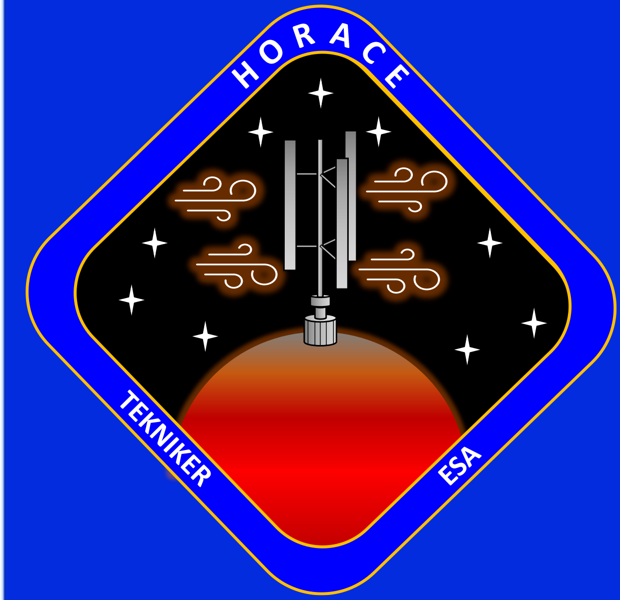
HORACE
Triboelectric energy harvesting for Mars exploration

Executive Summary

Requested by:	**European Space Agency (ESA)**
Code / Version:	2.0
Editor:	Dr. Borja Pozo
Approved by:	Ewelina Ryszawa
Date:	24/11/2023



Content

Document history

VERSION	DATE	EDITOR	COMMENTS
1.0	22/10/2023	Dr. Borja Pozo	*First version of the document*
2.0	13/11/2023	Dr. Borja Pozo	*Answers to officer comments and questions*

Reference document list

No.	DOCUMENT	VERSION
1	*Literature overview and system requirements (TN1)*	2.0
2	*Generator description and analysis report of the simulations (TN2)*	5.0
3	*Breadboard operation and analysis report (TN3)*	5.0
4	Breadboard design (TN4)	5.0
5	Breadboard manufacturing and assembly process (TN5)	4.0
6	Breadboard test plan and procedure (TN6)	4.0
7	*Breadboard Test Report (TN7)*	3.0
8	*All the PM*	2.0
9	Photographic and video files	1.0
10	All the Reports	1.0
11	HW deliverable (turbine)	1.0
12	All the milestones MoM documents	1.0
13	The 2 published papers	1.0
14	Project proposal	1.0

Document authors

Tekniker: • Dr. Borja Pozo • Iñigo Muñoz • Dr. Iban Quintana • Iñigo Arizaga	

1. Wind power in mars and environmental conditions

The aim of the work has been to develop an efficient and robust turbine demonstrator that can efficiently operate under Mars environmental conditions. A combination of low friction and high inherent triboelectric charge density materials have been integrated into the Triboelectric Generator (TEG) architecture operating under a freestanding mode and including 4 generators. Each generator is compounded by Al+PTFE stator and H-DLC+Al rotor and the complete efficient design has 2 rotors and 4 stators. Then the vessel where the generators are located is pressurized achieving an Earth atmospheric pressure value (1000 mbar) and Mars atmospheric composition (96 % CO2) because the power generation is increasing by 31.84 % in comparison with power generated under Earth atmospheric composition and 98 % under Mars atmospheric pressure. Moreover, the turbine mechanical elements such as blades, sealings, and vessel have been designed, simulated, manufactured, assembled, and tested to achieve the correct operation based on Mars's environmental requirements.

The human and robotic exploration for Mars will require total independence from Earth, and as in the Earth, the energy stable availability will become crucial to allow permanent habitats . In addition, Mars dust storms can last more than 6 months becoming solar energy unusable for that period, consequently causing a lack of available energy for future astronauts. This work wants to take advantage of Mars's environment to convert wind energy into electrical energy and use it as the auxiliary energy source of solar cells. However, the usual Electromagnetic Generators (EG) are unsuitable for planetary exploration due to their heavy weight, leading to high launch costs. The alternative to EG could be the Triboelectric Generator (TEG), a relatively new technology which converts external mechanical energy into electricity by a conjunction of the triboelectric effect and electrostatic induction.

The main atmosphere parameters that change on Mars regarding the Earth are density and velocity. The atmosphere density on the Earth is 1.217 kg/m3 and on Mars 0.020 kg/m3, both at surface level. The wind speeds measured on Mars give a range between 5 and 30 m/s. The benefit of the power production equation is that the extraction potential for wind power is a function of velocity cubed and only proportional to density. So, the effect of the Mars atmosphere density parameter has a smaller impact than the velocity, for the power that can be extracted from the winds. This work has been developed using real data measured by NASA's Insight mission at the Elysium Planitia to find out how the turbine works in real Martian conditions. In addition, Table 1 shows the summary of Mars's environmental conditions.

Table 1. Summary of Mars airflow and environment conditions.

		Mars	**Earth**
Airflow factors	Air density (kg/m^3)	0.02	1.225
	Wind velocity (m/s)	25.8-41.0	6.2-11.5
	Wind power density (W/m^2)	172-689	147-932
Environmental factors	Atmospheric pressure (Torr)	1-10	760
	Majority composition	CO2	N2,O2
	Average temperature (K)	218	288
	UV-C & UV-B intensity (W/m^2)	46	6
	Gamma ray intensity (rad/year)	26.3	0.03

The main question is that even though on Mars there are wind seasons with high-speed winds, the atmosphere density is very low. It is not obvious that a wind turbine would move under those conditions. The good part of the power production equation is that the extraction potential for wind power is a function of velocity cubed and only proportional to density. So, the effect of the Mars atmosphere parameter is less worthwhile than the velocity regarding the power that can be extracted from the winds. Figure 1 shows the Martian meteorology of three typical sols experienced by InSight, which shows a diversity of scales involved from the planetary scale to local turbulent scales:

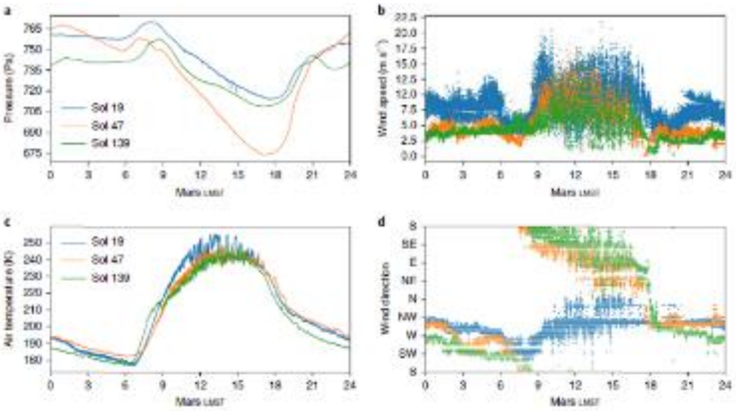


Figure 1. Measurements of pressure (a), wind speed (b), atmospheric temperature (c) and wind direction (d) are shown.

This turbine aims to convert the mechanical energy of the Mars winds to electric energy. For that, the turbine is designed to convert the wind mechanical energy into rotational movement, then the triboelectric generators which are moved with the rotation movement of the axis produce the electrostatic energy, and finally, the electrical energy must be achieved converting from the electrostatic energy with a power management.

2. Triboelectric generator

The functionality of TEGs is based on triboelectrification (or contact electrification) and electrostatic induction phenomena (see Figure 2). TEG architecture involves two materials with different charge affinity during contact. The freestanding TEG has more advantages of a contact separation mode as it does not require attachment to the moving triboelectric layer with an electrode and a lead wire. In this work, a freestanding mode as the one represented in Figure 2 is considered. In this scenario, a grating structure is manufactured in the rotator and stator where the output power depends on the material selection, contact surface characteristics, grating number, and electrode gap.

