Battery-Less Low Temperature Avionics and System Study - Executive Summary

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Abstract

Many types of science missions are aimed at targets in the solar system that have harsh thermal environments, such as Mars, the Moon, asteroids, comets, and other bodies at the fringes of the solar system. Traditional spacecraft avionics rely on the storage of electrical energy in electrochemical systems (typically secondary batteries) for covering peak energy demands and periods where no electrical energy is generated (Lunar/Martian/cometary night, etc.).

At present, most military specifications of electronic equipment call for operability down to -55C. Equipment capable of operating at lower temperatures and in ad-hoc architectures conceived for low temperature environments can reduce the electrical power consumption needed to maintain operational temperatures. This approach has the potential to extend mission operations, among other possible advantages. The European Space Agency has commissioned the present study which has identified the constraints of the target environments and, based on these, a variety of components and technologies which have been demonstrated to be operable over a substantial portion of a relevant target temperature range. This has resulted in the production of an inventory of technologies that for the first time provides a comprehensive overview of existing technologies for harsh thermal (mainly low temperature) environments that are available in Europe.

In order to assess the impact of these technologies (which have a variety of TRLs) and architectures on future missions, the team has used the architecture of the Lunar Volatiles Mobile Instrumentation (LUVMI) rover as a benchmark. LUVMI is an on-going EU-funded project, consisting of a low-mass, low-footprint rover designed to prospect resources in the Permanently Shadowed Regions of the Moon. LUVMI plans to use a baseline architecture involving batteries and heaters.

For the purpose of this ESA study, the baseline architecture of LUVMI is replaced with a low-temperature architecture using some of the key components and subsystems identified in the inventory as well as hypothetical equipment to be produced as part of identified technology development efforts.

The system concept is outlined, simulated, and evaluated in terms of mass, cost, system size, complexity, mission lifetime, operational flexibility, development time and AIT aspects. The expected performance operating inside a Permanently Shadowed Region is assessed, as well as the expected accomplishment of scientific objectives within the rover's estimated lifetime and available resources.

A demonstrator is proposed, having as a primary goal to design and develop the BLTAS technologies of interest for the exemplary low temperature architecture, and to verify and validate the technologies in the context of a reference mission.

1. Introduction

There is a major scientific and, recently, commercial interest in exploring locations in the solar system where extreme thermal conditions are present. Those include most notably Mars and the Moon, as well as asteroids, comets, and other bodies located in the extremes of the solar system. A typical spacecraft avionics architecture relies on converting solar energy into electric energy and storing it in secondary batteries. This permits the operational coverage of periods of peak energy consumption as well as the delivery of energy when no electrical energy is being produced. The latter is the case for eclipses, Lunar, Martian and cometary nights and similar situations.

At present, most military specifications of electronic equipment call for operability down to 218K. Equipment capable of operating at lower temperatures and in ad-hoc architectures conceived for low temperature environments can reduce the electrical power consumption needed to maintain operational temperatures. This approach has the potential to extend mission operations, among other possible advantages.

The objectives of the present activity consist of:

- The consolidation of requirements from candidate missions to harsh thermal environments,
- The compilation of an inventory of suitable technologies and implementation approaches supporting battery-less low temperature system development (including electronics design, materials, component selection, and Manufacturing, Assembly, Integration and Testing (MAIT); energy storage technologies; energy management concepts and technologies),
- The architectural designs of a battery-less (or reduced battery size) system including payloads based on the identified technologies and implementation approaches,
- Performing system simulations, optimization, and performance / capability assessments,
- Preparation of a development plan.

2. Avionics Requirements

Requirements towards avionics and other electronics have been collected in a first phase of the project and consolidated from several types of missions and their environments:

- Mars landers/surface vehicles or payload packages,
- Lunar landers/surface vehicles or payload packages,
- Asteroid and comet landers,
- Missions to moons of gas giants.

The collected relevant requirements have been categorized per mission type including the following aspects:

- Thermal environment, including temporal aspects,
- Available energy sources including their temporal aspects,
- Power generation options,

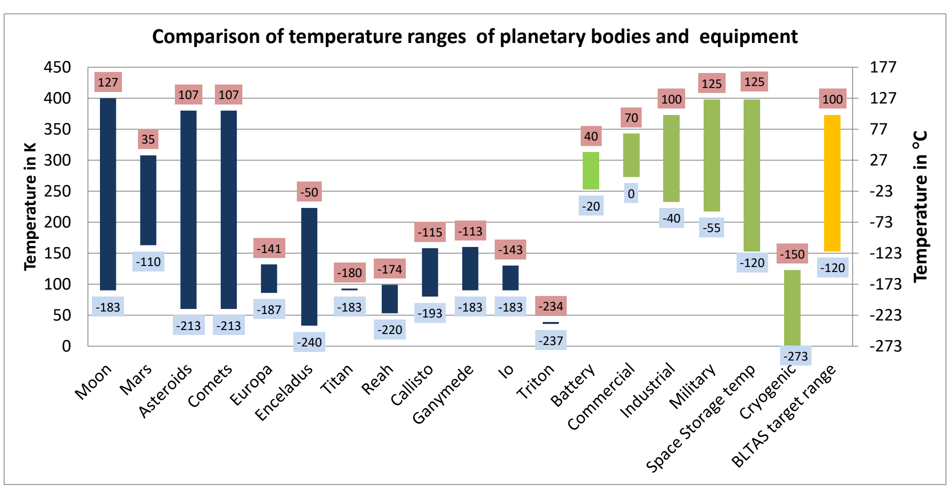

Figure 1 - Comparison of temperature ranges of planetary body surfaces and electronic equipment

- System/payload operational requirements as per reference mission,
- Energy needs and related storage needs,
- Energy consumption profiles,
- Mobility and other mechanical activity needs including their temporal aspects,
- Other relevant aspects.

Focus is given on near-term mission types such as Lunar and Mars missions.

Figure 1 provides a comparison of the temperature ranges of planetary bodies and those of standard equipment. The X-axis represents planets and other bodies in dark blue (such as the Moon, Mars, asteroids, comets and moons of gas giants) and equipment grade in green (such as industrial, military, cryogenic etc.) A target range, dubbed *BLTAS (*Battery-Less Low Temperature Architecture Study*) target,* has been specified for the purpose of the technology research. This range establishes a desirable range for the operation of the devices. The Y-axes represent temperature in Kelvin and centigrade.

Asteroids, Comets and Moons of Gas Giants have considerably extreme low temperatures due to the sheer distance from the sun. The Moon and Mars have generally higher temperature ranges (with the exception of Lunar Permanently Shadowed areas which are some of the coldest locations in the solar system, reaching down to 40K). Solar flux decreases with distance from the sun, making the use of solar panels highly suitable for a typical Moon mission, but less feasible to use in Gas Giant moon missions.

The number of thermal cycles, which is an important requirement for ensuring the lifetime of the avionics for the mission duration, in Asteroids and Comets, can be much higher than for other planetary targets (870-3500 cycles possible for a 2 year mission, while for targets like the Moon a hypothetical 2 year mission could have ~26 cycles).

In addition to the thermal requirements of the planetary environment, it is important for an avionics design to consider the sterilisation procedures that for the Moon are limited, but for Mars and gas giant moons are considerable, with equipment needing to be subjected to 383 to 473K (or other cleanliness/sterilization procedures).

Radiation requirements for Gas Giants moon missions, depending on the mission profile, can be some of the highest, with 2.9 Mrads used as a reference for a 9-year mission.

