Executive summary

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1 Introduction

The project MESG: Moon Energy Storage and Generation, funded by ESA (Contract Nr. 4000119561/17/F/MOS), demonstrated the feasibility of using processed lunar regolith simulant to store heat and, while releasing it, to produce electricity. The possibility to use adequately processed (compacted and eventually doped) lunar regolith for this purpose is a key development on the path to make sustainable long-term lunar habitation a reality. In addition, the accumulated heat can also be used to keep a rover, or other asset, warm (via system scale-up) and extend its mission through the lunar night.

The HEBAM project (HEat-based Battery for the Moon) aims to continue the technology development from the current status, raise the TRL by mitigating some of the identified issues (mainly improving thermal interfaces) and verify the scalability of the technology through a large scale demonstrator equipped with relevant technologies and materials compatible with the lunar environment.

This technology development, since in most of the cases a thermal improved interface is also a mechanically improved one, can also be applied to other developments relevant for lunar colonization, such as outposts construction.

1.1 Scope

The scope of this document is to summarize activities performed in the frame of joining EAC-1A samples with different types of materials and shapes of samples to assess feasibility and their thermal interface via a specifically developed test configuration.

The document follows the three main phases in which the project was as well split:

- regolith simulant and sintering techniques characterization;
- interface samples manufacturing and characterization;
- system assessment.

As discussed and agreed during the project, due to project delays and increased resources usage, it was not possible to manufacture and test a final “large scale” prototype.

1.2 Application

This document applies to the HEBAM project.

1.3 Abbreviation and Acronyms

AM	Additive Manufacturing
ASG	Azimut Space GmbH
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EAC	European Astronaut Center
ESA	European Space Agency
IF	InterFace
LHP	Loop Heat Pipe
MTVAC	Medium Thermal Vacuum chamber (ASG’s test facility)
N/A	Not Applicable
OW	Optical Waveguides
ID	Inner diameter
OD	Outer diameter

2 Regolith simulant and sintering techniques characterization

After trials on multiple initially planned sintering techniques, the actual project focused on the vacuum manufactured samples and its doping trials. These requested more resources and time than initially planned, due to unexpected manufacturing and characterization issues, here documented. As a consequence, the investigation of microwave, laser, and solar regolith sintering is lacking, as it is anticipated that these techniques would yield outcomes akin to those observed in vacuum oven sintering of regolith.

EAC-1A in general provides thermal properties quite similar to or improved in comparison with simulants investigated previously. Copper doping tested and assessed in the present report shows an increase in thermal performances (thermal conductivity), while aluminium doping demonstrated a poor mechanical stability.

While the higher the percentage of copper, the higher the thermal conductivity is expected, it's also to be considered that no large quantities of copper, not even obtained via recycling of Earth-made items will allow to recover enough copper to dope large blocks of sintered regolith on the Moon. Aluminium instead can be recovered in larger quantities and it's most likely to be used rather than copper in case of doping regolith to improve thermal conductivity. Based on the relative thermal conductance of copper (ca. 390 W/mK) and a likely to be found (eventually via recycling) aluinium alloy (180-200 W/mK), if the demonstrated interaction between aluminium and other minerals in the regolith (leading to poor properties) can be solved, it is possible to state that a X doping of regolith with aluminium can be simulated with ~X/2 doping based on copper. This would allow assessing a doping with aluminium with a reduced quantity of copper instead.

Although pressing with tons of load is unlikely to be possible on the Moon, currently and based on the development status of different sintering techniques, theoretical best values achievable with any of them can be considered similar to those of pressed vacuum samples on Earth. It is also to be noticed that following investigations using non-pressed samples will lead to poor results and definitely not comparable to what was obtained with the project precursor (MESG: Moon Energy Storage and Generation, funded by ESA Contract Nr. 4000119561/17/F/MOS).