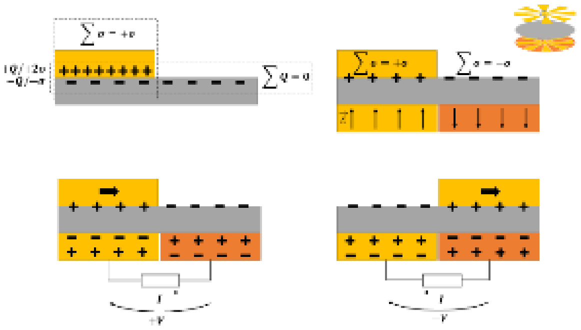


Figure 2. Electric charge and electric charge density generated on materials surface.

The Figure 3 shows the TEG generator trade-off design, together with the cut-out view of 4-layer TEG generator dividing the 4 stators and the 2 rotors. The stator blades to generate the positive and negative charges are fixed to PEEK support elements, which include 3 anti-rotation elements and the preload springs. Finally, each generator is connected to wires via the output point of connection to measure the power generated by the turbine.

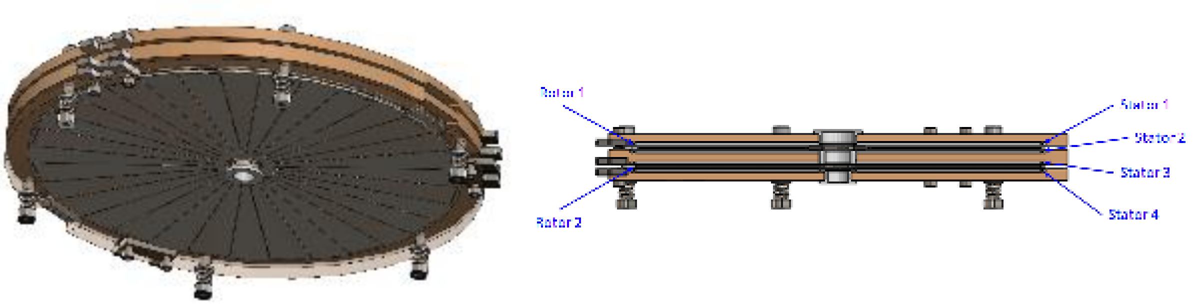


Figure 3. The TEG generators structure.

The pressure and the CO_2 are the two main parameters that affect the TEG's power generation which decreases at lower pressure levels (CO_2 effect is also decreased). In higher pressure levels the CO_2 effect (due to the Paschen law) on the materials increases the generated power in comparison with Earth's atmospheric conditions.

3. Turbine system

3.1 Turbine system design

The system has a basic operation principle, the total resistive torque must be reduced as much as possible to lower its impact on turbine performance and assure the possibility of rotation (starting point) even at low wind speeds, thus the system torque must be lower than the wind-generated torque to achieve the correct rotation operation. Thus, the system design must be oriented to accomplish this requirement. For that different types of loads acting on the wind turbine have been identified, simulated, and analysed: wind forces, centrifugal forces, internal pressure in the vessel, and thermal loads. During this work, the mechanical simulations including the aerodynamic design of the blades have been carried out, oriented to the system operation under Mars winds and conditions. Figure 4 shows the achieved results during these processes:

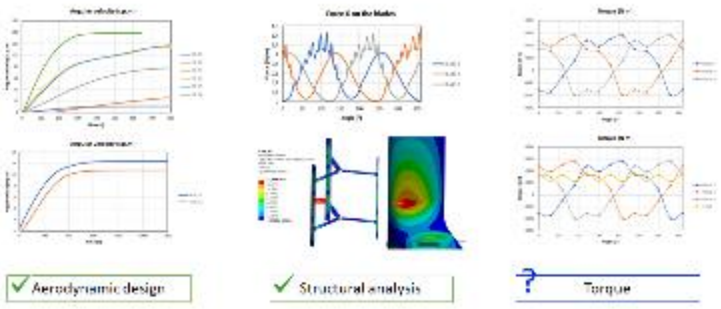


Figure 4.Results of aerodynamic, structural, and torque simulations and analysis.

As in usual Earth wind turbines, the TEG generator rotates thanks to the movement of the axis. To allow the rotatory movement with the minimum required torque while avoiding dust insertion and maintaining the pressure level the next elements have been included in the final design: the sealing element that allows the rotatory movement, the up bearing to support the radial and axial forces, the down bearing to support the radial forces, the labyrinth to void the insertion of the dust in the sealing rotatory system. In addition, the vessel is compounded by a skeleton architecture that ensures the pressurization of the vessel without any damage. Finally, the blades are made with space compatible carbon fiber and fixed to the axis. These elements are shown in Figure 5:

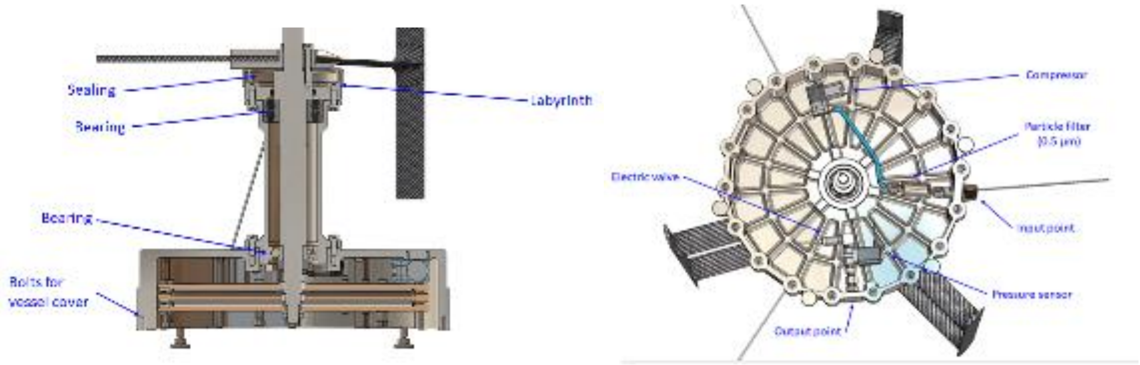


Figure 5. Mechanical view of the turbine from a cut view and pressurization and cleaning systems inside the vessel.

Figure 5 also shows the pressurization and cleaning system of the vessel. The pressurization system is composed of a nm particle filter to avoid the insertion of the Martian dust and damage the compressor which increases de vessel pressure. In addition, a pressure sensor is included to measure and control the vessel pressure. Then, the cleaning system is composed of an electrovalve which decreases the pressure in case that is necessary and at the same time cleans the vessel thanks to the difference in pressure between the vessel and the Martian atmospheric pressure.

Finally, a linear estimation (not very accurate but yes a reference to future estimations) of sealing lifetime versus axis different Ra value was calculated with the data provided by Bal Seal (sealing part designers and manufacturers). Table 2 shows the calculated estimations for the sealing lifetime under Martian atmospheric (temperature and pressure) and turbine operation conditions:

Table 2. Continuous working at 160 rpm as average value.

Ra (µm)	Lifetime (h)	Lifetime (days)	Lifetime (sols)	Lifetime (months)
0.4	4000	166.67	162.21	5.56
0.2	8000	333.33	324.41	11.11
0.1	16000	666.67	648.83	22.22
0.05	32000	1333.33	1297.66	44.44
0.025	64000	2666.67	2595.32	88.89
0.01	160000	6666.67	6488.3	222.22

4. Prototype manufcature and assembly

In this work a prototype has been manufactured, being the prototype dimension 12 kg of weight and 0.9 m of height. This system is totally scalable; however, the selected height has been based on the limitation set by the dimensions of the Mars wind tunnel testbench. Figure 6 shows the turbine totally assembled.

Figure 6. Prototype of the wind turbine for Mars.

In electromagnetic generators, the impedance is matching the changes of the system torque. In the TEG this effect is also detected but does not depend on the velocity, it remains constant. As has been detailed, the system must be pressurized to 1000 mbar to increase the power generation, affecting the system torque which is considered as the friction between the sealing and the axis, and the force made by the pressurization. Finally, the TEG torque is generated by the flatness of the TEG "sandwich", the preload set by the selected springs, and the contact area. The total torque total of the system is therefore:

$$T_{Total} = T_{TEG} + T_{Pres} + T_{IM} \qquad (1)$$

In the designed system, the pressurization torque is 0.3 Nm, the friction torque from sealing is 0.2 Nm and the TEG friction is 1 Nm for the 4 generators. Being the total system torque 1.5 Nm. Figure 7 shows the preload springs and the DLC rotor.

