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Pressure Changes During Lunar Regolith Simulant Movement in Dusty Thermal Vacuum Chamber

Karol Seweryn [1,2,*], Tadeusz Uhl [1] and Wojciech Teper [3]

[1] Faculty of Space Technologies, AGH University of Krakow, Str. Reymonta 13a, 30-059 Kraków, Poland; tuhl@agh.edu.pl
[2] Space Research Center of the Polish Academy of Sciences (CBK PAN), 18a Bartycka Str., 00-716 Warsaw, Poland
[3] Department of Drilling and Geoengineering, Faculty of Drilling, Oil and Gas, AGH University of Krakow, Al. Mickiewicza 30, 30-059 Krakow, Poland; teper@agh.edu.pl
* Correspondence: kseweryn@agh.edu.pl

Abstract

A dusty thermal vacuum chamber (DTVAC) equipped with a regolith simulant bin is a key infrastructure to validate space equipment planned to operate in the future lunar missions. The proper setup of such infrastructure is challenging since the regolith simulant needs to be outgassed; otherwise, it might affect the validation process. This paper presents the results of experiments conducted in a dusty thermal vacuum chamber. The experiment was designed to verify if lunar regolith simulants prepared and placed in the bin may preserve atmospheric gases after the chamber depressurization process. Such hypotheses were defined after testing a drill in vacuum conditions, the performance of which was higher than expected. The obtained results show that the preparation and placement of regolith in the bin should be performed under vacuum conditions regardless of the external temperature.

Keywords: moon exploration; dusty thermal vacuum chamber; lunar regolith analogs

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1. Introduction

Preparations for establishing a sustained human presence on the Moon are increasingly feasible and are expected to materialize within the coming decade. Major space agencies have already outlined their respective roadmaps, including the Artemis program [1] led by NASA, the Terrae Novae 2030 strategy [2] developed by the European Space Agency (ESA), and the Chinese Lunar Exploration Program [3] initiated by China. Establishing a permanent lunar settlement will demand large-scale civil engineering and mining operations [4]. During the initial stages, only a small number of astronauts will reside on the lunar surface, which will necessitate a much greater reliance on automated and autonomous construction technologies than is typical on Earth [5].

The lunar environment presents numerous challenges for settlement development (see details in [6]). The Moon possesses an ultra-low-pressure exosphere (approximately 3×10^{-13} Pa, effectively a vacuum) containing electrostatically levitated dust particles. Gravity is about one-sixth that of Earth, and the surface is subject to extreme temperature variations driven primarily by the lunar day–night cycle, ranging from roughly −170 °C to +130 °C. The terrain is characterized by impact craters, volcanic formations, lava flows, lava plains, hills, and tectonic fractures. Billions of years of continuous exposure to meteorites, comets, and micrometeorite impacts have produced a regolith layer of

variable thickness—approximately 4–5 m in the lunar mare regions and 10–12 m in the highlands [7].

During the Apollo and Luna programs, core drilling operations were conducted using specially designed equipment. The deepest boreholes were achieved during Apollo 15, Apollo 16, and Apollo 17, where drilling reached depths of up to 3 m using the Apollo Lunar Surface Drill (ALSD) percussion system [8], and continuous core samples were retrieved. Additionally, the Soviet Luna 16, Luna 20, and Luna 24 missions returned approximately 300 g of lunar material to Earth. More recently, China has conducted a series of successful robotic lunar missions. Chang'e 4 provided new insights into the Moon's subsurface structure. In 2020, Chang'e 5 returned 1731 g of lunar regolith to Earth [9], and most recently Chang'e 6 delivered nearly 2 kg of material from the Moon's far side.

Knowledge of regolith composition and geotechnical properties is largely derived from samples returned by the Luna program, the Apollo program, and the Chang'e program from midlatitude regions. The principal chemical components include SiO_2 (45.4%), Al_2O_3 (14.9%), FeO (14.1%), and CaO (11.8%) [10]. Three key factors significantly influence the geotechnical behavior of lunar regolith: (i) an approximately linear particle size distribution spanning from micrometers to millimeters [11], (ii) relative density increasing from about 65% near the surface to up to 90% below 30 cm, with bulk density reaching 1.9 g/cm^3, and (iii) the highly angular morphology of grains, particularly agglutinates and fragmented particles formed by meteorite impacts.

The Lunar Reconnaissance Orbiter (LRO) has gathered lunar data over a longer continuous period than any other recent lunar orbiter. Among its instruments, the Lunar Orbiter Laser Altimeter (LOLA) was used to produce highly accurate topographic maps of the Moon—an essential resource for the current renewed phase of lunar exploration. Beyond its own scientific payload, LRO also supported the Lunar Crater Observation and Sensing Satellite (LCROSS) mission. In this experiment, the Centaur upper stage of an Atlas V rocket was deliberately crashed into the Cabeus crater. The resulting ejecta plume was observed and analyzed by LRO, significantly enhancing our understanding of the presence and distribution of water on the Moon [12].

Since access to lunar regolith is limited, a range of lunar regolith simulants (also referred to as regolith analogs) were developed to enable research under terrestrial laboratory conditions. A comprehensive overview of these efforts was presented by Taylor et al. [13]. In that paper, the Chenobi simulant is indicated as recommended for geotechnical applications and the AGK2010 simulant developed by CBK PAN and AGH exhibits very similar material properties [14].

