Lunar Night Survivability of Cryocooled Instruments Using PALETTE Thermally-Switched Enclosures

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ABSTRACT

The Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) project is developing improved thermal management techniques that will allow cryocooled and/or ambient temperature science payloads to survive multiple lunar day/night cycles. The targeted science payloads are those slated to fly on upcoming commercial lunar payload services (CLPS) landers, none of which will likely be able to survive the first lunar night. This paper will provide a status update on those techniques, which include thermally-switched enclosures supported by Vectran tension cables, 3D-printable parabolic reflector radiators (PRRs), "spacerless" MLI whose layers hang from the Vectran cables, advanced thermal isolators using optimized polymeric (and Ti64) designs, and a few others. The paper will include the latest test data from the PALETTE project, which is a three-year effort (initiated in April 2020) funded by the NASA Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program.

INTRODUCTION

The focus by NASA on robotic exploration in extreme environments has highlighted a need for improved thermal capabilities to ensure science instrument survivability without the use of radioisotopes. Two years ago, JPL started work on the three-year Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) project, the intent of which was to develop an underlying architecture composed of high TRL (Technology Rediness Level) thermal "toolbox" elements that engineers could use to develop instrument designs in extreme environments. The solution to the problem depicted in Figure 1 is the thermally-switched, dual enclosure, ultra-isolative architecture depicted in Figure 2. Also listed in Figure 2 are the eight research tasks. This paper reports on PALETTE project status through year two. A final section describes mission infusion opportunities, one of which – *the Farside Seismic Suite (FSS) to Schrodinger Basin on CLPS CP-12* – is already underway. FSS began work in July 2021 and launch is planned for late 2024.

OBJECTIVES

PALETTE has four primary goals, six stretch goals, and eight project objectives as indicated in Figure 3. The primary goals and first four project objectives map directly to Tasks 1-4. The stretch goals and second four project objectives map directly to Tasks 5-8. Also depicted in Figure 3 are graphical representations of the PALETTE Primary/Backup thermal architectures (PTA/BTA, respectively). Additional details on these two architectures are provided below.

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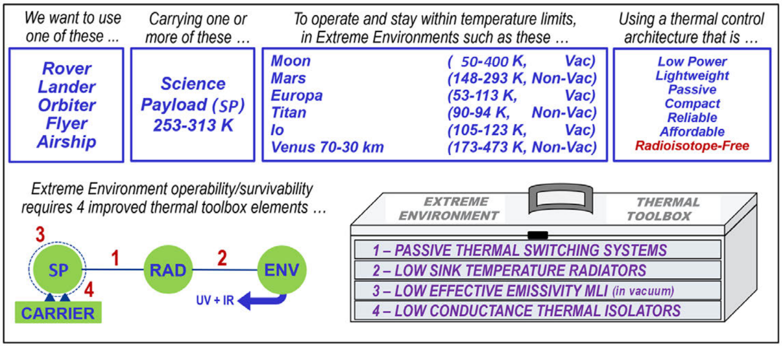
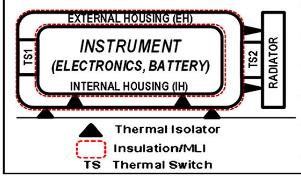


Figure 1. Underlying Problem Addressed by the PALETTE Project

PALETTE Thermal Architecture



PALETTE Research Tasks 1-8

Raise TRL via Design/Build/Test	Raise TRL via Analysis/Study
T1: Dual thermal switch instrument enclosures	T5: Gimbaled IR cameras for lunar water search
T2: Affordable parabolic reflector radiators (PRRs)	T6: Combined thermal switching/transport/storage
T3: "Spacerless" MLI with e* << 0.01	T7: Low heat loss feed-through architectures
T4: Thermal ultra-isolators w/ G << 0.001 W/K	T8: Scaling/extensibility/planetary use

Figure 2. Thermal Architecture and Task Structure of the PALETTE Project

Technology Goals	
Primary Goal-1	Develop better performing instrument thermal *enclosure* technology
Primary Goal-2	Develop affordable ambient parabolic reflector *radiator* (PRR) technology
Primary Goal-3	Develop better performing multilayer *insulation* (MLI) technology
Primary Goal-4	Develop better performing thermal *isolator* technology
Stretch Goal-1	Develop *gimbal* instrument architectures using bulk metallic glass (BMG) actuator tech
Stretch Goal-2	Develop *thermal switching* device technology applicable to compact instruments
Stretch Goal-3	Develop *thermal transport* device technology applicable to compact instruments
Stretch Goal-4	Develop *thermal storage* device technology applicable to compact instruments
Stretch Goal-5	Develop *deployable* device/antennae technology applicable to compact instruments
Stretch Goal-6	Develop low heat loss *feed-through* technology applicable to compact instruments
Project Objectives	
Objective-1	Develop/qualify *dual thermally-switched enclosures*; achieve TRL 5/6
Objective-2	Develop/demonstrate low cost ambient *parabolic reflector radiators*; achieve TRL 5/6
Objective-3	Develop/demonstrate *"spacerless" multilayer insulation* (MLI); achieve TRL 5/6
Objective-4	Develop/demonstrate *advanced polymer-based thermal isolators*; achieve TRL 5/6
Objective-5	Analytically evaluate multi-axis bulk metallic glass (BMG)-actuated *gimbal concepts*
Objective-6	Analytically evaluate *thermal switch/transport/storage concepts*
Objective-7	Analytically evaluate *low heat loss feed-through concepts*
Objective-8	Analytically evaluate thermal toolbox *scalability/extensibility/planetary uses*

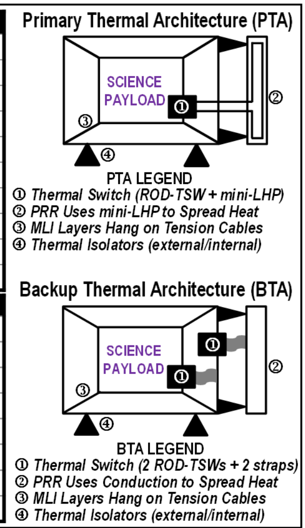


Figure 3. Technology Goals/Objectives and Key Architectures Associated with the PALETTE Project

The primary and backup thermal architectures (PTA & BTA) utilize dual nested enclosures (or housings), wherein the internal housing (IH) is supported from the External Housing (EH) by polymer tension cables. Hanging from the tension cables, without any internal spacers (hence the moniker "spacerless" MLI), are layers of double aluminized Mylar. Isolating the EH from the carrier (and from external components) are low conductance thermal isolators. The PTA uses a reverse-operation DTE thermal switch (ROD-TSW[1,2]) in series with a propylene mini-loop heat pipe (LHP) while the BTA uses a pair of ROD-TSWs (and thermal straps) in series. In the PTA, radiator heat spreading is aided by mini-LHP condensation, but the BTA relies only on conduction. And because the PTA has just two small diameter transport lines penetrating the spacerless MLI, and because it uses highly efficient two-phase heat transfer to spread heat out on the radiator, the PTA will always be the better performing architecture. In fact, because the PTA with just conventional (not spacerless) MLI significantly outperformed the Task 1A goal metric, BTA testing was omitted.