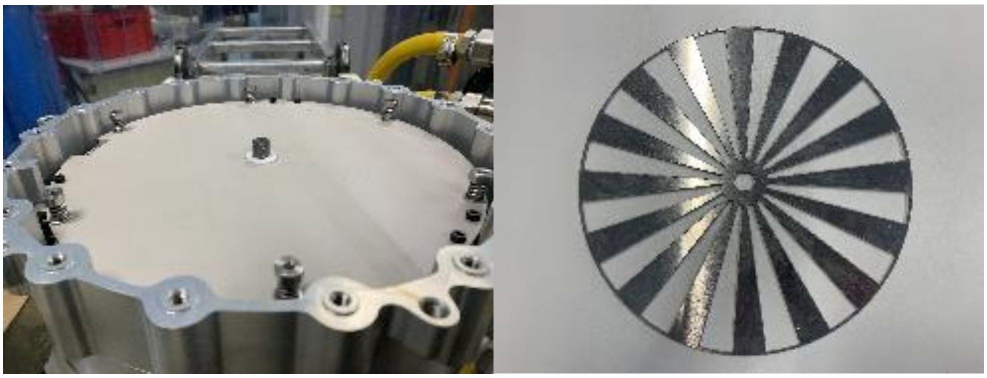


Figure 7. The vessel with holes for the enclosure, the preload springs, and the 4 TEG generators packaged and the DLC rotor.

5. Main test campaigns

The turbine has been tested to validate the pressurization behaviour of the vessel, the power generation, the preload values, the lifetime of the generator materials, and the operation in Mars wind conditions. All the tests have been carried out under different rotatory conditions.

5.1 Voltage and power generation

First of all, it must be considered that the distance between the generator and the measuring system or load affects dramatically the measurement due to the losses that are produced in the wire (low current signals are generated by the TEG).

The voltage and power generation tests have been carried out under Earth, Mars, and Mars pressurized conditions and different rotational velocities which have been: 50,100,150, 200, 250, 300, 350, 400, and 432 RPMs (being the origin of the aerodynamic design simulations). To simulate the Mars environmental conditions the Titan machine (available at Tekniker facilities) has been used which allows external control and measurement of the systems and is capable to generate the required 6 mbar and 96 % CO2 environmental conditions. The test setup for the voltage and power generation test campaign is shown in Figure 8.

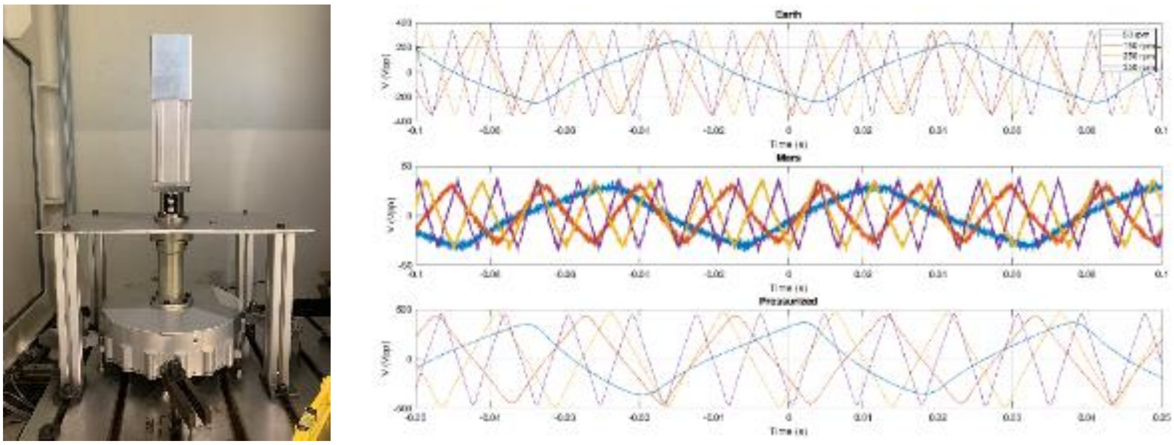


Figure 8. Test setup for generator with an engine to simulate the rotatory movement inside the test chamber and Generated voltage signals at different velocities under Earth, Mars, and Mars pressurized conditions.

5.1.1 Voltage generation

The first step has been to measure the voltage level generated at the different 3 conditions with the aim to understand the TEG's energetic capabilities. The voltage in the open circuit condition of the TEG must be measured in no-ground condition to have a real value of the voltage and don't lose any charge. Figure 8 also shows the voltage signal generation at different environmental conditions and angular velocities.

Note that the generated triangular signal is an effect of the mechanical triangles of the stator and rotor. In addition, the TEG generator is dramatically affected by the load that is connected (oscilloscope shunts in this case), reducing the real voltage generated. The no-ground condition must be used to measure the real generated voltage level, i.e., the positive and negative sides of the generated signals.

As can be seen in Figure 9, the maximum Voc is 953.98 V in Mars pressurized condition and at 200 rpm. The voltage increases until 200 rpm of angular velocity and decreases in higher velocities. As in trade-off tests, the system is not able to operate under Mars standard condition (pressure of 6mbar). The voltage level increases on average by 26.64 % when the turbine operates in Mars pressurized conditions. The increase of the voltage generated before 50 rpm is much more rapid than after 50 rpm. Thus, the system is operative to generate power after achieving 50 rpm of angular velocity.

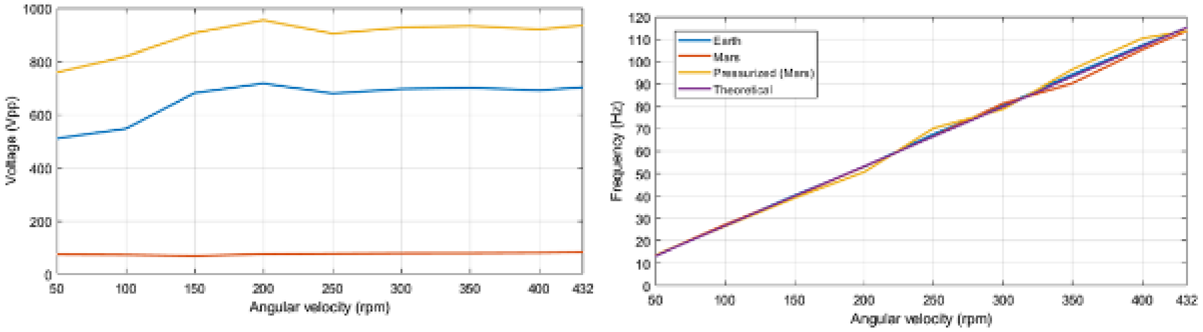


Figure 9. Voltage generated by the TEG generators at Mars, Earth, and Mars pressurized conditions and *Signal frequency of the TEG generators at Mars, Earth, Mars pressurized conditions, and theoretical value.*

The system is totally repeatable, the system remains stable in voltage generation and frequency value in each operation condition. The difference between the theoretical frequency of the generator at different velocities and the measured is less than 0.62 % on average, as is shown in above figure.

5.1.2 Power generation

The impedance matching condition will provide the maximum output power condition of the generator for each rotatory velocity. For TEG the impedance matching conditions are achieved with a RC load. The TEG is a capacitor in which the internal power must be extracted with a capacitor, and then with a resistive load act as usual in power generation systems.