Based on the above considerations and the additional trials performed with 5 and 10 % copper doping of EAC-1A samples, the following is considered a good compromise for the following project's activities:

- copper doping,
- 10 % weight of copper doping,
- vacuum and pressed samples (255 MPa),
- consequent estimate increase of thermal conductivity of a pressed sample in the order of ~40 % with respect to pure regolith simulant.

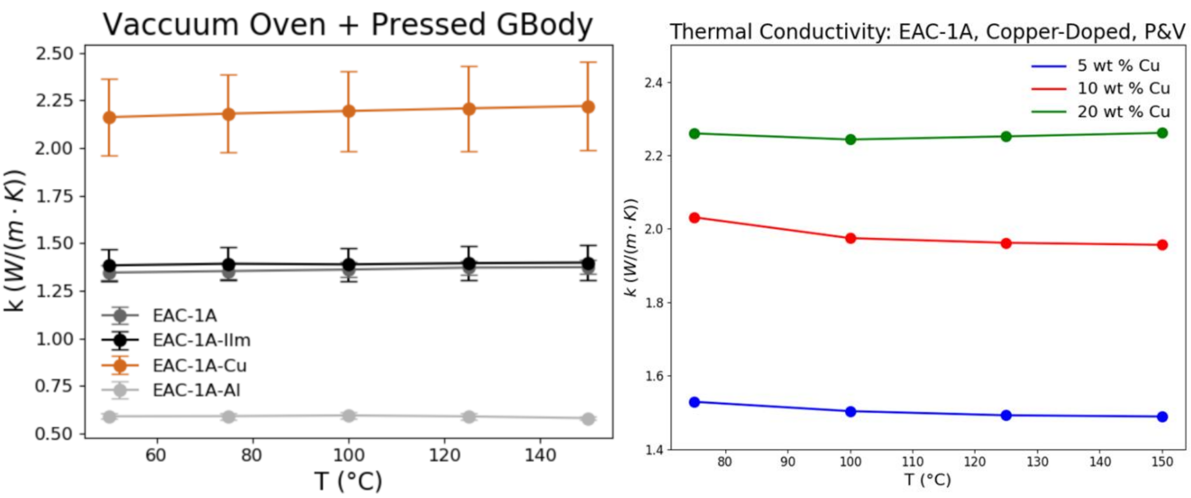

Figure 1 Comparison of pressed and doped samples

3 Thermal interfaces, preliminary assessment

Based also on previous work (MESG: Moon Energy Storage and Generation, funded by ESA Contract Nr. 4000119561/17/F/MOS) performed by the same project's consortium, the following considerations can be made for the desired thermal interfaces (to allow a better heat spread within regolith treated blocks).

- The preferred *mating technique* for heat transfer means to the thermal mass is the insertion of external objects inside the regolith while being sintered (although with limitations on materials selection due to the high sintering temperature).
  In the second place, inserting a place-holder while sintering can be used, to be removed at sintering completion and then substituted with the selected heat transfer means with "to be developed" filling materials and techniques to improve the thermal interfaces. Although interesting also for construction purposes, sintering the thermal mass in separated parts to be joined seems to be the most complex and more problematic approach.
- *Preferred shape* of these alien (inserted) parts can be easily summarized as cylindrical (applicable for both optical waveguide and rods or bars solutions). They might be either "full" (rods/bars) or hollow (pipes) eventually sealed at the endings with a fluid inside. An alternative which could be investigated are planar fins to increase the heat exchange.
- *The choice of alien materials' characteristics* are mainly driven by the sintering temperatures and high working temperatures:
  - quartz glass rods (for optical waveguides concept);
  - stainless steel LHP or HP filled with liquid metal (for lower temperatures and power levels), yet suitable for our "hot part" of the system; for demonstration activities this can be replaced by a stainless steel (304, 316) rod or tube; it has also the advantage to be functional for construction purposes;
  - inconel (or other Nickel alloy) LHP (or heat pipes) filled with sodium and working in the range 750-800 ˚C; for demonstration activities this can be replaced by a inconel (or other Nickel alloy) rod or tube;
  - copper rod or tube (can be used for fins).

