Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) Project Year One Results

David C. Bugby[1] and Jose G. Rivera[2]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 91109, USA

Shawn R. Britton[3]
NASA Langley Research Center, Hampton, Virginia, 23681, USA

This paper summarizes the technology development progress made during year one of the three-year JPL PALETTE project, which is funded by the NASA STMD Game Changing Development (GCD) Program. The project goal is to ensure that a full "palette" of flight-ready (high TRL) thermal "toolbox" elements is available so that engineers can create passive, ultra-isolative thermal designs for science instruments on a variety of carriers in lunar/planetary extreme environments. PALETTE is structured to meet the need via four design/build/test tasks and four analysis/study tasks. This paper focuses on Tasks 1-4, the four design/build/test tasks. Task 1 involves the development of nested thermally-switched enclosures featuring a reverse-operation DTE thermal switch (ROD-TSW) in series with a propylene miniaturized loop heat pipe (mini-LHP). Task 2 involves the development of a parabolic reflector radiator (PRR) for low latitude lunar sites. Task 3 involves the development of a low effective emissivity (e*) multilayer insulation (MLI) known as "spacerless" MLI. Finally, Task 4 involves the development of low conductance (G) thermal isolators. Available test results for all four tasks will be summarized in the paper, as will the plans for the remainder of the PALETTE project.

Nomenclature

DTE	=	differential thermal expansion
*e**	=	effective emissivity of MLI
G	=	conductance (WK^{-1})
k	=	thermal conductivity ($Wm^{-1}K^{-1}$)
mini-LHP	=	miniaturized loop heat pipe
MLI	=	multilayer insulation
q_{LOSS}	=	heat loss flux (Wm^{-2})
ROD-TSW	=	reverse operation DTE thermal switch
T_{SINK}	=	radiative sink temperature (K)

***note**: see Appendix for additional definitions*

I. Introduction

THE renewed focus by NASA on robotic exploration of extreme environments has created a need for improved thermal capabilities that enhance science instrument operability/survivability. If radioisotopes are to be avoided, existing thermal capabilities will not meet future needs. As a solution, JPL proposed the three-year Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) project, the intent of which was to develop high TRL thermal "toolbox" elements and an underlying architecture that engineers could use to develop/implement optimal instrument designs (e.g., magnetometers, seismometers, IR spectrometers, others) in extreme environments. The architecture, which is illustrated and contextualized in Figure 1, consists of a passive, thermally-switched, dual enclosure system with new ultra-isolative elements. This paper reports on year one progress and, paralleling typical NASA Space Technology Mission Directorate (STMD) GCD project emphases, it is organized into the following five remaining sections: objectives, technology, metrics, results, and mission impact.

[1] Technologist, Special Programs Thermal Engineering, T1708/107, 4800 Oak Grove Dr., Pasadena, CA 91109.
[2] Group Supervisor, Instrument/Payload Thermal Engineering, B125/220B, 4800 Oak Grove Dr., Pasadena CA 91109.
[3] Program Element Manager, NASA STMD/GCD, M/S 250, B1244/R203, 6 East Taylor Street, Hampton, VA, 23681.

➢ Technology Goal/Objective

- The Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) project is a 3-year effort to develop passive thermal management tools necessary for future instrument/system operation in extreme environments. The overarching goal is to ensure that a full palette of TRL6 or higher *"thermal toolbox"* elements is available so that engineers can create passive, ultra-isolative thermal designs for science instruments on a variety of carriers in lunar/planetary extreme environments.

➢ Technical Capability Areas to be Advanced

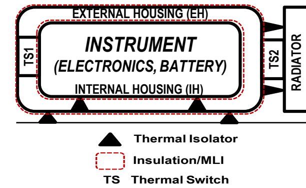
- PALETTE technical focus areas: 1-enclosures; 2-radiators; 3-insulation/MLI; 4-thermal isolators; 5-gimbals; 6-thermal switches; 7-thermal transport devices; 8-thermal storage devices; 9-deployables/antennae; and 10-low heat loss feed-throughs

➢ Exploration & Science Impact

- NASA has a renewed focus on lunar/planetary exploration that has resulted in science instruments being developed that are smaller, distributed, and possibly networked
- If radioisotopes are to be avoided, existing capabilities will not meet future needs
- Science instruments include magnetometers, seismometers, spectrometers (IR, mass), radiation detectors, particle analyzers, electric field instruments, and others.
- PALETTE is structured to meet the need by increasing thermal toolbox element TRL via ***4 design/build/test tasks*** and ***4 analysis/study tasks*** … see 2 tables at right