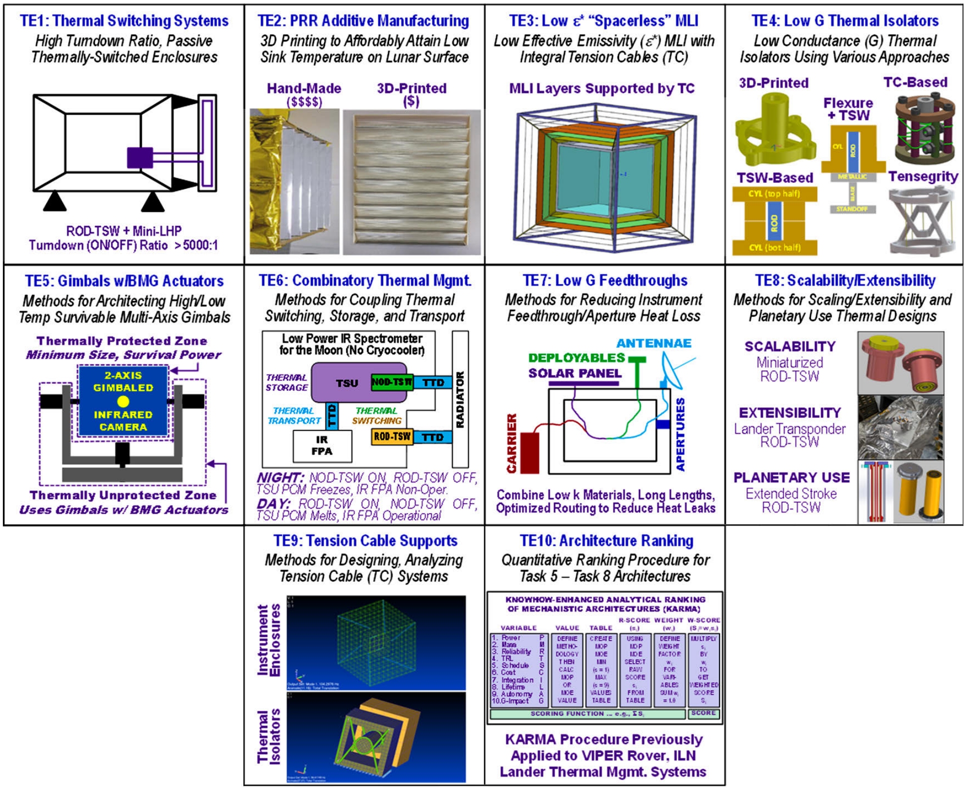


Figure 4. Technical Elements Associated with the PALETTE Project

TECHNOLOGIES

One of the first NASA GCD project activities involves deconstructing a given project technology area into its constituent technical elements (TE). The PALETTE project technical elements (TE1-TE10), developed at project outset two years ago, are depicted graphically in Figure 4. NASA's Game Changing Development Program (GCD) uses technical element breakdowns like this to catalog/track technology readiness level (TRL) and technology advancement degree of difficulty (AD_2). From a programmatic connectivity perspective, technical elements TE1-TE4 and TE9 are associated with Tasks 1-4 while technical elements TE5-TE8 and TE10 are associated with Tasks 5-8. In this paper, Figure 4 is intended solely to graphically illustrate the wide spectrum of applicable technologies. Additional descriptive information on each TE is provided later in the paper, but there are three TEs in particular that merit (very brief) additional commentary.

For science payloads in extreme environments, there are three key needs. The system must be able to: (a) support a large mass with the least thermally conductive cross-sectional area to length ratio possible; (b) radiatively isolate that mass to the highest degree possible; and (c) meter heat flow in/out passively based solely on temperature. The PALETTE project, through TE9 (tension cable supports), TE3 (low ε* spacerless MLI), and TE1 (thermal switching systems), respectively, meets those three key needs, and the test data presented herein will show how well.

The next section of the paper describes the performance metrics defined at project outset to evaluate technology development performance. Key Performance Parameters (KPPs) are used by NASA GCD as a scorecard to rate progress. Potential users of PALETTE technologies should be able to assess whether toolbox elements will benefit their prospective instruments based solely on the KPPs. If a measured KPP value misses a target, but analysis shows that a simple fix such as coating exposed PRR surfaces is corrective, small analytical KPP adjustments are acceptable.

Table 1. PALETTE Project KPP Metrics*

Task	KPP Number	KPP	Units	Current	Threshold	Goal
1	KPP1	q_{LOSS}	W/m²	12	6	3
2	KPP2A	T_{SINK}	K	250	225	215
2	KPP2B	$C_{RECURRING}$	$	100K	20K	5K
3	KPP3	e*	-	0.02	0.01	0.005
4	KPP4	G	W/K	0.002	0.001	0.0005

* The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

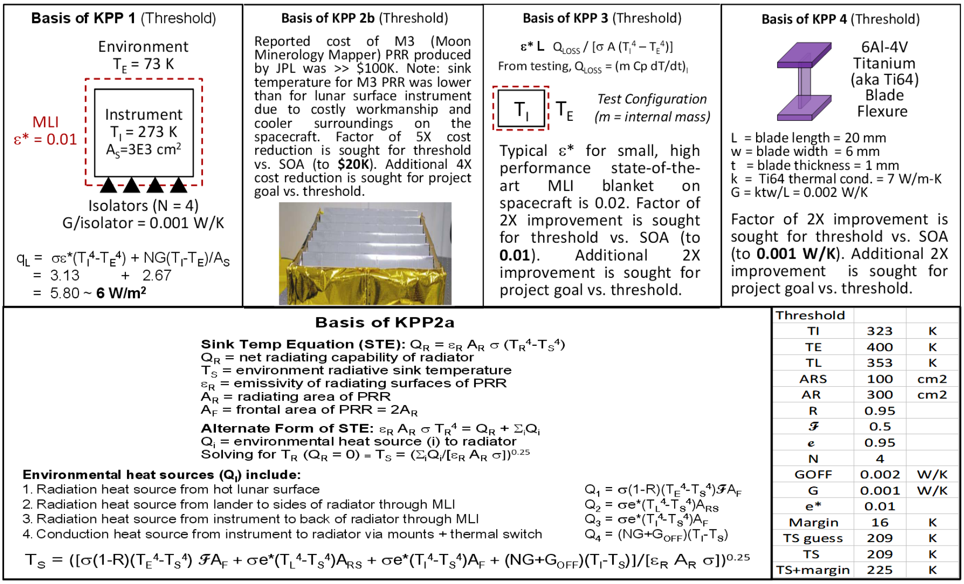


Figure 5. PALETTE Project KPP Threshold Values and Analytical/Anecdotal Bases

METRICS

For PALETTE Tasks 1-4, a total of five key performance parameter (KPP) metrics were identified as listed in Table 1. Three different levels of performance are provided for each KPP: ***(1) Current***, which represents the current state-of-the-art; ***(2) Threshold***, which represents the target level for minimum task/project success; and ***(3) Goal***, which is the target level for full task/project success. Figure 5 illustrates the different analytical or anecdotal bases of Task 1-4 threshold KPP values. At the time this paper was written (May 2022), candidate KPP metrics for Tasks 5-8 had been proposed. The Task 5-8 KPPs proposed by the authors involved architecture effectiveness measures that combined several variables (e.g., power, mass, volume, cost, etc.) together into a form similar to an optimization problem objective function. While that format is consistent with the analytical ranking of architectures planned for Tasks 5-8, it was not thought (by NASA GCD personnel) to be readily applicable to potential users. While this paper will not provide analytical results for Tasks 5-8 as those results are not yet available, it is unlikely that KPPs will be used as a means to assess analysis/study task progress and/or success.

