HEBAM project (HEat-based Battery for the Moon)

T1921.010-3-0

Summary

Introduction

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Following the precursor's project MESG: Moon Energy Storage and Generation, funded by ESA (Contract Nr. 4000119561/17/F/MOS), three main phases:

1. Regolith simulant and sintering techniques characterization;
2. interface samples manufacturing and characterization;
3. system assessment.

Summary

Regolith simulant and sintering techniques characterization

Focus on sintering/melting of regolith simulants using

- Oven, in vacuum or in atmosphere;
- concentrated solar energy;
- laser (Selective Laser sintering/SLM (SLS/SLM));
- microwaves.

While MESG focussing on JSC-2 simulant, HEBAM on **EAC-1A**.

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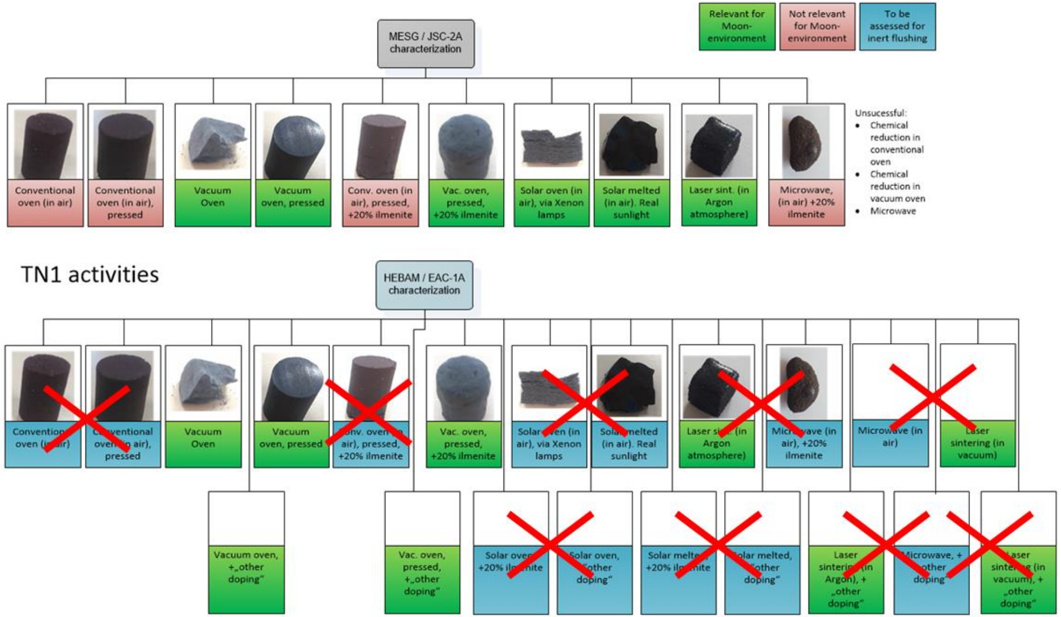
After multiple trials on the initially planned multiple sintering techniques, the actual project work focusses on the vacuum manufactured samples (yet, relevant for the Moon environment), due to difficulties encountered on the others.



