.pdf

A. Bulletti, E. M. Merlo, and L. Capineri, "Analysis of the accuracy in impact localization using piezoelectric sensors for Structural Health Monitoring with multichannel real-time electronics," 2020 IEEE 7th International Workshop on Metrology for AeroSpace (MetroAeroSpace), Pisa, Italy, 2020, pp. 480–484, doi: 10.1109/MetroAeroSpace48742.2020.9160275.

NASA. "Weather on the Moon." NASA Science, National Aeronautics and Space Administration.
https://science.nasa.gov/moon/weather-on-the-moon/

NASA. "Lunar Planetary Wireless Network Spec Sheet." National Aeronautics and Space Administration, Sept. 2024.
https://www.nasa.gov/wp-content/uploads/2024/09/18-lunar-planetary-wireless-network-spec-sheet-508.pdf?emrc=da7acc

NASA. "Advanced Modular Power Systems for Space Applications." NASA TechPort, Project 102925.
https://techport.nasa.gov/projects/102925

Kreuzer, M. (n.d.). *Strain measurement with fiber Bragg grating sensors*. HBM GmbH.
https://public.websites.umich.edu/~bkerkez/courses/cee575/Handouts/7FBGS_StrainMeasurement_mo.pdf