While Figure 5 indicates the analytical bases for PALETTE KPP threshold values, the equations displayed within Figure 5 can also be used to calculate KPP goal values. And any KPP goal value calculated in this way will also be self-consistent with the other KPP goal values. For example, with regard to KPP1, by substituting the KPP3 ε* goal value of 0.005 and the KPP4 (per-isolator) G goal value of 0.0005 W/K into the equation at the upper left of Figure 5, you will obtain the KPP1 q_{LOSS} goal value of 3 W/m². This approach also applies to the KPP2A goal value of 225 K. The next eight sections of the paper present very brief summaries of Task 1-4 design/build/test results and Task 5-8 analysis/study progress on a task-by-task basis.

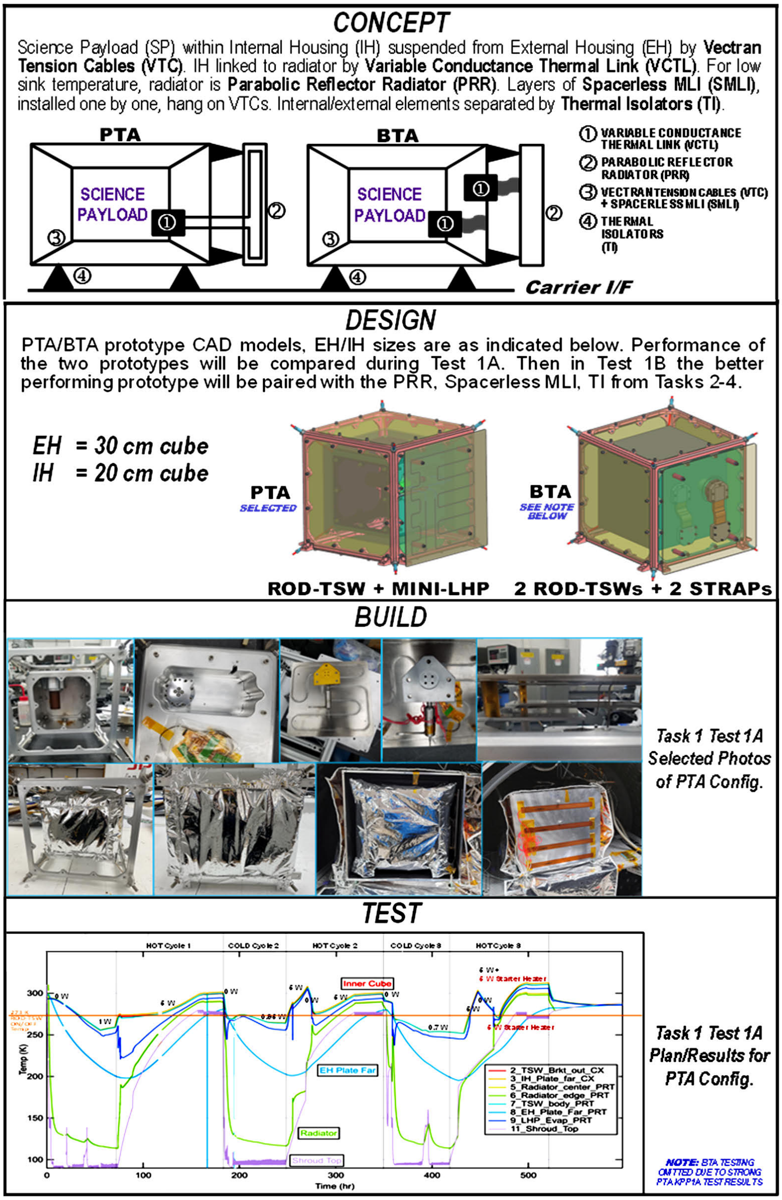


Figure 6. Task 1: Design, build, and test a dual nested thermally-switched enclosure system with Vectran tension cable (VTC) supports that can limit lunar night heat loss flux (q_{LOSS}) 3-6 W/m^2 or lower.

TASK 1: THERMALLY-SWITCHED ENCLOSURES

As indicated in the Figure 6 caption, the objective of Task 1 was to design, build, and test a dual nested thermally-switched enclosure system with Vectran Tension Cable (VTC) supports that can limit lunar night heat loss flux (q_{LOSS}) to 3-6 W/m^2 or lower. The results for Task 1 Test 1A, which used conventional MLI, indicate that this thermal enclosure was able to reduce q_{LOSS} to 1.3 W/m^2, which significantly outperformed the KPP1 target value in Table 1 of 3 W/m^2. The upcoming Task 1 Test 1B (to occur in July 2022) will use Task 3 spacerless MLI, Task 4 thermal isolators, but not a Task 2 PRR. This test, which will involve a pre-vibe Thermal Vacuum Test (TVAC), vibe to GEVS[3] protoflight levels, and a post-vibe TVAC, should show a KPP1 value of less than 1 W/m^2.

