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ESA Contract Nr. 4000119561/17/F/MOS

Executive summary report

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1 Introduction

The project "MESG: Moon Energy Storage and Generation" answers the open call AO/1-8712/16/F/MOS issued by the European Space Agency via EMITS in September 2016. Following the winning proposal phase a contract was established between the activity prime Sonaca Space GmbH and ESA under Contract Nr. 4000119561/17/F/MOS.

Its main objectives are:

- evaluation of different mission scenarios for lunar surface exploration (robotic and manned);
- technical surveys for heat storage and electricity generation from heat (Moon and Earth);
- trade-offs of a system concept able to accumulate heat during the lunar daytime and release it to a "user" in order to allow it surviving the lunar night, including the electricity generation out of the heat source;
- lunar regolith simulant analysis and thermal characterization;
- detailed design of the system concept and its performance assessment;
- design, manufacture and test of a system demonstrator.

1.1 Scope

The present document aims to provide a short overall summary of the project.

1.2 Application

This document applies to the "MESG: Moon Energy Storage and Generation" project.

2 Documents

2.1 Applicable Documents

[AD1]	MESG-SSG-RP-058-1-0	Final report

Table 1 List of applicable documents

2.2 Reference Documents

[RD1]		Valle Lozano, A., Development of a Lunar Regolith Thermal Energy Storage Model for a Lunar Outpost.
[RD2]		Faghri, Amir. "Heat pipes: review, opportunities and challenges." Frontiers in Heat Pipes (FHP) 5.1, 2014.
[RD3]		Maydanik, Yu F. "Loop heat pipes." Applied Thermal Engineering 25.5 ,2005,: p.635-657.
[RD4]	ISBN:188498911X	Spacecraft Thermal Control Handbook – D Gilmore, 2002
[RD5]		Nakamura, Takashi, et al. "Solar thermal power system for oxygen production from lunar regolith." AIP Conference Proceedings. Ed. Mohamed S. El-Genk. Vol. 969. No. 1. AIP, 2008.
[RD6]		Gordon, Pierce EC, et al. "Thermal energy for lunar in situ resource utilization: technical challenges and technology opportunities." (2011).

[RD7]		González-Pardo, Aurelio, and Thorsten Denk. "A novel off-axis solar concentrator providing a vertical beam." AIP Conference Proceedings. Eds. Vikesh Rajpaul, and Christoph Richter. Vol. 1734. No. 1. AIP Publishing, 2016.
[RD8]	MESG-SSG-RP-067012-1-0	Lunar regolith analysis and similar terrestrial applications
[RD9]	ISBN-10: 1881883108	Space Mission Analysis and Design, 3rd edition – J. R. Wertz, W.Larson, 1999
[RD10]		ISECG – Summary Report - The ISECG Reference Architecture for Human Lunar Exploration

Table 2 List of reference documents

2.3 Abbreviation and Acronyms

AI&T	Assembly, Integration & Test
COTS	Components Of The Shelf
DLR	Deutschen Zentrums für Luft- und Raumfahr
LHP	Loop Heat Pipe
MESG	Moon Energy Storage and Generation
PHP	Pulsating Heat Pipes
SSG	Sonaca Space GmbH
TEG	Thermo Electric Generator
TM	Thermal Mass
TVAC	Thermal Vacuum Chamber
UUT	Unit Under Test
wrt	With respect to

Table 3 List of abbreviations

3 Project context and objectives

One of the most critical points in the space exploration beyond Earth orbits is the provision of systems which ensure the survival of both crew and technological assets, such as rovers, landers, and others.

The utilization of the Moon, being as the next logical step in implementing the global strategy for colonizing the solar system, is in the focus of all the national and international space agencies.

In accordance to these two points, the first main objective of this project is to assess the potential of thermal energy storage systems as means of supporting future lunar exploration scenarios. In a more concise definition, the main objective is to perform numerical and experimental studies for the design of an efficient technology for storing thermal energy, and reusing it for the production of electricity in-situ.

In comparison to the environment of the International Space Station, a now established working environment for mankind, the one on the Moon is much harsher. Given that the lunar night can last, depending on the location, for as much as 14 earth days, the surface temperatures can vary between 100 K and 400 K. This makes any system designed for lunar applications complex and constrained by many factors. In order to address these challenges, a novel heat storage and electricity generation system has to be designed and studied.

A common approach of many studies is the utilization of the native regolith as a heat storage mean. This stored thermal energy could be at a later convenient time released in the system for direct heating purposes, or as an input to drive a heat engine, which can then transform it into electricity. For this purpose, an appropriate modified/processed simulant (artificial regolith substitution) will be used to test and to obtain the mechanical and thermal properties through characterization techniques and experiments within the proposed project.

The system foresees the implementation of a solar collector, reflector or concentrator as a mean to collect the sun energy available on the Moon. The thermal energy collected will be then transferred to the thermal mass for storing (regolith) by carefully designed heat transfer means. The solar energy collector and the thermal mass, together with heat transfer devices represent the hot side of the system. Together they provide the heat to the hot side of the engine. The cold side of the system, which function is to reject the waste heat from the engine, includes the heat transfer devices and the radiator. The characteristics of these elements will be acquired via numerical simulations.

In order to address properly the thermal energy transfer mechanisms and specific devices evaluated (between the individual parts of the system), multiphase flow models will be elaborated. Specific attention will be given to the interfaces between each part which are already identified now as critical points of the system.

Integral part of this study will be the analysis of the scalability of the proposed system. Keeping in consideration the functionality, costs and key parameters, the results will be used to design and manufacture a reduced scale practical demonstrator, which will be then tested and used to benchmark the numerical models.

To summarize, four main technical objectives were identified for this project:

- design assessment of an efficient thermal storing and electrical energy production system for lunar applications, through numerical and experimental studies;
- utilization of processed simulant regolith as a thermal mass of the system (including thermo-mechanical properties characterization);
- numerical assessment of the system performances via analysis;
- identifying the key parameters and cost of a small scale practical demonstration of the system, building it and testing it.