Regolith simulant and sintering techniques characterization

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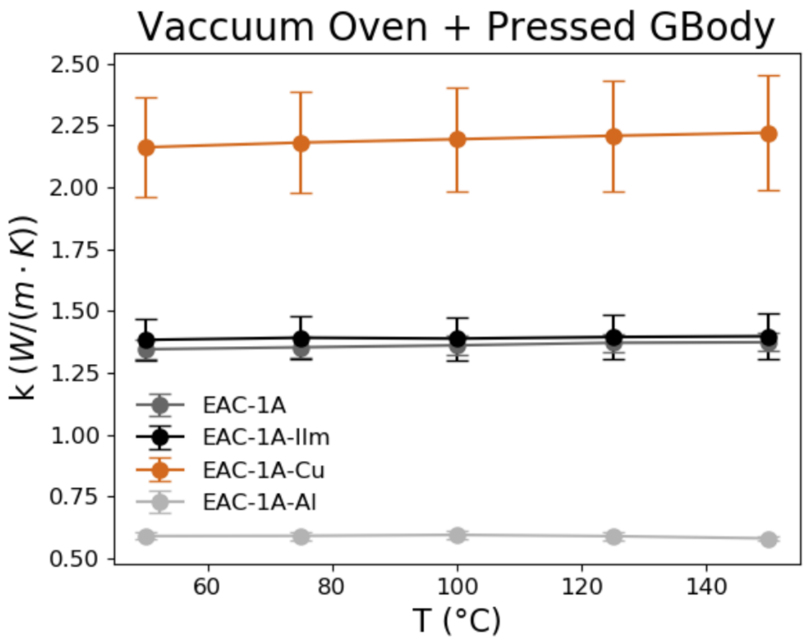
In order to improve the thermal performances of a quite insulating raw material as the (simulant) regolith, doping with metals has been attempted.

Despite its presence in the Moon regolith, doping with ilmenite didn't improve much the thermal performances.

Aluminium (obtainable from recycling activities from human exploration residues) doping instead demonstrated to compromise the structural integrity of the samples produced.

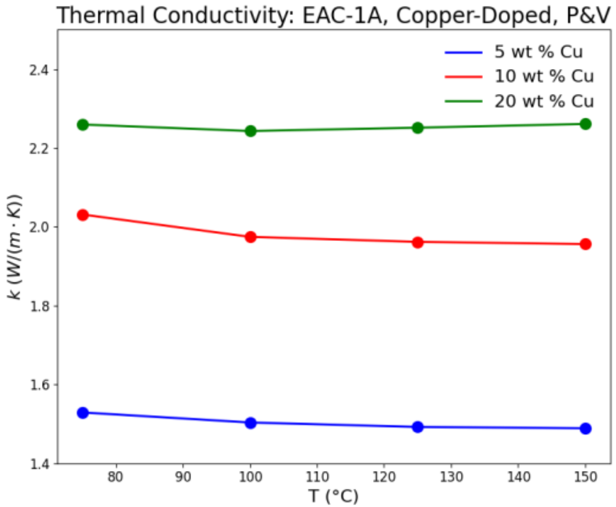
Copper doping instead, demonstrated good binding capabilities as well as in different %.



Doping with copper also allows the highest thermal conductivity improvement.

Regolith simulant and sintering techniques characterization

Different doping % was studied since copper cannot be found in quantities on the Moon, not indigenous, nor recycled from human activities.