3. Low-Temperature Technology and European Capability Inventory

The team has established the following Technology Areas, covering technologies crucial in the implementation of battery-less space systems:

- Low-temperature electronics technologies
- Low-temperature mechanical technologies
- Low-temperature energy storage options
- Energy generation technologies
- Others

An extensive literature review took place, followed by email exchanges and calls with developers. A second iteration was made consisting of critical analysis and integration of additional data.

This study identified, primarily from publicly available literature, a variety of components and technologies which have been demonstrated to be operable over a substantial portion of the BLTAS target temperature range defined in the study.

Custom tables dubbed Technology Snapshots were created, documenting the technology, from the point of view of the Design Reference Mission (DRM), its function, its description, its Technology Readiness Level (TRL), relevant parameters, and the technical challenges that provide insight for future developments.

The effort did not only address elements capable of operating or being stored in low temperatures, but also elements enabling lower use of power during operations.

The considerations on the applicability and challenges found on each of the technology areas are detailed in the following subsections, based on the compiled inventory. The detailed references for the technologies mentioned can be found in the inventory.

3.1 Low temperature electronics technologies

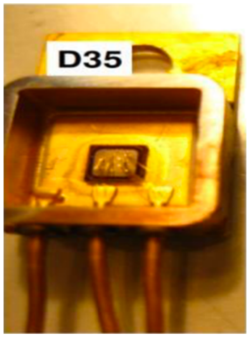

Figure 2 - Flight Qualified Schottky Diode (delidded) for BepiColombo and other ESA Mission. Image: Godignon et al., Alter Technology Group.

SiC semiconductors (A SiC Schottky diode can be seen in *Figure 2*) are typically used in high voltage, high power applications. Challenges in implementing silicon SiC semiconductors include their packaging design for extreme thermal cycling, as well as high sensitivity to Single Event Effects (SEE) from heavy ion radiation, which is problematic especially in power devices. The development of reliability testing regimen which screens for failure modes associated with low-temperature operation and wide temperature range excursions presents another challenge. The utility of minority carrier devices for Silicon SiC Semiconductors is limited to temperatures below ~100K due to carrier freeze-out, and this is most likely to affect asteroid/comet missions and gas giant moon missions. For the latter, SiC semiconductors need lower sensitivity to high energy particles/TID (Total Ionising Dose).

Si/CMOS (Complementary Metal Oxide Semiconductor) semiconductors are used in a wide variety of applications, both analogue and digital. Depending on the application, parameters related to switching speed, power dissipation, or other functions may be of primary importance. Circuits that are tolerant of large changes in these parameters will likely be necessary. A primary reliability concern for using CMOS at cryogenic temperatures is posed by Hot Carrier Effects. Traditional high-temperature 1000hr life tests do not account for this, as hot carrier induced failure modes have a negative activation energy; another qualification test must be performed. Design constraints should be implemented to minimize susceptibility to this degradation mechanism. Moreover, it has been found out that low temperature increases susceptibility to TID radiation effects for Si/CMOS semiconductors.

There is a need for better characterisation of reliability of Si/CMOS semiconductors under extreme thermal cycling, particularly for lunar missions. They encounter the same challenges as SiC devices: packaging for extreme thermal cycling, the necessity of a reliability testing regimen to screen for failure modes related to low-temperature operation, and the fact that below ~100K, carrier freeze-out limits the utility of minority carrier devices (primarily affecting implementation in asteroid/comet and gas giant moon missions). Additionally, for the latter their radiation hardness to high energy particle radiation should be assured.

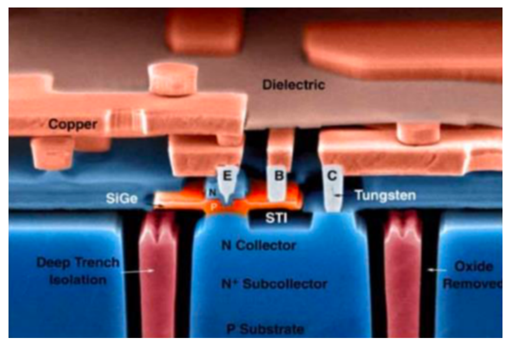

Figure 3 - SiGe HBT construction Image: Cressler, Georgia Institute of Technology

SiGe semiconductor devices, particularly Heterojunction Bipolar Transistors (HBTs), have been shown to be operational down to 0.7K and some figures of merit, e.g. transconductance, improve at low temperature compared to room temperature. They have also been shown to operate up to 573K. SiGe HBTs are inherently radiation hardened to Total Ionizing Dose (TID) exposure and Enhanced Low Dose Rate effect (ELDRs). TID exposure down to 77K has been tested. This technology is not inherently hardened to SEE, but this weakness can be mitigated with Radiation Hard by Design techniques. Radiation hardened SiGe BiCMOS ASICs can be stored and operated at cryogenic temperatures and have been shown to be functional at up to +573K.

Their reliability over extreme thermal cycling needs to be better characterized, in particular for lunar and asteroid/comet missions. Their radiation hardness needs improvement for gas giant missions.

GaN semiconductors are frequently used in switched mode power supplies and RF power amplifications; primary figures of merit are Rds(on), V threshold, and gate charge (and other parasitic capacitances). Enhancement-mode GaN High Electron Mobility Transistors (eGaN HEMTs -high-electron-mobility transistor) are becoming a mature technology. They have been successfully used in space applications and have been shown to be intrinsically hardened to TID and Heavy Ion radiation. A few commercial devices have been tested at cryogenic temperatures with favourable results.

Challenges for GaN semiconductor implementation include packaging for wide temperature cycling, the development and verification of wide temperature models for commercial GaN foundry processes, the development of reliability testing regimen which screens for failure modes associated with low temperature operation and wide temperature excursions. Their operational temperature needs to be extended, particularly below 120K to enable their use in Asteroid/Comet and Gas Giant Moon missions. Radiation hardness to high-energy particles needs to be assured.

Discrete resistors of several types, including some Commercial Off The Shelf (COTS) parts, have been demonstrated to be operational and somewhat parametrically stable over a wide temperature range. Little to no reliability literature was found for cryogenic or wide temperature operation. Many types of resistors have been shown to perform well at low temperatures, such as wirewound, metal foil, and thin, thick, and precision film (film chemistry dependent). Carbon composition and ceramic composition resistors were shown to perform poorly over temperature, with large drift in resistance values.

Parameter drift (both primary and parasitic parameters) should be inspected and determined to be within application specific tolerances for each case. Thermomechanical reliability testing should also be conducted over the temperature ranges set out by the various DRMs.

Discrete capacitors, including some COTS parts, have been demonstrated to be operational and somewhat parametrically stable over a wide temperature range. Part performance over temperature is dependent on dielectric material properties. Satisfactory performance over temperature is, of course, application dependent. At low temperatures, capacitors with fluid dielectrics should be avoided categorically, as their capacitance is close to zero once the dielectric freezes. Challenges include packaging for wide temperature cycling, the development of reliability testing regimen which screens for electrical and mechanical/packaging failure modes.

Capacitor requirements vary vastly between applications (e.g. Electro-magnetic interference EMI vs. power supply filter). Thermomechanical reliability over relevant thermal extremes should be ensured for each DRM. Moreover, parameter drift should be inspected and determined to be within application specific tolerances for each case.

Discrete magnetics for space applications are frequently custom wound so few, if any, extended temperature studies of COTS have been published. At low temperatures, winding resistance tends to decrease, due to the thermal coefficient of resistance of the conductor, but magnetic losses tend to increase, due to temperature dependence of core permeability

Discrete Magnetics need better characterisation over thermal cycling, especially with respect to thermomechanical reliability. For asteroid/comet and gas giant DRMs, their operability at temperatures below 83K needs to be confirmed.

