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Freezing through the Lunar Night: A Power System Concept for Small Lunar Experiments to survive Multiple Day/Night Transitions

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In the wake of upcoming large-scale lunar exploration missions (e.g. ARTEMIS) and advances in medium-sized commercial cargo missions the availability of ride-share opportunities enables a new class of independent small payloads. The department of Avionic Systems of the Institute of Space Systems (German Aerospace Center, DLR) is currently developing an experiment to measure the electric field during the day/night transition of the moon (Lunar Surface Charging Experiment, LUCENT). For LUCENT to achieve the goal of capturing multiple transitions, it has to operate into and survive the lunar night. Furthermore, to minimize external disturbances it is designed as a standalone experiment of about 5 dm^3 total volume. The combined requirements of small size and surviving the lunar night require a new approach for the overall design allowing the system to completely cool down. The scope of this paper is the design and development of a small-scale power system for long-term lunar surface operations as well as the supporting thermal tests of batteries, electronics and switches. Finally, a prototype to validate the operational scenario in terms of temperature cycling and lighting is presented. Although tailored for the application in the LUCENT experiment, this approach could be suitable for many small sensor systems that can tolerate low temperatures and limited night time operations.

Key Words: Lunar Surface, Power System, Low Temperature Electronics

Nomenclature

A : area, m^2
EPS : electrical power subsystem
TID : total ionizing dose
LUCENT : lunar surface charging experiment
LN2 : liquid nitrogen
TVAC : thermal vacuum
SEE : single event effect
SAS : solar array simulator
Subscripts
0 : initial

1. Introduction

In recent years space systems, especially for low-earth orbit (LEO), became more and more miniaturized. This allows to save launcher space and costs while concentrating resources on scientific payloads. Today, CubeSats and nanosats offer opportunities for universities and research institutes to test new technologies or perform small experiments in space with a reasonable reliability.[1]

The upcoming missions to Moon and Mars raise opportunities for small payloads to be deployed in the orbit of other celestial objects or even to be placed on the surface. Especially the surface is a challenging environment for payloads due to temperature, dust and radiation. One of these missions is the Lunar Surface Charging Experiment (LUCENT) proposed by DLR Bremen to investigate the charging of the lunar surface, especially during the day/night transition. The topic is of special interest due to its influence on the lunar dust – a growing problem for current and future moon missions.[2] Due to the limited volume and mass available on the flight opportunities, the thermal design is an integral part of the overall system. Particularly the temperature of the battery and the scientific instruments need special attention.

A previous mission with similar scope is the Apollo Lunar Surface Experiments Package (ALSEP) as it was a long-term (1 year design life) stand-alone experiment to be operated after the Apollo crew left. ALSEP supplied multiple experiments with power and relayed their data back to earth. Furthermore, it provided thermal control for all experiments. However, it weighed in at over 160 kg and relied on a radioisotope thermoelectric generator (RTG) to provide electric energy & heat during the lunar night to keep its systems at nominal temperature.[3]

As the use of an RTG is impossible for LUCENT due to availability, handling and mission type the topic of this paper is a power system concept that survives low temperatures and enables the long-term operation of small temperature insensitive payloads on the lunar surface. Through miniaturization this approach could enable systems below five kilograms overall mass for long term lunar surface operations.

2. State of the Art

Currently only the large Chinese Chang’e landers are operational on the lunar surface. They use solar cells for power generation but rely on a radioisotope heating unit (RHU) to prevent complete cooldown during the nearly 15 days of lunar night.[4]

Additionally, multiple commercial companies are aiming at landing robotic missions on the moon in the near future. One example is the Astrobotic Peregrine lander. Compared to the Chinese long-term missions it is designed specifically without survival of the lunar night in mind and avoids the use of radioactive materials.[5] These commercial landers are large systems due to the necessary landing and propulsion systems as well as catering at paying customers.