One category of mechanical systems that may interact with lunar regolith includes sampling tools and excavation devices. A comprehensive review of currently developed sampling and excavation technologies was presented by Zhang et al. [15], while Just et al. [16] provided a parametric analysis of various laboratory-scale mining equipment models and excavation methods. To better categorize excavation processes, a primary distinction can be made between discrete and continuous excavators. Discrete excavators require periodic disengagement from the soil between cuts, either to clear the cutting surface or to unload the collected material. Typical examples include front-end loaders, bulldozers, and backhoes, which can be further classified into scrapers and scoopers [17]. Several sampling and excavation devices have been developed by CBK PAN, including the Chomik device designed for the Russian Phobos-Grunt mission [18] and the Rotary Hammering Device (RHD), also known as Packmoon [19]. More recently, two additional systems were created under the ESA-funded DIGGER project: the Oscillating Corer Device (OCD) at AGH and the Rotary Clamshell Excavator (RCE) at CBK PAN [20]. The latter

has also been utilized as a platform for an RF sensor able to detect the amount of collected regolith [21].

A thermal vacuum chamber equipped with a bin of regolith simulant—commonly referred to as a dusty thermal vacuum chamber (DTVAC)—is essential for testing and validating equipment intended for lunar surface missions [22]. Several vacuum chambers have been developed to evaluate hardware performance, under conditions involving lunar regolith and vacuum [23–26]. Operating a DTVAC with a regolith simulant bin presents major challenges related to: (i) the preservation of atmospheric gases after the chamber depressurization process, (ii) the high outgassing rate of dust, and (iii) dust contamination during the pump-down process. Altogether, these factors can disturb the soil and create inadequate validation conditions in the DTVAC. Previous studies have reported vacuum pump failures caused by dust intrusion, necessitating the use of dust-resistant pumping systems [23]. Maintaining the initial state of the soil bed during pump-down has also been identified as a significant difficulty, especially for drilling experiments [23,27].

To mitigate these issues, several approaches have been proposed. Some researchers designed specialized regolith containers with perforated walls to limit soil movement [26], while others achieved reduced disturbance by carefully controlling the pump-down rate [28] using, for example, the pressure difference between the top and bottom of the lunar regolith simulant bed [17]. Consequently, preventing soil disturbance during the pump-down process remains one of the most critical challenges in DTVAC operation. Although a number of mitigation strategies have been reported, there is still a lack of an appropriate approach to solve this problem.

In this study, the results of experiments conducted in a dusty thermal vacuum chamber are presented. The experiment was designed to verify if lunar regolith simulants prepared and placed in the bin may preserve atmospheric gases after the chamber depressurization process. The results of this analysis have an impact on regolith handling in DTVACs, which is the main novelty described in this paper. The experimental design is presented in Section 2, whereas the obtained results are provided in Section 3. After that, a discussion of the main outcome as well as conclusions is given.

2. Materials and Methods

Proper validation of technologies intended for lunar surface exploration and utilization is critical to achieving the required reliability of components and subsystems. For processes involving interactions between mechanical hardware and regolith, three environmental factors are especially important: vacuum, regolith, and temperature. Equipment capable of simulating these conditions is known as a dusty thermal vacuum chamber (DTVAC). Preparation of regolith in a DTVAC is important for reproducing conditions on the lunar surface, especially in cases where a large amount of regolith is needed. This is the case for regolith sampling or excavation devices (such as the RCE), where at least a few kilograms of regolith are needed and a similar amount of regolith is mobilized (moved) due to interactions with mechanical devices. In this context, two past experiments are listed as examples of problems associated with regolith under vacuum conditions:

- The disturbance of lunar regolith during depressurization reported in [17]. During that process, cracks appeared on the regolith surface and continued to increase until the regolith simulant boiled (Figure 1 in [17]).
- The disturbance of the drilling process under vacuum conditions reported in [20]. During drilling in cellular concrete YTONG (see Figure 1), reduced force and torque were observed under vacuum conditions compared with normal conditions for the same technological parameters of drilling (rate of drilling 1 mm/s, tool rate 70 rpm). Under vacuum conditions, the axial weight on bit and torque were reduced by 15–20%.

The reason was the expansion of gas encapsulated in the pores and the sublimation of encapsulated water.