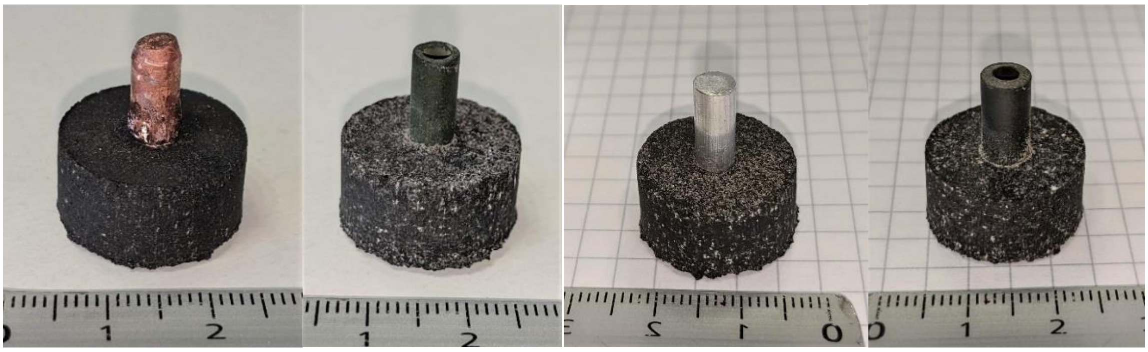

Figure 2 Pressed EAC-1 with Cu-rod, steel-tube, Al-rod, and Inconel tube

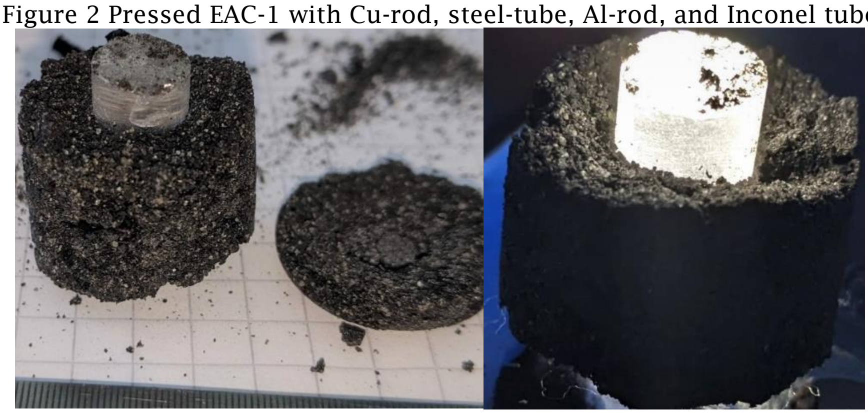

Figure 3 Unpressed EAC-1 with Quarz-rod

4 Interface samples produced

Based on preliminary samples trials, actual samples built and lessons learnt, a final set of each materials' combination has been produced.

This chapter contains a brief summary of all copper doped samples produced in the scope of the project. Additionally, the information on two extra stainless steel samples produced is provided here.

Table below presents a comprehensive summary of the various samples produced for the study, detailing the EAC-1A regolith simulant doped with and without copper dust and with the specific interface materials.