Reference 6) gives an overview of different approaches to survive the lunar night with a special focus on smaller missions. Besides the already noted nuclear energy sources, large scale shielding and burying of sensitive equipment underground are noted as alternative possibilities. Most interestingly a mathematical model for the scaling of battery powered systems with internal thermal control during the night using a given set of materials, insulation and internal temperatures is derived. Using reasonable assumptions about integration density (220kg/m³ for the system and monolithic batteries with 1250 kg/m³), heat transfer coefficients (0.04 W/m²K) and energy density (136 Wh/kg) it provides a mass ratio of system mass to energy storage mass. A ratio of 1 is interesting, as this is the limit case where internal thermal control is viable, but no additional payload can be supported. This model suggests a minimum overall system mass of about 2.5 kg for battery powered thermally controlled systems on the lunar surface. However, this theoretical value includes no payloads but only a thermally isolated battery heating itself. [6]

An alternative approach discussed in Reference 7) is to drop the requirement of continuous thermal control of the system. Recent research suggests, that lithium-based batteries are tolerant to low temperature environments when no current is drawn from them. Even multiple cycles of fast freezing (up to 50 K/min) in liquid nitrogen (-196 °C) seem to have minimum impact on the overall capacity of the batteries for low cycling applications. [7][8] Furthermore, electronics seem to operate well at far lower temperatures than indicated by their ratings and tolerate even lower temperatures when not operational. Enlarging the operational temperature ranges of components could reduce the necessary thermal management efforts and enable small and lightweight stand-alone missions. [9]
Although multiple publications about the components for a hibernating lunar experiment exist, those are either focused on single aspects or geared towards larger systems.. Concepts as published in Reference 10 and 11 use a similar approach to the one presented here but require active electronics for pre-heating and battery monitoring. Opposingly this publication tries to show the bare minimum approach relying solely on a thermo-mechanical switch to control the system state and no active battery control electronics. [10] [11]

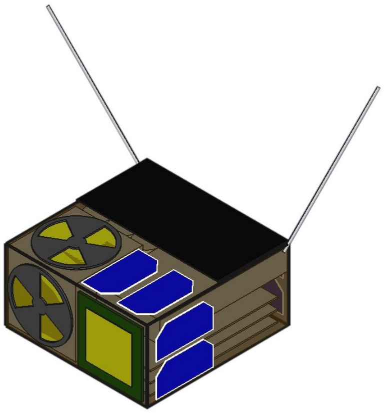

Fig. 1. First concept for the LUCENT experiment showing the accommodation of solar cells, field mills, Langmuir probes and antennas.

3. LUCENT Mission Overview

LUCENT is a concept for a small payload of max. 5l volume. It shall be transported to the lunar surface by one of the upcoming lunar missions and will measure the electric field on the surface. This data is especially interesting during the transition between day and night, as the changing influx of solar particles also changes the local electric field [12]. A possible application of the data is the improvement of the dust particle migration models by actually measuring the surface field during the transition instead of relying on the measurement of effects on orbital systems. The expected time frame of the change in electrical potential due to illumination is in the order of seconds. [13]

The collected data will be relayed to the lander and from there transmitted to earth. Figure 1 shows a first concept for LUCENT with the basic components accommodated in a 20 x 20 x 10 cm³ box.

Currently LUCENT is only a design study, thus the design is based on many preliminary estimations. As a first design assumption, LUCENT shall be able to operate 20 hours into the lunar night and only the dusk shall be observed. Furthermore, it shall be able to monitor at least three sunsets to supply comparable data about multiple sunsets. Due to the size constraints as well as the specific interest in the dusk and dawn changes, LUCENT will rely on battery power to supply its components. Primary batteries with high energy density are a possible solution to capture data during a time limited mission as demonstrated by MASCOT [14]. They can theoretically support the payload through a single dusk but will restrict operations to one science phase as the batteries can not be recharged. An alternative solution is using rechargeable batteries and a small solar array to enable the collection of data during multiple lunar days. The following paragraphs give a short overview about the expected environment, some design assumptions for the overall system, the basic design of the power system and the associated concept of operations from a thermal and power point of view.

3.1. Thermal environment

The central aspect making the lunar environment complicated for small systems is the length of the lunar day and night. With one cycle lasting over 29 earth days, the temperatures on the surface are varying between up to 123 °C during the day and down to -178°C at the end of the night. These variations are also varying significantly with the location on the surface and the local geological features.[15]

As a starting point for the design, a landing site at 75° longitude was selected for LUCENT. The high inclination reduces the thermal load during the lunar day, but also means a low solar influx for power generation. For this environment a thermal model to test the power system against was devised. As it was tailored for quick iteration, LUCENT is assumed as a monolithic box covered in MLI and placed on a 2 x 2 m² block of regolith[16-18]. A radiator is mounted on the top surface and keeps day-time temperatures low. The solar array is mounted on thermally insulating stand-offs to prevent additional heat input during the day. No thermal control is implemented and LUCENT dissipates a fixed power of 0.5 W continuously to mimic the expected losses due to basic operation during the day. Figure 2 shows the resulting internal temperature as well as the operational temperature limits for the components (-40 - 60 °C). It can be seen, that the internal temperature starts dropping below 0°C already well before the actual sunset begins.