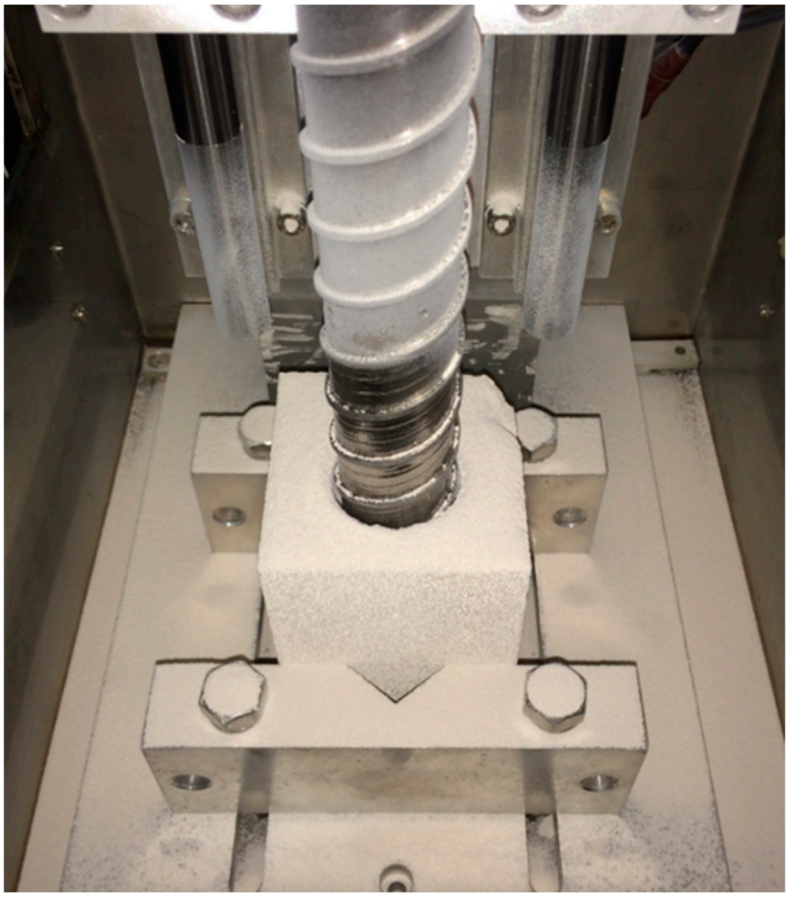


Figure 1. Drilling process in cellular concrete Ytong (Xella Poland, Milt, Poland). Visible drilling cuttings are scattered on the bottom of the chamber.

To quantify this effect, the experiment presented in Figure 2 was designed. In the DTVAC, the lunar regolith simulant (AGK2010, CBK PAN, AGH, Warsaw, Poland) was placed into the measurement bin (1) in two ways: before or after depressurization of the chamber. In all cases the desired pressure level was set to 5×10^{-3} mbar and one of three temperatures (−30 °C, 22 °C, or 72 °C). Placement of the regolith into the bin required an additional container (2) above the measurement bin, where the regolith was stored and slowly transferred to the measurement bin. Container was equipped with a sieve (3), and regolith movement was activated by turning on a vibrator (4) attached to the container. Inside the measurement bin, the cylindrical split-spoon sampler (CSSS) (5) was placed on a cord (6), which was attached to the spool (7) integrated with the motor (8). After regolith placement into the measurement bin and stabilization of the desired temperature and pressure, the motor was activated, and the CSSS was moved through the regolith. During the experiment, the pressure was monitored by sensors placed at two positions, (9) and (10). Comparison of the data measured by these sensors allows for the comparison of outgassing from regolith moved into the measurement bin under atmospheric and vacuum conditions. In addition, the system was equipped with three temperature sensors (11) placed on the bin, a camera to record visual data from the process (13), as well as devices to measure dust generation (12). The results from the latter are not included in this paper.

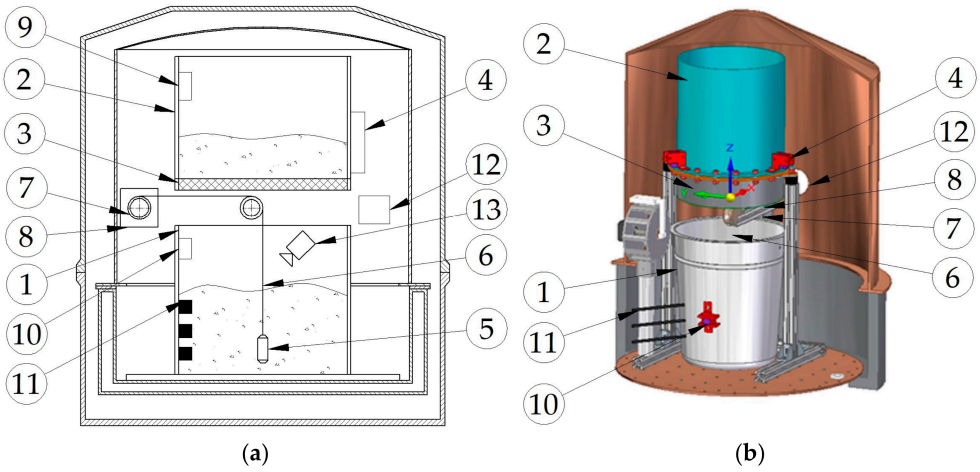


Figure 2. Experiment in DTVAC: (**a**) experiment concept; (**b**) CAD model.

The measurement bin is a rounded cylinder with a diameter of 200 mm and a total height of 250 mm, but is filled up with regolith only up to a height of 200 mm. The designed volume of regolith is 5.25 dm^3 and the measured mass of regolith is equal to 7.5 kg. This gives an average density of about 1.43 g/cm^3, which is equal to that of lunar regolith in a loose state measured on the lunar surface [6].