Integrated circuit designs usually include **integrated passive components** on the die. Most often these are resistors and capacitors, but low value inductors are also possible. Not much information on the performance of integrated passive components at temperatures outside of the MIL-STD temperature range is available. Process technologies and design rules should be carefully selected based upon the thermal extremes the device will experience in operation and storage.

Component-to-Board interconnection materials and methods have been identified. A primary concern of literature addressing cryogenic behaviour of solder joints is the formation of intermetallic compounds (IMC) (*Figure 4*), which can be brittle and lead to joint cracking and eventual electrical failure.

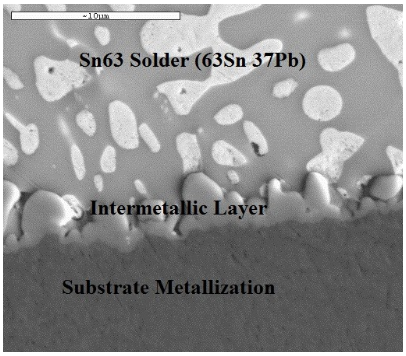

Figure 4 - Formation of intermetallic compounds in soldering. Image: Indium Corporation.

Pure indium solder has shown potential at cryogenic temperatures, as the Cu11In9 IMC formed during soldering does not change over cryogenic cycling, unlike intermetallics observed with SAC305 and other Tin alloys, which have been shown to become brittle over cycling. However, some brittle IMCs have been observed to form in thin Indium solder joints (t < 230um), which may adversely affect cryogenic reliability. More study on this topic is needed.

Conductive adhesives are a possible alternative to metallic solder, but data on cryogenic performance is lacking.

Component on Board (CoB) packaging technology has been examined under wide temperature cycling. Extreme care should be taken in the selection of substrate, die attach, and encapsulant (or conformal coating) materials due to stress placed on wire bonds by the encapsulant. Wirebonded chips inside of a hermetic package might be preferable if SWaP requirements permit. Low temperature co-fired ceramic (LTCC) substrate was shown to be considerably more reliable than alumina and polyimide for CoB applications. Flip chip on LTCC has been suggested as a possible alternative to avoid wirebond fatigue failure mode.

Limited wide temperature cycle testing (77K to 400K, 50 cycles) has been performed on flip chip technology. CTE matching remains important. CTE mismatch between underfill, solder, and substrate creates additional stress on solder bumps, which can lead to pad cratering and eventual mechanical failure of the solder joint.

Reliability of all of these interconnection materials and methods over extreme thermal cycling should be better characterized in benefit of all DRMs.

There is no single enabling technology for packaging for extreme thermal cycling or deep cryogenic environment. Packaging design for these environments should be a methodology rooted in careful material selection taking electrical, thermal, and mechanical properties into consideration. It has been found out that with appropriate design and qualification, packages can be designed to withstand wide temperature operation and cycling. Particularly, CTE mismatch between all constituent parts should be minimized to improve robustness over thermal cycling.

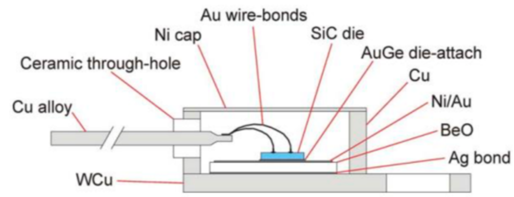

Figure 5 - Cross section schematic of TRL8 Schottky diode packaging qualified for 103K to 543K (-170C to +270C). Image: Godignon et al., Alter Technology Group.

Printed Circuit Board (PCB) materials suitable for space that have been studied over wide temperature are Polyimide, Alumina (Al203), and Low Temperature Cofired Ceramic (LTCC). There exists some literature on these three substrates over wide temperature, but this is mostly limited to small substrates for System-in-Package assemblies. Thermount is another material that shows promise due to its low CTE in the MIL-STD temperature range, but data outside of this range does not appear to have been published at this time. Little has been found on the performance of any of these materials when used in large, multilayer boards that would be required for a rover's power distribution electronics, for example.

It is likely that the reliability concerns associated with extreme thermal cycling are like those experienced at MIL-STD temperatures. Even over this limited temperature range, stresses due to CTE mismatch can be large enough to cause failures in vias (buried and through hole), traces, and pads. Thermomechanical stresses over the BLTAS target temperature range can reasonably be expected to be higher. More research is required to verify this assumption and develop wide and low temperature PCB design guidelines.

More study of PCB performance and reliability over wide temperatures is needed. The robustness of vias due to CTE mismatch during extreme thermal cycling should be better characterized.

Active pixel sensors (APS) are photodetectors with integrated active amplification for each pixel. They are commonly used in star trackers, optical navigation cameras, sun sensors, and mission-specific imaging payloads. The only low temperature performance data identified in literature is a study of a single pixel (silicon photodiode) and integrated amplifier fabricated in "standard 0.35um CMOS" technology published in 2014 (Rosario, Salles, Mello, & De Lima Monteiro, 2014). The results of this study were promising, with the detector and APS electronics functional between 40K and 300K.

Low temperature capable APS may need to be designed from the ground up. Another possibility is to study the feasibility of extending the operational temperature range of existing flight qualified units, e.g. STAR1000.

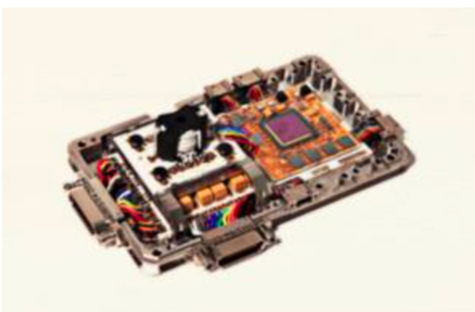

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Figure 6 - Motion control chip (MCC) for Exomars – Image: AAC Microtec

Low temperature **motor control electronics** exist in Europe (*Figure 6*) that can be stored but not operate in low temperatures.

Amplifiers are available in Europe for cryogenic applications (up to 4.2K), however would require increasing the upper boundary of their range to extend it to a suitable range (ideally above 300K)

Navigation and imaging payloads still need to be developed and qualified for extreme environments. At this time, no navigation assemblies (star tracker, Sun sensor, navigation camera, Earth sensor, etc.) which operate outside of the standard space temperature range (218K to 398K) have been identified. One supplier, Sodern, replied that even their deep space navigation systems on JUICE and Europa Clipper missions operate in this range.

Cryogenic imaging payloads are limited to IR (infra-red) sensors and support electronics, such as Teledyne Imaging Sensors H2RG NIR (near infra-red) sensor and SIDECAR Image Processing ASIC (application-specific integrated circuit). These are qualified for operation at 37K on JWST and were installed on the HST during the last servicing mission (operating temperature unknown). The Mid-Infrared Instrument for JWST is slated to be operated at 6.7K or less.

Their robustness over extreme thermal cycling needs to be determined. For lunar temperature ranges, near- and mid-IR cameras have been qualified for the lower end of the relevant temperature range but not the upper end. The temperature range of visible spectrum cameras needs to be extended below 150K in benefit of lunar, asteroid/comet and gas giant moon missions.

Inertial Measurement Units Micro Electro Mechanical System (MEMS) -based need to be extended in operational temperature ranges below 193K in benefit of lunar, asteroid/comet and gas giant moon missions. Their robustness to extreme thermal cycling must be verified, and radiation hardness to TID and high energy particles must be determined for gas giant moon missions. Although they are used on the Mars surface, it is currently understood that this happens inside a warm electronics box. No information was available on fibre optic or hemispherical resonating gyros for extreme environments.