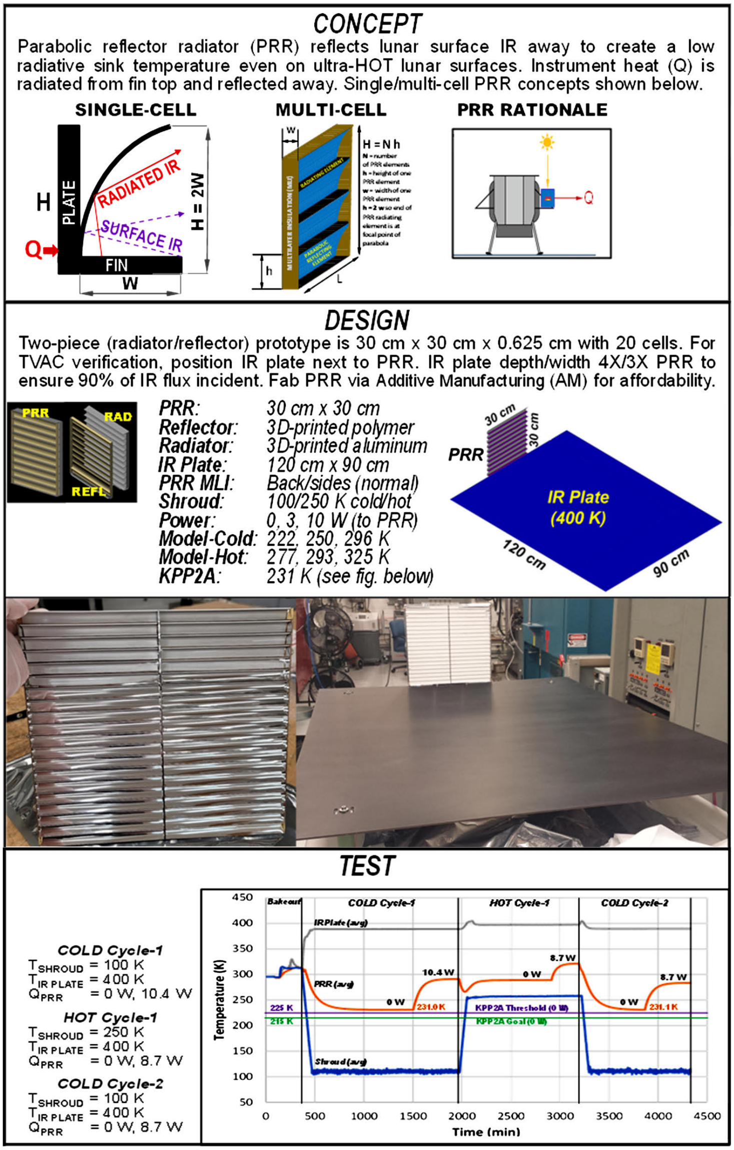


Figure 7. Task 2: Design, build and test 3D printable parabolic reflector (PRR) with a recurring cost of \$5-20 K or less that can reduce the lunar surface sink temp to 215-225 K or lower.

TASK 2: PARABOLIC REFLECTOR RADIATORS

As indicated in the Figure 7 caption, the objective of Task 2 was to design, build, and test a 3D-printable parabolic reflector radiator (PRR) with a recurring cost of \$5-20 K or less than can reduce the lunar surface sink temperature to 215-225 K or lower. The result of the Task 2 test is a KPP2A sink temperature of 231 K, which is lower than the state-of-the-art value in Table 1 of 250 K, but is higher than the threshold value of 225 K. The KPP2B recurring cost of \$7.4 K is less than the Table 1 threshold value of \$20 K. Although difficult to see in the Figure 7 photo, unreflective edges (of the vertical stiffening ribs) and small open gaps are two items that, when corrected, would reduce the KPP2A test value of 231 K to the 225 K threshold level.

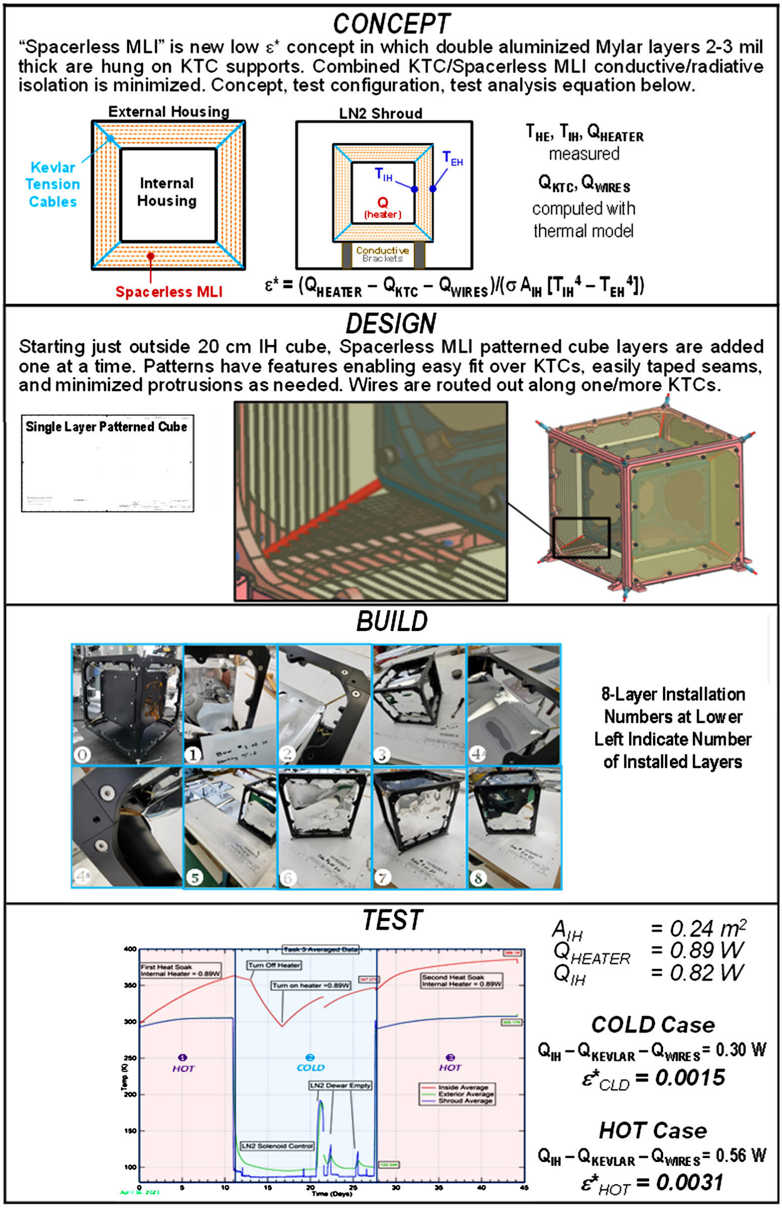
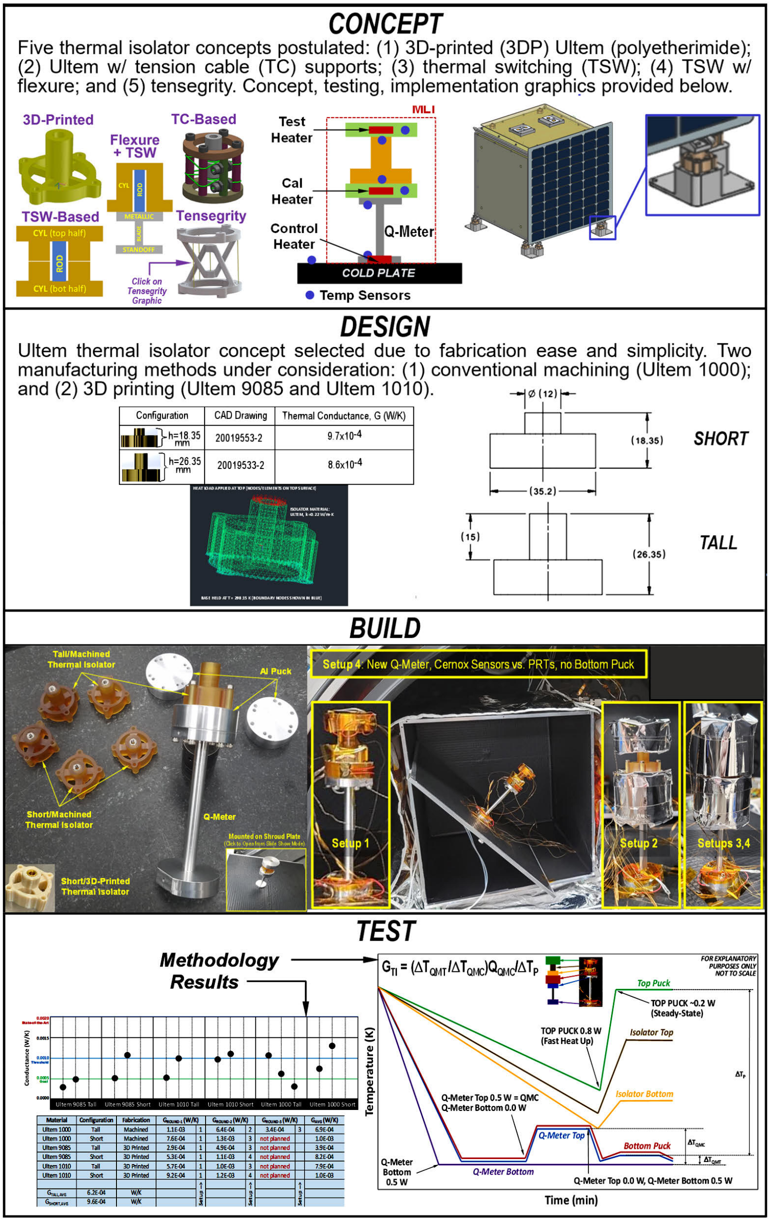