3.1 Lunar environment

The requirements for the design of rovers and sample collecting devices for the Moon are driven mostly by the harsh and diverse thermal lunar environment. Since first lunar missions many information about the Moon and its thermal environment have been collected. The most critical ones for the present development, most relevant for the system and small scale demonstrator design, are the pressure levels, night duration depending on the position on the surface, temperature environment. In particular, the Moon has very thin atmosphere (around 25000 kg) generating a surface pressure at night in the order of $3*10^{-15}$ bar. Similar conditions to that of the Moon in terms of temperature and pressure can be reproduced inside a thermal vacuum chamber.

In the South Pole regions, which theoretically should be permanently illuminated by the Sun, due to the small tilt of the Moon's axis with respect to the ecliptic, the night can last up to 52 hours [RD1], whereas in most of the lunar locations, the longest possible night can last even 384 hours. The rim of the Schakleton Crater, located at the South Pole, has been regarded as one of the ideal locations for a human-made permanent base. The rim of the crater is at higher elevation than most geographical entities in its surroundings, allowing an excellent illumination.

4 Energy demands for potential lunar missions

The thermal issues and the power demand during lunar nights are two of the biggest challenges for any future lunar surface mission. Depending on the mission scenario, the relevance of the two aspects varies. For a robotic mission the main criterion is to survive the lunar night only, e.g. in a hibernation mode with optimized power management and reduced duty cycle. This means that the temperature must be kept in a certain range, which requires a highly-optimized thermal control system and an efficient method of energy storage to enable the survival of the assets. For a crewed lunar habitat on the other hand, the energy demand increases rapidly and the aspect of electricity generation becomes much more important.

Three landing site scenarios, resulting in different durations of the lunar night, have been analysed.

A landing near the lunar South Pole is assumed to have minimum shadow time of about 120 hours. This duration is longer than the one mentioned in section 3.1 (52 hours) – in this way the solution obtained will be more robust and not constrained to a few spots on craters' rims at the South Pole. Depending on the exact position in the polar region, the lunar night duration could increase to up to 200 hours. Choosing landing sites with lower latitudes, e.g. closer to the equator, would extend the lunar night duration up to about 335 hours and represent the worst case lunar environment from a heat storage and electricity generation point of view.

To sum up, the energy needs of the mission scenarios considered are: 120, 200 and 335 hours of lunar night; they are summarized in Table 4, for typical users foreseen, also based on the current road maps for space exploration form ESA [RD10].

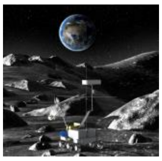
User		**Power consumption**	**Energy demand during lunar night:**		
			120 h	200 h	335 h
Rover		11 W	1320 Wh	2200 Wh	3685 Wh
Lander		115 W	13.8 kWh	23.0 kWh	38.5 kWh
Pressurized rover **Hibernation when uncrewed**		~ 100 W	12 kWh	20 kWh	33.5 kWh
Pressurized rover **Crewed**		up to 1.2 kW	144 kWh	240 kWh	402 kWh
Habitat - Uncrewed		~ 1.0 kW	120 kWh	200 kWh	335 kWh
Habitat - Crewed		up to 6.0 kW	720 kWh	1200 kWh	2010 kWh

Table 4 Energy demands summary

5 System design

In order to efficiently design a system that could store heat on the Moon, possible configurations were assessed starting from:

- an assessment of previous studies performed on the same topic;
- a detailed analysis of the possible technologies to be used for each one of the building blocks of the system.

In parallel, regolith simulant options have been analysed and characterized (from a thermal point of view). The objective was to identify the most suitable combination of raw material and processing method for the implementation of the system on the Moon surface as also for the manufacturing of a small scale demonstrator.

For this study, vacuum sintered parts are fabricated under a similar atmospheric condition to the Moon (lack of atmosphere, i.e. 7E-6 mbar). Based on this, the obtained results regarding the vacuum sintered parts are more suitable for the system concept analysis.

However, as fabrication of a brick for the experimental part of the project (demonstrator) is only feasible using a conventional oven under air (due to the available oven/machine size at DLR site); therefore the material for the demonstrator activity was chosen different from the one foreseen for the system.

5.1 Concept description (system's blocks)

The system concept foresees collection and storage of heat during the lunar day and using it to produce electricity and optionally as heat source during the night. To do so, the system needs to be able to collect the heat, transfer it to the storage medium, then transfer it to the heat engine to convert it to electricity, which can be then delivered to the user. Moreover, the wasted heat from the engine needs to be rejected. The available heat during the night can be also used directly for thermal control of a user (e.g. for warming up a rover – User 2 in Figure 1).

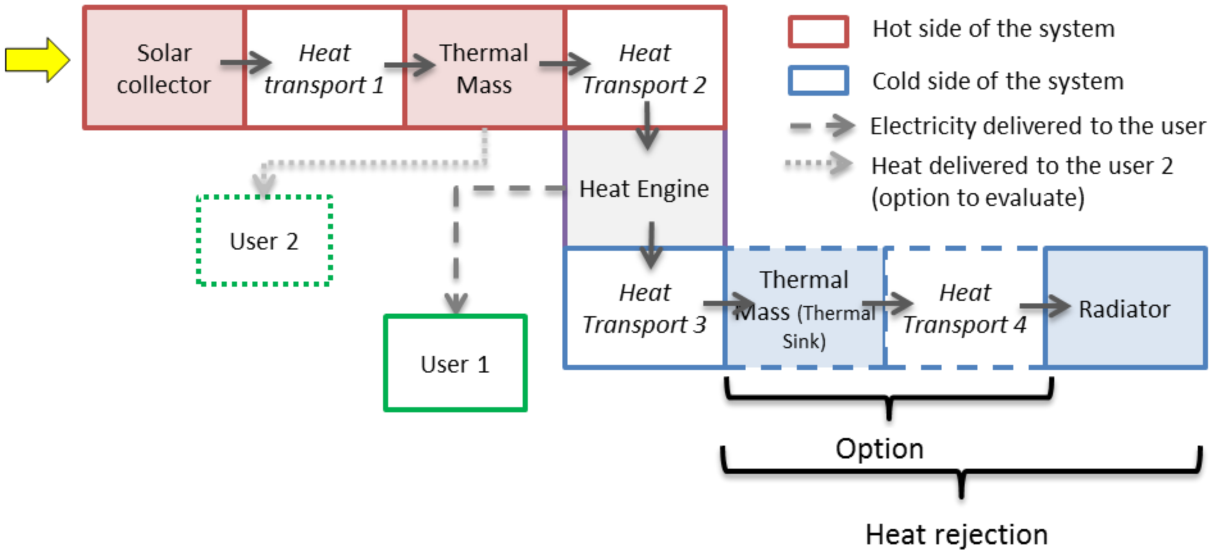


Figure 1 The system concept: block diagram

The complete system is presented on Figure 1. It includes a group of blocks representing each element of the system:

- **Solar collector**: it is needed for collecting the solar energy for storage in the thermal mass. It is foreseen to use system of mirrors and lenses to collect and concentrate enough solar energy to supply the heat engine during the lunar night.
- **Heat transport 1**: it is a path where the heat or solar rays are received from the solar collector and are transported to the thermal mass.