After extensive investigation and to the knowledge of the consortium, little to no low-temperature **LIDAR** assemblies are being operated or have been qualified for extreme environments. The only wide temperature LIDAR identified is the Cyclops Single Pixel Lidar system, designed at INESC TEC (The Institute for Systems and Computer Engineering, Technology and Science), was designed for but never tested at temperatures as low as 173K (Araújo, Magalhaes, Correia, Farahi, & Carmo, 2014).

Low temperature **transceivers** with higher power rating are yet to be developed and qualified. Integrated transceiver assemblies for orbital vehicles typically reside in a warm electronics boxes (WEB). A typical box is rated for operation between 240K and 344K. A 2013 Georgia Tech article(England et al., 2014) describes the development and test of an SiGe BiCMOS wireline transceiver (RS-485 and ISO11898) developed for a Remote Electronics Unit. It is claimed to be operational between 90K and 390K up to 2Mrad and Single Event Upset (SEU) -hardened.

The operational temperature of transceivers needs to be extended below 90K for wireline units (in benefit of asteroid/comet and gas giant moon missions) and below 173K for wireless units (for lunar, asteroid and gas giant moon missions). Their radiation hardening to TID and high energy particles needs to be determined.

For **Command and Data Handling (C&DH) Subsystems**, microcontrollers, processors, mass memories, FPGAs, and other C&DH subsystems for low or wide temperature use should be able to operate reliably in the appropriate environment for the required duration of mission. There are some examples of cryogenic microcontrollers including one in the SIDECAR Cryogenic ASIC, qualified for operation between 30K and 300K. SIDECAR also includes onboard memory, but the technology used to realize it is not discussed in available literature.

Another temperature- and radiation-hardened microcontroller for motor control applications was designed to be functional between 85K and 400K in 2008; its current status is unknown. It is to be 8051 compatible and was designed to operate asynchronously, relying on handshaking instead of a system clock in order to improve reliability over a wide temperature range (Bourne et al., 2008). Various mass memory technologies have been shown to work at low temps, including CMOS DRAM (Dynamic random-access memory), RRAM (resistive random access memory), and both STT-MRAM (Spin-transfer torque - magnetic random-access memory). None of them are known to have been tested for reliability at these temperatures, however. For DRAM, at low temperatures, leakage current tends to decrease and threshold voltage tends to increase.

Flash memory has also been studied down to liquid nitrogen temperature; in this study, flash IC failures were observed along with a batch to batch dependence on failure rate. An admonition that applies to all components used outside of their rated temperature range: design changes which do not noticeably affect performance in the rated temperature range, but may have a large effect on performance or reliability at cryogenic or high temperatures. Some FPGAs, used in all manner of DSP (digital signal processor), COMM, I/O, and other reconfigurable subsystems have been shown to be operational down to 120K

There is a challenge in the development of mass memory assemblies for reliable wide-temperature operation, and of a microprocessor capable of wide temperature operation or qualification of existing radiation hardened microprocessors for extended temperatures. Robustness to thermal cycling must be verified for all C&DH subsystems. The radiation hardness to TID and high energy particles must be determined, especially if the hardware is to be used for Gas Giant Moon missions.

For **LED/illumination units**, discrete COTS LEDs have been shown to be operational down to 6K. Forward voltage drop tends to increase at low temperature. At low temperature, the output of some LEDs tends to display a "blue shift"; some devices have also been observed to develop a secondary or tertiary peak emission wavelength. An array of COTS LEDs was qualified for cryogenic spaceflight on the EUCLID mission for use as a calibration unit for the onboard Visible Imager instrument.

There are challenges related to the integration of discrete LEDs into a reliable illumination unit assembly. Robustness to extreme thermal cycling must be demonstrated. Radiation hardness to TID and high energy particles must be determined.

Key areas which are lacking low-temperature capable solutions: Radhard Microprocessor, LIDAR unit, Inertial Measurement Units (particularly FOG and HRG). Further investigation of thermomechanical reliability is needed for most technology areas covered, particularly in the temperature ranges defined in the Lunar and comet/asteroid DRMs.

3.2 Low temperature mechanical technologies

Piezoelectric actuators are able to work at wide temperature range (from 77K to 353K). Cedrat (supplier) customises actuators for radiation environment. The stroke length of these actuators is very small (50-100 microns); a series of actuators could support higher stroke lengths (up to 5 mm). The actuators are typically used for precision works such as optics and robotics.

Several space-qualified types of **harness** exist for wide operational temperature range (5K to 472 K).

Materials for radiation shielding such as aluminium, titanium, lead, tantalum, are investigated for various radiation environments in e2rad project. The study shows that for equivalent shielding mass a reduction of a factor ~2 is possible in total ionizing dose as compared to Al shielding, when Ta or Pb shielding is used(Wind, 2014).

Equipment that could withstand cryogenic exhaust gases without becoming dangerously brittle is important for **gas handling** in ISRU and propulsion applications. The technology snapshot identifies an equipment that could handle cold cryogenic gas. The challenges include lifetime in thermal cycles of the equipment and influence of radiation on the material.

Cryocoolers are coolers that are used for cryo applications. Cryocooler from AIM Infrarot-Module GmbH is based on Stirling and Pulse-Tube cryocoolers for infrared and high-temperature superconducting applications. Main challenges for space qualified cryocooler is to achieve long life and high MTTF.

The principle of operation of contactless **angular sensors** is to exploit a biasing permanent magnet generating a magnetic field in a gap of suitable geometry. The main technical challenges for this technology are operating temperature range and drift of measurement with temperature.

In order for **gears** to work at low temperatures, standard gears either have to be adjusted in terms of materials and lubrication or a new type of gear has to be used. It is also possible to buy a COTS product and replace crucial parts of it in such way that it can operate at cryogenic temperatures. A promising technology for low temperature applications is magnetic gears being developed by MAGSOAR. The company Harmonic Drive is currently developing a gear (HarmLES) to be used at cryogenic temperatures by using appropriate lubrication and optimized geometries.

Both variants of gears have to prove their capability to work in space. For HarmLES the main challenge is lubrication whilst for OPTIMAGDRIVE the main challenge is to show that it is a reliable and robust technology. The mass of magnetic gears could also be reduced.

Bearings can operate at cryogenic temperatures if proper materials are applied. This has to be considered in terms of CTE and lubrication. While there are no COTS products available directly from suppliers, most of them can manufacture a customized solution. The standardized calculation process of ball bearings does not account for conditions in space. There are also ceramic bearings available that might have no need for lubrication at all (depending on material pairing and lifetime) and offer a wide operational temperature range, but flight heritage is limited. Hybrid bearings combine ceramic with metallic materials. In order to work at cryogenic temperatures, most suppliers can use one of their products and customize it with dry lubrication. In general, operation at cryogenic temperatures seems to reduce lifetime of bearings, but all other performance values are unchanged if materials are selected properly.

Challenges include increasing lifetime of bearings at cryogenic temperatures and increasing the flight heritage for ceramic materials such as $ZrO2$.

Rotary mechanisms can be found in many different applications in space such as shutters, joints for robotic motions, solar array drives, and antenna pointing mechanisms. Specific solutions generally have to be produced individually, also for cryogenic applications. Usually these mechanisms make use of stepper motors or DC motors. Gears and mechanical guidance is also needed to drive rotary mechanisms.