Figure 8. Task 3: Design, build, test 'spacerless' MLI system that works with the tension cable supports for the Task 1 dual enclosure architecture that can reduce MLI effective emissivity (ε*) to 0.005-0.01 or lower.

TASK 3: SPACERLESS MLI

As indicated in the caption of Figure 8, the objective of Task 3 was to design, build, and test a "spacerless" MLI system that works with the tension cable supports for the Task 1 dual enclosure architecture that can reduce MLI effective emissivity (ε*) to 0.005-0.01 or lower. At the time of this test, PALETTE was using Kevlar instead of Vectran as the tension cable material. That material choice, though, does not affect the results. The spacerless MLI ε* was determined to be 0.0015 for the COLD case and 0.0031 for the HOT case. The KPP3 goal value for this task from Table 1 was an ε* value of 0.005, thus the measured performance was at least three times better than the goal value.



Configuration	CAD Drawing	Thermal Conductance, G (W/K)
h=18.35 mm	20019553-2	9.7×10^{-4}
h=26.35 mm	20019533-2	8.6×10^{-4}

Material	Configuration	Fabrication	$G_{ROUND-1}$ (W/K)	Setup	$G_{ROUND-2}$ (W/K)	Setup	$G_{ROUND-3}$ (W/K)	Setup	G_{AVG} (W/K)
Ultem 1000	Tall	Machined	1.1E-03	1	6.4E-04	2	3.4E-04	3	6.9E-04
Ultem 1000	Short	Machined	7.6E-04	1	1.3E-03	3	not planned		1.0E-03
Ultem 9085	Tall	3D Printed	2.9E-04	1	4.9E-04	3	not planned		3.9E-04
Ultem 9085	Short	3D Printed	5.3E-04	1	1.1E-03	4	not planned		8.2E-04
Ultem 1010	Tall	3D Printed	5.7E-04	1	1.0E-03	3	not planned		7.9E-04
Ultem 1010	Short	3D Printed	9.2E-04	1	1.2E-03	4	not planned		1.0E-03
$G_{TALL,AVG}$	6.2E-04	W/K							
$G_{SHORT,AVG}$	9.6E-04	W/K							

Figure 9. Task 4: Design, build, and test a new thermal isolator using low k polymers or other methods that can reduce per thermal Isolator conductance (G) to 0.0005-0.001 W/K or lower.

TASK 4: LOW G THERMAL ISOLATORS

As indicated in the caption of Figure 9, the objective of Task 4 was to design, build, and test a new thermal isolator using low thermal conductivity (k) polymers or other methods that can reduce the per thermal isolator conductance (G) to 0.0005-0.001 W/K or lower. Of the five options shown under the Concept quadrant, the 3D-printed polymer design was selected. Two printable polymers (Ultem 9085, 1010), one machinable polymer (Ultem 1000), and two sizes (short, tall) were tested. Two or three tests for each combination were run. The measured G value averages were 6.2E-4/9.6E-4 W/K for the tall/short versions, which met the threshold KPP4 value of 0.001 W/K in Table 1.

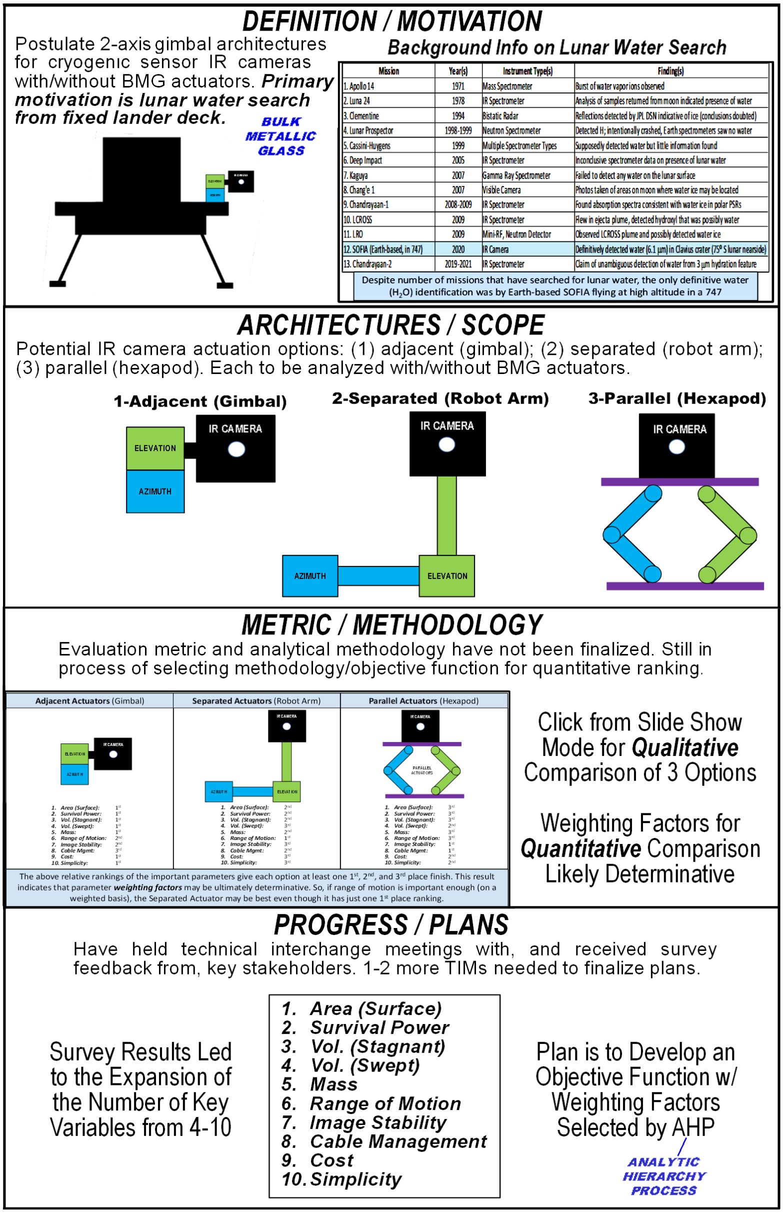


Figure 10. Task 5: Postulate architectures for future multi-axis gimbaled IR camera instruments with or without BMG actuators. Develop methodology to rank architectures and identify highest ranked architecture.