- **Thermal mass**: it is the medium where the thermal energy is stored before it is used to supply the heat engine.
- **Heat transport 2**: it is a path where the heat is transported from thermal mass to the heat engine.
- **Heat Engine**: it converts thermal energy to electrical energy which is delivered to the user.
- **Heat transport 3**: is the heat path where the waste heat from the engine is transported to the radiator.
- **Radiator**: it is used to reject the waste heat from the thermal engine to the environment.
- **Thermal Mass (Thermal Sink) and Heat transport 4 blocks:** are optional as they can improve the performance of the heat waste path. However they are not included in the baseline concept design.

Solar collector, Heat transfer 1, Thermal mass and Heat transport 2 blocks represent the **hot side of the system**. The temperatures expected on this side of the system are between 650 K and 1000 K (typical temperatures to allow the heat engine working).

Heat transport 3 and Radiator (also Thermal Sink and Heat transport 4 if included in the design) are the **cold side of the system**. Here the temperatures expected are below 300K.

5.2 Trade-off strategy

In order to define the concept of the Moon Energy Storage and Generation system, round of trade-offs has been done.

First of all, the requirements for the system and criteria for technologies comparison have been selected. Then, for each requirement/criterion an **importance weight** has been assigned. Each technology has been then evaluated if it fulfils the requirement completely (2 “**points**” assigned), partially (1 “point” assigned) or does not fulfil the requirement (0 “points” assigned). At the end, for each technology considered, a **grade** has been calculated as the sum of each point multiplied by the relative importance weight for each criterion/requirement.

“Grade of a technology” = Σ(“importance weight of the requirement””points assigned”)*

The grades obtained together with points and requirements have been implemented into the house of quality analyses diagram [RD9]. Moreover, information about the interfaces between consecutive blocks has been added to the house of quality. In that way the scheme created is showing clearly which technologies fulfil the project criteria the best, which one can be discarded and how good they can be interfaced between each other.

With all information collected, the baseline for the system concept can be defined.

5.2.1 Requirements and criteria selected

Table 5 presents all the requirements and criteria selected for the evaluation with the importance weights assigned. Importance weights are assigned according to 4-level scale:

9-highest importance;
6-medium/high importance;
3-medium importance;
1-low importance.

Evaluation parameters		Importance Weight	Comments
Landing location	Polar	9	
	Equatorial	6	
User case	Rover (11W)	1	
	Lander (115W)	9	
	Manned Rover	6	

	Lunar Base	3	
High technology maturity / Relevant heritage		9	
Minimal mass to be brought from Earth		3	
ISRU		6	
Simple technology and reliability		6	
Easy to transport from Earth		3	
Operational in high temperatures (up to 1000K on the hot side of the system)		6	
Practicality of the demonstrator		3	
Scalability of the concept (in terms of user power demand)		6	
~~Heat supply to the user~~		~~6~~	Heat supply to the user criterion was in the end discarded at this stage since it is merely an option of the system, focussed on interfacing issue. As so, it might only be considered in later stages for configurations' evaluation.
High performance/efficiency		6	
REQ-01: The designed Thermal Energy Storage (TES) system shall provide the required thermal energy for the survival of a rover (or similar equipment) during lunar night periods.		9	Requirement defined in the proposal
REQ-02: The TES shall be able to produce electrical energy from the in-system stored thermal energy.		9	Requirement defined in the proposal
REQ-03: The TES shall be designed to be operational under lunar environment conditions.		9	Requirement defined in the proposal
REQ-04: Regolith, i.e. modified regolith shall be used as the thermal mass of the system, where the heat will be stored.		9	Requirement defined in the proposal
REQ-05: The thermal energy stored in the regolith must be sufficient to power a heat engine (electrical energy generator).		9	Requirement defined in the proposal

Table 5 Requirements/criteria and importance weight assigned

5.3 Outcome of trade-offs

The initial idea about how to use the outcome of this trade-off analyses assumed that from each block 2-3 technologies shall be selected and one will become baseline solution with the option of changing technology to another other one in case of low system's performances. However, the analysis of the interfaces between the blocks showed that in some cases it may not be possible just to switch between the chosen technologies. In order to be prepared for this possibility, a slightly different strategy is going to be used:

1. the building block with the most wide range of technologies will be identified;

2. for each selected technology from this block other parts of the system will be selected, creating a whole configuration (built with the selected parts for each block).

In that way one baseline system concept can be defined while other design options are identified and can be selected in case the baseline does not present good enough performances. This approach is necessary since some technologies are completely different and need a deeper analyses based on mathematical models in order to be evaluated in the complete system's architecture, instead of simply technology piece by piece.

The block which has technologies that differ the most between themselves and have different interfaces is **Heat transfer 1**. The concept designs will be based on a reduced number of technologies selected from this block. Then for each technology from Heat transfer 1 appropriate solar collector will be chosen (choice based on the points collected and the interfaces evaluation), while with the same approach the rest of the system "behind" the heat engine will be selected.

Three Heat Transfer 1 technologies were selected as the most promising and at the same time the most different ones between each other (using even different physical principals for heat transfer):

- optical waveguides [RD5], [RD6];
- loop heat pipe (liquid metal as a working fluid) [RD2], [RD3];
- direct illumination.