Table 1 I/F samples summary

Sample	Sintering configuration	Description	Picture
Copper Tube in EAC-1A + 10 wt % Copper	Placeholder sample. Sintered with a placeholder. Copper tube was later substituted. Glued interface is implemented after that.	EAC-1A regolith simulant, enriched with 10 wt% copper, is agitated for 2 minutes before being compressed at 255 MPa for 10 minutes into a 20mm external diameter washer with a 5mm internal diameter. This compacted sample undergoes a 9-hour thermal treatment in a vacuum oven for 3 hours at 1090°C, with a heating pace of 400°C/h and a minimal pressure of 5E-5 mbar. A copper tube is inserted into the central bore post-sintering. *This sample has been further assessed via thermal vacuum test.*	
Aluminium Rod in EAC-1A + 10 wt % Copper	Sintered with a placeholder. Glued interface is implemented.	EAC-1A regolith simulant, enriched with 10 wt% copper, is agitated for 2 minutes before being compressed at 255 MPa for 10 minutes into a 20mm external diameter washer with a 5mm internal diameter. This compacted sample undergoes a 9-hour thermal treatment in a vacuum oven for 3 hours at 1090°C, with a heating pace of 400°C/h and a minimal pressure of 5E-5 mbar. An aluminium rod is inserted into the central bore post-sintering. *This sample has been further assessed via thermal vacuum test.*	
Aluminium Tube in EAC-1A + 10 wt % Copper	Sintered with a placeholder. Glued interface is implemented.	EAC-1A regolith simulant, enriched with 10 wt% copper, is agitated for 2 minutes before being compressed at 255 MPa for 10 minutes into a 20mm external diameter washer with a 5mm internal diameter. This compacted sample undergoes a 9-hour thermal treatment in a vacuum oven for 3 hours at 1090°C, with a heating pace of 400°C/h and a minimal pressure of 5E-5 mbar. An aluminium tube is inserted into the central bore post-sintering. *This sample has been further assessed via thermal vacuum test.*	

Inconel Tube in EAC-1A + 10 wt % Copper	Sintered together with the inserted inconel tube. Bonding via sintering is unsuccessful. Glued interface is implemented.	EAC-1A regolith simulant, enriched with 10 wt% copper, is agitated for 2 minutes before being compressed at 255 MPa for 10 minutes into a 20mm external diameter washer with a 6mm-wide nickel-inconel tube inside. This compacted sample undergoes a 9-hour thermal treatment in a vacuum oven for 3 hours at 1090°C, with a heating pace of 400°C/h and a minimal pressure of 5E-5 mbar. A nickel-inconel tube is inserted into the central bore pre-sintering. *This sample has been further assessed via thermal vacuum test.*	
Quartz Rod in EAC-1A + 10 wt % Copper	Sintered with a placeholder. Glued interface is implemented.	EAC-1A regolith simulant, enriched with 10 wt% copper, is agitated for 2 minutes before being compressed at 255 MPa for 10 minutes into a 20mm external diameter washer with a 8mm internal diameter. This compacted sample undergoes a 9-hour thermal treatment in a vacuum oven for 3 hours at 1090°C, with a heating pace of 400°C/h and a minimal pressure of 5E-5 mbar. A quartz rod is inserted into the central bore post-sintering. This sample has been further assessed via thermal vacuum test *This sample has been further assessed via thermal vacuum test*	
Stainless Steel Tube in EAC-1A + 10 wt % Copper	Sintered together with the inserted St. steel tube. Bonding via sintering is unsuccessful. Glued interface is implemented.	EAC-1A regolith simulant, enriched with 10 wt% copper, is agitated for 2 minutes before being compressed at 255 MPa for 10 minutes into a 20mm external diameter washer with a 5mm-wide stainless steel tube inside. This compacted sample undergoes a 9-hour thermal treatment in a vacuum oven for 3 hours at 1090°C, with a heating pace of 400°C/h and a minimal pressure of 5E-5 mbar. A stainless steel tube is inserted into the central bore pre-sintering. *This sample has been further assessed via thermal vacuum test.*	
Copper Rod inserted pre-sintering in EAC-1A + 10 wt % Copper [Sample from 15.08.2023]	Sintered together with the inserted copper rod. Bonding is successful.	EAC-1A regolith simulant, enriched with 10 wt% copper, is agitated for 2 minutes before being compressed at 255 MPa for 10 minutes into a 20mm external diameter washer with a 5mm-wide copper rod inside. This compacted sample undergoes a 9-hour thermal treatment in a vacuum oven for 3 hours at 1090°C, with a heating pace of 400°C/h and a minimal pressure of 5E-5 mbar. A copper rod is inserted into the central bore pre-sintering. *This sample has been further assessed via thermal vacuum test.*	

5 Thermal interfaces characterization: tests performed

Experimental setup is designed in order to characterize the thermal interface between sintered regolith simulant and a material that is inserted into sintered block.