The AGK2010 lunar soil analog was produced on the basis of the Chenobi (Deltion Innovations Ltd., Capreol, ON, Canada) and JSC1A (ORBITEC, Madison, WI, USA) lunar soil analogs, which are analogs of the lunar soil collected by the Apollo 17 mission. The analogs were created for research purposes. Similarities between these analogs are provided in detail in [14] and include grain-size distribution, physical properties (bulk density 1.295 kg/dm^3, color), and mechanical properties (shear strength, internal friction angle 37.67°, cohesion 3.85 kPa). Before the tests, the regolith was stored in a closed container in laboratory conditions. During the preparation period for particular tests, a new sample of regolith was exposed to laboratory conditions (ISO 9 class [29], 22 °C, and 50% humidity) for 3–4 h. The regolith was not subject to a pre-drying procedure, since in some applications this process may affect the regolith properties.

The DTVAC (Tepro, Koszalin, Poland) available at the Spacive company (Warsaw, Poland) was equipped with rotary and diffusion pumps, as well as a number of pressure sensors. The pump-down procedure was the same for each run and covered the following steps:

- Turn on the rotary pump (Alcatel-Annecy PASCAL 2033 SD)—23.3 CFM pumping speed.
- Turn on the diffusion pump (Balzer DIF 200; pumping speed 2000 L/s, power 2000 W) when the pressure inside the chamber reaches 0.2 mbar.
- Wait approximately 4 h (12 h in the low-temperature case) to reach 1×10^{-4} mbar pressure before starting the experiments.

Two dedicated Pirani (Heimann sensor, Dresden, Germany) pressure sensors were positioned proximal to the regolith sample (217 mm and 237 mm from the DTVAC base plate). Specifically, one sensor was mounted on the aluminum frame external to the regolith container, while the second was placed directly above the regolith surface. Measurements were done in Wheatstone bridge configuration. Sensor voltage was measured with 16-bit resolution. Both sensors were calibrated using an Edwards WRG200 (Edwards Vacuum, Burgess Hill, UK) pressure sensor in Spacive's standard TVAC (Spacive, Warsaw, Poland).

The CSSS has a diameter of 25 mm, and its motion was actuated by a motor under the following conditions:

- Displacement: 140–160 mm;
- Speed: 21 mm/s;
- Duration: 7–8 s;
- Penetration depth: 100 mm (half of the measurement bin).

3. Results

3.1. Experimental Case Description

The experimental setup was developed and is presented in Figure 3. All components defined at the concept stage as well as the design stage were implemented according to the requirements relevant to operation under vacuum conditions. Specifically, materials with low outgassing performance were used. The actuators and sensors were selected for their ability to operate under vacuum conditions. In the test plan, six experiments were defined at three temperature levels: (i) laboratory temperature 22 °C, (ii) high temperature 72 °C, and (iii) low temperature −30 °C. At each temperature, two single-run experiments were conducted: in the first, the regolith was moved into the measurement bin under atmospheric conditions; in the second the regolith was moved into the measurement bin under vacuum conditions. The regolith movement process was the same in each case. The sequence of the experiment consists of the following phases: (1) movement of regolith into the measurement bin (under atmospheric or vacuum conditions), (2) reaching the desired temperature, (3) movement of the CSSS through the regolith, and (4) turning off the chamber. All of them are listed in Table 1. The results of the experiments are presented as a comparison of pressure changes during different experiments.

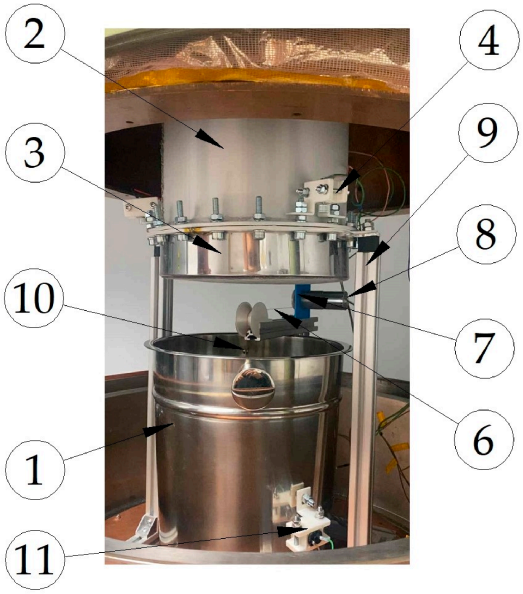


Figure 3. Experimental setup in the DTVAC. The numbering is aligned with the description related to Figure 2.

Table 1. The parameters of conducted experiments.

Exp. No.	Temperature	Regolith Placement	Time of Phases (s)
1	22 °C	in atmospheric conditions	120/600/10/86,400
2	22 °C	in vacuum conditions	120/600/10/86,400
3	72 °C	in atmospheric conditions	120/21,600/10/86,400
4	72 °C	in vacuum conditions	120/21,600/10/86,400
5	−30 °C	in atmospheric conditions	120/28,800/10/86,400
6	−30 °C	in vacuum conditions	120/28,800/10/86,400

3.2. Vision Data Recorded During the Experiments

During all experiments, vision data was recorded by a camera placed inside the measurement bin. In Figure 4, selected frames from the experiment under vacuum conditions are presented, showing CSSS movement through regolith.