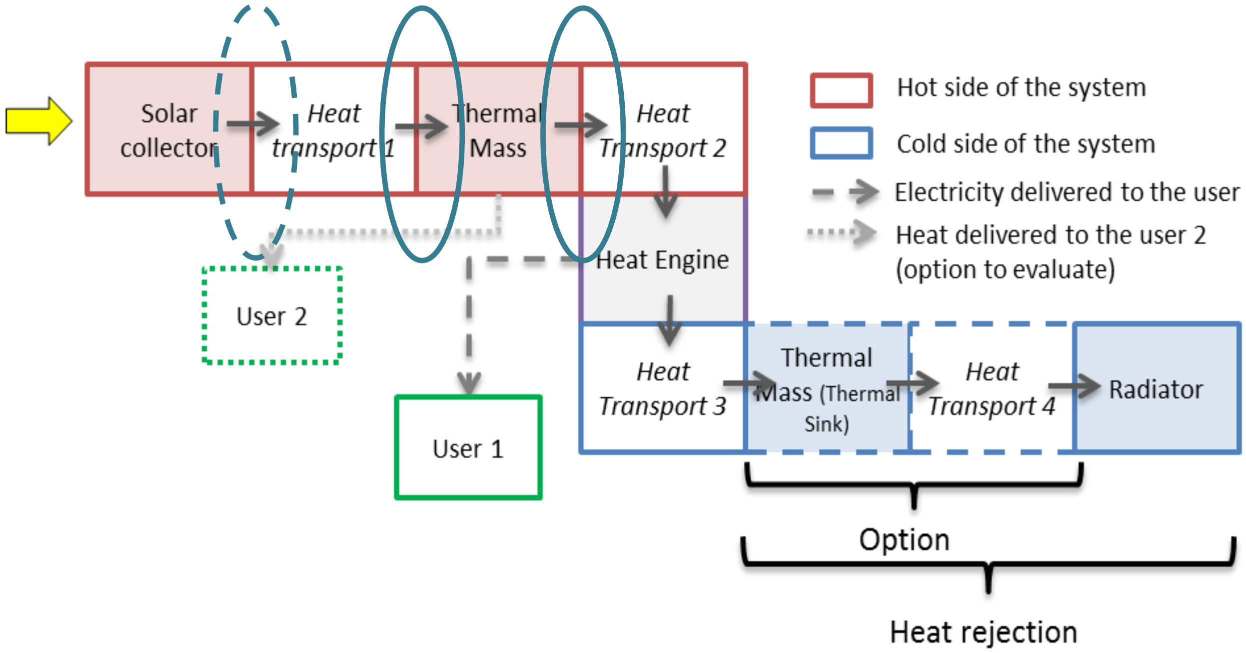


Therefore a 10% doping (by weight) was considered a good compromise, given the similar thermal performances achievable with a higher quantity (20%) of aluminium after solving in a close future the current issues in doped sintering.

Summary

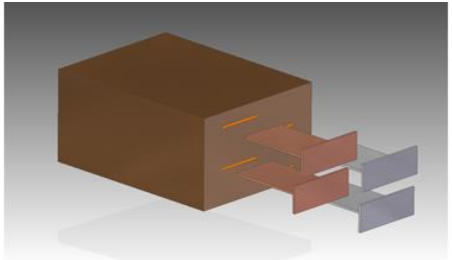
Interface samples manufacturing and characterization

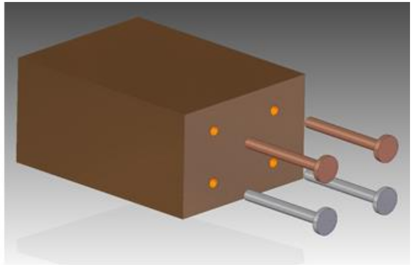
Scope: Improve thermal performances of the regolith and its interfaces in the system to improve the whole system thermal performances (heating/cooling faster and more uniformly).

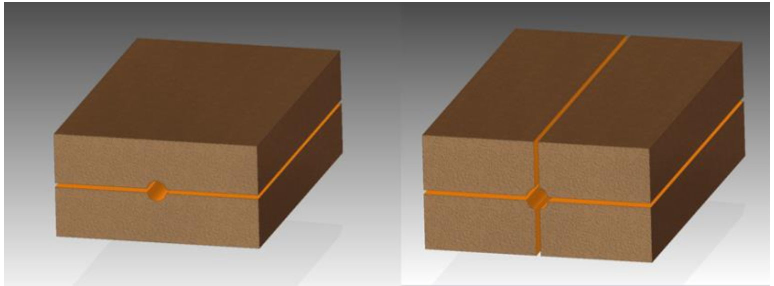


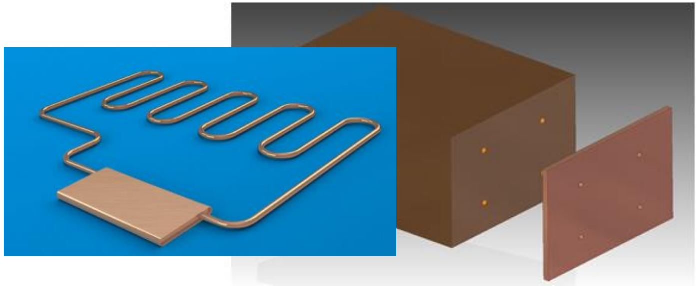
Interface samples manufacturing and characterization

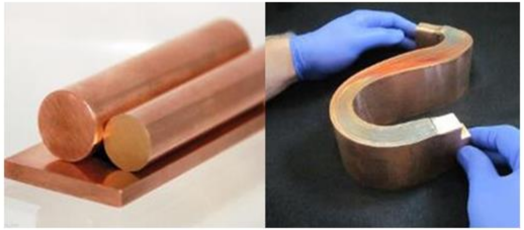
- Different materials / materials’ combinations
- Different shapes











Interface samples manufacturing and characterization

- 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 temperature).

