THERMAL DESIGN AND TVAC TEST CORRELATION OF A LUNAR ROVER PROTOTYPE

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ABSTRACT

The lunar surface thermal environment is particularly harsh amongst planetary bodies in the solar system. Lunar nights last over 14 Earth days, and without a radioactive heat source (RHU or RTG), all components must survive with limited heater power. During the equally long lunar days, constant solar radiation bakes the surface regolith, and the need for solar cells limits real estate for radiators, further constraining the thermal design.

To further develop the thermal design of rovers and other assets destined for the moon, Canadensys Aerospace and Maya HTT collaborated to support the Canadian Space Agency on their Mobility & Environmental Rover Integrated Technology (MERIT) lunar technology development project. The work integrated long-range lunar mobility with lunar night thermal resilience, and included the development and test of a TRL6 Thermally Regulated Electronics Enclosure (TREE) prototype in a lunar thermal vacuum environment.

To survive this environment, the TREE established several thermally-insulated zones within the rover body, leveraging a carefully tailored combination of thermostatically-controlled loop heat pipes (LHP) from Allatherm SIA - evacuating the heat during the day and isolating the modules during the extended nights, Bi-metallic Valve Thermostatic Switches (BVTS) providing system temperature switch control for the LHPs below a setpoint temperature, and additional insulation in the form of MLI and thermal standoffs.

The TREE assembly was TVAC tested at the CSA's David Florida Laboratory. The lunar environment was simulated by flooding the TVAC shroud with liquid nitrogen, driving it down to -190°C. Test results showed a better than expected thermal performance during lunar night and

that the equipment would well survive. Results from the hot daytime operations provided valuable data for the future development of the loop heat pipe systems, and underscored the challenges of modelling loop heat pipe behavior especially in transient conditions.

Test results were used to correlate the thermal model. The correlation of the lunar night proved to be challenging, with minimal dissipations, high thermal resistances and a cryogenic environment in which the temperatures had not settled after several days. Some imponderables, such as the heat brought in by test harnesses, could not be ignored. Furthermore, the temperature-dependency of the thermal standoffs had to be factored in. The test results were correlated with adequate accuracy, and a lunar night transient simulation provided reliable estimates for the temperatures and power consumption.

INTRODUCTION

Mobility and longevity on the lunar surface have been key themes within Canada's lunar surface preparations for over a decade, and a number of capabilities continue to be advanced with a view to supporting and enhancing missions over the next 5-10 years of international lunar exploration. From a global science perspective, these missions will be guided by a number of science and technology themes including "Know your Environment", "Prospect for Resources" and "Safe and Healthy Astronauts". Rovers will rove on the surface of the Moon to access, explore and discover remote areas of interest and across these areas, rovers will continuously gather new scientific and engineering data and imagery. This data will feed national and international science communities to help increase our understanding of the Moon and other planetary bodies.

The reference mission considered herein takes place near either the north or south pole of the Moon, areas where water ice and other volatiles are the most likely to be present in extractible quantities. Proper prospecting and mapping will require the rover to acquire measurements and data over long distances, which in turn will take time. The rover has thus to be rugged and agile to operate and deal with the harsh lunar environment over an extended period of time.

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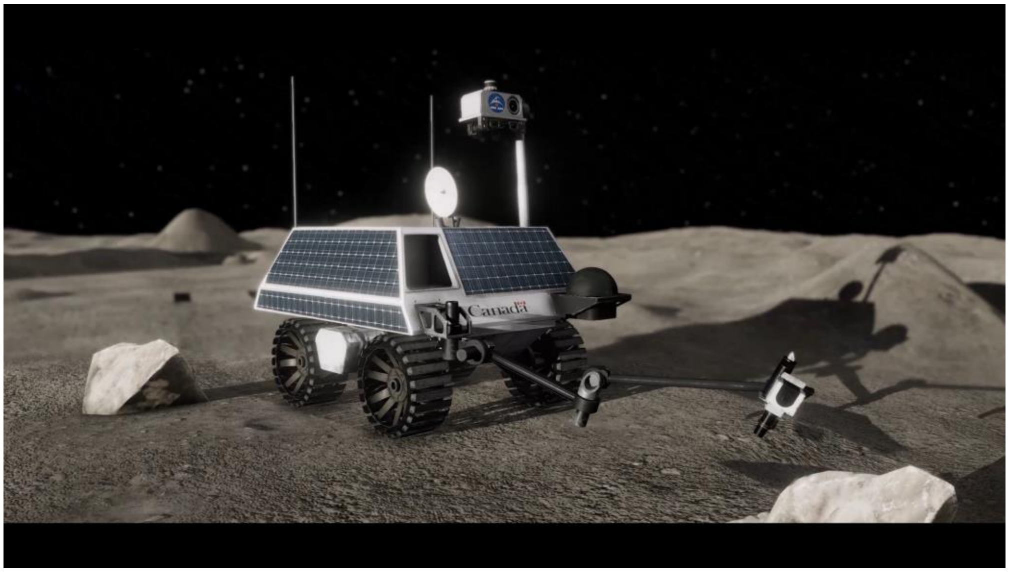