The maximum achieved power is 15.144 kW in Mars pressurized condition, 432 rpm, and RC of 10 Ω and 0.094 µF. The maximum achieved power in Earth's atmospheric condition is 4.09 kW at 400 rpm, and RC of 10 Ω and 0.094 µF. The power level increases on average by 31.37 % when the turbine operates in Mars pressurized condition. Figure 10 shows the achieved results:

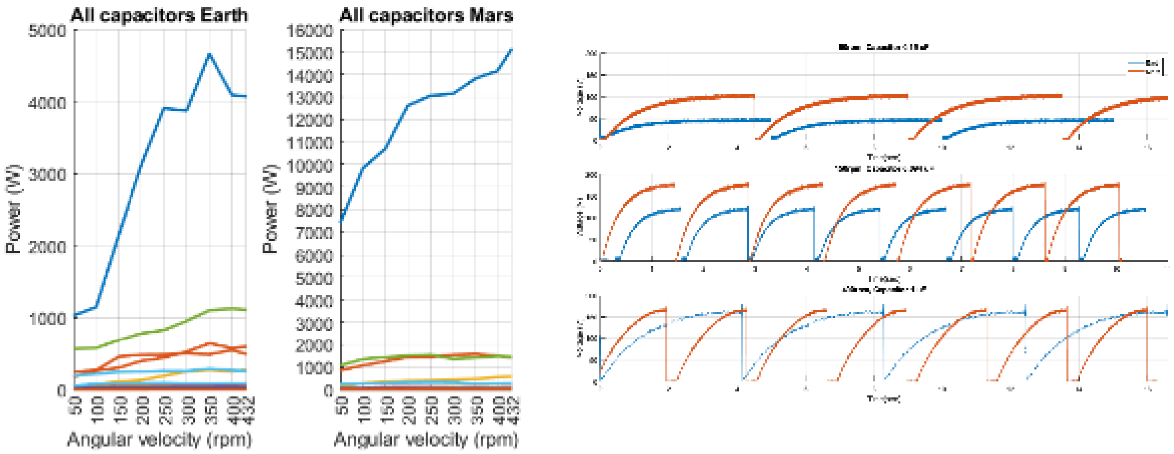


Figure 10. Produced electrostatic energy by the turbine at Earth and Mars pressurized conditions and Charge and discharge of different C loads and effect of Earth and Mars pressurized conditions.

The generated power increases with the angular velocity and lower RC load. The charge time of the capacitor decreases with higher angular velocity and lower capacitor value. The discharge time is always the same (with the same RC load), i.e., doesn't vary with the environmental condition (Earth and Mars). In addition, the charge time decreases in Mars pressurized condition with regard to Earth's atmospheric condition. This allows the quicker charge of the capacitor, so, quicker power extraction of the TEG. Figure 10 also shows results with different capacitors and the same resistive load for Earth and Mars pressurized conditions.

However, the electrostatic energy is not directly usable for any electronic/electrical system. A power management element is required to carry out the power conversion. In the section 4.2 of the TN8 Mars turbine technology improvements and roadmap deliverable a possible PM for this system is described. And in line with this issue, the usability of the turbine for different applications is deeply analysed in the section 5 of the Final Report document.

5.2 Mars wind tunnel

Mars Simulation Laboratory of Aarhus University has a Mars wind tunnel which simulated the Mars atmosphere and winds. The facility shown in Figure 11 has a cross section of 1 m x 1 m within which they can generate winds up to 25 m/. In addition, the wind tunnel performs dust exposure testing and has been used to test the wind turbine.

5.2.1 Turbine operation under Mars winds

The objective of this test campaign has been to verify and validate the complete turbine behaviour in a wind tunnel analysing the system structural behaviour and rotative movement in a similar Mars environment, as can be seen in Figure 11. In addition, during this test campaign, the self-starting capability of the turbine has been verified, the achieved results have allowed to make a comparison between the mechanical simulation results with real tests measured results (for scalability and performance in Mars) and have been analysed the dust effects on the turbine behaviour and turbine sealing system verification. The tested pressures have been such as 8, 11, 14, 16, and 50 mbar (the last one is not possible on Mars but is useful for the simulations correlation task).

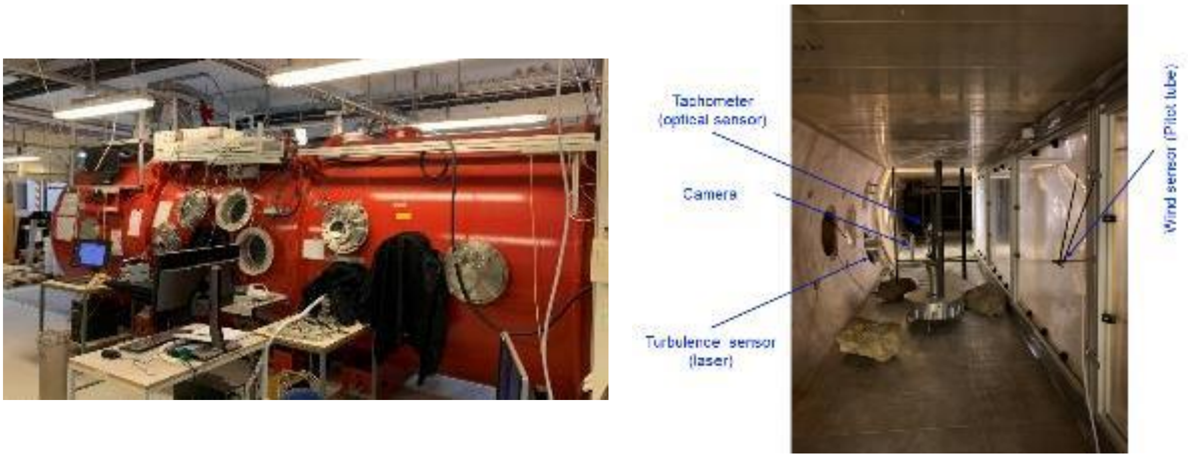


Figure 11. Mars wind tunnel facility at Aarhus University and the wind turbine installed in the Mars wind tunnel to carry out the test campaign and attachments to rocks to maintain stability.

The turbine has rotated at different pressures and wind velocities, so, it is possible to use Mars winds to move wind turbines. As has been expected, the higher is the pressure or/and the wind velocity the turbine's angular velocity increases. The attachments of the rocks (simulation of Mars environment) work correctly and maintains the turbine stable. However, with the current dimensions of the blades, the turbine doesn't rotate when the wind velocity is between 5 and 9 m/s. One of the reasons is the behaviour of airflow in the wind tunnel. At low angular velocities, the "opposite" blade to the wind flow acts as a brake due to the compensation of forces. The achieved rotational velocities of the turbine vs pressure and vs wind velocity are shown in Figure 12:

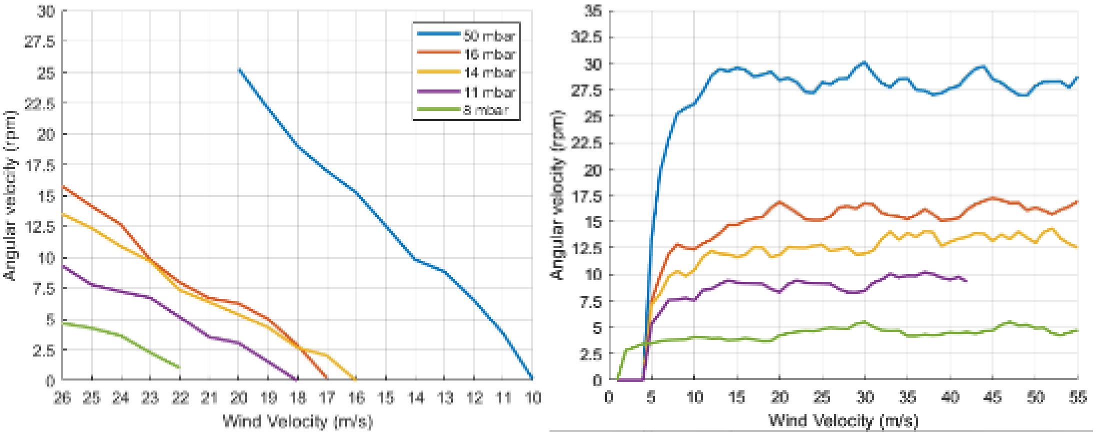


Figure 12. Turbine rotational velocities at different pressures and wind velocities and self-starting curves at different pressures and maximum wind velocities.

A maximum deviation of 28.58 % and a minimum of 3.10 % have been measured as stability at different velocities.,with the average deviation or stability of 16.65 %. As turbulences inside the tunnel are estimated as 20 %, the turbine movement can be considered stable for all the wind velocities. Also, as has been expected, the starting time changes with the pressure and wind velocity, where the above figure shows the achieved results.

5.2.2 Dust exposure

Controlled dust exposure within the facility entails injecting a known mass of Mars analogue dust together with a known (relatively small) volume of gas (typically at 1 bar pressure). This amount of gas is extremely small compared to the volume of the chamber however the resulting jet may temporarily disturb the wind flow. Depending upon the wind speed and the gas density the dust will become deposited after some time (typically a few minutes at low wind speeds).