NOTE: *BMG = Bulk Metallic Glass*

PALETTE Thermal Architecture



PALETTE Research Areas/Tasks

Raise TRL via Design/Build/Test
T1: Dual thermal switch instrument enclosures
T2: Affordable parabolic reflector radiators (PRRs)
T3: "Spacerless" MLI with e* << 0.01
T4: Thermal ultra-isolators w/ G << 0.001 W/K

Raise TRL via Analysis/Study
T5: Instrument gimbals with BMG actuators
T6: Combined thermal switch/transport/storage
T7: Low heat loss feed-thru architectures
T8: Scaling/extensibility/planetary uses

Figure 1. PALETTE Project Overview

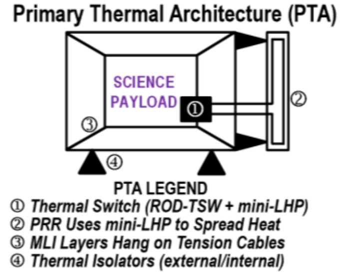
II. Objectives

The PALETTE technology goals/project objectives are identified in Figure 2. The primary goals are to: (1) develop better performing instrument thermal enclosure technology; (2) develop affordable ambient parabolic reflector radiator (PRR) technology; (3) develop better performing multilayer insulation (MLI) technology; and (4) develop better performing thermal isolator technology. The project also has six stretch goals – *relating to gimbaled systems, thermal switching, thermal transport, thermal storage, deployable mechanisms, and low heat loss feed throughs* – that the project will also focus on. Based on those ten goals, eight project objectives and eight corresponding project tasks were developed. The PALETTE project tasks (T1-T8) are listed at the bottom right of Figure 1. This paper will focus on the first four tasks (T1-T4), and the images at the right of Figure 2 indicate the two specific thermal architectures under development and the areas that are being emphasized to protect science payloads from extreme environments.

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 technology
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*** (PRR); 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***

Primary Thermal Architecture (PTA)



Backup Thermal Architecture (BTA)

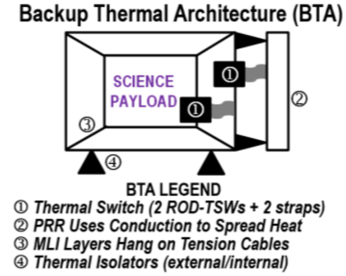


Figure 2. PALETTE Project Objectives

On the right hand side of Figure 2 are the two architectures under consideration for PALETTE. The primary thermal architecture (PTA) is composed of an in-series arrangement of a ROD-TSW and a mini-LHP. The backup thermal architecture (BTA) is composed of an in-series arrangement of a ROD-TSW/thermal strap and a ROD-TSW/thermal strap. The PTA is preferred for two reasons. First, the mini-LHP has a much higher ON/OFF ratio than the ROD-TSW (10000:1 vs 2500:1), so the PTA will perform better from a thermal switching standpoint. In addition, due to the small diameter of the mini-LHP transport lines (1.5 mm outer diameter), the heat leak inducing protrusions through the MLI layers between the EH and IH are minimized. The BTA is lower risk, however, as the PTA thermal switching system (ROD-TSW + mini-LHP) has not yet been verified, while the BTA thermal switching system (ROD-TSW/thermal strap + ROD-TSW/thermal strap) has been verified by breadboard testing as explained later.

III. Technology

One of the first things done on NASA GCD projects is to perform a technical assessment. In a technical assessment, project technology development is deconstructed into a series of its intrinsic technical elements. For PALETTE, there were ten technical elements that were identified. Figure 3 illustrates those technical elements (TE), which include the following: ***TE1*** *– Thermal Switching Systems*; ***TE2*** *– PRR Additive Manufacturing*; ***TE3*** *– Low e* "Spacerless" MLI*; ***TE4*** *– Low G Thermal Isolators*; ***TE5*** *– Gimbals with Bulk Metallic Glass (BMG) Actuators*; ***TE6*** *– Combinatory Thermal Management*; **TE7** *– Low G Feedthroughs*; ***TE8*** *– Scalability/Extensibility*; ***TE9*** *– Tension Cable Supports*; and ***TE10*** *– Architecture Ranking*. This paper will focus on TE1-TE4 and TE9. Future papers will address TE5-TE8 and TE10. In parallel with the technical assessment, NASA GCD projects develop a series of metrics, known as key performance parameters (KPPs), which are used to quantitatively assess project performance. The next section of the paper addresses the PALETTE project KPP metrics.