Figure 1: Representation of a lunar rover collecting a sample of lunar soil. Courtesy: CSA.

The Canadian Space Agency's Mobility and Environmental Rover Integrated Technology (MERIT) program was conceived to close strategic knowledge gaps in the areas of lunar rover thermal control and mobility through prototyping and a series of tests. Canadensys Aerospace Corporation has supported CSA over a number of projects over the last 7 years ruggedizing spacecraft systems and components for lunar and deep-space applications, and specifically developing a number of critically enabling technologies for lunar rovers and lunar shadow / night survival and operation. Maya HTT Ltd. has been a key collaborator with Canadensys on the thermal design, analysis, and prototyping of several such systems.

This paper summarizes some of the thermal control design and analysis activities relating to the Thermally Regulated Electronics Enclosure (TREE) on the project, and the resulting thermal vacuum test campaign with correlation of the thermal analysis to the TVAC test results.

DESCRIPTION OF THE FLIGHT REFERENCE SYSTEM

The MERIT thermal control prototype used as the basis of its design a lunar rover concept developed for CSA as part of the HERACLES international lunar architecture work several years ago, known as the Precursor to Human and Scientific Rover (PHASR). The PHASR was a medium-sized rover for the lunar surface, designed to survive at least one year on the surface and drive at least 400 km, demonstrating many of the critical technologies necessary in the lead-up to the return of a human presence to the lunar surface. PHASR was to perform a number of science tasks as well, collecting samples of lunar rocks and soil from both sunlit and Permanently-Shadowed Regions (PSRs) using its manipulator arm, and using its other scientific payloads to take measurements and capture imagery of its surroundings.

PHASR was a 4-wheeled, 330 kg-class vehicle, measuring roughly 2 m long by 1.5 m wide by 1.2 m high in its stowed configuration. As a solar-powered system, it did not rely on radioactive elements such as Radioisotope Thermoelectric Generators (RTGs) or Radioisotope Heater Units (RHUs), and therefore relied heavily on a thermal control system to provide isolation from the lunar night environment.

TREE Thermal Control Prototype

The MERIT TREE essentially demonstrated the thermal management of an integrated small spacecraft / avionics stack with on-board computer (OBC), power conditioning & distribution unit (PCDU), battery, motor drive amplifiers (MDAs), drivetrain / dynamometer, and a number of sensor elements, for optimum test fidelity.

The design combined a number of thermal control technologies and techniques including:

- Internal avionics within thermally regulated enclosures
- Mass-efficient MLI blankets
- Low-conductance standoffs for additional isolation
- Loop heat pipe (LHP) technologies from Allatherm SIA

The heat pipes leveraged passive valve switching technology and a modular evaporator design, based on Allatherm patented technology called ALTOM. Each of the evaporators is built from a varying number of Altoms to comply with the specific requirements for the area it is controlling. This architecture allows for a simplification in the design process since it is possible to comply with different interface dimensions and specifications, with a wide range of heat transfer capacities, effective conductances, and overall lengths by integrating different numbers of Altoms and Compensation Chambers (CCs).

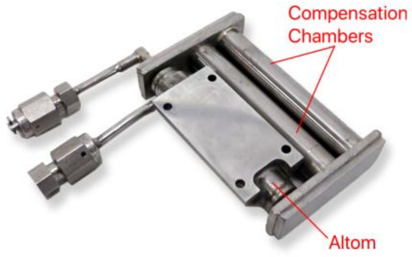

Figure 2: Heat pipe evaporator block

After LHP acceptance testing at Allatherm in Latvia, the LHPs were discharged, disassembled, packed and delivered to Canadensys for reassembly, charging and re-testing. Two high purity fluids were used for LHP tests in ambient conditions and one chosen as the baseline fluid for this application based on its low melting point.