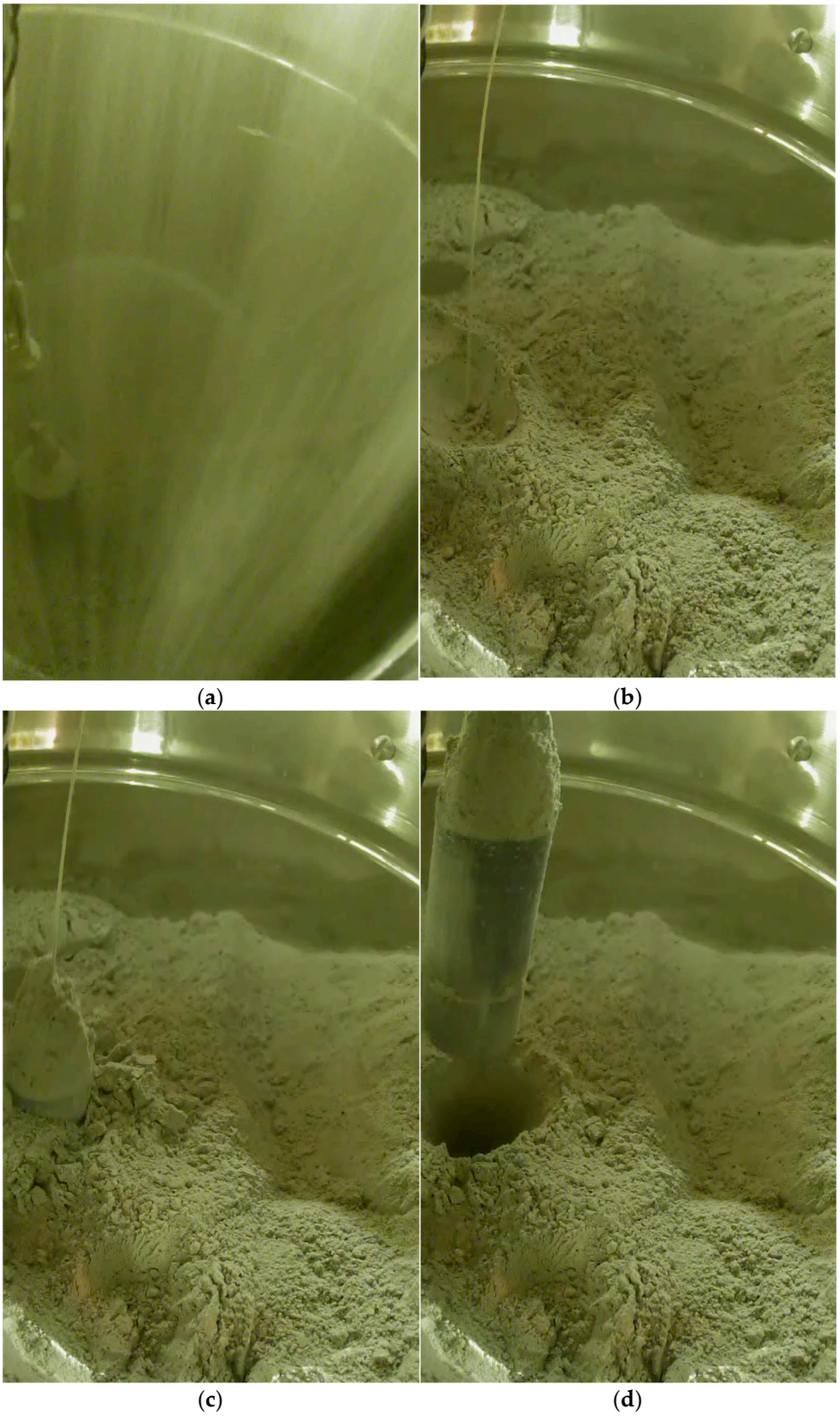


Figure 4. Images recorded during the experiment. The CSSS visible at different stages of motion through the regolith: (**a**) the CSSS placed on the bottom of the measurement bin during regolith transfer into the measurement bin, (**b**) beginning of the CSSS movement through the regolith, (**c**) the CSSS visible on the regolith surface, (**d**) the CSSS above regolith surface.

3.3. Pressure Measurements

In Figures 5–7, the pressure changes observed in phase 3 of the experiments are presented. The pressure presented in those figures was averaged from the two sensors used in the experiment. The summary of results is presented in Table 2.