- In a second place, inserting a place-holder while sintering can be used. The placeholder is to be removed at sintering completion and then substituted.

- Preferred shape of this alien part can be easily summarized as cylindrical (applicable for both optical waveguide, and rods or bars solutions), either "full" (rods/bars) or hollow (pipes).

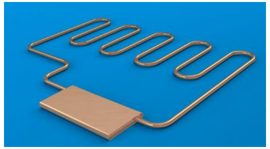
Interface samples manufacturing and characterization

- Alien materials characteristics are mainly driven by the sintering temperatures and high working temperatures:

    - Quartz glass rods (for optical waveguides concept);
    - Stainless steel LHP/HP filled with potassium (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).

- Final samples' list produced:
  - Copper rod + EAC-1A & *Copper rod + EAC-1A 10% copper doping*
  - Copper tube+ EAC-1A & *Copper tube+ EAC-1A 10% copper doping*

  - Aluminium rod + EAC-1A & *Aluminium rod + EAC-1A 10% copper doping*
  - Aluminium tube+ EAC-1A & *Aluminium tube+ EAC-1A 10% copper doping*



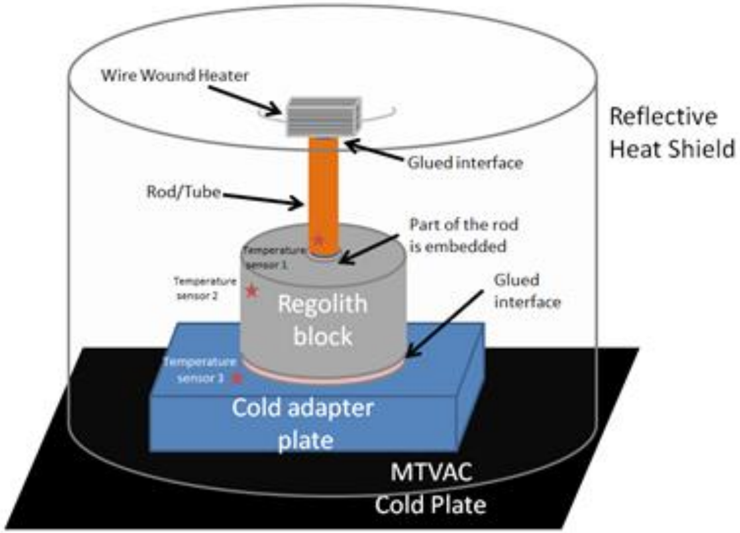
  - Stainless steel tube + EAC-1A & *St. Steel tube+ EAC-1A 10% copper doping*
  - Inconel tube + EAC-1A & *Inconel tube+ EAC-1A 10% copper doping*
  - Quartz rod + EAC-1A & *Quartz rod + EAC-1A 10% copper doping*

Interface samples manufacturing and characterization

- Only successful integration of alien material into the sintered regolith simulant on copper rod.

- All the other interface samples built with placeholder and replaced with preferred insert + adhesive.

- Thermal vacuum tests to assess the thermal interfaces in the sample.