The following diagram illustrates the basic principle of the test setup for a single sample.

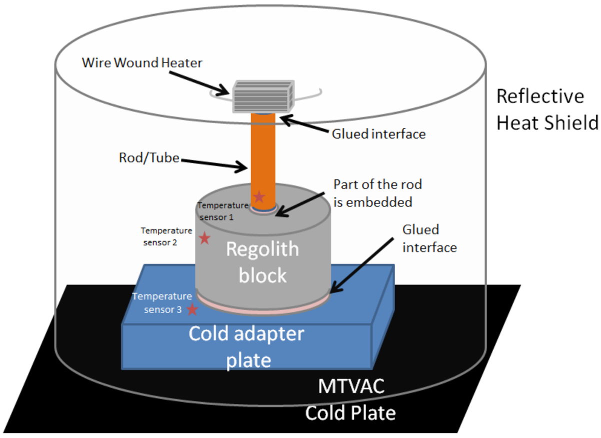

Figure 4 Experimental setup for a single sample

Since steady state technic for characterization of thermal interface is utilized, each sample is placed on a cold adapter plate and equipped with a wire-wound resistor that acts as a heat source. Resistors are attached to exposed tips of rods/tubes with high temperature vacuum adhesive. Same adhesive is used to mount samples of sintered regolith on the adapter plate.

On the diagram above, those interfaces where the adhesive is present referred to as “Glued interface”.

In order to determine ΔT across the interface, one temperature sensor is placed on the exposed part of rod/tube while the second sensor is located on the sintered regolith simulant. The sensors are placed as close to the interface as possible. One additional sensor is placed next to each sample on the cold plate so that local temperature at the adapter plate could be recorded.

Furthermore, each sample is given a cylindrical heat shield that is made of stainless steel and polished to achieve low emissivity values. This is done to minimize heat losses and radiatively decouple samples from the shroud or other samples.

The intention during the test was to characterize and compare the interface between the samples with the same inserted material for two types of sintered regolith simulant: doped EAC-1A+10%Cu with copper and simple EAC-1A. Thermal vacuum test is followed by a correlation process where temperature profiles obtained during the test are compared to those in the thermal model under the same inputs – boundary conditions. By varying different parameters of the model iteratively, temperature levels are modified to match the experimental results as close as possible. In order to ensure accuracy of the results obtained, the temperature differences during the test and in the thermal model shall stay within the range of ±3°C. Temperature deviations from this temperature range (if applicable) is going to be covered separately later on.

Results obtained after thermal model correlation are summarized in the following table.

Table 2 Inserts/regolith simulant interface

	Regolith simulant	Interfacing material	Interface type	GS rod/tube and regolith [W/m²K]	Notes
Batch 1	EAC-1A+10%Cu	Copper rod	Sintered	140.1	-
	EAC-1A	Copper rod		116.0	-
	EAC-1A+10%Cu	Aluminum rod	Glued	159.0	-
	EAC-1A	Aluminum rod		610.0	-
	EAC-1A+10%Cu	Aluminum tube		462.0	-

	EAC-1A	Aluminum tube		232.0	-
Batch 2	EAC-1A+10%Cu	Copper tube	Glued	1050.3	-
	EAC-1A	Copper tube		380.3	-
	EAC-1A+10%Cu	Inconel tube		510.3	-
	EAC-1A	Inconel tube		250.3	-
	EAC-1A+10%Cu	St. Steel tube		175.3	-
	EAC-1A	St. Steel tube		-	-
Batch 3	EAC-1A+10%Cu	Quartz rod	Glued	55.3	-
	EAC-1A	Quartz rod		67.3	-
	EAC-1A+10%Cu	Copper rod	Sintered	101.1	-
	EAC-1A	Copper rod		61.0	-
	EAC-1A+10%Cu	Inconel tube	Glued	69.3	-
	EAC-1A	St. Steel		28.3	-