The Mars dust analogue used in these tests is produced by milling and sieving (<20µm) the commercial MGS-1 Mars regolith analogue. Size determination gives an average grain diameter of 3µm. This fulfils ESA requirements; RV-GDIR-2454 / RV-PLAT-647 / T, A and RV-SAA-2050, RV-GDIR-5411. Two target dust concentrations have been sued during dust exposure. These were 75mg/m^3 and 90µg/m^3. In addition, during the dust exposure tests a sensor system has been used to monitor the dust concentration. This system measures the laser light power transmitted through the environmental chamber, i.e., across the wind tunnel. Suspended dust within the wind tunnel will obscure (absorb) light depending upon the grain size and concentration (independent of wind speed). The figure 13 shows the light transmission measurements during the dust exposure cycles (11 injections of 1.9g).

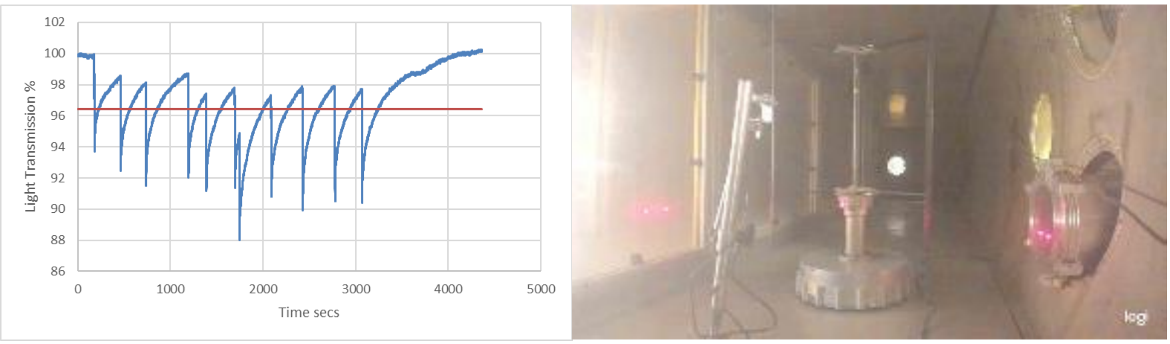


Figure 13. (blue); measured light transmission power in % of original-final value, the red line is the average over the 1 hour (3600 seconds) of dust exposure and turbine dust exposure test inside the Mars wind tunnel.

The average measured dust concentration (opacity) during the 1 hour of dust exposure was around 96.4% corresponding approximately to the concentration following the first injection of 1.9g of dust, i.e., a concentration of around 75mg/m^3. The test chamber status at the end of the dust exposure test can be seen in Figure 13.

Using the opacity measurements (light transmission) and knowing the average size of a single MGS-1 dust grain, it has been possible to determine the (average) dust concentration during this dust exposure being equivalent to 70 sol.

Finally, after the dust exposure test the turbine has been analysed to detect any structural damage or dust insertion into the vessel. Satisfactory results have been achieved without any damage and without the detection of any dust particles inside the vessel. Figure 14 also shows the dust deposition in different parts of the turbine.

Figure 14. Dust deposition in different mechanical parts of the turbine.

5.3 System lifetime tests

The final test campaign of the HORACE project has been an initials lifetime test to know and analyse the quantity of cycles that the generators and the system can achieve, the degradation of the system after n cycles and set the base information for a future long time lifetime test campaign.

The first step has been to build the test setup, which is detailed in the next points:

- The rotatory movement of the turbine will be performed with a motor and controlled with a PC and a PLC. The rotatory velocity of the motor is set from an application and the system torque is measured constantly.
- A mechanical adapter 1:4 has been added to the axis to reduce the exigence of the motor for the possible long-time test.
- The voltage level generated from the tested generator will be measured with the oscilloscope used in the previous tests.
- A CO2 bottle with a regulator inserts the CO2 in the vessel and maintains the 2 bar pressure inside the vessel. To simulate the pressurization inside the vessel, in this case, the vessel will be pressurized at 2 bar and outside pressure will be 1 bar. Thus, the pressure difference (force) of 1 bar of the system on Mars is achieved.

Finally, the figure 15 shows the test setup:

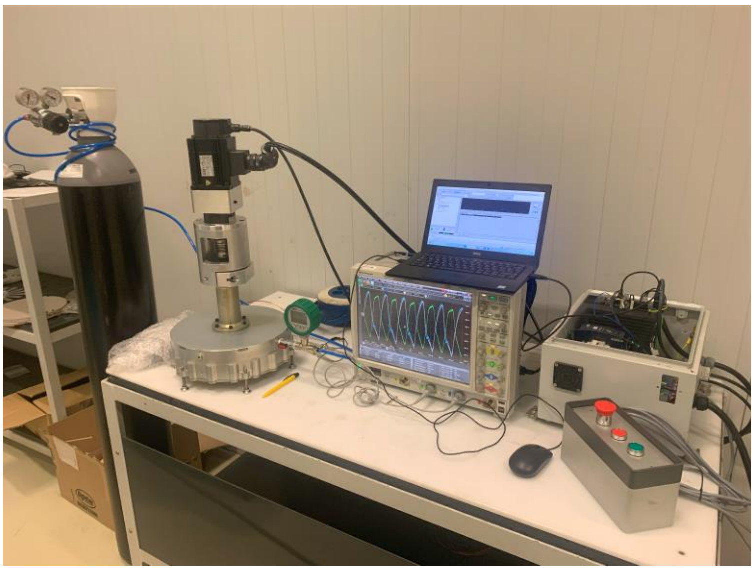


Figure 15. Prepared test setup to carry out the lifetime test campaign.

In the next key points, the numbers of the test campaign are shown:

- Total test hours: 363 h
- Contant angular velocity: 100 RPMs and right direction rotation (clockwise)
- Total performed cycles: 2,178,000 cycles
- During this test campaign (at the start), only 1 TFM disc was new. The other 3 TFM parts have been used during the all-test campaigns.
- The conclusion is that the turbine stopped producing energy due to the reduction of the preload, so, there was not real contact between TEG parts. Being the lack of operation of the preload springs due to the thickness reduction of the old TFM parts.
- Also was analysed the other TFM parts (the old ones). The degradation of these ones was much higher.
- Then, the preload springs were changed assembling ones with higher K. After starting to move the generators with the motor, the generation of voltage came back. So, the reason for not working was proven and verified.
- The 3 TFM disc were changed by 3 one (stop and re-start states)
- After the re-start (higher torque value) a constant voltage signal level: a bit more than 800 V (out of range of the oscilloscope)
- From 308 hours onwards, a voltage decrease was detected, i.e., with 1,846,000 cycles.
- Constant voltage signal level: a bit more than 800 V (out of range of the oscilloscope)
- After that, 332,00 cycles have been carried out with a maximum decrease of 250 V, last measurement 170 V of decrease (it has detected that the voltage level varies after the decrease of the constant value)
- %21.25-31.25 of signal decrease
- Finally, the test campaign was stopped due to the lack of time.
- More than the 30 % of final lifetime of the system has proven a simplified test.