The combination of vacuum and cryogenic temperatures requires the use of dry **lubricants** such as Molybdenum disulphide ($MoS2$), Titanium carbide (TiC), and Tungsten disulphide ($WS2$). Dry lubricants are a well-proven solution with flight heritage. However, they do not offer long lifetimes and have higher contamination rates compared to wet lubrication. Dry lubricants can be applied by different means. One solution is the application as soft metal films (Au, Ag, Pb, In, Ba). Another one is the usage of lamellar solids (Dichalcogenides $MoS2$, $WS2$, $MoSe2$, Pthalocyanines, $CdCI2/PbCI2$, Intercalated graphite, Boron nitride) or coatings with polymers (PTFE/FEP/polyacetal/ polyimide/ PEEK/UHWPE, Phenolic and epoxy resins). It is also possible to use other low shear strength solids (Oxides Cd, Co, Zn), sulfides (Bi, Cd), or fluorides (Ca, Li, Ba, rare earths). Sometimes gold coatings are used as well (Maxon motors for MER, MSL). Operational temperature of oils and greases can be as low as -73 °C but viscosity is much higher at such temperatures compared to room temperature.

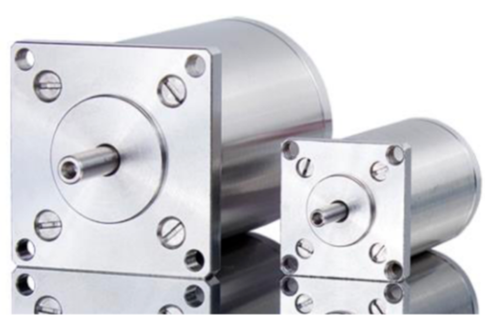


Figure 7 - Phytron VSS/VSH stepper motors, with a temperature range between 4 and 473K. Image: Phytron.

At cryogenic temperatures, **stepper motors** are the best solution for long lifetime. Their operational temperature can be as low as 4 K. Nearly every supplier of stepper motors can manufacture a version that works in vacuum at cryogenic temperatures, built to customer requirements. Phytron offers a product range for space applications (see *Figure 7*). Brushed DC motors can also be adapted in order to work at low temperatures. However, due to the different construction (brushes only work with specific materials) and sometimes the usage of plastics they do not work at cryogenic temperatures and their lifetime is reduced drastically. Examples include the modification of Faulhaber DC-brushed micromotors to allow operation in vacuum at low temperatures and the application of novel, ultra-thin solid lubricant coatings to the commutator for the Rosetta lander Philae. Maxon motors were re-lubricated for the use on Beagle-2, also used on MER and MSL (operational temperature 218K). If the rotational position of a motor has to be known, stepper motors should be used because otherwise sensor are needed that are not available for operation at cryogenic temperatures. Accuracy is then less than with DC and sensor.

The lifetime of brushed DC motors should be improved as it mainly depends on material behavior of commutator at low temperatures. Operational temperatures of brushless DC motors should be lowered- it mainly depends on the internal electronics.

There are various **materials for structures** available which can be used at cryogenic temperatures. These are mainly aluminium alloys, some high-performance plastics, and few austenitic steel alloys. Aluminium alloys are the most common materials utilized for cryogenic application but their tensile strength and yield strength change with lower temperature. Also, some high-performance plastics such as VESPEL and PTFE meet specifications for operation at cryogenic temperatures. Only few austenitic steel alloys (304, 316) can be used at cryogenic temperatures.

Developments of **actuators** for operation at cryogenic temperatures are sparse. One potential type of actuation can be realized by implementing shape memory alloys as suggested for a dust wiper for operation on Mars and also used for HDRM by Arquimea. Another example is the MSL drill which uses electric motors and gears with operational temperatures down to 203K.

Eddy current dampers can be used for absorbing shock loads (e.g. Rosetta-Philae lander) as well as damping vibrations of low load levels. It still has to be shown that higher vibration loads can also be dampened. The dampening relies on magnetic effects which allows the eschewal of wet fluids and consequently a wide temperature range compared to conventional dampening techniques with fluids.

The standard solution for **wheels for planetary surface** operation is to use the aluminium alloy Al7075. All successful Mars rovers of NASA relied on this alloy. Recent research focuses on plastics such as PEEK and other polymers. Those materials still have to prove their reliability for usage on wheels.

3.3 Low temperature energy storage options

Batteries are primarily used in spacecraft for power generation (**primary batteries**) and energy storage (**secondary batteries**). The key parameters for batteries in the context of low temperature environments are operating temperature and energy density.

Primary batteries possess high energy density and comparatively low operating temperatures. This technology is beneficial for short-lived missions. Secondary batteries could be used for several charging cycles and could store electrical energy from sources (solar, nuclear, others). The available energy density of either primary or secondary batteries reduces with operation temperature. Batteries require thermal management system to make sure charging/ discharging process are performed according to given specifications (usually >253K for discharging, >243K for charging and with >248K as the optimal temperature to retain full capacity).

Current space qualified secondary cells possess lower energy density (<200 Wh/kg) compared to terrestrial secondary cells (~450 Wh/kg). Research on secondary batteries with various cathode and anode materials is ongoing to enhance performance such as specific energy, energy density and operating temperature range. However, these batteries require additional qualification for space applications.

Supercapacitors are finding an increasing number of applications in automotive, defence and aviation applications. The specific power density of super capacitors (10-20 Wh/kg) is no match to batteries. However, due to high power discharge capacity, supercapacitors could support power supply from fluctuating as loads change and deliver bursts of high power for equipment such as pyrotechnic separation mechanisms and radars.

Regenerative **fuel cells** are used for high-power applications. A fuel cell consists of an H_2 feed, an O_2 feed and a proton exchange membrane (acting as an electrolyser if reversible). For a given power, the size of the membrane is fixed and energy storage varies with mass of fuel. Therefore, for a given power, the energy density increases for a larger capacity. Their main function of interest is that fuel cells can also generate heat energy and could be used to heat up avionics and other systems. Challenges remain in the sizing of fuel cells for small payloads and spacecraft.

Flywheel energy storage systems are primarily used in terrestrial applications and seldom in space applications. The energy is stored in a spinning flywheel and depends on its rotation rate and mass. The specific power of a flywheel is higher than that of batteries, but due to high mass of the flywheel, the specific energy is very low. Challenges remain in their space qualification.

Cryogenic storage is primarily used in grid energy storage, but due to very low temperature on planetary bodies the gasses (air/O_2/N_2) could be liquefied (for energy storage) and redirect the liquid back to turbine to generate electricity. Current commercial systems are in range of 35 kW and higher. For space missions the desired power rating is about 100W to ~5kW. Scaling down the pilot plant is one of the key technical challenges for future developments

3.4 Energy generation technologies

Solar cells are majorly used in the space industry for power generation from solar radiation. However, for missions beyond the Moon, the solar intensity reduces with increasing distance from the Sun. Also, the intensity of solar illumination decreases on the Martian surface during dust storms. The development of Low-Illumination Low-Temperature (LILT) cells is meant to address the illumination and temperature issues present at various planetary destinations, allowing operation down to 123K. Other technology that increases solar cell efficiency by reducing optical losses is antireflection coatings. A thin nano-layer coating on surface of solar cells could efficiency of solar cells from 3 to 5%. Main challenges of this technology are thermal cycling of coating and influence of dust on coatings.

The power density of radioisotope-based power generation systems (5-8 W/kg) is very low compared to photovoltaic cells. However, the system continuously produces power (day/night) and provides heat to systems. There are several ways to convert heat from the radioactive material into electricity. Some of these energy conversion technologies include thermionic converter, Thermophotovoltaic cells and dynamic generators (such as Stirling cycle generators). A Stirling radioisotope generator from Sunpower Inc achieves overall efficiency of 29%.

Some of the technical challenges and solutions include: a) efficiency of generator which can be achieved by increasing temperature ratio of cold and hot ends of the generator b) wear and tear of equipment which could be reduced by employing non-contacting moving parts, non-degrading flexural bearings, and a lubrication-free and hermetically sealed environment c) vibration which can be eliminated as a concern by implementation of dynamic balancing or use of dual-opposed piston movement.