Due to difficulties during the correlation process, samples EAC-1A+10%wt Cu with Copper rod, EAC-1A+10%wt Cu with Inconel tube were tested once more as a part of batch 3. Additionally, since the sample EAC-1A with St. Steel tube failed during the test, it was also included and tested in the last batch. On top of that, batch 3 was tested with a lower heat load of 1 W in order to avoid excessive delta T in the sample with quartz that possesses a low thermal conductivity compared to other samples.

As the outcome of these additional tests, extra data was generated and compared with the previous results (except for the sample with St. Steel tube.) The following points were identified after the comparison:

- sample EAC-1A+10%wt Cu with Copper rod was tested twice. During the second testing campaign (batch 3), the correlation yielded different results. The cause might be in this case the reduced power leading to larger errors (measurement and therefore correlated data);
- sample EAC-1A+10%wt Cu with Inconel tube was also tested twice and similar to the previously discussed sample, the outcome of the 1st correlation (batch 1) are considered;
- lastly, example EAC-1A with St. Steel tube was tested successfully just once with batch 3.

6 System assessment

Due to the difficulties encountered during the previous phases of the project and the consequent longer durations of those activities, the system assessment and scalability assessment have been reduced. In particular no final larger prototype has been produced and tested. The results of the interface samples' tests have been instead applied to the system thermal model to assess numerically performances' improvement.

The results of thermal correlation have been introduced inside the thermal model originally created for the project's precursor, MESG (the model was re-run to verify performance identical to the previous results) for the relevant interfaces, for both the baseline and the backup concepts, using both the non-doped (EAC-1A) as well as the doped (EAC-1A+10%wt Cu) regolith simulant data.

Table 3 Comparison between the system and the demonstrator design

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 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 working fluid); (alternatives: heat pipe / another "shape")
Heat engine	Stirling system	Stirling system
Heat transfer 3	Loop heat pipe (liquid metal as working fluid); (alternatives: heat pipe / another "shape")	Loop heat pipe or LHP (conventional working fluid); (alternatives: heat pipe/another "shape")
Heat rejection	Metal plate with shield	Metal plate with shield