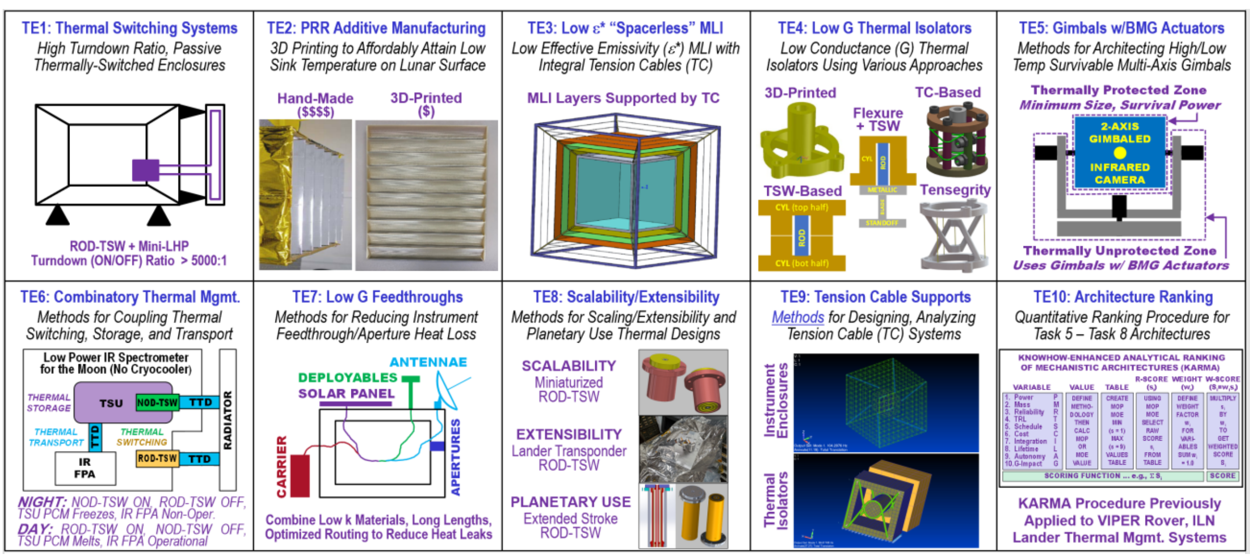


Figure 3. PALETTE Project Technical Elements

IV. Metrics

For PALETTE Tasks 1-4, a total of five KPP metrics were identified as listed in Table 1. For each KPP metric, there is a state-of-the-art value that indicates current technology capability, a project threshold value that indicates the minimum acceptable level of performance, and a project goal value that indicates the targeted level of performance. For Task 1, KPP1 is the heat loss flux (q_{LOSS}) from the thermal enclosure during the thermal cold case. For lunar science payloads, this cold case temperature is less than 100 K during lunar night. For Task 2, KPP2A is the sink temperature (T_{SINK}) during the thermal hot case and KPP2B is the recurring manufacturing cost of a PRR. For lunar science payloads at low latitudes, the lunar surface can rise to nearly 400 K during lunar day. For Task 3, KPP3 is the effective emissivity (e*) of spacerless MLI. Lastly, for Task 4, KPP4 is the conductance (G) of the thermal isolator (per isolator). The analytical or anecdotal bases for the ***threshold*** values listed in Table 1 are illustrated graphically and/or depicted mathematically in Figure 4. The equations indicated in Figure 4 will yield the ***current*** and ***goal*** values in Table 1 if the inputs are adjusted accordingly. KPPs for Tasks 5-8 will be defined by PALETTE after year two.

Table 1. PALETTE Project KPP Metrics

Task Number	KPP Number	KPP	Units	Current	Threshold	Goal
1	KPP1	q_{LOSS}	W/m^2	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