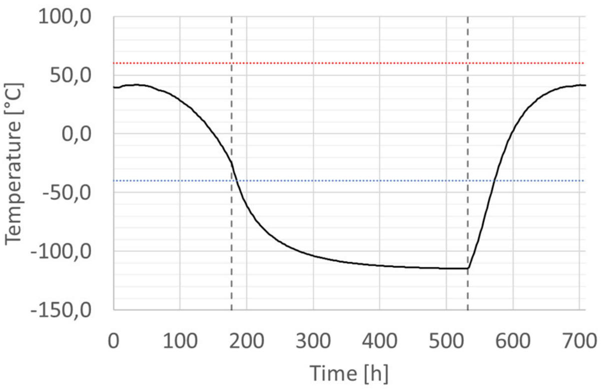

Fig. 2. LUCENTs internal temperature during one lunar cycle starting at noon. Red and blue indicate operational limits for the components. The vertical lines indicate dusk and dawn.

3.2. Power System Concept

Normally, the battery of a spacecraft is thermally controlled to prevent it from operating outside of its specified operational temperature range. Since the lunar night lasts 14 days and LUCENT does not offer the volume to equip it with a lot of battery capacity, it is planned to dismiss continuous thermal control of the rechargeable battery and instead let the system cool down into hibernation once its battery is depleted. The battery heater will be used to extend the operational phase of the system until the battery is discharged. The novel idea in this paper is to use a mechanical thermostat switch to disconnect the rechargeable battery once it reaches a critical temperature. Besides providing a means for battery isolation during the night, the switch also reconnects the rechargeable battery once the temperatures reached a sufficient level for charging.

Figure 3 gives and overview about the operational concept for this kind of power system. At dawn, the system is still cooled down from the lunar night, the battery is discharged and with the rising sun the system slowly warms up. As soon as the solar array receives some light, the available energy is directed to the internal heater. This speeds up the warming of the rechargeable battery. As soon as the mechanical battery switch gets above its switching temperature, the battery is connected to the power bus and starts charging. Depending on the scaling of the solar array, charging may only start once the heater is turned of completely. With stable power input and heated to nominal operating temperature, any excess power can be used for the payload as well as radio communication. As indicated by the green block in the background, payload operations can extend into the night for as long as the battery is connected. During the day, the temperature of the system will rise above the set heater levels, but as indicated by the preliminary thermal analysis, stays within operational limits. The power system fully charges the battery from the solar array and any excess energy is either used up by experiments or dissipated by the solar array. With the battery fully charged, all operational power is drawn directly from the solar array, until the solar input is not sufficient for nominal operation any more. The battery starts supplying the remaining energy and the system