TASK 5: GIMBALED IR CAMERAS

As indicated in the caption of Figure 10, the objective of Task 5 is to postulate architectures for future multi-axis gimbaled IR camera instruments with/without BMG (bulk metallic glass) actuators, develop a method to rank the architectures, and identify the highest ranked architecture. The motivation is identifying lunar water from fixed lander decks. IR camera actuation options include adjacent, separated, and parallel. Thus, with or without BMG actuators, there are six architectures to rank. The ranking method will use the parameter list shown with survey-generated weights and an appropriate scoring method.[4,5] Parameter weights are likely determinative, thus additional survey data is needed in order to proceed.

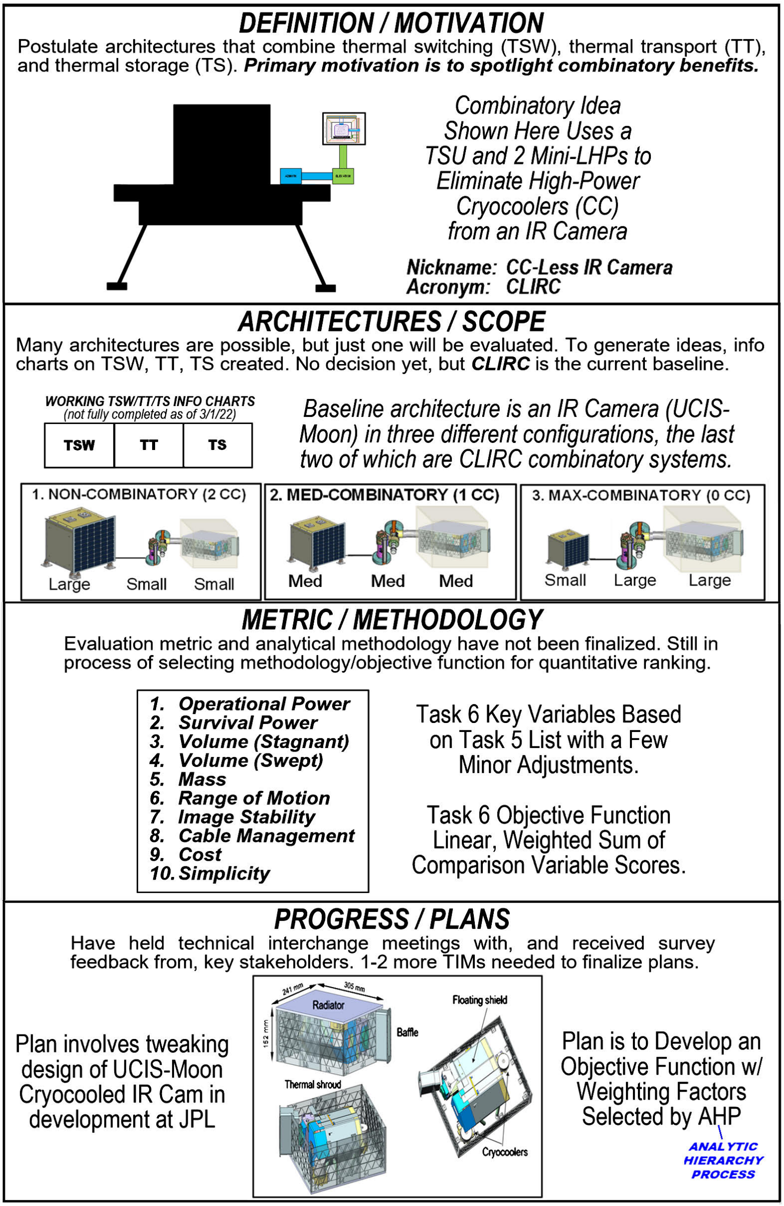


Figure 11. Task 6: Postulate architectures that could combine thermal switching, thermal transport, and thermal storage. Develop methodology to rank architectures and identify highest ranked architecture.

TASK 6: COMBINATORY THERMAL SYSTEMS

As indicated in the caption of Figure 11, the objective of Task 6 is to postulate architectures that can combine thermal switching/transport/storage, develop a method to rank the architectures, and identify the highest ranked architecture. The motivation is simply to spotlight the benefits of combinatory systems. The combinatory idea shown uses a Thermal Storage Unit (TSU) and two mini-LHPs to remove cryocoolers (CC) and their power needs from an IR camera. The ranking method will use the parameter list shown with survey-generated weights and an appropriate scoring method. The three architectures to be ranked include non-combinatory (2 CCs), medium combinatory (1 CC), and a maximum combinatory (no CCs).