5.4 Preliminary and detailed design

A first round of preliminary thermal modelling allowed to reduce the configuration from a total of three to one baseline (with clearly the best performances) and a backup one (with the third one, direct illumination discarded because of large system mass disadvantages.

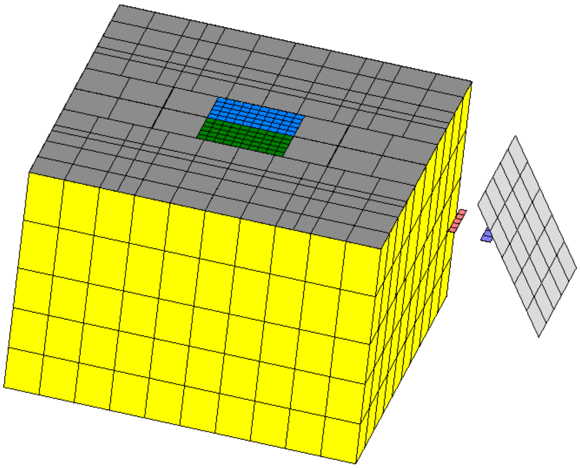


Figure 2 Components which have geometrical representation: thermal mass (in the middle), regolith (with top layer) -grey and yellow-, flanges –pink and purple- and radiator –light grey-

System block	**System design Concept 1 (baseline)**	**System design Concept 2 (backup)**
Solar collector	Parabolic dish	Parabolic trough
Heat transfer 1	Optical waveguides	Loop heat pipe (liquid metal as a working fluid) (alternatives: heat pipe (another "shape"))
Thermal mass	Modified regolith	Modified regolith
Heat transfer 2	Loop heat pipe (liquid metal as a working fluid) (alternatives: heat pipe (another "shape"))	Loop heat pipe (liquid metal as a working fluid) (alternatives: heat pipe (another "shape"))
Heat engine	Stirling system	Stirling system
Heat transfer 3	Loop heat pipe (liquid metal as a working fluid) (alternatives: heat pipe (another "shape"))	Loop heat pipe (conventional working fluid) (alternatives: heat pipe (another "shape"))
Heat rejection	Metal plate with shield	Metal plate with shield

Table 6 Comparison between the system and the demonstrator design

The analysis performed, done on one user (the lander case) in order to simplify the assessment of the results, showed the feasibility of both the configuration able to deliver the requested power to the user identified, using technologies which are already available or currently under development.

	System design Concept 1 (baseline)	**System design Concept 2 (backup)**
Solar collector technology	Parabolic dish	Parabolic trough
Needed concentration ratio (calculated)	622	100
Area of the collector [m²]	6.57*	220
Dimensions of the mirrors and the assembly of the solar collector	Area of the solar collector: 6.57* m^2	3 collectors each: 18.3 m x 5 m (assumption: aperture is 4 m)
Receiver area [m^2]	0.011	2.2
Mass of the solar collector	*80 kg*	*3348 kg*
Heat transfer 1 technology	Optical waveguides	Loop heat pipe (liquid metal as a working fluid)
Heat transfer 1 mass	*20 kg*	*Total:* *Loop HP: 219.8 kg*
System start-up time	Long (~30 cycles after warm up time)	Shorter than in Concept 1 (~14 cycles after warm up time)
Heat transfer 1 assembly within the thermal mass	Relatively easy	Complex mounting to the TM (interface between metal and rocky structure)
Temperatures reached in the thermal mass	Maximum temperature slightly exceeds the limit (by around 40 °C)	Maximum temperature exceeds the limit by around 300 °C
Temperature distribution in the TM	Easy to make uniform distributing the waveguides outputs	Possible to make it more uniform, but not as flexible as Concept 1

Table 7 Solar collector + heat transfer 1 technologies comparison (* for simplification, flat surface considered)

System block	**Technology**	**Dimensions**	**Mass [kg]**
Thermal mass	Brick of modified regolith	1.3x1.3x1.6 m^3	6995
Heat transfer 2	Conventional or loop heat pipe	Evaporator: 0.8x0.4x0.015 m^3 Condenser: 0.7x0.2x0.02 m^3 Adiabatic part: 1m (1 m of liquid line and 1m of vapour line for LHP)	Conventional HP: 67.5 LHP: 68.3
Heat engine	Stirling engine	unknown	102 (estimated)
Heat transfer 3	Conventional or loop heat pipe	Evaporator: 0.8x0.3x0.015 m^3 Condenser: 0.8x0.2x0.015 m^3 Adiabatic part: 1m (1 m of liquid line and 1m of vapour line for LHP)	Conventional HP: 54.5 LHP: 54.0
Heat rejection	Aluminium panel	2.2x2.25x0.03m^3	400

Table 8 Technologies used in system blocks

The main advantage of Concept 1 with respect to the other two can be summarized in:

- “embedded” diode function of the optical waveguides heat transfer mean;
- limited losses of the concentrator part both during day (optical waveguides transfer light

instead of heat, limiting the high temperatures and therefore the heat exchange of the concentrator part to the environment) and during night (optical waveguides operates as a thermal diode, not transferring heat but only light);
- smaller concentration area needed thanks to the lower heat losses;
- more uniform and easier distribution of heat within the thermal mass.

Concept 1 with the smallest mass and dimensions and very good performance (good temperature distribution, appropriate maximum temperature reached in the thermal mass) is then considered as the system baseline.

Concept 2 is heavier and less performant than Concept 1. However it is believed that it can be significantly improved with some optimization activities (e.g. new shape of the condenser flange, multiple condenser flanges to equalize heat distribution, smaller exposure of the evaporator flange to the environment) and thus it is going to be considered as a backup option for the system design.

A system scaling allows deriving possible system configuration for different users than the one used for the system detailed modelling, in particular:

- rover user (wrt the lander case as sized): system scale-down by a factor of 10;
- non-operational crewed pressurized rover (wrt the lander case as sized): same system sizing as for the lander (summarized in the previous sections);
- operational crewed pressurized rover (wrt the lander case as sized): scale-up by a factor of 10 of the system for lander user case;
- non-operational lunar base (wrt the lander case as sized): scale-up by a factor of 10 of the system for lander user case;
- operational lunar base (wrt the lander case as sized): scale-up by a factor of 60 of the system for lander user case (although considered non-realistic due to the extreme size of such a system).