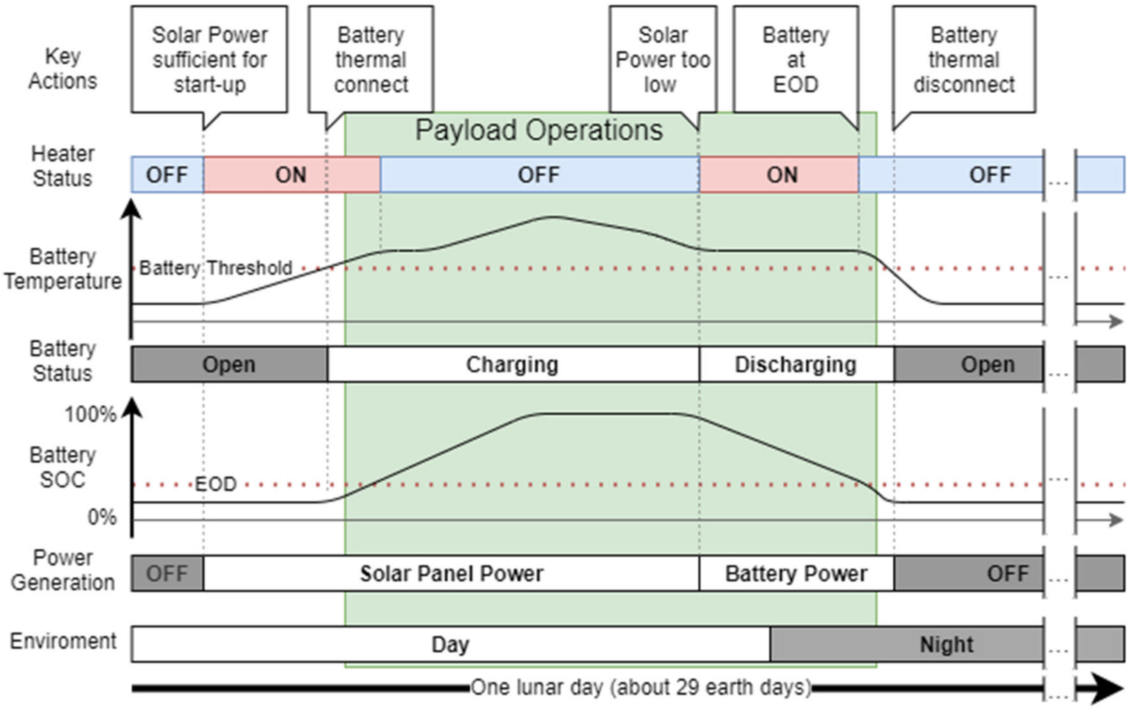

Fig. 3. Operational overview of power generation and temperature control for the proposed power system. Temperature curves are only qualitative.

slowly transitions to being powered exclusively from the battery. The heater is controlled to keep the system 5 K above the switching threshold of the battery switch to ensure stable operation. In this configuration the system is fully operational and can monitor the sun down and the early lunar night until the battery is discharged to its designated End of Discharge voltage (EOD). Once EOD is reached, the heater is turned of and the system starts cooling down. Additional data can be collected until the mechanical thermostat disconnects the battery and forces the system into hibernation. During the lunar night all systems are turned off and the battery is electrically isolated from all consumers and possible leakage currents.

The central aspect of this approach is to enable long-term missions with low weight and small size. Avoiding constant thermal control allows to use smaller batteries as they do not need to provide energy for heating through the entire lunar night. Using a mechanical thermostat switch avoids any active electronics for activation and deactivation of the hibernation state and ensures a controlled electrical environment for the rechargeable battery during the cooldown phase.

4. Power System Design

This chapter gives an overview about the design considerations for a power system to operate according to the previously described concept in the expected environment. The basic assumption for the design is the survival of 10 lunar days to ensure the repeated collection of scientific data.

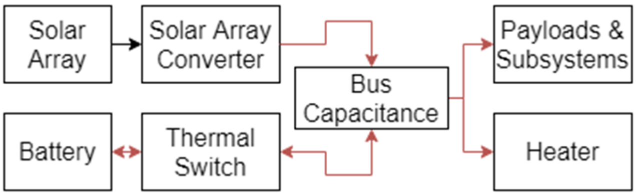

Fig. 4. Block diagram of the necessary Power System Components.

Figure 4 shows the necessary components needed to implement the system and their interconnections. The power source is a solar array, that is connected through a voltage converter with maximum power point tracking and a constant-current/constant-voltage characteristic. This limits the charge voltage of the battery when connected but also the initial current into the central bus capacitance. This bus capacitance is required as stable operation of the system without a connected battery occurs after the night has ended but the battery is still cold. From the bus capacitance all loads are powered. This includes heaters, other subsystems and the scientific payload. The rechargeable battery is connected to the bus capacitance through a thermostat switch that disconnect the battery connection below a specific temperature.

4.1. Battery Considerations

The batteries main task is to supply power to payloads and heaters when the sun is setting and generation is not sufficient to satisfied power demand. All of the supplied power is converted to heat inside of the system. Thus, the battery is basically only storing energy to heat itself to a sufficient operating temperature. It has been shown that there is an optimum for operating temperature for batteries in this case. Furthermore, the data suggests that commercial high energy-density lithium ion cells are best suited for the application. The higher energy density offsets the extended operational temperature range of specialized low-temperature cells when self-heated to the optimum temperature. [9] Thus, a commercial lithium based rechargeable battery is selected for further analysis and the operational temperature during heating is set to -10°C as a starting point.