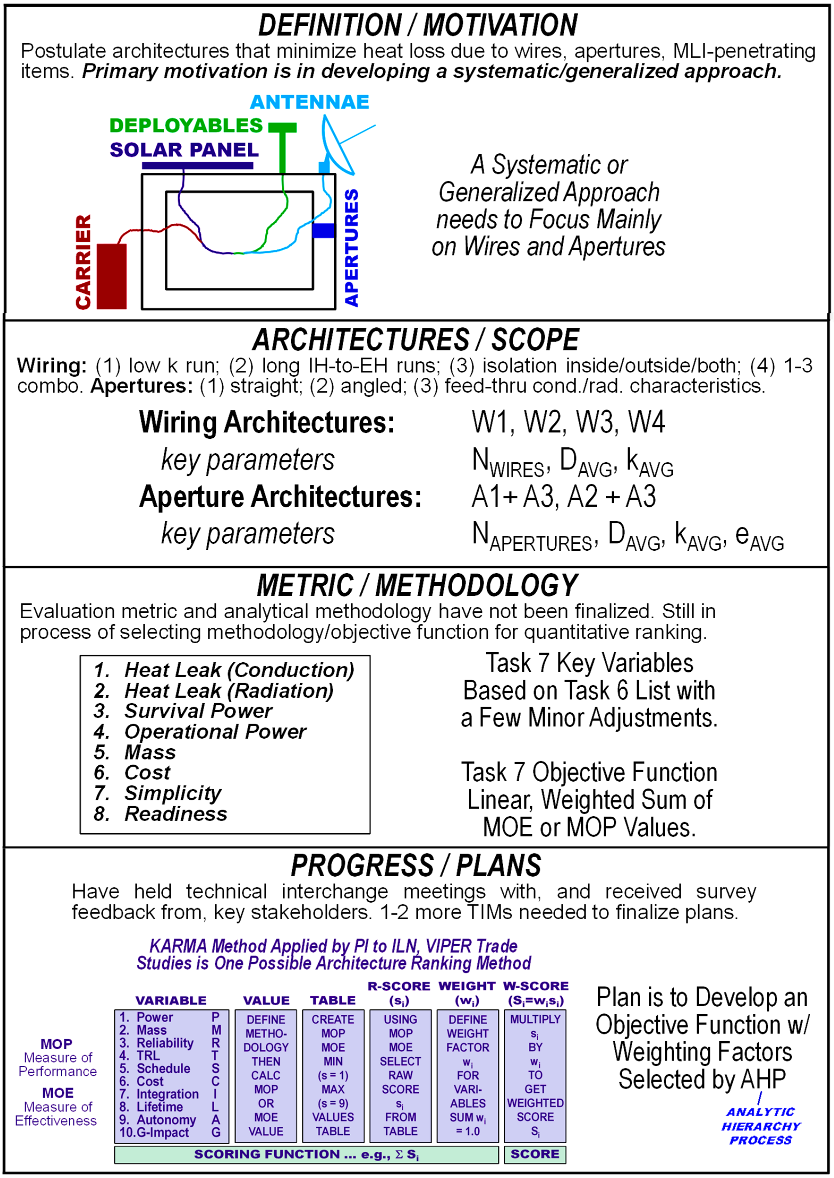


Figure 12. Task 7: Postulate architectures that can reduce the heat loss due to wires, apertures, antennae, deployables. Develop methodology to rank architectures and identify highest ranked architecture.

TASK 7: LOW HEAT LOSS FEED-THROUGHS

As indicated in the caption of Figure 12, the objective of Task 7 was to postulate architectures that reduce the heat loss due to wires/apertures/antennae/deployables, develop a method to rank the architectures, and identify the highest ranked architecture. The motivation is in developing a systematic/generalized approach. As indicated, there are four wiring architectures and two aperture architectures. The ranking method will use the parameter list shown with survey-generated weights and an appropriate scoring method. The parameters differentiating the wiring/aperture architectures are so noted. The objective function chosen will be a linear weighted sum of Measure of Effectiveness/Measure of Performance (MOE/MOP) based scores.

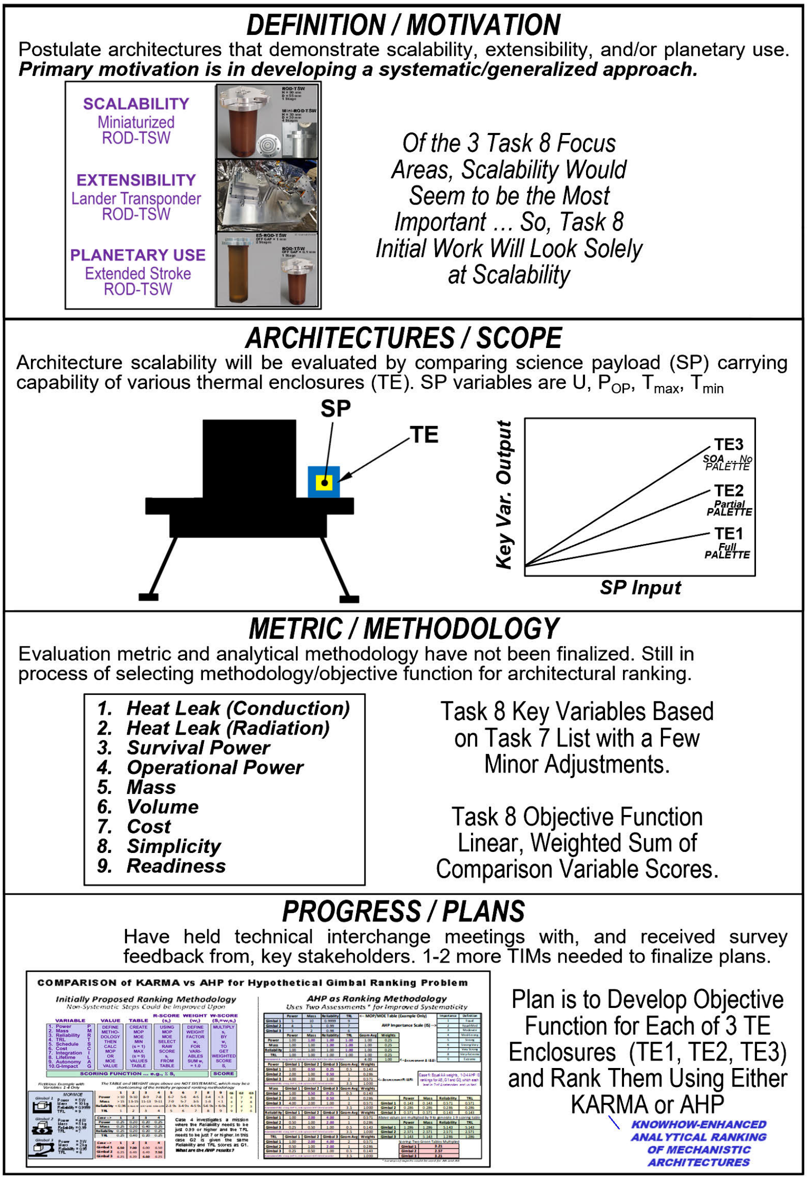


Figure 13. Task 8: Postulate architectures for key instruments that allow scalability, extensibility, planetary use to be assessed. Develop methodology to rank architectures and identify highest ranked architecture.

TASK 8: SCALABILITY, EXTENSIBILITY, AND PLANETARY USE

As indicated in the caption of Figure 13, the objective of Task 8 was to postulate architectures for key instruments that allow scalability, extensibility, and planetary use to be analytically assessed. The motivation is in developing a systematic/generalized approach. As indicated, the analysis/study task will focus primarily on scalability related to the packaging of science payloads (SP) in PALETTE enclosures. The ranking method will use the parameter list shown with survey-generated weights and an appropriate scoring method. The SP thermal enclosures (TE1, TE2, TE3) are differentiated based on U, P_{OP}, T_{MAX}, and T_{MIN}. The objective function will be a linear weighted sum of MOE/MOP-based scores.