TVAC TEST

Following assembly, integration and testing at Canadensys, MERIT TREE TVAC testing took place at the David Florida Laboratory (DFL) in Ottawa, Ontario, Canada, from 2 to 13 March, 2020. The TREE was placed inside of DFL's TV3 chamber, which provided flight-like cooling and vacuum conditions (see Figure 3). Bench top power supplies simulated solar panels, and DFL's integrated facility system provided power for simulated solar heating loads as well as externally controlled heaters. The prototype's own electrical systems powered and controlled various components inside and outside the TREE structure. The TREE interfaced with test operators via control stations located outside of TVAC. Thermocouples placed throughout the prototype connected to the facility's control and display system.

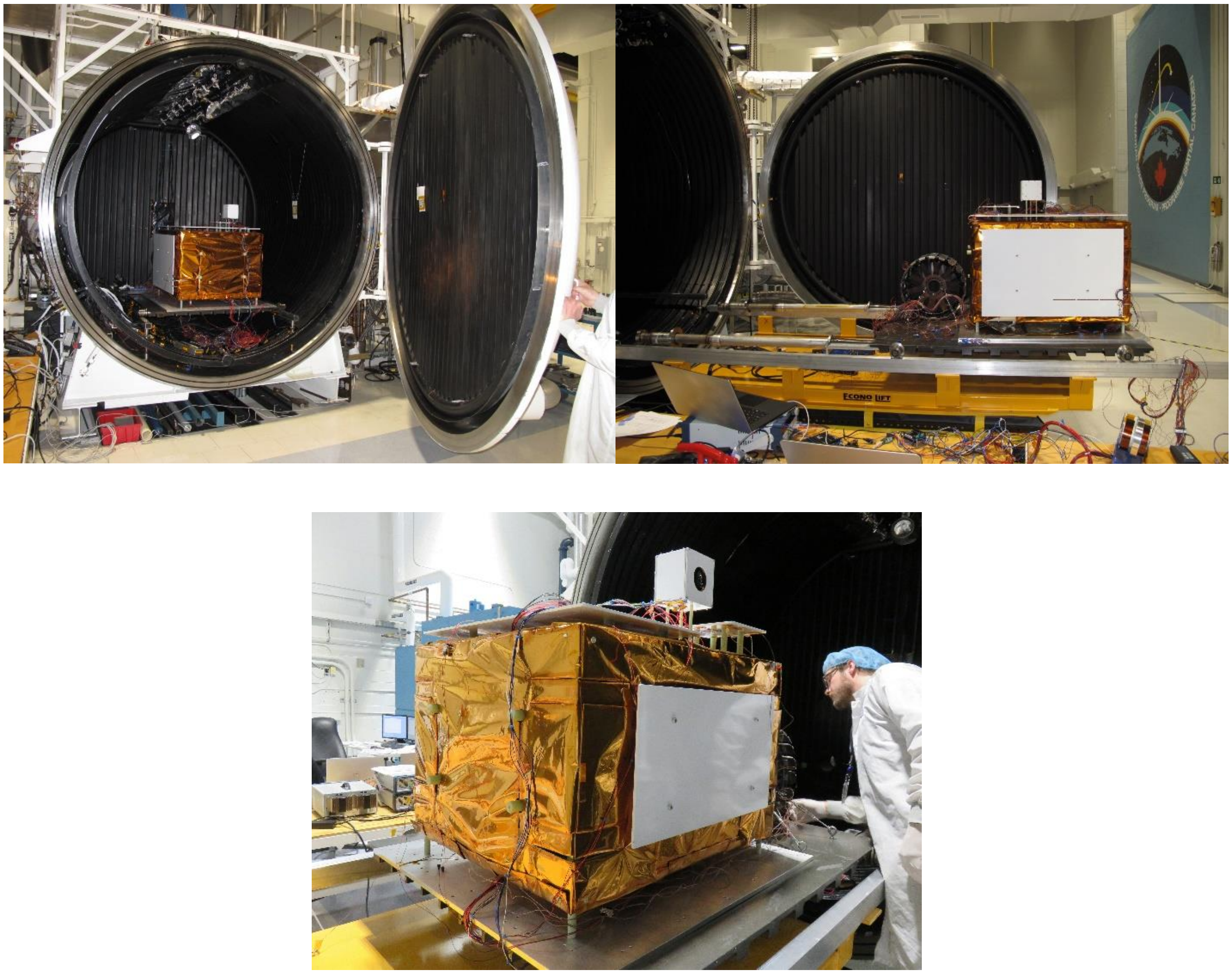

Figure 3: MERIT thermal control prototype preparing to enter DFL's TV3 chamber

The TVAC test profile consisted of the following test cases:

1. hot (sunlit) operational steady state thermal balance test (hot op), with solar loading heaters and solar array circuits operational and the prototype dissipating a maximum amount of power internally,
2. cold (shadowed) operational steady state thermal balance (cold op), with solar loading heaters and solar array circuits disabled but a similar internal dissipation to the hot op case,
3. cold (shadowed) standby steady state thermal balance (cold standby), similar to 2. but with minimal internal dissipation,
4. follow-on hot op tests, to determine changes to the system as a result of the cold cases,
5. lunar night survival steady state, with all loads switched off except the battery's management electronics and survival heaters allowed to switch on and off as thermostatic control switches fell to their setpoints
6. final hot op, to determine changes to the system as a result of the night survival simulation

In general, the test achieved a number of successes, verifying key aspects of the Canadian TREE design and demonstrating a level of lunar night survival performance above and beyond the baseline requirements, which in turn results in a smaller battery being required and valuable improvement to mission and vehicle mass.

TVAC CORRELATION

With the TVAC test data, the thermal model could now be correlated. The primary objective of the correlation was to provide confidence in the estimates of required heater power to survive lunar night. The model was developed and solved using Simcenter 3D Space Systems Thermal. Structure, electronics, MLI and radiators were modeled explicitly while heat pipes were modeled using simplified representation and G10 fiberglass washers were introduced in the model as temperature-dependent thermal couplings.

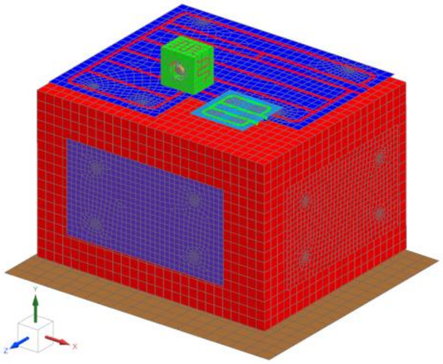

Figure 4: MERIT Thermal Model

The thermal model was correlated using two different sets of data. The first set was the temperatures at the end of the lunar survival phase, which corresponds to the test case #5 presented previously. At the end of this phase, the thermostatically-controlled heaters were turned off and replaced by equivalent steady dissipations. The assembly was allowed some time to further stabilize. The temperatures at this end of this phase were used for correlation.