The figure 19 shows the system behaviour (torque and voltage) and the different states during the lifetime test campaign:

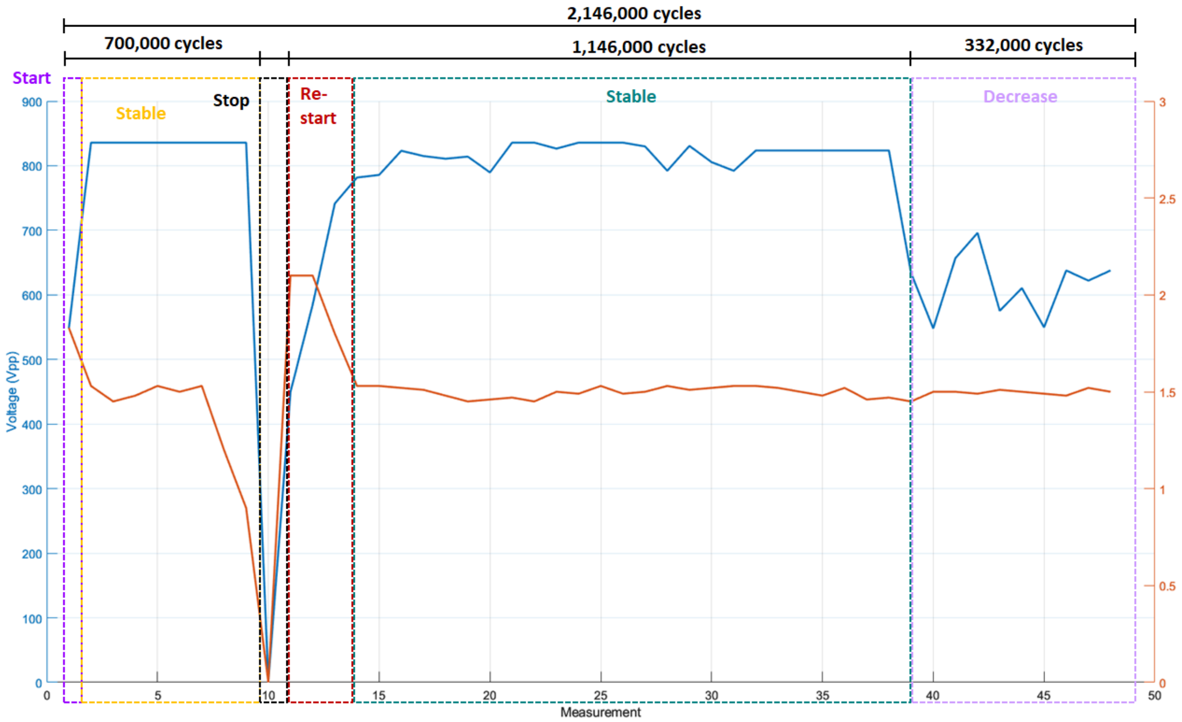


Figure 16. Test performance results and states (voltage and torque).

After the finalisation of the test campaign two type of inspection have been carried out, the visual inspection and metrological measurements.

Starting with visual inspection, it was detected that the PTFE spacer washer (or cup, which is fitted at the bottom of the axis) was totally degraded, as is shown in the figure 17:

a) Before test. **b) After test.**

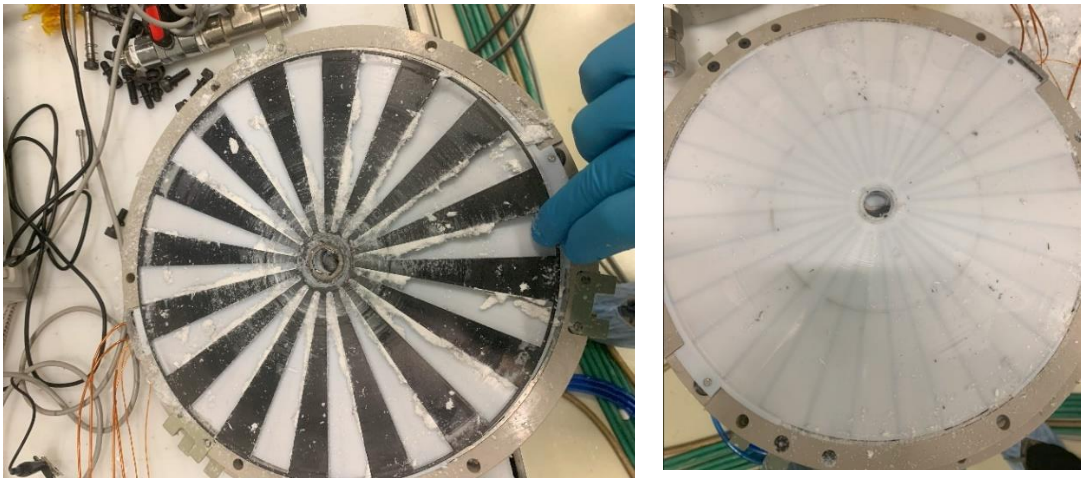
Figure 17. Cup part.

In the current prototype, the washer is necessary, without it the generator is axially free indeed. Due to the friction and that the springs may have touched the tank the generator has remained in its position, which happened due to the malfunctioning of the bushing. This part was not designed to rotate, it was supposed to be static next to the stator and the shaft was expected to rotate on it. To avoid this, the PTFE sleeve can be removed and restrain the static part of the generator axially.

In addition, it was detected that the generated TFM particles are a lot. However, after a visual inspection, the particles detected are only PTFE, and no DLC or aluminium particles (not DLC rotor damages). So, in the future, with the cleaning system, the particle quantity will be low during the operation. The figure 18 shows the amount of TFM particles detected inside the vessel after the test campaign:

Figure 18. Presence of TFM parts in the vessel after the completion of the lifetime test campaign.

The DLC part has not any damage and the TFM adheres to the DLC as was observed during the trade-off tests, as can be seen in the figure 19:



a) DLC rotor. **b) TFM stator.**

Figure 19. TEG generator after the test campaign.

And the total weight of the TFM stator is 105.6 g, during the first stop the TFM stator weight was 114.60 g so, we have lost only around 120g.

In addition, the bearings (COTS) have some corrosion (due to the CO2 atmosphere), as can be seen in the figure 130:

Figure 20. Corrosion detected in the bearings (COTS) produced by the CO2 atmosphere.

Finally, it has detected some PFTE adhesion in the axis from the sealing element. Minor degradation of sealing has been detected as can be seen in figure 131a:

a) Sealing. **b) Axis.**

Figure 21. Adhesivon detected between the sealing PTFE and the polished axis.

Then, the metrological measurements have been carried out to analyse in detail the system behaviour and state after the 2,178,000 cycles:

<u>DLC Blades Roughness</u>

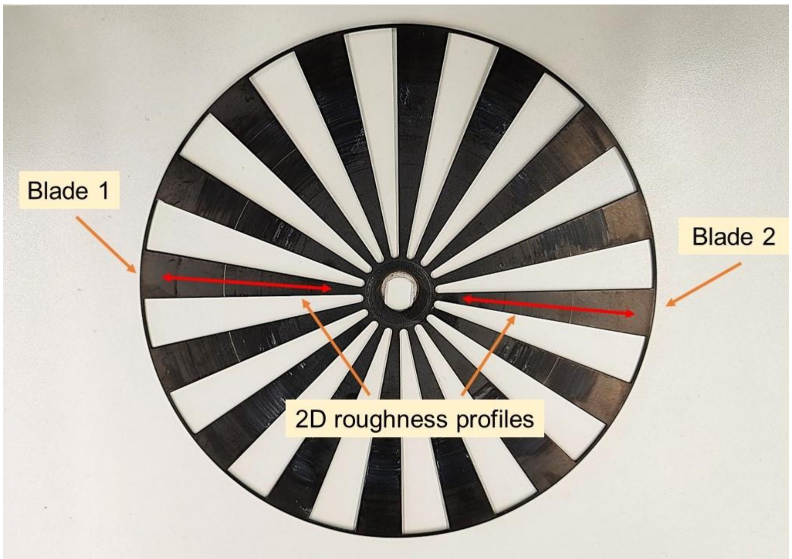


Figure 22. Reference names for the measurements taken on the DLC rotor.

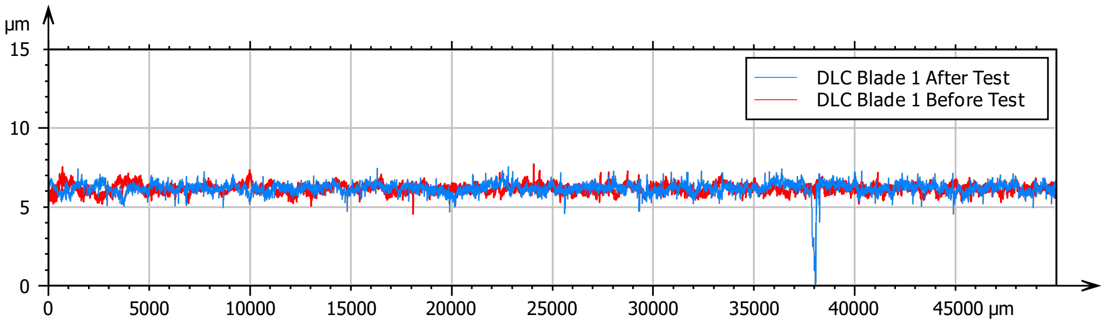


Figure 23. Profiles of Blade 1 after the tribology test.