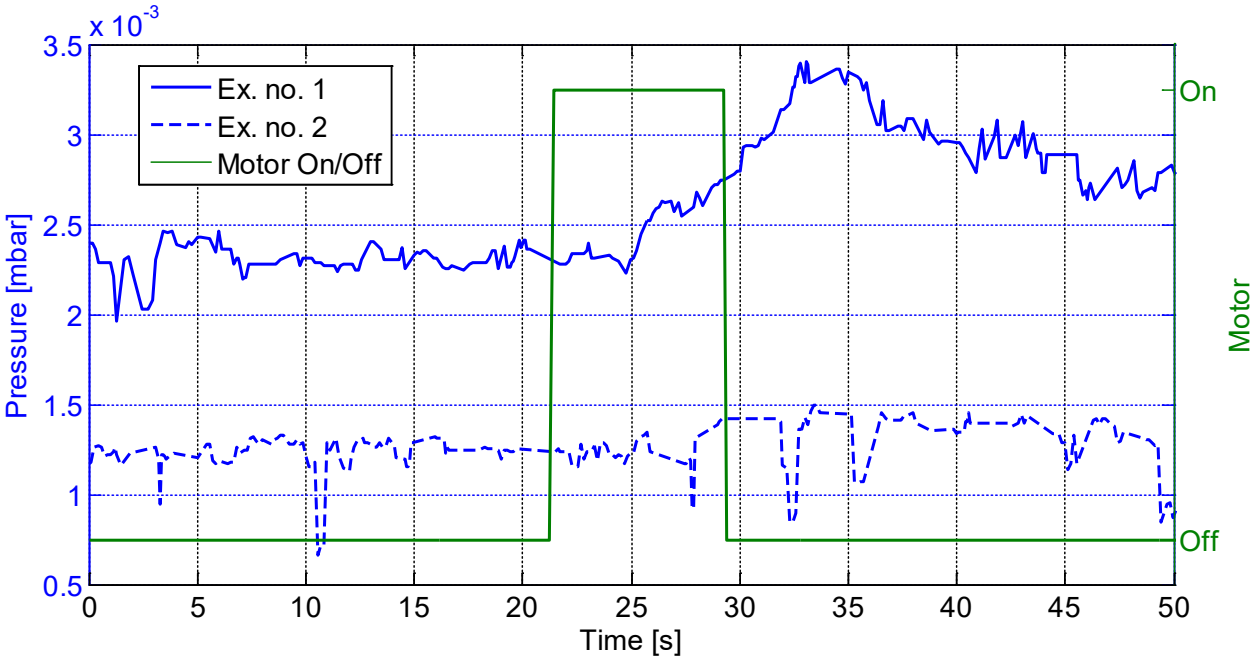


Figure 5. Pressure changes (blue) and the CSSS motor status (green). The solid line indicates placement of regolith under atmospheric conditions. The dashed line indicates placement of regolith under vacuum conditions. Pressure in 10^{-3} mbar units.

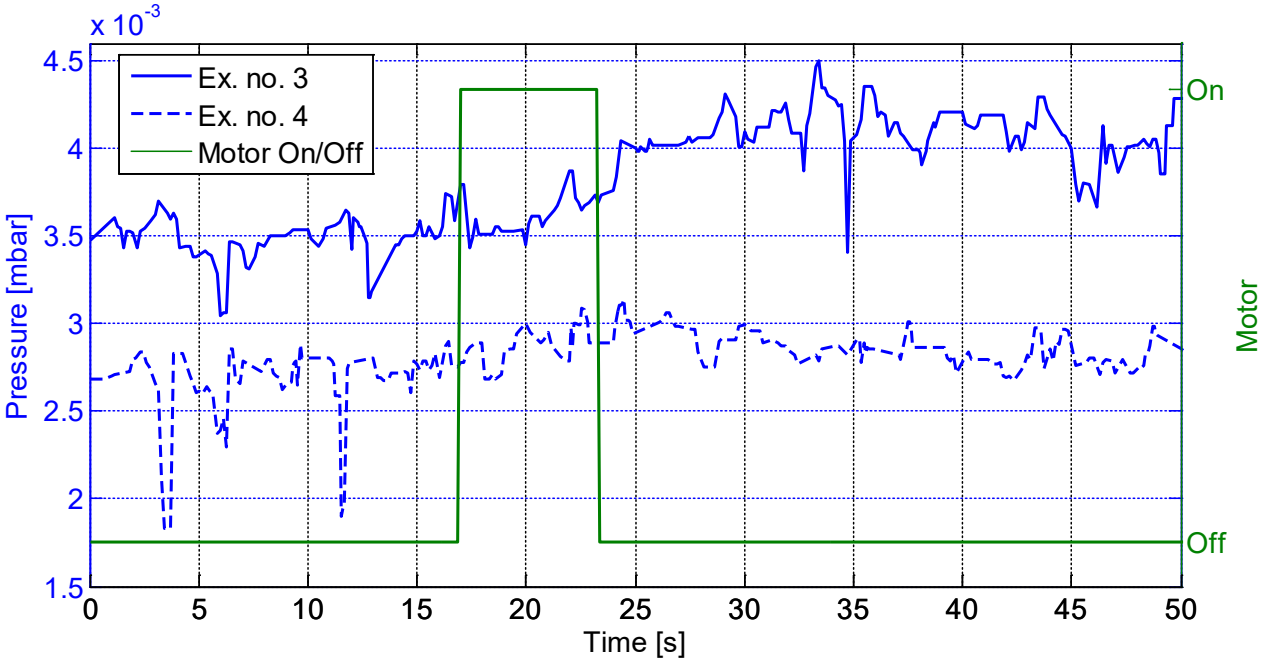


Figure 6. Pressure changes (blue) and the CSSS motor status (green). The solid line indicates placement of regolith under atmospheric conditions. The dashed line indicates placement of regolith under vacuum conditions. Pressure in 10^{-3} mbar units.