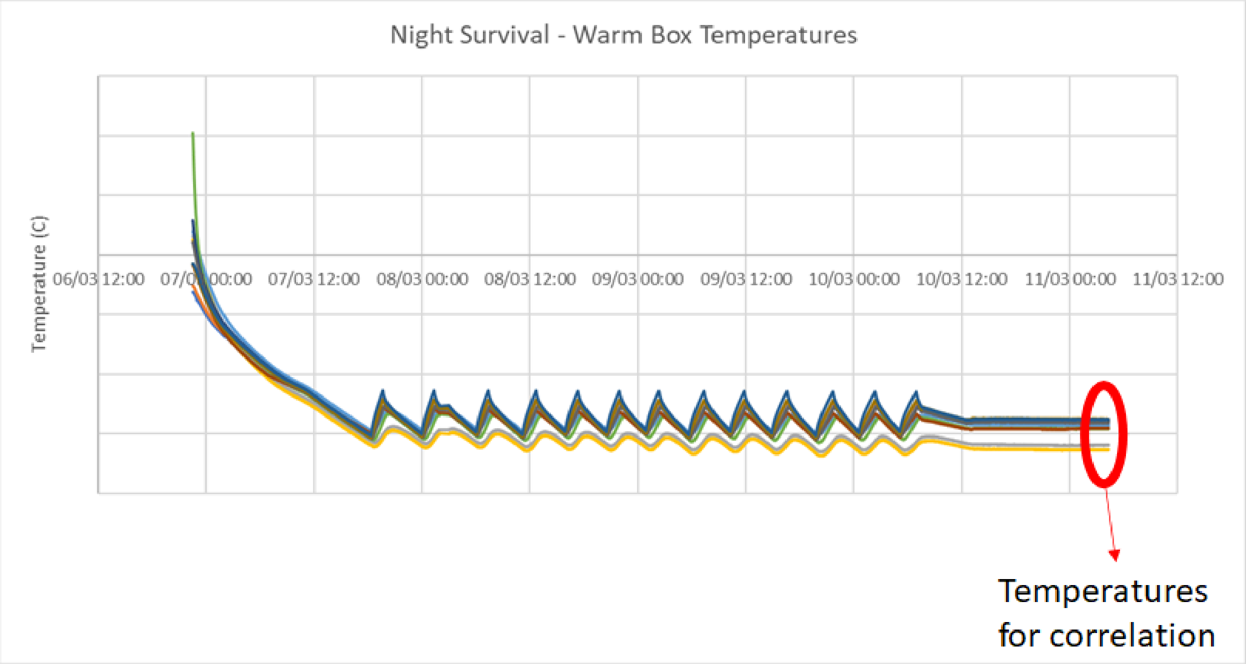

Figure 5: Temperature Set for First Correlation

In order to achieve correlation, the thermal model was first fed to a Design Space Exploration program (HEEDS). The significant parameters were allowed to vary, and Response Surface Models were built to provide a rough order of magnitude for the coupling values. Precise temperatures could not be achieved with DSE – it became apparent that some imponderables had to be accounted for. These imponderables, which were not included in the thermal model, were for example the heat brought in by test harnesses, the modified surface emissivity due to the presence of test heaters, and variability in the thermal conductance of similar mounting points. With manual tuning of the thermal model based on test observations, most temperatures were correlated within 5°C. A better precision could not be achieved, mainly due to the fact that temperatures on some of the main structural components had not fully settled after 4 days.

The second data set chosen for correlation is the test case #4. Heat dissipation was present in the internal components, and the solar heat load was represented by dissipations applied on the radiators by test heaters. The total dissipation inside the system was 750 W, from which 475 W were applied onto an external radiator to simulate solar heating. The environment was at -190°C. With the data from the first correlation exercise, most temperatures could be correlated within a few degrees.

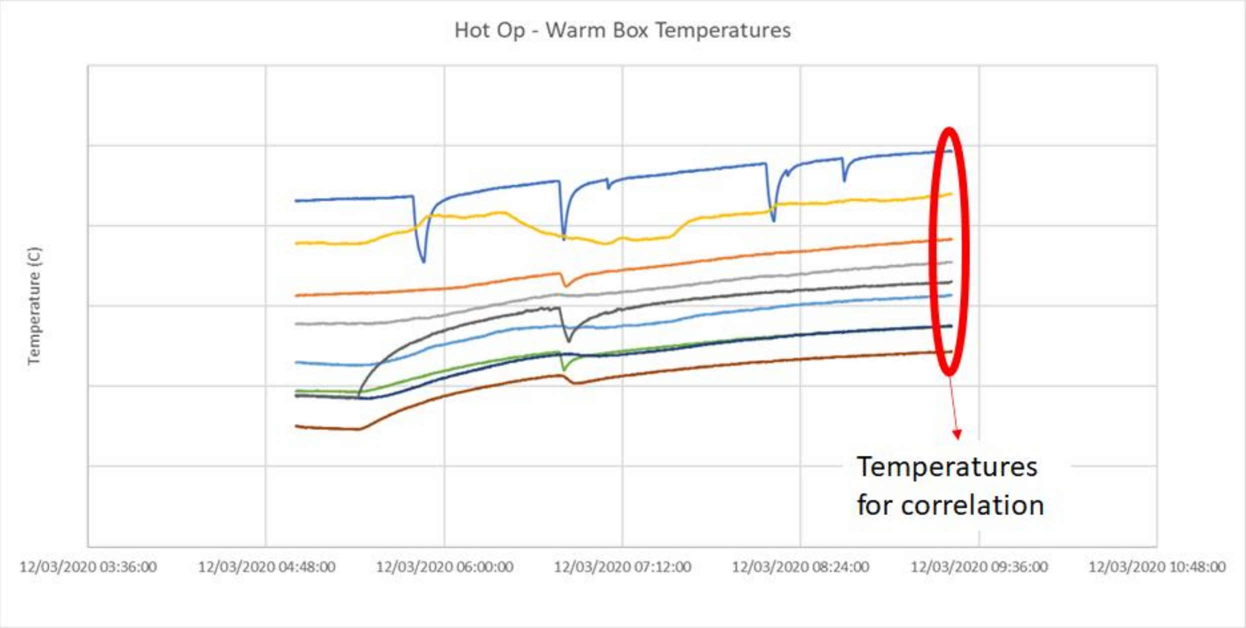

Figure 6: Temperature Set for Second Correlation

The main objective of the correlation exercise was to verify the heater power consumption over the lunar night. For this purpose, a transient simulation from lunar sundown to sunrise was performed with the correlated model.