Table 3. 2D roughness results of Blade 1.

ISO 21920 - Roughness (S-L)				

S-filter (λs): Gaussian, 2.5 µm						
F: [Workflow] Leveled (TLSL)						
L-filter (λc): Gaussian, 0.8 mm						
Evaluation length: All λc (62)						
Height parameters		Context	Mean	Std dev	Min	Max
Rq	µm	Average of values on: All λc (62)	0.259578	0.000617	0.258754	0.260378
Rz	µm		1.736310	0.016916	1.709655	1.762799
Ra	µm		0.159856	0.000172	0.159675	0.160144

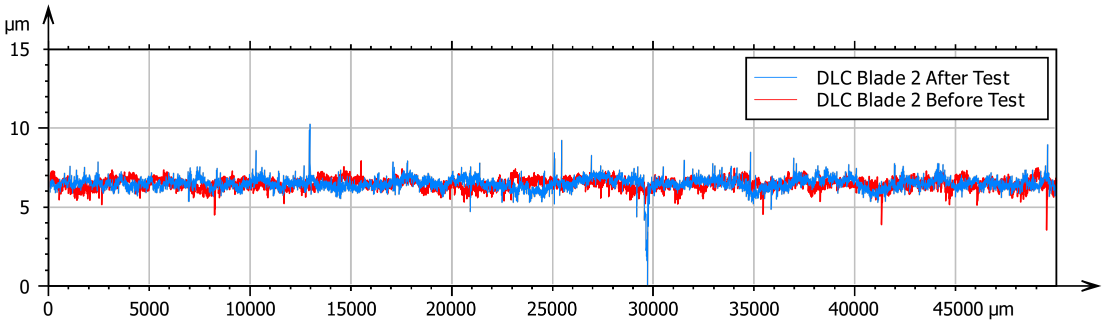


Figure 24. Profiles of Blade 2 after the tribology test.

Table 4. 2D roughness results of Blade 2.

ISO 21920 - Roughness (S-L)						
S-filter (λs): Gaussian, 2.5 µm						
F: [Workflow] Leveled (TLSL)						
L-filter (λc): Gaussian, 0.8 mm						
Evaluation length: All λc (62)						
Height parameters		Context	Mean	Std dev	Min	Max
Rq	µm	Average of values on: All λc (62)	0.264372	0.001437	0.262831	0.267056
Rz	µm		1.504742	0.033118	1.478403	1.562608
Ra	µm		0.158680	0.001095	0.157689	0.160789

Teflon Disc’s Step Height Evaluation

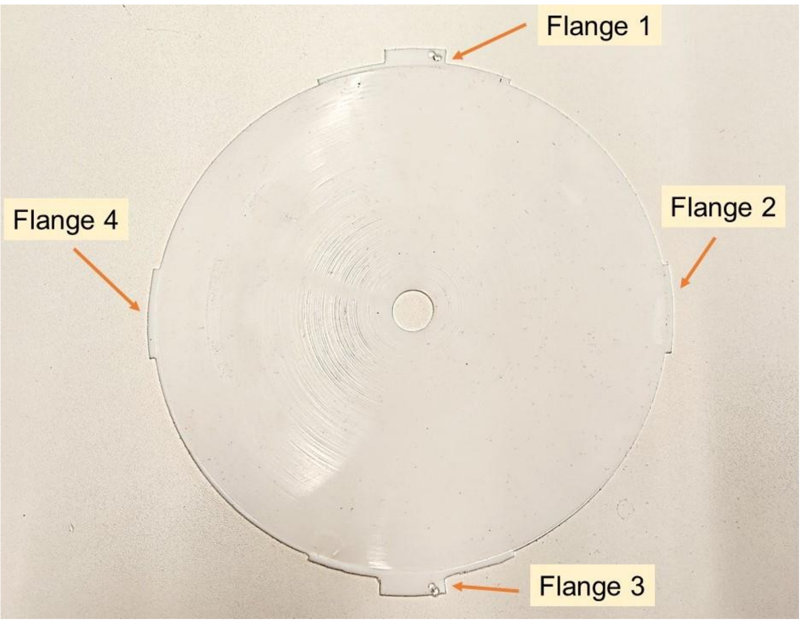
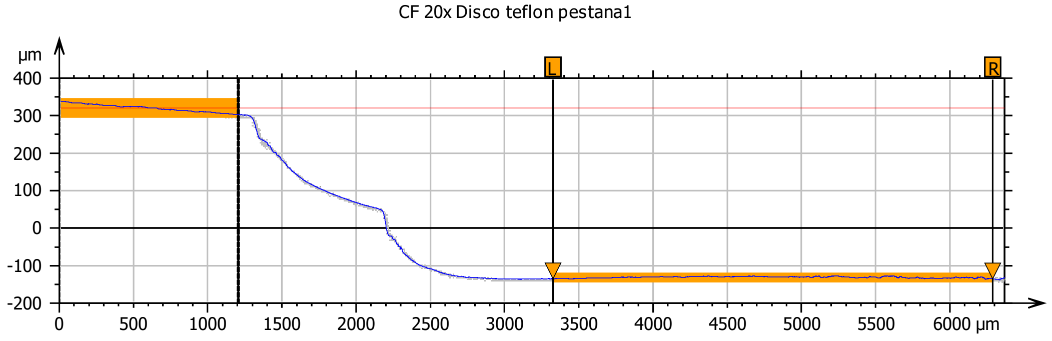
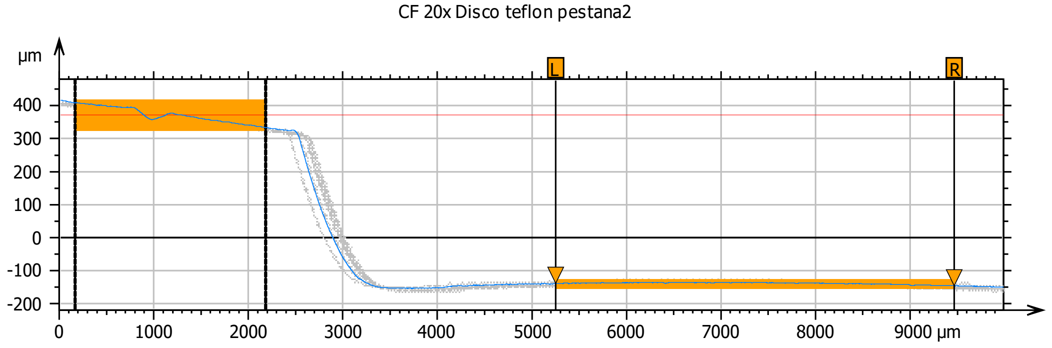


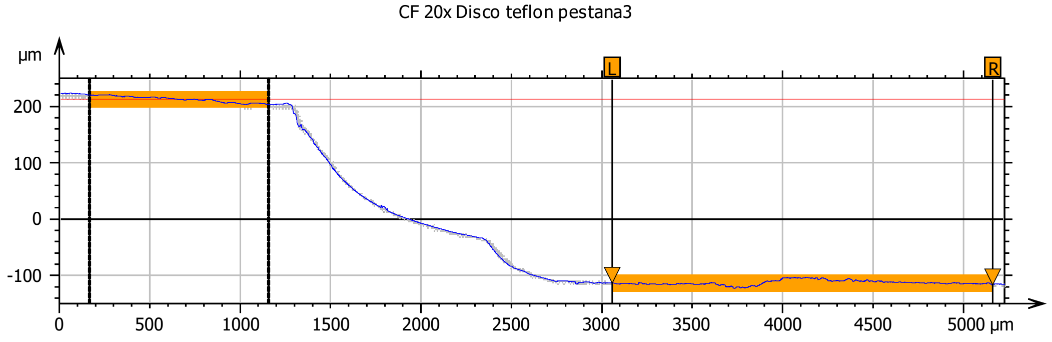
Figure 25. Reference names for the step measurements taken on the TFM stator.