6 Demonstrator design and assessment

The main goal of the demonstrator activity is to verify the capability of the modified regolith to store heat and use it to generate electricity in (as much as possible) similar conditions (environmental and design) to the system (pressure levels and environmental temperature conditions requiring a thermal vacuum chamber test environment).

Due to the limited sizes and the absence of direct solar illumination or simulator, some modifications to the system configuration were necessary.

System block	System design Concept 1(baseline)	Demonstrator design
Solar collector	Parabolic dish	Substituted by simple heaters attached to the thermal mass' top surface
Heat transfer 1	Optical waveguides	Interface between the heaters and the thermal mass, for example pressure sensitive adhesive
Thermal mass	Modified regolith	Modified regolith
Heat transfer 2	Loop heat pipe (liquid metal as a working fluid) (alternatives: heat pipe (another "shape"))	Interface between the thermal mass and the hot side of the heat engine
Heat engine	Stirling system	Thermo Electric Generator
Heat transfer 3	Loop heat pipe (conventional working fluid) (alternatives: heat pipe (another "shape"))	Interface between the engine's cold side and the heat rejection block
Heat rejection	Metal plate with shield	Metal plate (no shield is needed since no sun radiation is present), thermally controlled by an external oil circulator machine.

Table 9 Comparison between the system and the demonstrator design

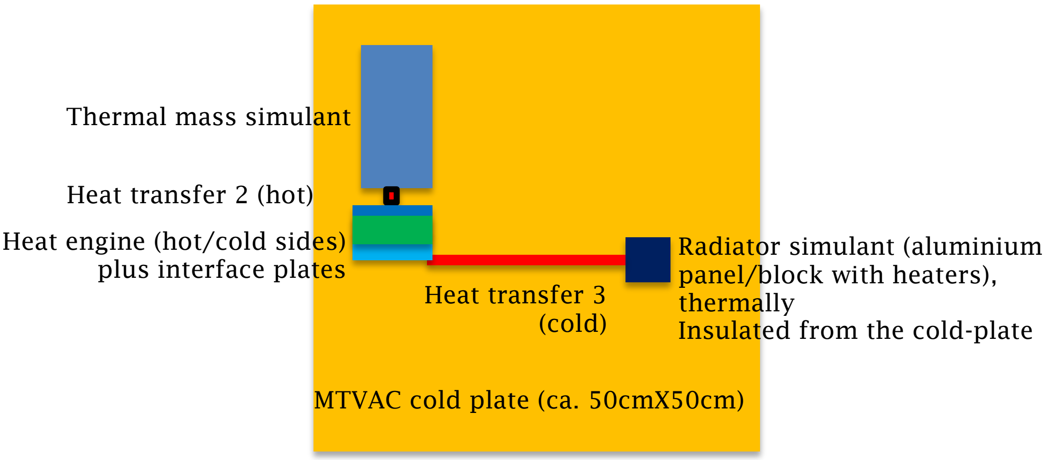


Figure 3 Demonstrator concept

Figure 3 shows the main difference wrt the system concept, the deletion of the solar collector part, since in order to simulate properly, a solar simulator plus concentrator and optical fiber lines would be needed making the test budget exploding. The heat input is replaced by heaters placed on the top of the modified regolith mass.

The final configuration of the demonstrator, after a series of breadboarding activities, control and monitor software development, is summarized in Figure 4 as thermally modelled, as CAD model and as built and tested.