- Following: thermal modelling and correlation (target: test minus model < |3|°C)

Interface samples manufacturing and characterization

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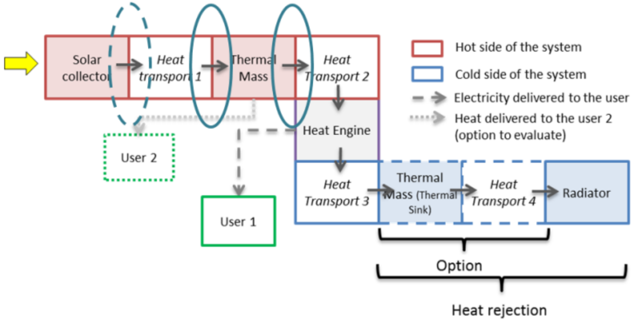
- High workmanship impact
- No reliability assessed
- Unexpected low performances of the sintered copper rod
- In general, better interfaces with doped EAC-1A

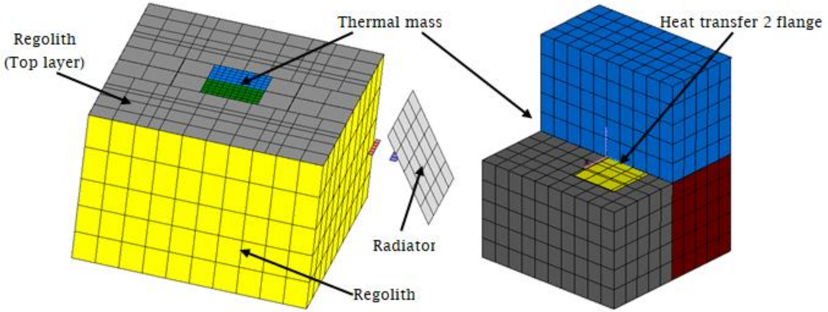
	Regolith simulant	Interfacing material	Interface type	GS rod/tube and regolith [W/m²K]	Notes
Batch 1	EAC-1A+10%Cu	Copper rod	Sintered	140.1	-
	EAC-1A	Copper rod		116.0	-
	EAC-1A+10%Cu	Aluminum rod	Glued	159.0	-
	EAC-1A	Aluminum rod		610.0	-
	EAC-1A+10%Cu	Aluminum tube		462.0	-
	EAC-1A	Aluminum tube	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

Summary

System assessment

- System assessment and scalability assessment have been reduced.
- No final larger prototype has been produced and tested.
- The results of the interface samples' tests are instead applied to the system thermal model (MESG model, re-assessed) to assess numerically performances' improvement.