3.5 Thermal control

The applications of **Multi-Layer Insulation (MLI)** are constrained by the ambient gas pressure on the respective planetary body. Technical improvements for MLI include the reduction of fixation points and seams where the insulating effect is lowest due to compression of the individual layers. Integrated Multi-Layer Insulation (IMLI) and Load Responsive Multi-Layer Insulation (LRMLI) are innovative new technologies to improve the spacing of the layers in general and under load. Another challenge for highly variable thermal environments is the high-temperature capability of the materials used for MLI (both reflective layers and netting).

The selection of the right **Phase Change Material (PCM)** is challenging in the design of cryogenic systems. The utilized medium must be operating reliably in a given temperature range, which can be an issue if broader temperature ranges are experienced. Besides this, another technical challenge, which needs further research, is the homogenous transfer of heat into and out of the PCM to enable a reliable thermal control.

Similar to MLI, **aerogels** have very good thermal insulation performance in a vacuum. If the gas pressure in the voids of the microporous material increases, the insulation efficiency is significantly lower. The main challenge for incorporating aerogels in a low-temperature system is the low structural integrity under load. Generally, the porous materials with lower density have a lower thermal conductivity. Aerogels exist in the form of blankets and plates. However, the latter non-flexible aerogels with very low thermal conductivity are also very brittle and hence susceptible to static and dynamic stresses. Higher stress resistance can be achieved with carbon fiber reinforced aerogels, which are either aerogels that incorporate carbon or aerogels that are encapsulated in carbon shells (such as Ultramet TPS). One of the advantages of aerogels besides their thermal insulation is the high-temperature capability, which makes them a good choice for extreme temperature applications.

The choice of the right medium is crucial to the efficiency of an either passive or pumped **fluid loop** system. Similar to PCM, the phase changing medium has only a limited operating temperature range and hence the design requires a detailed thermal analysis of the operating environment. Another factor for fluid loops is the dependence on gravity. Higher gravitational forces in the wrong direction might lead to reduced flow of the liquid phase through the capillaries. The geometry and length of the fluid loop pipes and their capillary design must therefore be adapted to the respective mission and system requirements.

Radiators are generally robust passive thermal control systems. The main challenge in the design is the choice of surface composition, a homogenous temperature distribution along the radiator, and thermo-optical properties to achieve an efficient heat transfer via radiation in the given thermal environment. For a highly changing thermal environment, adaptive radiators can be of advantage. New technologies in this area include thermochromic or shape-morphing adaptive radiators. For dusty environments, such as the Moon, Mars, or comets, a certain surface degradation through dust contamination must be taken into account. This mainly alters the thermo-optical properties of the surface and might lead to a reduced efficiency of the radiator.

While the information above is a summary of the findings of the research made for implementing the catalogue of technologies, requests for more detailed information on this catalogue and its contents, and to be included in it can be made at *bltas@spaceapplications.com*.

4. <u>Extreme Temperature Architecture Design Study</u>

4.1 Case Study

LUVMI (Lunar Volatiles Mobile Instrumentation) is an EC H2020 project started on Q4 2016, and coordinated by Space Applications Services, with a consortium that includes the Technical University of Munich. LUVMI has been initiated based on the Lunar Exploration Analysis Group (LEAG) Volatiles Specific Action Team (VSAT) findings, which conclude that 4 of its top 5 scientific priorities can be fully addressed with a mobile payload that has the capability to access depths of 20cm and the 5th priority can be partially met. (Only a rover capable to drill to >1m depth fully meets all 5 priorities, but this comes at a high cost in terms of mass, funding and time).

Figure 8 – LUVMI Rover early prototype

- The rover will work on the surface nominally, for up to 14 days in a region where sun exposure and a DTE link is available; and it will be able to traverse a (non-permanently) shadowed area (70 meters in 70 minutes), enter PSRs that have a direct view of Earth and travel within the PSR. The rover will enter the PSR by performing a 100-minute traverse. It will then initiate an operational cycle consisting in a) taking a panorama of the site (20 minutes), b) dump data

via X-band (20 minutes) and c) performing a sampling operation (145 minutes). After further operational cycles can be performed (available energy allowing), each consisting of a 10-minute traverse to a new site, taking a panorama, dumping data and sampling in the same manner as in the first cycle. The remaining battery capacity at the end of X operational cycles shall be enough to allow for a traverse out of PSR (Permanently-Shadowed Region), with an energy margin.
- The operations are made through a combination of direct teleoperations and supervised autonomy, depending on the mission conditions.
- The rover can be exposed to the night for 17.7 hours in hibernation mode in areas that remain shadowed for much less than 14 days (areas present only in high latitudes, target of the LUVMI baseline mission).
- With the intention of being able to piggy-back on available flights, LUVMI is designed to have a degree of flexibility regarding landing sites and missions to piggyback in.

Figure 9 LUVMI simulated night-time operations with early prototype, in an Earth analogue environment

An initial design guideline was created for the early rover concept analysis:

- LUVMI has a baseline payload composed by a Volatiles Sampler, a Volatiles Analyser and a set of imagers. These instruments are provided locomotion by a robotic platform, allowing to measure rapidly and at many points covering a wide area, the volatiles present below the surface.
- The Locomotion subsystem will make use of a set of 4 wheels allowing dampening the mechanical impact of the terrain and obstacles on the rover. The distributed drive wheels are installed on a parallelogram-based active suspension system.
- The robotic platform provides a way for the Volatiles Sampler to drill into the lunar ground up to 20 cm deep, through a combination of a lowering actuator, and the use of the active suspension to further provide travel range and stability.
- After drilling, a central heating rod inside the drilling cylinder of the Volatiles Sampler, heats up the regolith, releasing the volatiles that then diffuse towards the Volatiles Analyzer, where they are characterized.
- The hardware is protected from the extreme lunar environment through a hybrid architecture involving both technologies requiring dedicated heating (in a centralized Warm Electronics Box, and in peripheral warm assemblies) and technologies that are ruggedized up to the thermal cycling and extreme temperature levels involved in the operation in and out of shadowed sampling areas. Of interest is the fact that harnesses that are exposed to the cold environment are sufficiently rugged.
- The power system uses a combination of solar power and rechargeable batteries. It provides bus voltages of 28V and an average power for the mission of 150 W. The use of non-regenerative fuel cells has been considered, and remains an option, however the initial approach is to use a battery-only solution to reduce complexity. The system uses a sail-like solar panel rotating on a single gimbal, as the sun is at very low elevations in the target latitudes.

Table 1: LUVMI baseline mission

Mission	LUVMI
Destination:	Lunar South Pole, latitudes >80 degrees
Surface Duration:	14 days
Primary Spacecraft:	Rover
Power Strategy:	Solar cells and rechargeable batteries
Communications Strategy:	DTE link (relay satellites and communication through lander also possible but not part of LUVMI baseline configuration)
Survey Track	5.4 km (mission-dependent)

Mission	LUVMI
Science	Volatiles Sampler, Volatiles Analyser, imager, ground temperature sensor, ground penetrating radar.
Mission Energy	1400 W-hr available
Mission Average power	~150 W
Platform Mass (no payload)	38.8 kg
Max payload mass:	~20 kg
Payload mass used in model	7 kg
Launch Vehicle:	Flexible
Mission Profile	LEO to LLO of up to 1-month TBC Holding in LLO up to 4 months TBC

4.2 Architecture study and simulation methodology

The objectives of the simulation effort as part of the BLTAS project are to:

- Characterise the preliminary individual performance (power/thermal) of different architecture strategies expected to improve the performance of LUVMI in an extreme environment,
- Provide an indication of the specific strategies that provide the best performance enhancements and combine them in a single approach, dubbed BLTAS architecture.