Data published on the cryogenic freezing and prolonged storage of lithium ion batteries suggests no significant degradation of the capacity occurs for up to ten cycles. However, these measurements happened either in open circuit condition or with a measurement system with an internal resistance of over 1 GOhm. The influence of leakage on the cell´s behavior has not been studied yet, thus the design aims at minimizing leakage currents from the battery during freezing and hibernation. [7-9] To achieve this, voltage and current sensing for the battery happen downstream of the thermostat switch. Furthermore, the battery shall not have a balancer due to the associated losses. As LUCENT is a small system with low-power components, the balancer can be avoided by using a battery with cells connected in parallel. Lastly the thermostat switch is used to disconnect the positive terminal of the battery from the system to avoid any leakage.

4.2. Switch Considerations

Besides providing battery isolation, the thermostat switch also takes active part in the control of the system by reacting to the system temperature. This primarily ensures the batteries proper operation, but also means no external electronical trigger is needed for actuation making the switch´s operation independent of the systems current operational status. This could be specifically interesting for radiation induced upsets of the controller, since each lunar night leads to a restart of the system.

Currently the use of a bimetallic thermostat switch is envisioned. Opposed to a semiconductor-based solution, this provides galvanic isolation as well as tolerance towards high energy particle irradiation. Furthermore, bimetallic switches in hermetically sealed cans have been used repeatedly in space and standardized parts are available [19]. This level of heritage is especially interesting, since the battery switch is a critical part of the system leading to a loss of mission in case of failure in either way. Although in general a COTS approach is envisioned for LUCENT, the existence of fully qualified components is a possible fallback option. Furthermore, switches with tightly controlled temperature behavior are necessary to allow stable operation near the switching temperature.

4.3. System Scaling

Based on the rough thermal model described earlier, a preliminary scaling of the power system is done to show the achievable operational time for the experiment after sunset.

Due to the early stage of the thermal model and system design, the heater power profile is not modeled as a stabilizing controller with internal dynamics, but as a fixed profile to make quick iterations. The overall system is assumed to consume 0.5 W continuously for data acquisition and occasional data downlink during the lunar day and a high-rate data collection mode consumes around 3W during the terminator crossing. For

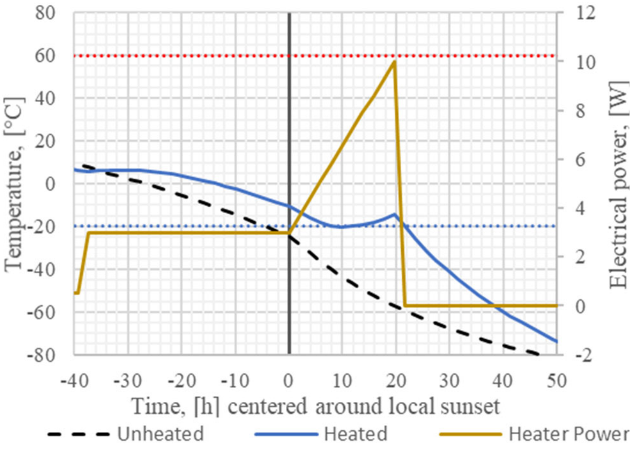

Fig. 5. Simulated internal temperature after local sunset. The dashed black line shows the passive case without heating while the solid blue line indicates a heated case with the heater power shown in yellow.

night time operations a maximum of 10 W of heater power is available. The optimum self-heating temperature for the battery is assumed to be -10 °C and the disconnecting temperature for the thermostat switch is -20 °C. The temperature and heater power profile for this operation is shown in figure 5. It can be seen, that the internal temperature stays above -20 °C for more than 20 hours after sunset.

This heating and science power scheme requires 244Wh during the time frame shown before the system goes into hibernation. Furthermore, additional energy is needed to supply the 0.5 W baseline consumption when solar input is not sufficient. This consumption is depending on solar array scaling and orientation. As a starting point 30 Wh are assumed for a zenith pointing solar array. Thus 274 Wh need to be stored, requiring around 360Wh of battery capacity to limit the discharge to 70% for contingency and operational safety. This rather deep discharge is accepted because of the low cycle count. 360 Wh of Li-Ion cells can be packaged within less than 2 l volume with current technology.