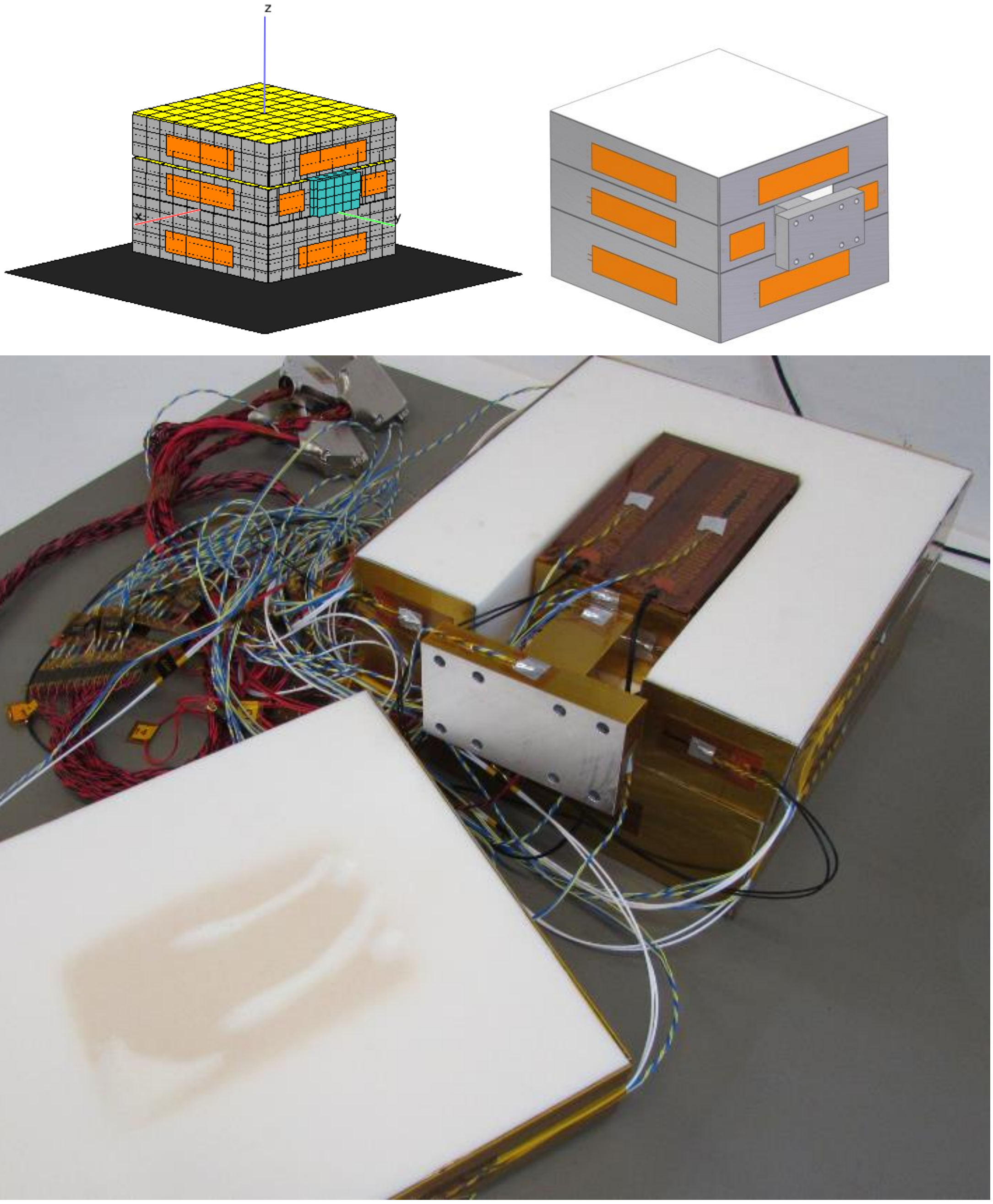


Figure 4 Demonstrator as built (thermal model, CAD model, hadware)

7 Demonstrator testing

The main test objective is to verify the capability of the system to store thermal energy and while cooling down, to generate electricity. Therefore, the test plan follows the results obtained from the demonstrator's thermal analysis, with main focus on obtaining stable "charged" phases and characterizing electricity production during "discharging" phases, in which, due to an artificially created temperature difference between the hot side and the cold side of the heat engine (TEG in this case), the production of electricity shall be observed and measured.

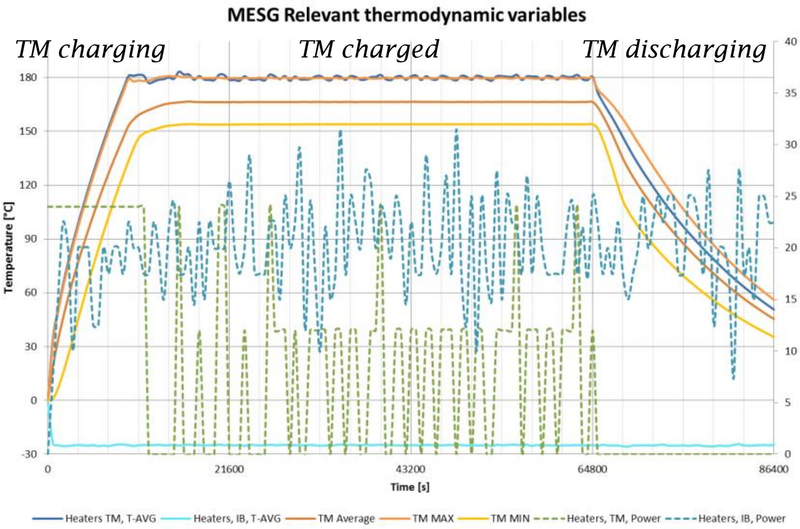


Figure 5 Test plan: foreseen charging - charged - discharging

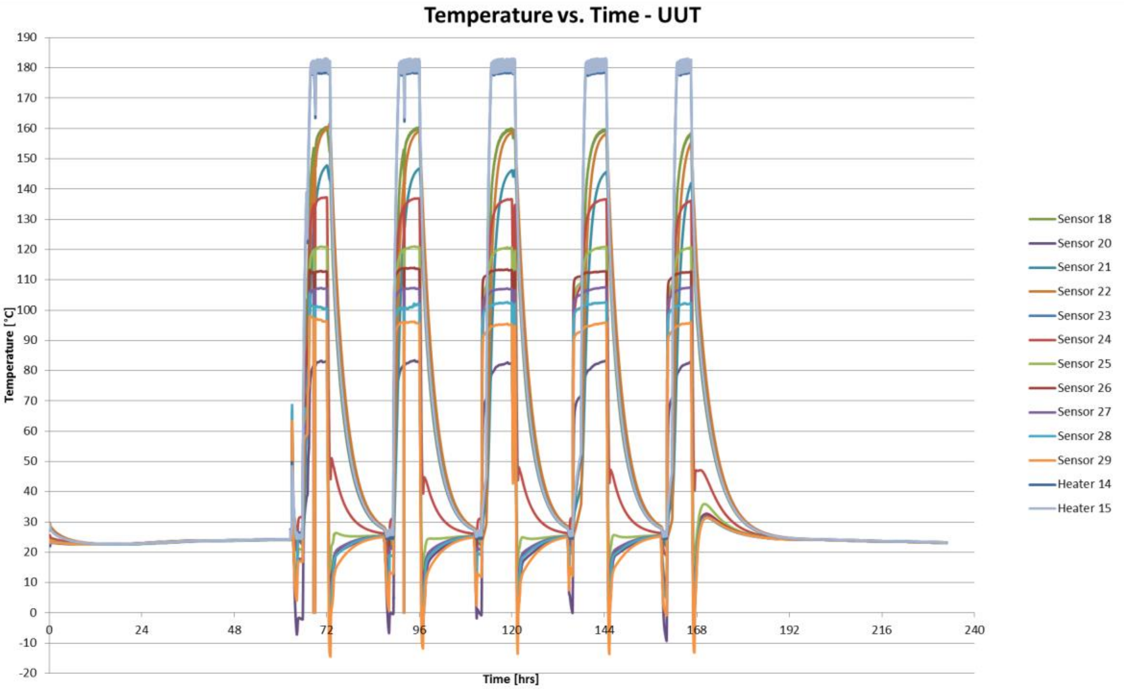


Figure 6 Temperatures across the demonstrator during test: thermal mass, up to the radiator simulant