The simulations were conducted using a MATLAB thermal model of the architecture. Several simplifications were made with respect to an originally available ESATAN thermal geometrical model of LUVMI in order to facilitate the fast iterations required for this short study. It was assumed that the radiation between components is negligible, and each component was a single node the temperature of which was changing equally over its entire volume.

Several alternatives were identified based on the technology survey performed during the BLTAS project. In the study, a simulation of the benchmark architecture is initially performed, then the study established the influence of different individual architecture solutions (4 test architectures) with a focus on Low-Temperature avionics in combination with different energy storage solutions.

Once the 4 test architectures were simulated, a final architecture was proposed that integrated the architectural choices that brought in the most benefits.

Benchmark architecture: Regular avionics with heaters preventing the components from dropping below survival temperatures

Architecture 1: the regular avionics was replaced by dedicated low-temperature avionics, with lower survival temperatures and consequently lower heater power requirements. The power supply and thermal control are the same as in the baseline, allowing for the estimation of relative performance of the two options when implemented in the rover.

Table 2: Benchmark and Architecture 1 mass breakdown

Benchmark and Architecture 1 mass breakdown		
Component group	**Mass [kg]**	**Mass [%]**
Rover	29.8	71%
Battery	12.0	29%
TOTAL	**41.8**	

Architecture 2: In Architecture 2, Phase Change Material components for thermal control were added to Architecture 1 to evaluate their influence on the power required by the heaters to keep all components within operating temperature ranges.

Table 3: Architecture 2 mass breakdown

Architecture 2 mass breakdown		
Component group	**Mass [kg]**	**Mass [%]**
Rover	29.8	70%
Battery	12.0	28%
PCMs	0.8	2%
TOTAL	**42.6**	

Architecture 3: In Architecture 3, the battery power supply from Architecture 2 was replaced with a fuel cell and a backup 200Wh battery of the same combined capacity. The use of the dissipated heat from the fuel cell to heat up cold components and lower the required heaters power was investigated.

Table 4: Architecture 3 mass breakdown

Architecture 3 mass breakdown		
Component group	**Mass [kg]**	**Mass [%]**
Rover	29.8	69%
Support battery	2.0	5%
Fuel cell	11.7	27%
TOTAL	**43.5**	

Architecture 4: In Architecture 4, Phase Change Materials were implemented together with the Fuel Cell from Architecture 3.

Table 5: Architecture 4 mass breakdown

Architecture 4 mass breakdown		
Component group	**Mass [kg]**	**Mass [%]**
Rover	29.8	67%
Battery	2.0	5%
Fuel cell	11.7	26%
PCMs	0.8	2%
TOTAL	**44.3**	

In addition, the influence of the initial temperature of the rover components on survival time and/or additional traverse time available was investigated.

Note that no architecture makes use of radioisotope-based devices. This is an intentional decision by the team to favour the exploration of architectures based on the many other low temperature technologies investigated during the study that address the thermal issue in alternative ways, and also due to the expected difficulty of obtaining permissions to utilise these devices in the foreseeable future for a rover like LUVMI.

4.3 Simulation Results

Modelling the thermal behaviour of the baseline architecture in a Permanently Shadowed Region and Night Survival scenarios showed that the standard avionics and baseline thermal approach is sufficient to conduct basic operations in the PSR and a comparatively fast traverse back. This baseline architecture will be the lowest in terms of cost of development, however, has drawbacks in that the operations durations are short, and there is little flexibility in trading operations duration for reduced risk (i.e. more time and energy allowed for traversing back to the illuminated area).

The benchmark architecture was evaluated by the time available until the battery reaches a critical level (ie. has enough energy left to traverse out of the shadowed region in the PSR scenario and is fully depleted in the Night Survival scenario).

The benchmark architecture implements the regular avionics as used in the baseline LUVMI design. Thermal control is achieved via passive heat switches for the few components likely to overheat and heaters providing power to the components the temperature of which is dropping during operations.

It is assumed that radiation between different nodes is negligible, and so the outer parts of the rover radiate to space or ground only.

For additional insight results were also obtained for a preheated benchmark architecture with component initial temperature at 313K (as opposed to 263K).

The following are the results obtained for the benchmark architecture:

Table 6 - PSR and Night Survival performance of the Benchmark architecture

Scenario	**Time until battery at critical level [hr]**
PSR	6.38
PSR (preheated to 313K)	7.36
Night Survival	17.70
NS (preheated to 313K)	19.80

Based on these times, the baseline architecture is not sufficient to perform more than one operational cycle (as designed) and could not achieve a 14-day lunar night survival requirements (as is the case for all explored architectures in this small rover). The high survival temperatures of regular avionics necessitate high heater power requirements, causing fast battery depletion.

4.3 Simulation Results and BLTAS Architecture performance

The thermal control and all component characteristics, as well as operations durations and characteristics remained unchanged between architectures to allow for meaningful comparison. The preliminary results provide insights into the functioning of different architectures.

The full temperature evolution plots for the new architectures are included in Appendix B and energy depletion plots in Appendix D.

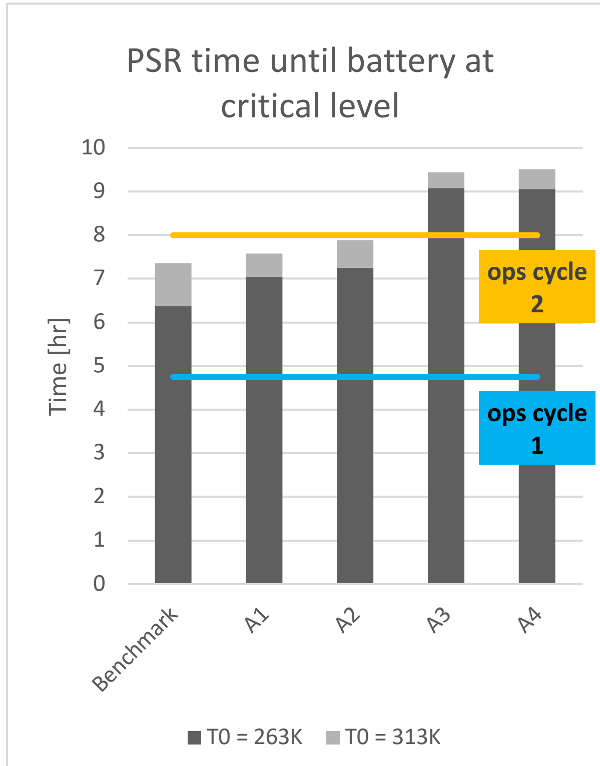
Incursion into a Permanently Shadowed Region (PSR)

The following results were obtained for different architectures in the PSR scenario:

Table 7 - PSR performance of the 4 investigated architectures

Architecture	Time until battery at critical level [hr]
Arch. 1	7.05
Arch. 2	7.26
Arch. 3	9.08
Arch. 4	9.06
A.1 preheated to 313K	7.58
A.2 preheated to 313K	7.88
A.3 preheated to 313K	9.44
A.4 preheated to 313K	9.52

Figure 10 - Operational time inside the Permanently Shadowed Region for the various architectures



While the influence of the Phase Change Materials used in Architecture 2 is noticeable, it is expected to be a complex implementation that could be matched with a small increment in the battery size. PCMs do not improve the survival time at all in the FC architecture. However, it is clear that using a fuel cell and optimizing the heat dissipated by it significantly extends the operational time while also saving mass.