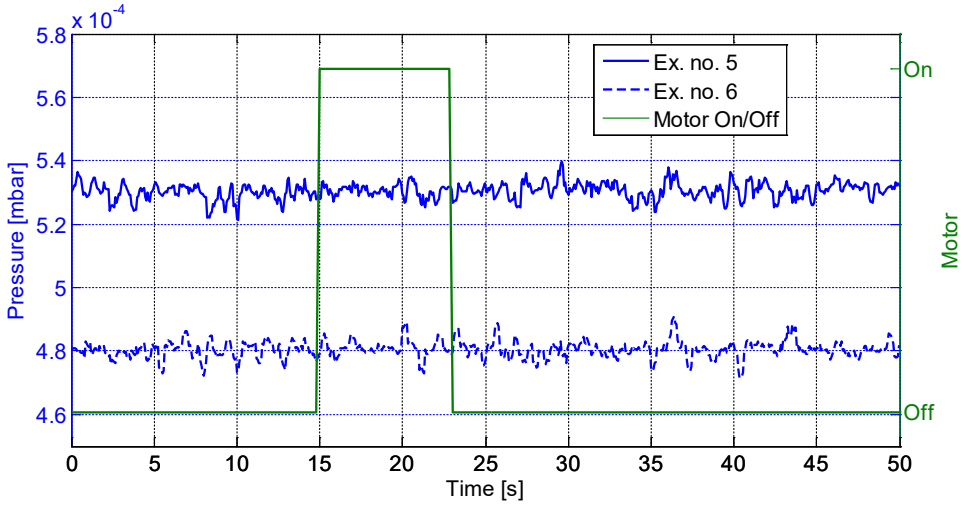


Figure 7. Pressure changes (blue) and the CSSS motor status (green). The solid line indicates placement of regolith under atmospheric conditions. The dashed line indicates placement of regolith under vacuum conditions. Pressure in 10^{-4} mbar units.

Table 2. Results summary.

Exp. No.	Measured Temperature (°C)	Baseline Pressure (10^{-4} mbar)	Peak Pressure (10^{-4} mbar)	Pressure Rise (10^{-4} mbar)	Recovery Time (s)
1	22.1	23	34.5	11.5	25
2	22.3	12	14	2	5
3	71.4	35	45	10	50
4	65.4 *	27	31	4	25
5	−32.9	5.3	5.4	0.1	-
6	−33.6	4.8	4.8	0	-

* In this experiment, the temperature deviates from the desired value by 6 °C due to heater limitations and their impact on temperature stabilization in the DTVAC.

4. Discussion

The results in the previous section show how activation of lunar regolith analogs by the CSSS impacts pressure inside the vacuum chamber. The results compare two cases: regolith placed in the measurement bin under atmospheric conditions and under vacuum conditions. Significantly lower pressure change was observed when the material was placed under vacuum conditions.

The pressure levels after regolith curation at different temperatures are in line with expectations—higher temperatures create higher regolith outgassing and higher pressure. At low temperature, the pressure was 5×10^{-4} mbar; at laboratory temperature, it was 2.4×10^{-3} mbar; and at high temperature, it was 3.5×10^{-3} mbar. In room and high temperature conditions, the pressure increases after regolith movement induced by the CSSS. From those measurements, it was inferred that the regolith itself is not able to release all volatiles encapsulated between grains even after 6–8 h of regolith curation under vacuum conditions. High temperature has an impact on this process, since the pressure increase under laboratory conditions is around 50%, while at high temperature it is around 20%. At low temperature (−30 °C), the pressure increase was not observed. Altogether, this allows us to formulate the hypothesis that water encapsulated between regolith analog grains is a main contributor to volatile outgassing in the presented experiments. With this hypothesis, the water likely sublimates after regolith activation and escapes from the activated regolith. High temperature reduces water content in the regolith after 6–8 h of

regolith curation, and therefore the pressure change is smaller. At low temperature, the encapsulated water is in a solid state, and therefore the pressure increase was not observed. Such a significant change was also observed in the experiment presented in [9].

The hypothesis presented above was tested by analysis of the motor power used to move the CSSS through the regolith during the conducted experiments. In Figures 8 and 9, results are shown in the form of time evolution of the current measured on the motor used to actuate the CSSS. In Figure 8, experiments no. 1 and no. 2 were compared, and it is clear that gases encapsulated in experiment 1 help the CSSS move through the regolith which, as a consequence, resulted in a lower current measured in experiment no. 1.

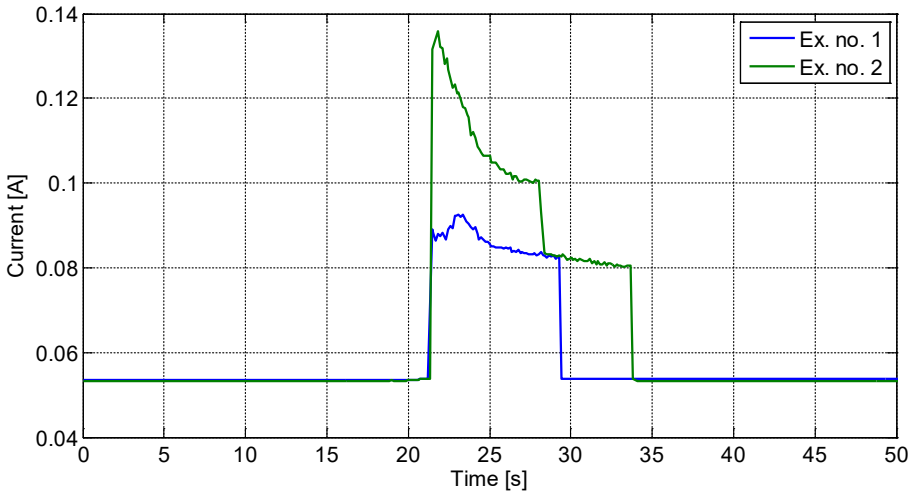


Figure 8. Current in the CSSS motor. Blue color—experiment at room temperature (22 °C) under atmospheric conditions, green color—experiment at room temperature (22 °C) under vacuum conditions.