From the simulation results, the time before the initial heater click-on and the heater duty cycle over the lunar night could be retrieved. One of the heaters never clicked on as its temperature did not get as low as anticipated prior to the TVAC test. These values were in line with the test observations, and provide confidence in the analytical results.

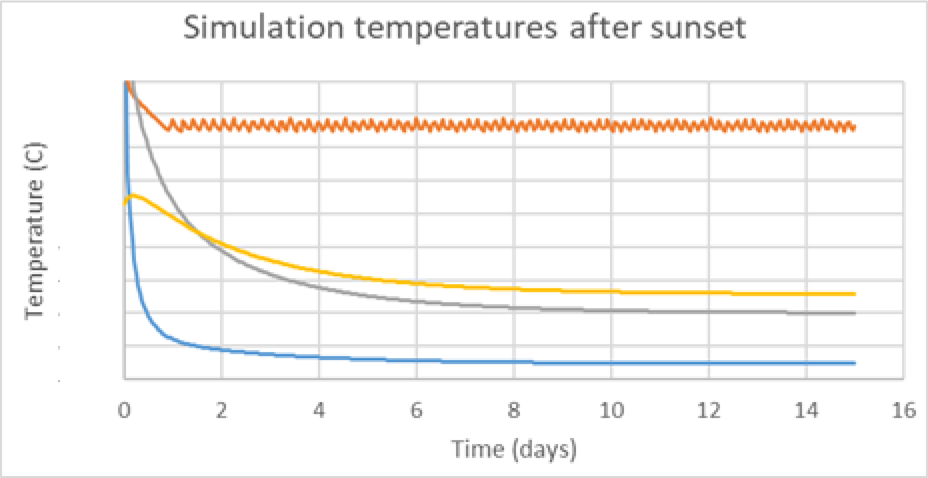

Figure 7: Transient Simulation Temperatures

CONCLUSIONS

CSA's MERIT project successfully demonstrated a number of mobility and thermal control technologies required for lunar rovers and other surface systems over the next 5-10 years to survive the long and cold lunar night, avoiding the high costs complexity of RHUs and RTGs.

A number of thermal control technologies, from novel LHP technologies such as modular Altom evaporator blocks, thermostatic control valves, a dismountable LHP design and a novel industrial delivery approach, to low temperature capable subsystems were developed and validated in the frame of this project.

Thermal models were correlated with promising accuracy using the TVAC test results. The use of design space exploration software proved practical to obtain quick rough order of magnitude for coupling values, with minor manual correlation work to account for test setup variabilities, number of monitoring points etc.

The TVAC test and correlation improved confidence in both the thermal design of the Canadian MERIT lunar night survival system, as well as the thermal simulation and analysis tools and techniques used. Thermal performance exceeded expectations, with lower power consumption and fewer heater activations than baselined in mission design specifications.

The CSA MERIT project resulted in several strategic knowledge gaps in the field of lunar rover mobility, lunar night survival and general thermal control being addressed, and a number of critical technology elements were advanced. Thanks to the modular nature of the thermal architectures employed, they can be used on a number of different lunar rover and surface system size classes, and have strong utility for the upcoming era of Canadian and international lunar surface exploration.

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NOMENCLATURE, ACRONYMS, ABBREVIATIONS

LHP	Loop Heat Pipe
DSE	Design Space Exploration
CSA	Canadian Space Agency
TVAC	Thermal Vacuum
MERIT	Mobility & Environmental Rover Integrated Technology
RTG	Radioisotope Thermoelectric Generator
HEEDS	Hierarchical Evolutionary Engineering Design System
TMG	Thermal Model Generator
DFL	David Florida Laboratory
TREE	Thermally Regulated Electronics Enclosure
OBC	OnBoard Computer
IMU	Inertial Measurement Unit
MDA	Motor Drive Amplifiers
PCDU	Power Conditioning and Distribution Unit
LAE	Lunar Ascent Element
ISSPE	In-Space Sample Preservation Element
DSG	Deep Space Gateway
PHASR	Precursor to Human And Scientific Rover
RHU	Radioisotope Heating Unit
BVTS	Bi-metallic Valve Thermostatic Switch
LEAP	Lunar Exploration Accelerator Program