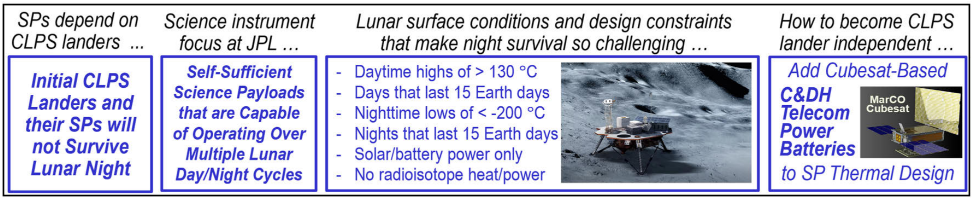


Figure 14. JPL Strategy to Fly CLPS Lander-Independent Science Payloads (SPs

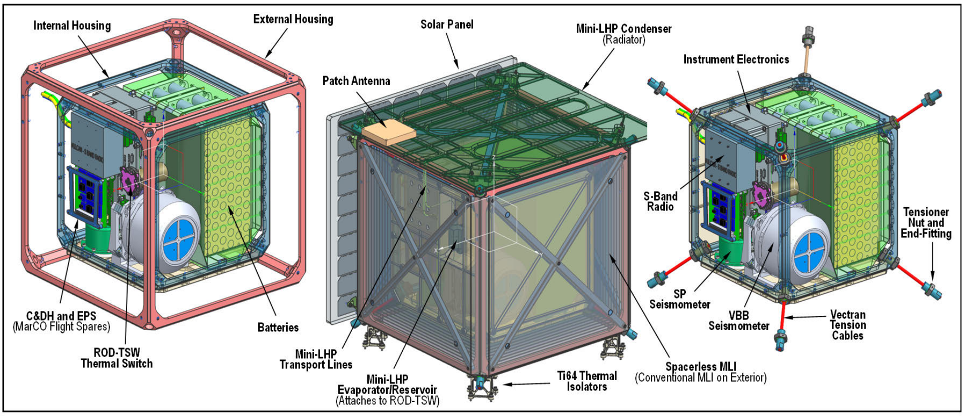


Figure 15. Farside Seismic Suite (FSS) Implementation of PALETTE Technologies

NOTE: values shown are conservative, but not margined

	Medium	Small-1	Small-2
Power (day/night)	**20 W / 5.0 W**	**11 W / 1.2 W**	**11 W / 2.5 W**
Cube Dim. (Env/Ext/Int)	50/40/30 cm	40/30/20 cm	40/30/20 cm
Total Mass (no payload)	**35.2 kg**	**15.9 kg**	**20.7 kg**
CDH	0.2 kg	0.2 kg	0.2 kg
Power	20.0 kg	5.9 kg	10.8 kg
Batteries	18.5 kg	4.4 kg	9.3 kg
SA/EPS	1.5 kg	1.5 kg	1.5 kg
Comm	0.7 kg	0.7 kg	0.7 kg
Structure	10.8 kg	5.5 kg	5.5 kg
Thermal	3.5 kg	3.5 kg	3.5 kg
External Volume	64U	27U	27U
Payload Volume*	**10-15U**	**3-5U**	**2-3U**

** Payload needs to provide its own electronics to interface with C&DH. Packaging of battery, C&DH, radio, ROD-TSW, and mini-LHP modestly adjustable to fit various payload shapes (accommodatable payload volume range indicated above). Medium configuration is essentially the FSS flight unit w/o seismometers and interface electronics. External booms and/or deployables as well as internal-to-external apertures can be accommodated with additional design effort and could reduce nighttime power due to higher parasitic loads.*

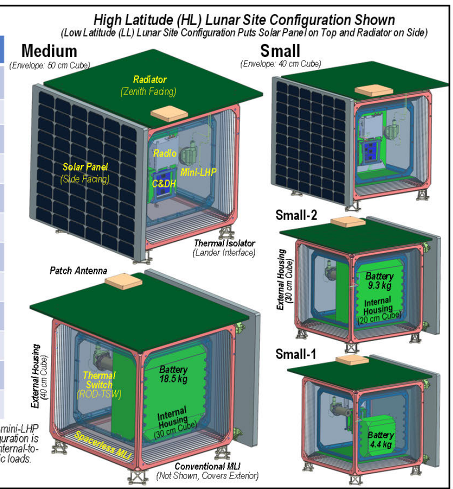


Figure 16. PALETTE Thermal Packaging for Future (Arbitrary) Science Payload (SP) Concepts

MISSION INFUSION

The goal of any NASA GCD project is to infuse the technologies into future missions. For PALETTE, that process has been unusually rapid. In June 2021, the Farside Seismic Suite (FSS) was selected to fly on a NASA Commercial Lunar Payload Services (CLPS) mission (CP-12) to Schrodinger Basin. A second opportunity involves arbitrary science payloads (SP) as part of future lunar lander opportunities. A third opportunity involves the UC Berkeley-led Lunar Surface Electromagnetics Experiment (LuSEE)-night mission. Lastly, JPL is a developing the ARTEMIS-T/M vector helium magnetometer (VHM) instrument. All four opportunities couple PALETTE technology with Mars Cube One (MarCO) cubesat-based C&DH, telecom, solar power, and batteries using the strategy described graphically in Figure 14. CAD layouts for FSS, the SP concept, and the ARTEMIS-T/M test system are provided in Figures 15-17. No figure is included for LuSEE-night.

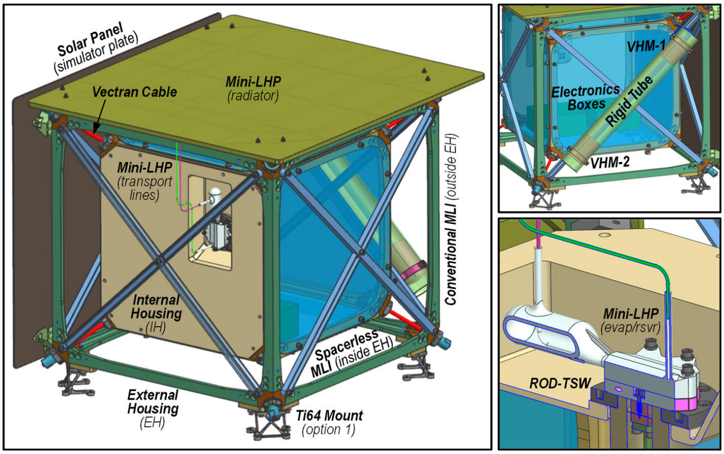


Figure 17. JPL ARTEMIS-T/M TVAC Test Implementation of PALETTE Technologies

CONCLUSION

Through the NASA GCD-funded PALETTE project, JPL is developing new thermal toolbox elements that will enable future lunar/planetary instruments to operate in extreme environments. The new thermal toolbox elements include: (1) dual thermally-switched enclosures; (2) low sink temperature (T_{SINK}) parabolic reflector radiators (PRRs); (3) low effective emissivity (ε*) "spacerless" MLI; and (4) low conductance (G) thermal isolators. JPL is currently working to incorporate those features into lunar instruments that will survive for multiple day/night cycles.

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REFERENCES

1. Bugby, D., Rivera, J., and Britton, S., "Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) Project Year One Results," 2021 ICES Conf., ICES-2021-409, July 2021.
2. Bugby, D. and Rivera, J., "High Performance Thermal Switch for Lunar and Planetary Extreme Environments," 2020 ICES Conference, ICES-2020-145, July 2020.
3. *General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects*, GSFC-STD-7000A, NASA Goddard Space Flight Center, Greenbelt, MD, Revalidation date: 4/22/2019.
4. Richardson, T., and Jan, D., "A Trade-off Study of the Spacecraft Carbon Dioxide Management System using the Analytical Hierarchy Process," 2018 ICES Conf., ICES-2018-332, July 2018.
5. Bugby, D., Farmer, J., et al., "Two-Phase Thermal Switching System for a Small, Extended Duration Lunar Surface Science Platform," 2010 SPESIF Conf., JHU-APL, MD, February 2019.