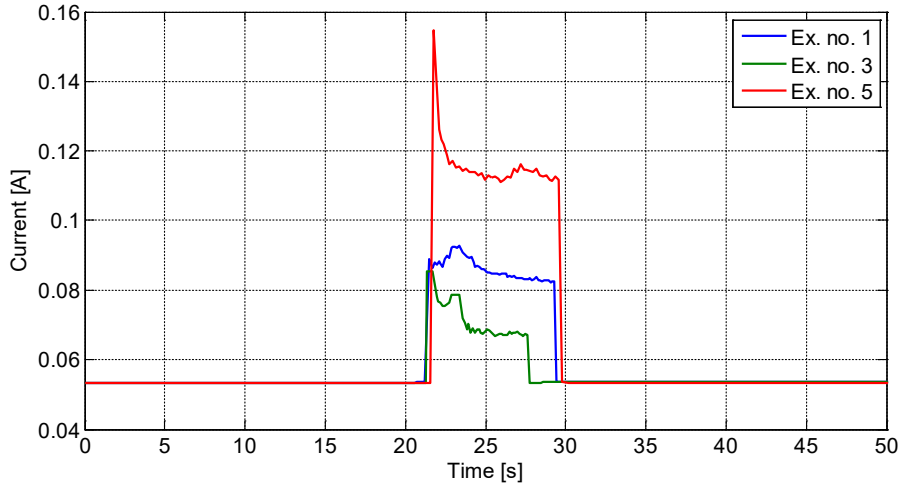


Figure 9. Current in the CSSS motor. Blue color—experiment at room temperature (22 °C), green color—experiment at high temperature (72 °C), red color—experiment at low temperature (−30 °C).

At low temperature (Figure 9, red color), the average current is around 30% higher than under laboratory temperature conditions (blue color). Bearing in mind that no pressure change was observed, frozen water is a possible explanation for this effect. The other possibility is increased stiffness of the regolith at low temperature. The comparison between laboratory and high temperature conditions (green color) is less clear, since considering that pressure changes are smaller at high temperature (see Figure 6), the motor current should be higher.

5. Conclusions

In the context of future lunar exploration realized by space agencies around the world, such as the Artemis program or the CLEP program, a number of technologies must be verified under vacuum, dust, and temperature conditions in a relevant terrestrial environment. The dusty thermal vacuum chamber, lunar regolith analog, and devices that interact with regolith are key components of such tests. The proper setup of these elements is crucial for applying relevant loads on the tested equipment.

In this paper, the results of experiments conducted in a dusty thermal vacuum chamber were presented. The experiments were designed to verify whether lunar regolith simulants prepared and placed in the bin could preserve atmospheric gases after the chamber depressurization process. The experiments were conducted as single runs at different temperatures and at the 10^{-4} mbar pressure level. At each temperature, two experiments were conducted: in the first, the regolith was moved into the measurement bin under atmospheric conditions; in the second, the regolith was moved into the measurement bin under vacuum conditions. Comparison of the data measured by pressure sensors allows comparison of the outgassing process. The following conclusions were reached during this analysis:

1. The obtained results show that the preparation and placement of lunar regolith analogs (such as AGK2010) in the bin should be done under vacuum conditions, regardless of external temperature. Dirty/dusty thermal vacuum chambers operating at the 10^{-4} mbar level should have a capability to place or handle regolith under vacuum conditions.
2. The gases encapsulated in the lunar regolith analogs (such as AGK2010) not placed into the bin under vacuum conditions may influence planned experiments where regolith mobilization occurs—for example, drilling experiments (as in [27]), regolith sampling (as in [20]), and regolith excavation. At laboratory and high temperature, this influence might reduce the power requirements of the tested device. At low temperature, this impact can be the opposite.
3. Water vapor or other atmospheric gases encapsulated between regolith analog grains is a possible main contributor to volatile outgassing in the presented experiments (10^{-4} mbar level, room and 72 °C temperature). This conclusion is based on experience with testing under vacuum conditions; however, at this stage there is no direct evidence that other adsorbed atmospheric gases are not a source of this effect.
4. The split-spoon sampler moving through the regolith and the pressure sensors provide a good approach to validate proper preparation of regolith in TVACs.
5. New versions of the DTVAC should be equipped with systems allowing the reduction in water vapor and other atmospheric gas content in regolith and rocks.
6. Standard geotechnical tests of granular matter (such as angle of friction and cohesion) may differ depending on the conditions (atmosphere, vacuum) in which the regolith was prepared. To prove this statement and determine uncertainty of this effect, more experiments are needed.

In future investigations, it is planned to focus the analysis on determining the transport of gases in regolith under low pressure conditions, including its moisture content as well as the range of gases accessed. This might be interesting in the context of planned mining operations on celestial bodies. There is also a need to conduct more experiments to estimate the uncertainties associated with the conclusions presented above.

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supervision, K.S.; funding acquisition, T.U. All authors have read and agreed to the published version of the manuscript.

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