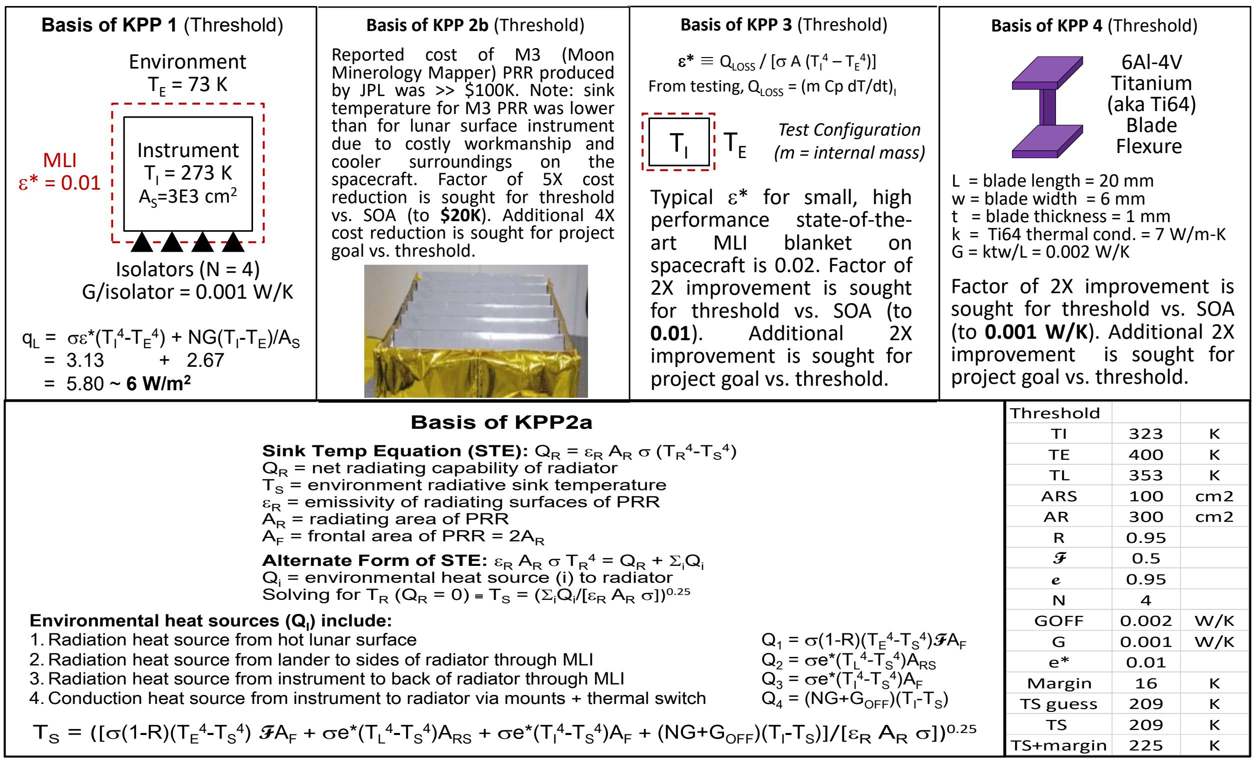


Figure 4. PALETTE Project KPP Threshold Bases ***(note: SOA = state of the art)***

V. Results

The four PALETTE tasks addressed in this paper (Tasks 1-4, where Task 1 has parts A and B) are each structured with seven programmatic steps that increase overall readiness from TRL3 to TRL5/6. Those steps are: (1) requirements definition; (2) breadboard testing; (3) design/CAD; (4) analysis; (5) drawing preparation; (6) fabrication/assembly; and (7) prototype testing. PALETTE was awarded in September 2019 but did not start work until April 1, 2020. In the roughly one year since project kickoff, Steps 1-6 have been completed for each task. Step 7 will commence in April 2021 and it will conclude in February 2022 upon completing the following prototype test sequence → *Task 3, Task 2, Task 1A, Task 4, Task 1B*. The prototype test (Step 7) for Task 1A is a test of the dual-enclosure architectures illustrated in Figure 2 with conventional radiator, MLI, and thermal isolator technologies. The prototype test for Task 1B is a test of the best-performing Task 1A dual-enclosure architecture with the new set of PALETTE radiator, spacerless MLI, and thermal isolator technologies developed in Tasks 2-4. Figures 5-8 respectively illustrate the Step 1-7 progress made (focusing primarily on Steps 1- 4 and 7) on Task 1A, Task 2, Task 3, Task 4, and Task 1B. However, before addressing those results, a brief explanation is required to explain how Step 2 breadboard testing came about.

PALETTE breadboard testing was added to the project at its outset after an internal JPL project called ARTEMIS (Architecture for a Thermal Enclosure of Moon Instrument Suites) changed course. ARTEMIS began in July 2019 and it was focused on developing the same set of thermal toolbox technologies as PALETTE. Once PALETTE was awarded, JPL management decided that ARTEMIS would transition from a technology development focus (including the breadboard testing that was ready to commence) to a science instrument design/accommodation focus. As risk reduction for PALETTE development, the ARTEMIS breadboard tests were added to the PALETTE project.