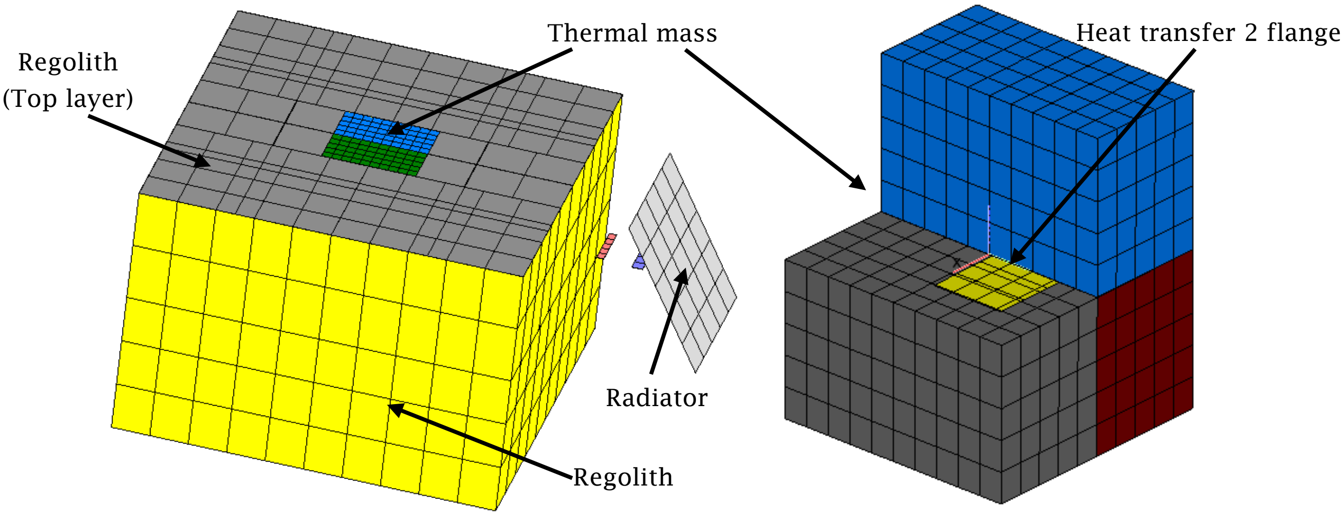

Figure 5 Geometrical thermal model (left) and the flange inside the thermal mass (right)

The results obtained can are summarized in sections 6.1and 6.2 below.

6.1 Conclusions for Concept 1

Conclusions relevant for Concept 1 are as follows.

- Concept 1 is feasible and capable of generating the required amount of electrical power for all material/regolith combinations except for EAC-1A with St. Steel (glued interface).
- The GS values between the heat pipes' flange and the TM shall be relatively high (GS=150W/m^{2}K is the safe threshold based on the original system) in order to avoid temporary shut-down of the engine and interruption of power generation.
- Further increase of GS does not result into significant improvements to the system. There is practically no difference in performance of the system between combinations of EAC-1A+10%wt Cu with St. Steel tube (GS = 175.3W/m^{2}k) or Inconel (GS = 510W/m^{2}k).
  - This further suggests that Heat transport 2 is critical to the systems performance and independent from Heat transport 1.
- The difference between Inconel and St. Steel is minimal in terms of the contribution of dry GLs. This is explained by very similar material properties.
- Doped regolith in the TM improves temperature distribution while slightly decreasing the peak temperature of the Tm itself and the engine's hot side, without affecting the performance of the systems in terms of power generation.

The recommended material combinations for Concept 1 are EAC-1A+10%wt Cu and St. Steel or Inconel tube with a glued interface. These combinations yield quite similar results and offer improved temperature uniformity and stable generation of the electrical power.

In comparison to the system with the original parameters, the updated parameters for Concept 1 improve temperature uniformity of the TM but do not significantly affect generation of the electrical power. This can nevertheless lead to an overall more efficient configuration and a better scalability of the system.

6.2 Conclusions for Concept 2

Similar to the previous section, the conclusions specific for Concept 2 are outlined below:

- Concept 2 is feasible and able to deliver the required amount of power to the end user for all material/regolith combinations except for EAC-1A with St. Steel (glued interface).
- Contact conductance values between the heat pipes' flange and the TM have to be kept relatively high (GS=150W/m^{2}K is the safe threshold based on the original system) in order to avoid temporary shut-down of the engine and interruption of power generation.
- Higher GS does not bring significant improvements to the system. There is practically no difference in performance of the system between combinations of EAC-1A+10%wt Cu with St. Steel tube (GS = 175.3W/m^{2}k) or Inconel (GS = 510W/m^{2}k).
  - This further suggests that improved contact conductance is not imperative to the system's performance as long as it is higher than a critical value.
- The difference between Inconel and St. Steel is minimal in terms of the contribution of dry GLs. This is explained by very similar material properties.
- Doped regolith in the TM significantly improves temperature uniformity increasing the temperature of the engine's hot side by about 50˚C which corresponds to 7.4 % improvement compared to that with the regolith without doping.

The recommended material combinations for Concept 2 are EAC-1A+10%wt Cu and St. Steel or Inconel tube with a glued interface. These combinations result into very similar system's performance marked by an improved temperature uniformity and stable generation of the electrical power.
With the updated parameters, Concept 2 shows an improved temperature uniformity of the TM, as well as moderate improvement of the temperature of the engine's hot side, leading to an overall system's efficiency improvement as well as a better scalability.