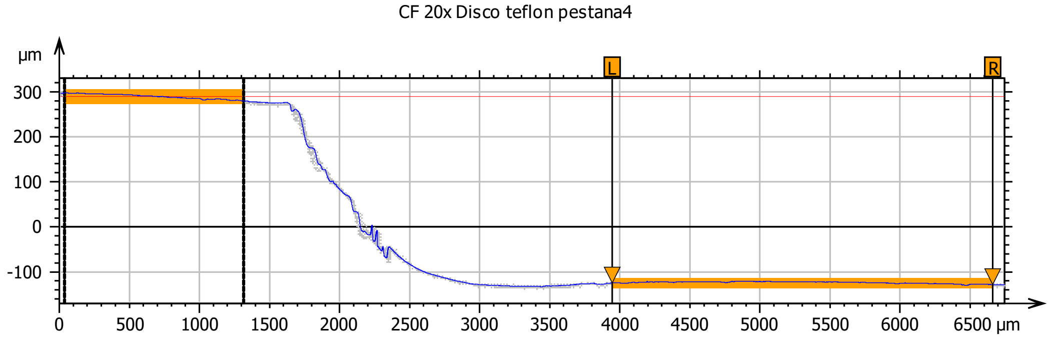
a) flange 1.



b) flange 2.



c) flange 3.



d) flange 4.

Figure 26. Teflon disc's step profiles.

Table 5. Step heigh evaluation results.

	Teflon Disc	
Flange	**Height (µm)**	**St. Dev. (µm)**
1	449.032798	0.722399

2	508.552881	4.517091
3	326.208777	1.053187
4	408.779634	0.867473

Sealing roughness

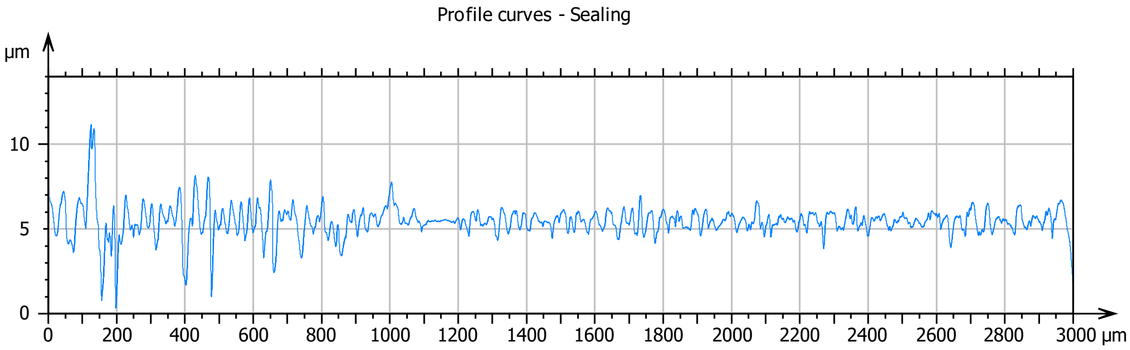


Figure 27. 2D roughness profile of the sealing after the test.

Table 6. 2D roughness results of the sealing after the test.

ISO 21920 - Roughness (S-L)						
S-filter (λs): Gaussian, 2.5 µm						
F: None						
L-filter (λc): Gaussian, 0.8 mm						
Evaluation length: All λc (37)						
Height parameters		Context	Mean	Std dev	Min	Max
Rq	µm		0.589138	0.053740	0.491253	0.685820
Rz	µm	Average of values < on: All λc (37)	1.951132	0.191733	1.632785	2.254061
Ra	µm		0.404300	0.032519	0.355236	0.461946

Axis

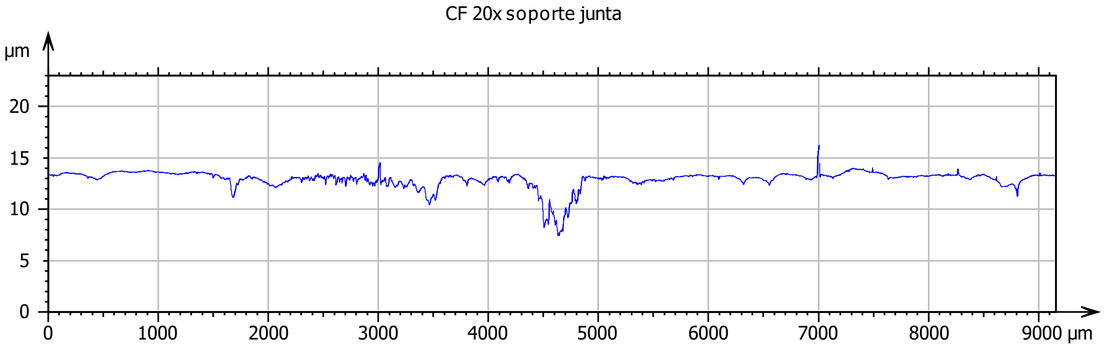


Figure 28. 2D roughness profile of the sealing mount after the test.

Table 7. 2D roughness results of the sealing mount after the test.

ISO 21920 - Roughness (S-L)						
S-filter (λs): Gaussian, 2.5 µm						
F: None						
L-filter (λc): Gaussian, 0.8 mm						
Evaluation length: All λc (11)						
Height parameters		Context	Mean	Std dev	Min	Max
Rq	µm		0.449758	0.117690	0.259142	0.626234

Rz	µm	Average of values on: All λc (11)	2.264401	0.601901	1.480646	3.404647
Ra	µm		0.247022	0.042215	0.185818	0.335039

<u>Conclusions</u>

- The Ra roughness values of the rotor blades are 0.16 microns for both blades. The roughness values are similar to those measured before the tribological test (around 0.15 microns).
- The Ra roughness value of the sealing is 0.40 microns. That result is lower than the roughness measured before the test, which was around 1 micron,
- The obtained wear steps have high variability for the different measured flange around the disc. The highest step has 508 microns of depth, and the lowest step has 326 microns of depth.
- The piece where the sealing was assembled has been characterized to obtain its roughness, being the Ra value for the piece is 0.25 microns.

6. Conclusions

The purpose of this work has been to research and develop the possibility of using the Mars winds to generate energy. The main driver of the present work has been the challenge of making a compromise between the lifetime of the system, the power generation, and the operation under Mars environmental conditions.

- It has been calculated, simulated, designed, manufactured, assembled, tested, and verified a wind turbine based on triboelectricity, to operate under Mars environment conditions (winds, pressure, Martian dust).
- Verification and validation of the system with a wide range of test campaigns under Mars pressure, wind, and dust exposure conditions was performed
- Wind turbine was equipped with the pressurized mechanism, allowing the movement of the axis and avoiding dust insertion using an ad-hoc sealing element.
- The triboelectric materials pair (Al+DLC, TFM) was developed, which resulted in a combination of excellent tribological, mechanical, triboelectric properties, and energy generation under Mars extreme conditions.
- A maximum power generation of 15 kW as electrostatic energy has been achieved with Martian pressurized condition and at 432 rpm of angular velocity, having a 31 % of power generation increase in comparison to Earth atmosphere conditions, and under a range operation of 50 and 432 rpm.
- The wind turbine rotated under different Mars winds (26-16 m/s) and pressure (8-16 mbar) conditions and with stable rotation movement.
- It has been verified the triboelectric generators lifetime for 2,176,000 cycles, of which 1,846,000 with stable electric signal generation and system torque under a constant velocity of 100 rpms, ambient temperature and CO2 pressurized conditions. .
- The system has scaling possibilities both for turbine (blades) and generators.

To achieve TRL7 by 2027 the updated design of the turbine needs to be developed. The current design was not subjected to the structural analysis or verification which needs to be included in the scope of the new design. Also, selection of materials, processes and electrical components has to be performed in line with operational conditions (vacuum during cruise, low pressure on Mars) and required reliability. A power management must be implemented to achieve usable electric power. And finally, a wide-range test campaign in relevant representative conditions shall be performed, including: TVAC, lifetime, functional tests, vibration & shock, humidity exposure, Mars wind tunnel, dust exposure, EMC, radiationThe work developed in this project has contributed to demonstrating the possibility of the use of wind turbines on Mars based on triboelectric generators as secondary energy source systems to power applications connected to Mars exploration and habitability strategies in the near future (2030 decade).