Figures 5-8 illustrate the PALETTE year one results with a specific focus on the KPPs in Table 1. Figure 5 indicates that the Task 1 thermally-switched enclosure prototypes (PTA and BTA) will likely meet/exceed the KPP1 threshold of 6 W/m^2 heat loss during lunar night as the breadboard unit, even with bare aluminum surfaces (no MLI), achieved a KPP1 of 10 W/m^2. Figure 6 indicates that the Task 2 PRR will likely meet/exceed the KPP2A threshold of a 225 K sink temperature during lunar day as the subscale breadboard unit achieved a KPP2A of 223 K. Figure 7 indicates that the Task 3 Spacerless MLI prototype will likely meet/exceed the KPP3 threshold of 0.01 as the breadboard test, albeit with a heated plate that was smaller than the internal housing and not necessarily high emissivity, achieved a KPP3 of 0.0047. Lastly, Figure 8 outlines the procedure for determining thermal isolator G (KPP4). The current plan is to use an existing Q-meter from ROD-TSW[1] OFF conductance testing. No Task 4 breadboard testing was performed.

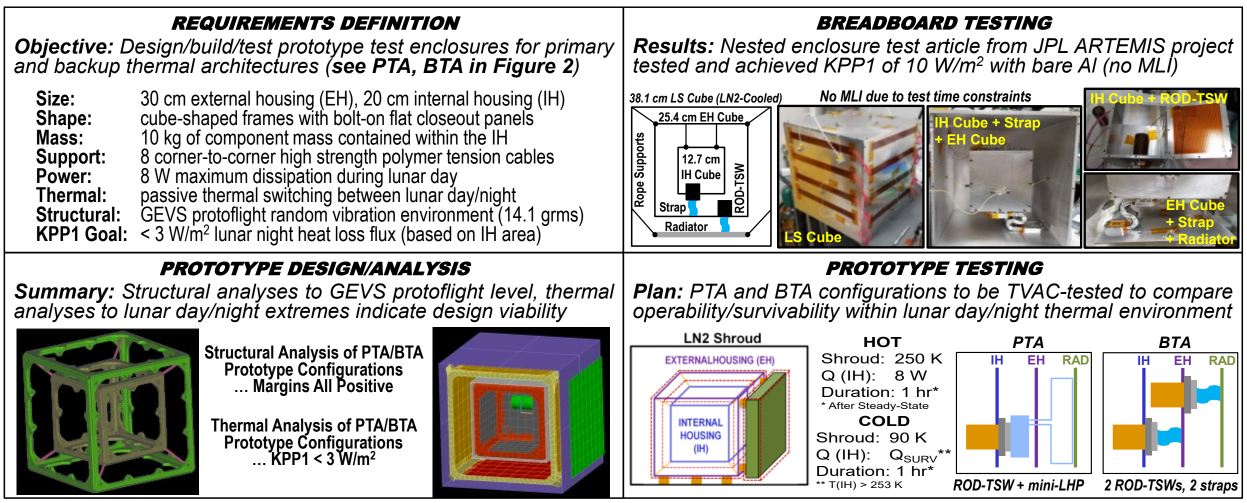


Figure 5. PALETTE Task 1 Thermally Switched Enclosure Results

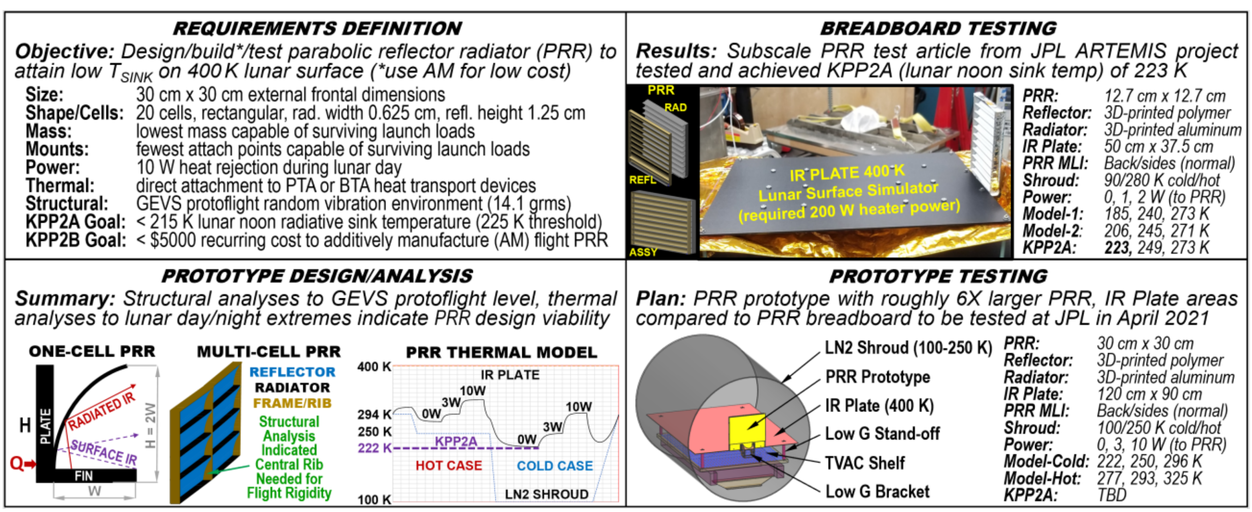


Figure 6. PALETTE Task 2 Parabolic Reflector Radiator (PRR) Results

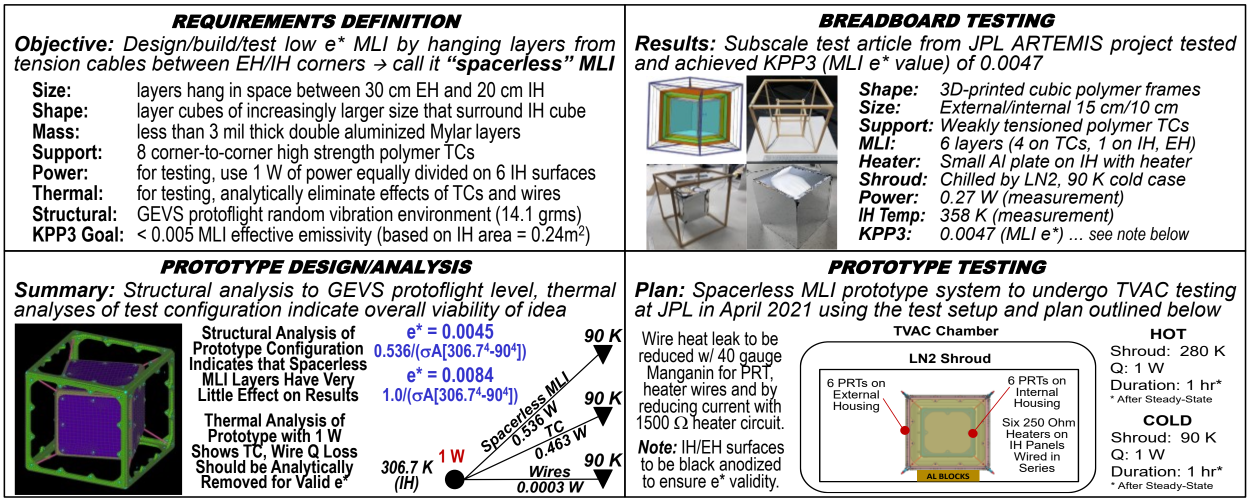


Figure 7. PALETTE Task 3 Spacerless MLI Results

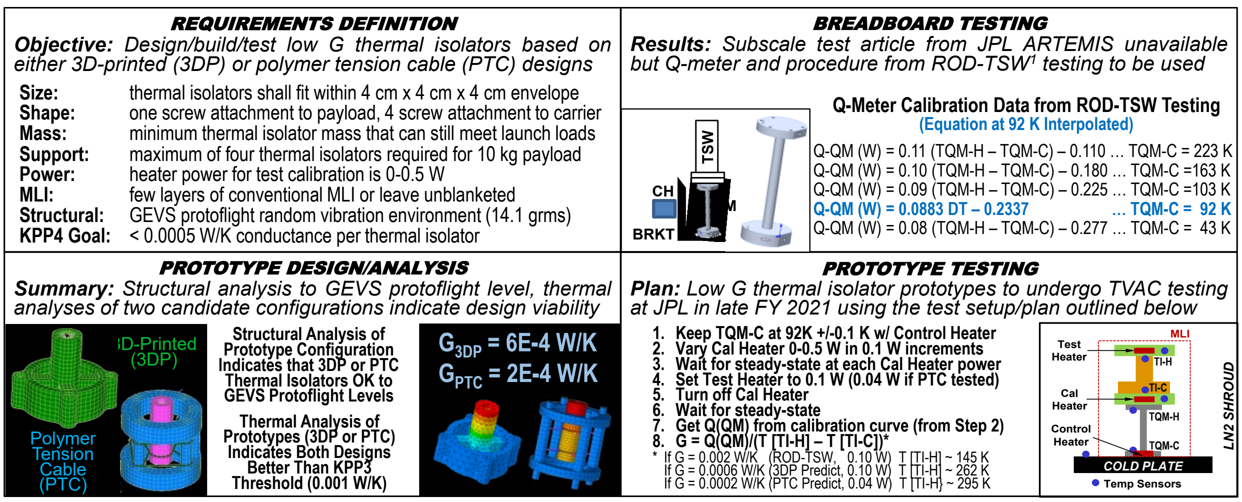


Figure 8. PALETTE Task 4 Low G Thermal Isolator Results

VI. Mission Impact

NASA GCD project success relies on: (a) infusing its new technologies into future missions; and (b) benefitting a wide spectrum of potential users. Stakeholders of PALETTE technologies include NASA centers, JPL, other FFRDCs, aerospace companies, universities, and other organizations, many of which are developing instruments for extreme environments. PALETTE is developing advanced thermal toolbox elements that can enable/facilitate instrument operation in extreme environments (without radioisotopes) and such tools will always be highly sought-after.