7.1 Test conclusions

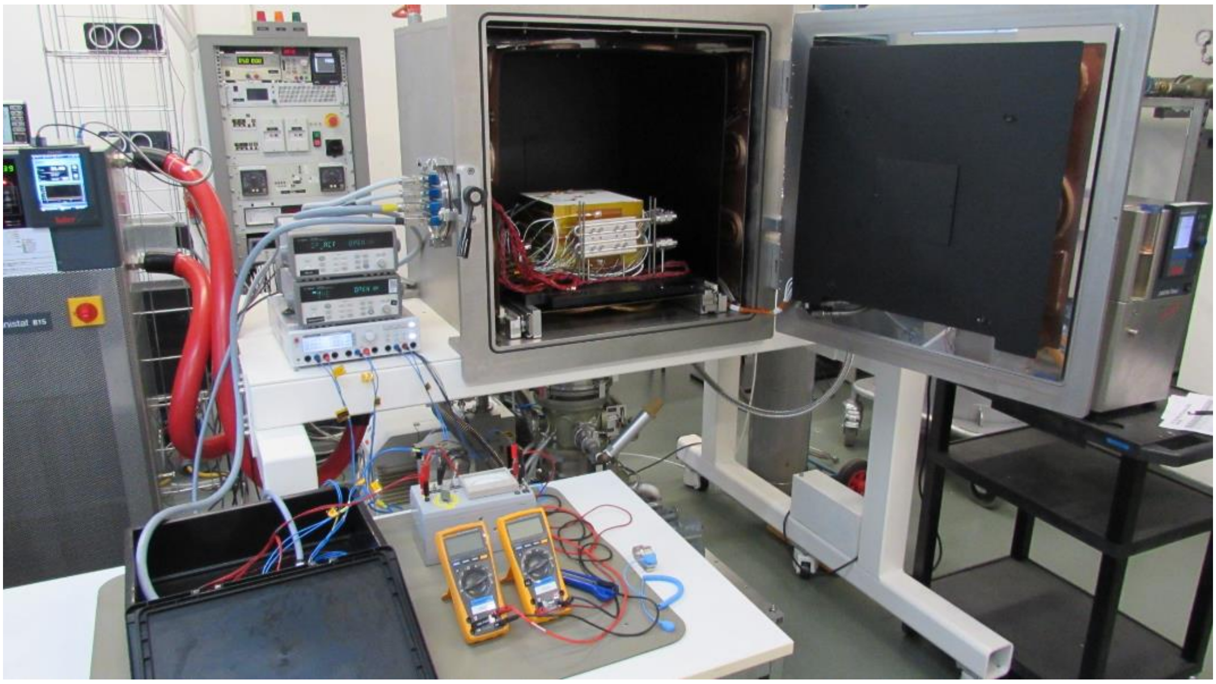


Figure 7 Demonstrator test configuration

- The main test objective to verify the capability of the system to store thermal energy, and, while cooling down, to generate electricity was successfully verified.
- Power generation in the TEG was measured during cooling down phases and compared to the temperature difference across the element and absolute temperature in order to assess the overall performances.
- Steady or "quasi-steady" thermal conditions over all the experiment and the internal environment during charged phase was not possible due to the technical limits of the vacuum chamber in this type of operations (intermittent liquid nitrogen flow, limiting the temperature stability of the MTVAC door) and the relatively big size of the demonstrator with respect to the chambers' interiors (demonstrator actively heating up parts of the to-be-kept-cold shroud). This did not allow performing thermal model correlation activities.
- The following test behavior conclusions can be nevertheless derived in comparison to those simulated:
  - charging and discharging phases behaved during the test in a similar way with respect to those simulated;
  - thermal conditions on the insulation box due to the heaters control on the sides, to the cold plate on the bottom and the shroud on top have been similar to the simulated environment although with only temperatures reached on the shroud between -130 /-150 °C instead of the -170 °C simulated;
  - the requested power for the heaters installed on the demonstrator for boundary conditions control and thermal mass heating procedures showed values in line with those simulated; only a small difference in the power needs for the heaters (14 V instead of 12.5 V) for the insulation blocks heaters was noticed.
- The only noteworthy discrepancy in the obtained results in comparison to the expected ones is the low power generated with the TEG. Whereas 500mW resulted from the simulation was expected, only 40mW was measured. Analyzing more in detail the results, explanations can be found:
  - Figure 8 and Figure 9 show the temperature difference across the TEG: within the simulation a constant temperature difference of almost 50 °C during charged phase is present, while during the test this was measured to be ca. 13 °C.
  - In the graphs it is clearly visible how the temperature difference across the TEG varies from ca. 50 °C during charged phase and increasing up to 90 °C during discharging, while during the test it varies between 13 and ca. 35 °C.
  - Figure 10 and Figure 11 depict on the temperature difference across the thermal

mass (ca. 30 °C both in the analysis and within the test) at the end of the charged phase and the temperature of the TEG hot side interface.

- In the graphs it is evident how the TEG hot interface “follows” the temperature of the thermal mass within the analysis (yellow and orange curves), while during the test the temperature decrease is very rapid (pink curve).
- As a consequence, instead of going from 50 to 90 °C temperature difference, in reality we obtain 13 to 40 °C, cutting the TEG capability to generate high amount of power (directly dependent on the temperature difference). This is identified as the main source of power generation capability loss for the system, which is directly connected to the interface between the TEG hot side and the thermal mass. In order to obtain better performances a better interface is needed, which will “gather heat” from the inside of the thermal mass which remains hot for long after the discharge phase. This interface issue was well known since the first steps of the project. However, it was not possible to address this problem with, for example, metallic fins inside the thermal mass, because of the regolith simulant manufacturing processes.