Solar Array scaling at this point assumes a single array on the top surface pointing towards zenith. As no information is available on possible orientation and transportation on the lunar surface, this is assumed as a conservative starting point, necessitating only the flat positioning on the surface without orientation around the zenith axis. The current power budget is based on a single array that provides enough power to recharge the battery for the sunset monitoring phase and intermittent operation of the payload during the day. An 8 W solar array supplies sufficient energy to achieve this balance, although the configuration is very sensitive to pointing errors due to the low incident angle. To compensate for these errors the adaptation of the daytime operations may be necessary. An 8 W array can be mounted next to the top side radiator, requiring around 200 cm^2.

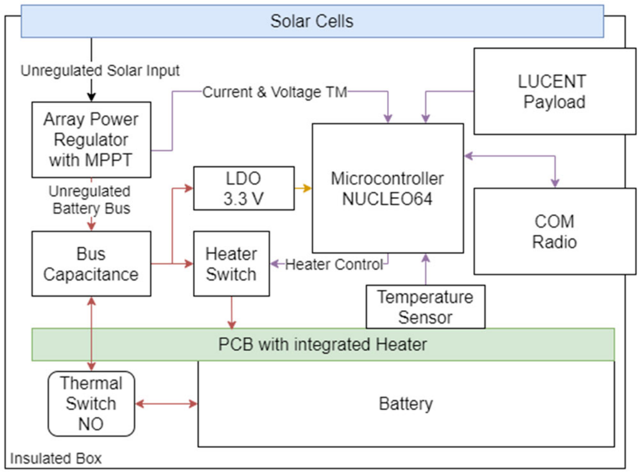

Fig. 6. Block diagram of the prototype.

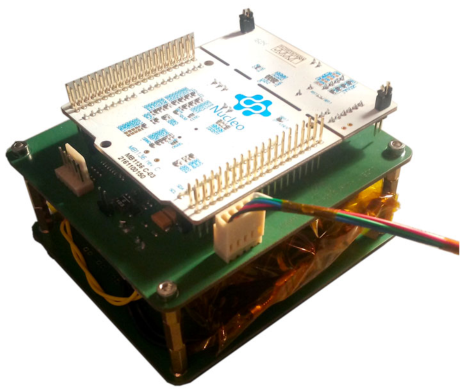

Fig. 7. Prototype for testing of the power system concept.

Further studies are needed as soon more information about possible landing sites and deployment options are available.

4.4. Prototype design

To test the validity of the proposed power system, a demonstrator to test components, operations and different configurations is designed. Figure 6 shows the overall block diagram of the demonstrator consisting of a PCB with integrated heater, a solar array interface with MPPT, a COTS microcontroller board and a rechargeable battery. Figure 7 shows the current hardware of the prototype after functional testing of the MPPT and battery. The goal of this demonstrator is to be a first proof of concept in a simulated lunar environment (TVAC chamber), allow the comparison of different battery cells and to test the performance of potential electronic components for flight missions. The demonstrator is not scaled for lunar day and night times but for shorter test cycles under comparable environmental conditions.

A first test campaign using submersion in liquid nitrogen is planned to test the system and verify compatibility with the thermal environment. This simple test approach provides low temperatures, but subjects the hardware to nearly instantaneous temperature changes not encountered in the final mission.

A second campaign using a thermal vacuum chamber to test operations in vacuum and on a more realistic timescale is planned for later in 2023.

5. Outlook

To check the assumptions made in this paper, system level testing of a power system prototype is planned for the second half of 2023. Besides the qualitative testing of assumptions, a goal of theses tests is to identify potential hardware for a future mission. Additionally, component level tests for battery characterization are planned. Current published test data is based on freezing with no load connected during the freezing, but no data is available on varying load conditions. This data is necessary for system and components designers to specify allowable leakage currents in the battery circuits. The current approach avoids this by using a mechanical switch.

The thermal design is currently based on a strictly passive strategy due to cost as well as the early project phase but initial analysis suggests, that a cover for the radiator to reduce heat loss during the night would greatly improve battery performance. Further research on the system level implications and possible implementations is needed to evaluate the potential for LUCENT.

6. Conclusion

In this paper a power system concept for a small-scale lunar science experiment of less then 5 liters total volume is described. The concept aims at hibernating through the night without any active components relying on the potential low temperature tolerance of electronics and batteries as published in recent literature. A first scaling for an experiment studying the lunar electric field environment during the terminator crossing is proposed to show the potential operational envelope for simple missions without active thermal control. And finally, a prototype for the described system is shown with an outlook on future testing activity aimed at improving component characterization for subsystem design.

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