For wide applicability, the PALETTE infusion plan has multiple threads of attack including: (1) responding to NASA solicitations (e.g., PRISM and others); (2) direct infusion into projects that team members are currently supporting (e.g., VIPER, COLDArm, and others); (3) direct infusion into JPL technology development projects (e.g., ARTEMIS and others); (4) indirect infusion into related efforts (e.g., miniaturized lunar rovers, miniaturized lunar instruments, and others); and (5) presenting papers/presentations at conferences (e.g., ICES, STCW, ISSC, and others).

One relevant example involves a new JPL focus on developing self-sufficent lunar science instruments. Figure 9 illustrates this strategy, which involves incorporating PALETTE thermal tools (spacerless MLI, advanced isolators, parabolic reflector radiators, and thermally-switched enclosures) and common cubesat capabilities (C&DH, telecom, solar panels, and batteries) into the instruments to enable multiple lunar day/night operability. These JPL instruments will significantly outlive the initial set of Commercial Lunar Payload Services (CLPS) landers.

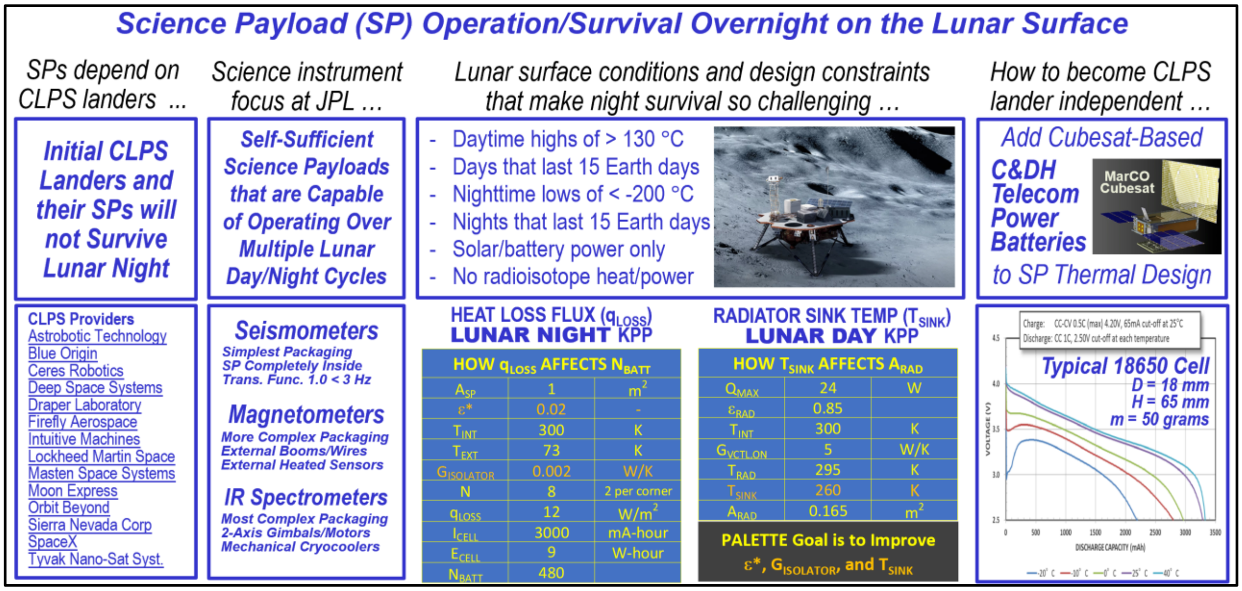


Figure 9. PALETTE Technologies Will Enable Science Payload Multiple Lunar Day/Night Operation/Survival

The benefits of PALETTE tools becomes most apparent when assessing their impact on the number of batteries required for lunar night operation/survival. The two spreadsheets at the bottom-center of Figure 9 indicate that with current technology – *that is, with an MLI e* of 0.02, thermal isolator G of 0.002 W/K, and T_{SINK} of 260 K* – 480 battery cells and a radiator area of 0.165 m^2 are required. If MLI e* is reduced to 0.005, thermal isolator G is reduced to 0.0005 W/K, and T_{SINK} is reduced to 200 K, 360 fewer batteries are required, reducing mass by 18 kg, and the radiator area is cut in half. Figure 10 illustrates how the two spreadsheets in Figure 9 would change with updated PALETTE e*, G, and T_{SINK} values. At the Astrobotic lander price of $1.2M/per kg, these reductions would save almost $22M.