The operational time gained in each of the cases can be translated into additional operations (increasing the science/prospecting throughput) or additional time to exit the PSR (lowering the risk). With this, operational flexibility is also gained.

(Short Polar) Night survival

The following results were obtained for different architectures in the Night Survival scenario:

Table 8 – Night survival performance of the 4 investigated architectures

Architecture	Time until battery depletion [hr]
Arch. 1	41.40
Arch. 2	42.00
Arch. 3	55.20
Arch. 4	56.90
A.1 preheated to 313K	43.70
A.2 preheated to 313K	44.60
A.3 preheated to 313K	58.90
A.4 preheated to 313K	59.60

The benefits of including a fuel cell instead of a battery are even more evident in the Night Survival simulation, where we see an almost 14-hour increase in survival time. The results also contribute to a decision to discard Phase Change Materials from the BLTAS architecture, as their contribution to the survival time is very small.

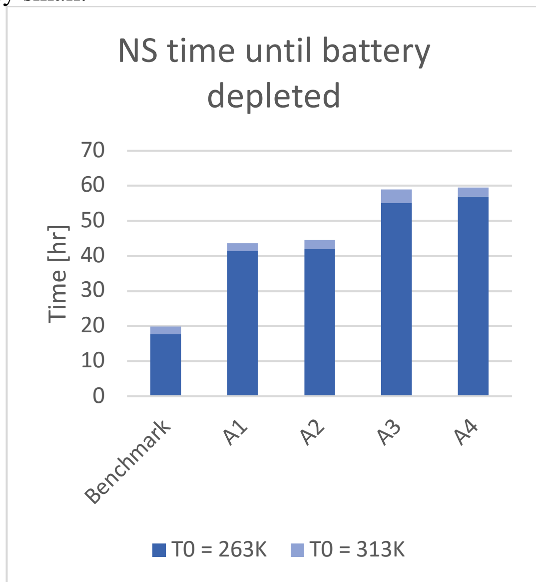


Figure 11 – (Short Polar) Night survival time for the various architectures

The team selected Architecture 3 as future reference low-temperature architecture as the PCM mass can be more effectively replaced by additional fuel cells or batteries (see Table 9) with the benefits of less development complexity. Further optimization work is to be performed regarding the fuel cell size and capacity.

Table 9 - Energy capacity for the different means of energy storage

Energy capacity (approximate) [Wh/kg]	
Battery	116
Fuel cell (small cell in rover)	318
PCM (Dodecane) (phase change heat)	58

4. Impact analysis

An impact analysis was made of the proposed architecture (BLTAS Architecture 3) when compared to the Benchmark LUVMI architecture. This analysis is is summarised below:

Aspect	BLTAS vs LUVMI architecture
Size	Slightly higher due to volume of RFC and ancillary equipment
Mass	Slightly higher, as fuel cell has lower energy density
Cost	Higher due to technology development
Complexity	Higher, mainly due to additional complexity of fuel cell integration
Mission lifetime	Equal (by definition the mission ends at start of long lunar night for the reference mission).However multi-lunar day missions become possible in a larger number of polar areas.
Operational Flexibility	Increased flexibility in site selection and in exploration target selection (differently sized PSRs) Possibility to perform shorter and longer incursions in PSR with variable risk.
Science output	As A3 and A4 allow a second ops cycle, the science output doubles
Maximum possible duration of operations inside Permanently Shadowed Region (PSR)	Longer in single incursion and at overall mission level, or less risky in equally long incursions. (Multiple incursions: Total duration of 2.58 earth days for BLTAS and 2.11 earth days for LUVMI)
Maximum possible duration of (short) night survival	Longer or less risk in equally short periods(2.5 earth days for BLTAS and 0.83 earth days for LUVMI)
Total duration of operations necessary to accomplish mission objectives	Minimum mission objectives accomplished by both in the allocated timeframe. BLTAS allows an enhanced science output (is traded with risk)
Operations Feasibility and risk	Operations feasible in both cases, reduced risk in the case of BLTAS (is traded with science output)
Reliability	All other elements being equal, BLTAS architecture introduces extra redundancy in the Power Subsystem, providing a level of additional reliability
Development time	Higher due to technology development

Aspect	BLTAS vs LUVMI architecture
AIT aspects	Additional complexity due to regenerative fuel cell configuration and necessary GSE.
Planetary Protection	Equal

5. Technology Demonstrator

A demonstrator is proposed, having as a primary goal, to design and develop the BLTAS technologies of interest for BLTAS architecture 3, and to verify and validate the technologies in the context of a reference mission (LUVMI). The technical scope of this technology demonstrator includes the development of technologies or test articles to demonstrate and a testbed that serves the purpose of providing a platform to demonstrate the technologies in an integrated operational scenario in a relevant environment.

This proposed effort has as an input the work performed in the LUVMI and LUVMI-X projects, in particular in terms of system and electromechanical design (baseline architecture).

The development consists of:

- A short study consolidating the architectural solutions
- Development of a. Structural and Thermal Model of LUVMI
- Engineering and Qualification Models of the Low Temperature Architecture products (low, medium and high TRL)
- Integrated environmental testing with mission profiles

The proposed demonstrator activity has a duration of 2.5 years. Various combinations of activities have been identified to meet future priorities and/or programmatic constraints.

Exemplary Development	Cost (KEUR)
Fuel cell-focused activity (Rover STM and Fuel Cell)	4 000 to 6 000
Wide variety of COTS products for extended temperature ranges (Rover STM and avionics)	6 000

Exemplary Development	Cost (KEUR)
Full-fledged technology development	9 000 – 16 000

6. Conclusions

Technologies for low temperature electronics assemblies remain at low TRL in a portion of the BLTAS temperature range. Enabling design and test methodologies, behavioural models need to be developed before components and products can be developed. Only one TRL9 (100K-540K) qualified component was identified (SiC Shottky from Alter technologies).

At a device/component level, continued development of development models is required as well as the development of low temperature and rad-hard design libraries. Live and qualification tests perceptive to low temperature failure modes are required.

For packaging and interconnect aspects, low/wide temperature capable materials are required, as well as related packaging design and fabrication methods. Life and qualification tests for low temperature and wide temperature cycle environments is necessary.

Regenerative fuel cells are a promising means of energy storage for planetary missions as they can also generate heat energy and could be used to heat up avionics and other systems. Challenges remain in the sizing of fuel cells for small payloads and spacecraft.

The technology to use mechanisms in a low temperature, ultra high vacuum environment is already available. However, hardly any COTS components are on the market and the chosen solution might require intensive test campaigns to prove its TRL because especially tribological behaviour at cryogenic temperatures is hard to predict. Also, available thermal control components can withstand harsh conditions if proper materials are chosen. The main challenge for thermal control is the wide range of temperatures.

A preliminary assessment using a reference thermal architecture model was performed for the case of a PSR incursion and short polar night survival. This assessment allowed to preliminarily observe that a combination of a) fuel-cell based architecture b) the replacement of standard temperature avionics for low temperature avionics and c) the use of alternative energy storage means, has the potential to improve by almost 30% the performance of the rover inside a PSR, and to improve the night survival time by 200%. This is a relevant improvement, even if still far from low-latitudes lunar night survival which would be challenging for a small lunar rover without the use of Radioisotope Heating Units. This improvement has the potential of enabling multi-year rover missions with small rovers in highly illuminated areas.

Given the needs for science missions in the following decades and the potential strong commercial interest in exploring areas with extreme conditions, technology development in the area of low temperature avionics, batteries, fuel cells and thermal control technology is encouraged, in particular in view of the significant number of near future lunar missions.

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