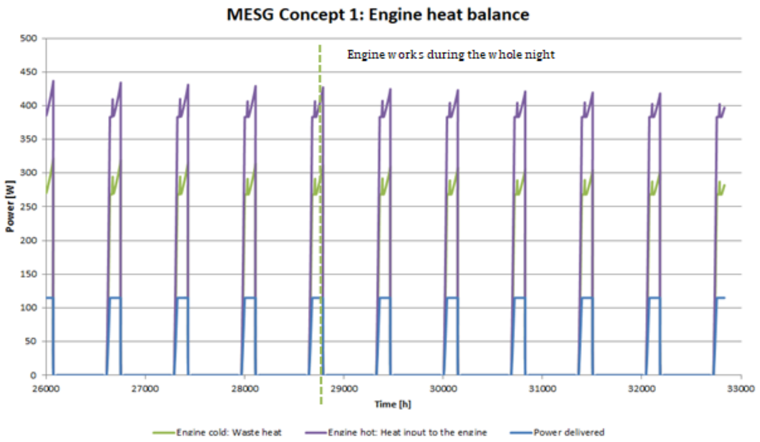


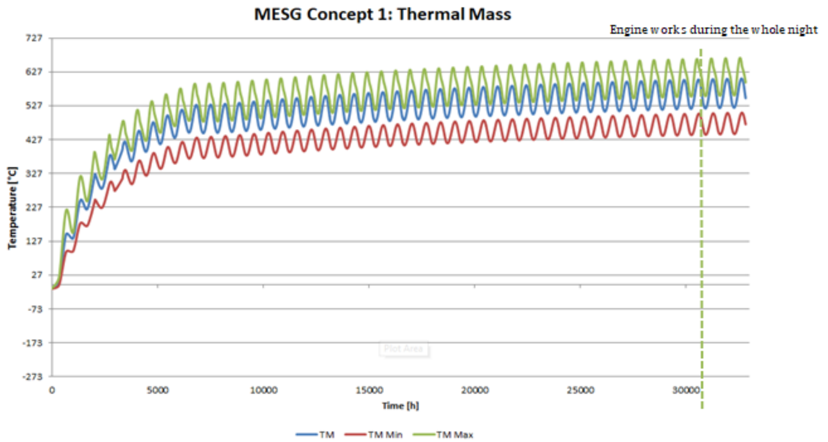
System assessment

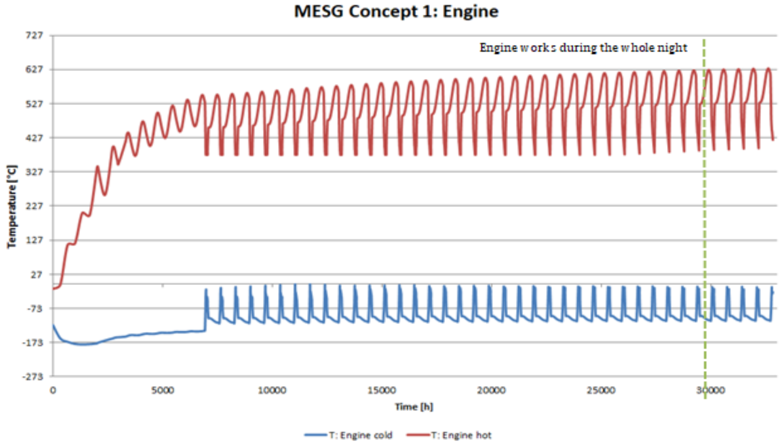
- Model run with both EAC-1A characteristics, as well as doped EAC-1A (10 %wt Cu), with either stainless steel and Inconel inserted tubes (and their interfaces from the I/F tests).
- Both concept 1 and 2 assessed.
- The original values adopted for MESG project include a contact conductance of 150W/m^{2}K (for all relevant interfaces mentioned above) and the regolith properties: *k* = 1.21W/mK, *Cp* = 1200J/kgK.

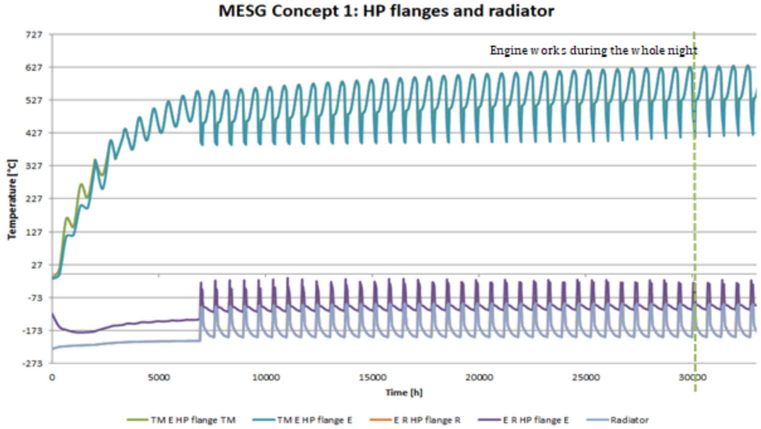
System assessment

Example of results assessment









System assessment

- Both concepts are feasible except for EAC-1A with St. Steel (glued interface) → too low GS.

- The GS values between the heat pipes' flange and the TM shall be relatively high (GS = 150 W/m^2K is the safe threshold based on the original system) in order to avoid temporary shut-down of the engine and interruption of power generation.

System assessment

- 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 = 175.3 W/m^2k) or Inconel (GS = 510 W/m^2k).

- 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.

System assessment

- **Concept 1:** 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.

- **Concept 2:** 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.

System assessment

- For both concepts the recommended materials' combination is EAC-1A+10%wt Cu and St. Steel or Inconel tube with a glued interface.

- In comparison to MESG models:
  - **Concept 1** no significant improvements, except better temperature distribution in the TM.

  - 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.