HOW q_{LOSS} AFFECTS N_{BATT}		
A_{SP}	1	m^2
ε*	0.02	-
T_{INT}	300	K
T_{EXT}	73	K
$G_{ISOLATOR}$	0.002	W/K
N	8	2 per corner
q_{LOSS}	12	W/m^2
I_{CELL}	3000	mA-hour
E_{CELL}	9	W-hour
N_{BATT}	480	

Reducing ε* from 0.02 to 0.005 → Saves mass of 280 cells (14 kg)

HOW q_{LOSS} AFFECTS N_{BATT}		
A_{SP}	1	m^2
ε*	0.005	-
T_{INT}	300	K
T_{EXT}	73	K
$G_{ISOLATOR}$	0.002	W/K
N	8	2 per corner
q_{LOSS}	5	W/m^2
I_{CELL}	3000	mA-hour
E_{CELL}	9	W-hour
N_{BATT}	200	

HOW q_{LOSS} AFFECTS N_{BATT}		
A_{SP}	1	m^2
ε*	0.005	-
T_{INT}	300	K
T_{EXT}	73	K
$G_{ISOLATOR}$	0.002	W/K
N	8	2 per corner
q_{LOSS}	5	W/m^2
I_{CELL}	3000	mA-hour
E_{CELL}	9	W-hour
N_{BATT}	200	

Reducing G from 0.002 to 0.0005 W/K → Saves mass of 80 cells (4 kg)

HOW q_{LOSS} AFFECTS N_{BATT}		
A_{SP}	1	m^2
ε*	0.005	-
T_{INT}	300	K
T_{EXT}	73	K
$G_{ISOLATOR}$	0.0005	W/K
N	8	2 per corner
q_{LOSS}	3	W/m^2
I_{CELL}	3000	mA-hour
E_{CELL}	9	W-hour
N_{BATT}	120	

HOW T_{SINK} AFFECTS A_{RAD}		
Q_{MAX}	24	W
e_{RAD}	0.85	
T_{INT}	300	K
$G_{VCTL,ON}$	5	W/K
T_{RAD}	295	K
T_{SINK}	260	K
A_{RAD}	0.165	m^2

Reducing T_{SINK} from 260 K to 200 K → Cuts Radiator Area in Half

HOW T_{SINK} AFFECTS A_{RAD}		
Q_{MAX}	24	W
e_{RAD}	0.85	
T_{INT}	300	K
$G_{VCTL,ON}$	5	W/K
T_{RAD}	295	K
T_{SINK}	200	K
A_{RAD}	0.083	m^2

Figure 10. Mass/Radiator Area Benefit of PALETTE Thermal Toolbox Technologies

VII. 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 (e*) "spacerless" MLI; and (4) low conductance (G) thermal isolators. JPL is currently working to incorporate those features into its designs for lunar seismometers, magnetometers, and IR spectrometers. Very shortly, PALETTE will begin testing near-flight-sized prototypes to verify thermal performance and qualify the architecture and its elements for use on future flight projects. Future papers will report on those test results.

Appendix

Many terms/acronyms were omitted from the Nomenclature section so the Introduction section would appear on the first page of the paper. To rectify this omission, an Appendix is included with additional definitions. Any remaining undefined terms should be easily discernable based on their units and/or usage context.

C&DH = command and data handling
COLDArm = Cold Operable Lunar Deployable Arm
FFRDC = federally funded research and development center
FPA = focal plane array
$\mathcal{F}$ = geometric shape factor
GEVS = General Environmental Verification Standard
G_{ON} = conductance of thermal switch in ON state (WK^{-1})
$G_{VCTL,ON}$ = conductance of variable conductance thermal link in ON state
ICES = International Conference on Environmental Systems
ISSC = Interplanetary Small Satellite Conference
ILN = International Lunar Network
LN2 = liquid nitrogen
LS = lunar shroud
N, N_{BATT} = number of isolators, number of batteries
PRISM = Payloads and Research Investigations on the Surface of the Moon
R = reflectance
STCW = Spacecraft Thermal Control Workshop
TC = tension cable
TE = environment temperature (K)
TI = internal temperature or instrument temperature (K)
TL = lander temperature (K)
TQM, TR = Q-meter temperature (K), radiator temperature (K)
TRL = technology readiness level
TTD = thermal transport device
TVAC = thermal vacuum
VCTL = variable conductance thermal link
VIPER = Volatiles Investigating Polar Exploration Rover

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