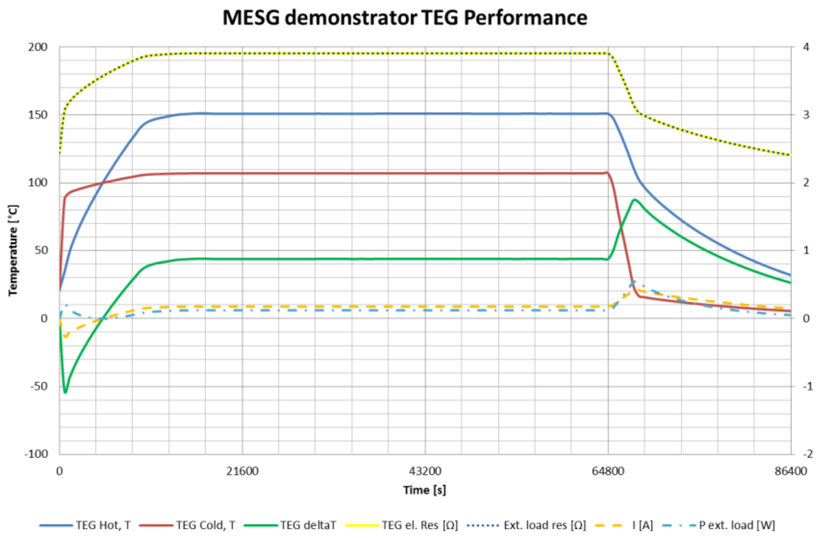


Figure 8 Temperature difference across the TEG within the simulation

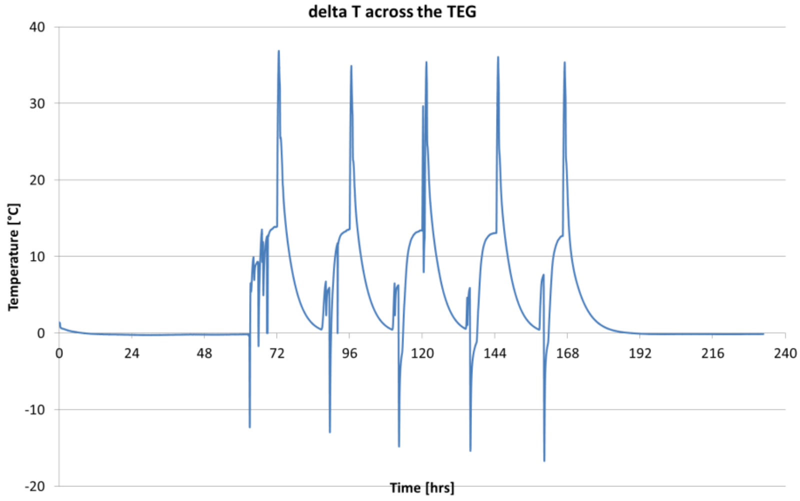


Figure 9 Temperature difference across the TEG during the test

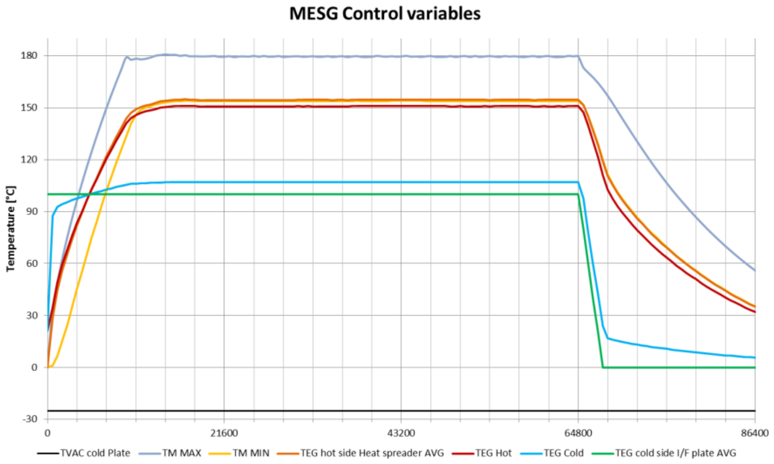


Figure 10 Temperature distribution inside the TM and on the TEG hot side interface, simulated

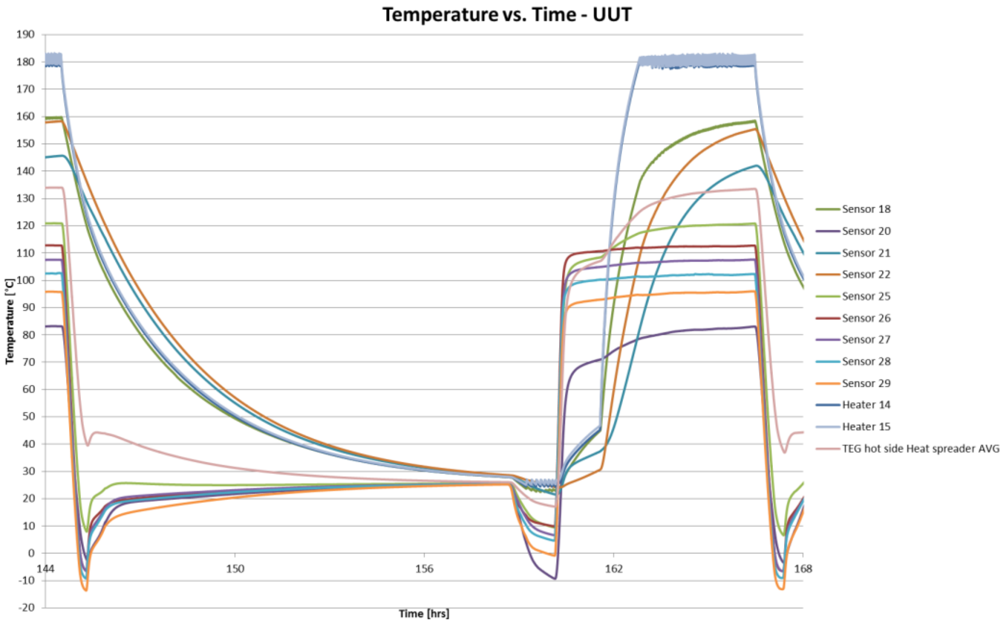


Figure 11 Temperature distribution inside the TM and on the TEG hot side interface, test

8 Project conclusions

The project effectively demonstrated, both via analysis for the system and via testing with the small scale demonstrator, the possibility to store heat inside properly processed lunar regolith and use it to produce electricity during cooling down phases.

Different materials to be used as lunar regolith simulant has been assessed and processed in order to manufacture a proper thermal mass to be used for the demonstrator activities.

The system has been sized for different possible users derived from Moon exploration concepts and road maps.

One baseline and one backup configuration for the system design has been identified and sized splitting them into building blocks and assessing the most performant and currently available or under development technologies. The scalability of the system was assessed for different sizes of users (power demands) allowing to identify also the most suitable users for this technologies and those not (higher power needs, such as a human habitat).

The demonstrator activities proved via testing the basic principle of using processed regolith (simulant) for storing heat, and while releasing it, to generate electricity.

Future optimization activities have been identified and documented for possible activity follow-ups and future developments.