Effect of a Regolith Liberated by a Rocket Plume Impingement – Executive Summary Report

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1 EXECUTIVE SUMMARY

The current interest in landing on various bodies in the solar system, whether to study material in-situ, return samples to Earth or for other purposes, brings with it the need to understand how the plumes of rockets used to control descent during landing affect the surface regolith. The principal bodies of interest at the current time are Mars, the Moon and smaller bodies such as Asteroids or small moons such as Phobos. This covers varying levels of gravity, atmospheric densities and regolith characteristics. Mars has a thin atmosphere about 1 % of the density of the Earth's and a surface pressure of around 600 Pa. All other bodies mentioned here have no atmosphere to speak of. Gravity varies from just over a third of Earth's for Mars, about one eighth for the Moon and negligible for small bodies. Regolith characteristics vary in their physical properties, Martian regolith will be eroded whereas the Moon's is sharp edged.

Rocket plumes can move regolith about and create craters and dust clouds. They can also contaminate the regolith with exhaust chemicals. Both of these aspects are important but here we concentrate on the consequences of the movement of the regolith. A parallel project funded by European Space Agency (ESA) has examined the contamination question. The movement of regolith due to rocket plumes creates cratering in the surface and launches material from the surface. The cratering process is of interest to know how the surface will look after landing and hence determine sampling strategies, for example. The liberated regolith can affect the navigation during landing, can damage the spacecraft and surrounding infrastructure and obscure optical, radio and other electromagnetic radiation. This can affect navigation devices such as radar altimeters. The effects of the liberated regolith need to be understood so that the landing spacecraft can be designed accordingly.

The physics of regolith movement in the presence of rocket plumes is complex with a number of relevant factors coming into play. The nature of the plume itself is not trivial and, when in a low density atmosphere or no atmosphere at all, predicting these is difficult. The interaction of this plume with the surface involves possibilities of continuum and rarefied flow regions along with shock structures demarcating subsonic and supersonic flows. The process of the entrainment and launch of regolith materials is also non-trivial and not well understood. Modelling capabilities are not fully developed and experimental work is needed to provide better observations and data. This project was established to make progress in both aspects, primarily with the construction of a suitable experimental facility and also developing initial modelling capabilities to support the experimental work.

The top level requirements for the facility were defined by ESA and essentially cover the key aspects discussed above. The objectives for this project were:

1. “Assessment of scaling phenomena, vacuum effects and pulsing of rockets.
2. The erosion effect of the plume impingement on the planet surface (airless bodies and Martian conditions).
3. The lateral extent and depth of regolith contamination due to rocket plumes.
4. The impact of the plume/regolith interaction on the spacecraft (forces and moments).
5. The effect of the regolith liberated by the rocket plume impingement on the spacecraft forces and moments and particularly on the engine and engine-nozzle during lunar/planetary landing operations.
6. Brown out due to plumes and surface dust.

Furthermore, existing theoretical tools shall be improved in parallel to the facility development and verified with the generated set of experimental data in order to obtain a set of engineering tools at the end of the study with which the results of the measurements can be transferred to design considerations of space exploration missions.”

The facility must be able to generate a vacuum down to about 1 Pa and maintain this for a sufficient time to allow meaningful measurements to be taken, realistically of order 10 s. A suitable thruster device will be required to create the equivalent of a supersonic gas plume. A regolith holding device and suitable regolith materials are needed to form the basis of the studies. The thruster must be movable so that different altitudes and angles can be studied. Simulants for spacecraft bases are needed to determine effects of the liberated regolith on navigation and witness plates for recording pressures and heat fluxes. Various measuring instruments must also be provided for use, including pressure sensors, infra-red (IR) and optical cameras to record the regolith motion, particle tracking devices to follow the particle motion, Schlieren cameras to detect shocks and radio transmitters and receivers to determine attenuation due to the regolith cloud.

The requirements specified by ESA were analysed to determine what the specifications of the facility should be. The types of rocket motors expected to be used during the landings discussed above are a minimum of 20 N and such motors cannot realistically be used in experimental facilities such as the one proposed for this project. A 20 N bi-propellant motor was fired in the large vacuum chamber STG facility at DLR Göttingen in 2023 but it was only possible to fire for 0.25 s before the vacuum pumps were unable to maintain the pressure. To obtain the run time desired here, it will be necessary to used scaled down thrusters. To make this meaningful, various non-dimensional parameters that determine the physical behaviour of the system need to be kept the same, or at least, close to the values for the full size system. A detailed similitude analysis was carried out to determine how the facility should be designed to be able to properly test the problems of interest. This led to a hierarchy for requirement specifications starting from the top level given by ESA and progressing down to the numbers that would drive the design.

The key design parameters that were derived from the similitude analysis are:

- The gas to be used for the thrusters is Nitrogen delivered at a pressure of 1 bar and flow rates up to 20 g/s. Other gases or mixtures of, for example, Methane with Nitrogen can give a better match of the ratio of specific heats but this is outweighed by problems with handling such gases that are either flammable or toxic.

- To ensure that the vacuum conditions required are maintained for long enough a total facility capacity of 72 m^3 will be required. The pressure rise should be limited to 7 % over a period of 2 s. Target pressures are 600 Pa for Mars and <10 Pa for airless bodies.

- The thruster gas will need to be heated to match the required viscosity similitude. The necessary temperature will be up to 1000 K though above 750 K should be sufficient.

- Pulsing of the thruster at rates up to 30 Hz is desirable but this is acknowledged as being difficult.

- Regolith simulants must have relatively low density to accommodate the differences in gravity between the target bodies and Earth. This requires the use of ground walnut shells for Martian simulations and 100 micron sized glass bubbles for the Moon and small bodies. The matching for the latter is not ideal but less dense simulants have not yet been identified.

- Two scaled thrusters, one for Martian conditions and the other for Lunar and small bodies. These must be able to be positioned at different heights from 1 to 100 nozzle diameters and angles up to 60 °.

- The facility, particularly the pump, must be able to cope with a dust laden environment.

Requirements for instrumentation are as follows:

- Optical Access for optical and IR cameras.

- Vacuum monitoring to ensure correct operation.

- Particle Tracking System to record regolith simulant motion.

- Extent of plume (Schlieren) and heat flux (thermal camera).

- Spacecraft base plate with integrated thruster.

- Witness Plates.

- Pressure transducers with range 1 to 104 Pa.

- Electromagnetic transmissibility.

A variety of facility configurations were examined before choosing the final version. Accommodating the facility volume within the host building was a significant constraint. In addition, the need to ensure that the test section provided a symmetrical exposure to the thruster and experiment environment limited the location of the connections to the pumps etc. The design process was supported with modelling work, particularly in relation to the gas heater.

The final design consists of two main chambers, test and ballast, connected with a large pipe to allow gases to freely flow back and forth as well as the connections to the pumps and ancillary components. The test chamber is a cylinder with rounded ends that sits vertically so that the experiments can be placed inside with gravity acting straight down. A circular door has been placed on one side to allow easy access for setting up the experiments. The pipe from the top of the test chamber has a large valve to control flow to the ballast tank and smaller valves for the connections to the pump. This latter connection has two routes, either side of the large valve to accommodate different modes of operation. This combination allows the two chambers to be pumped individually or together as required.

After a suitable competition, the contract to design, build and install the facility was awarded to Busch UK. The design evolved to some extent to accommodate the site and the size of the buffer tank. Installation was far from straight forward and required the buffer tank’s legs to be removed to get the tank inside and then raised up again. Once assembled the control system was added along with system monitoring instruments and leak detectors. Initial commissioning identified some minor leaks which were subsequently cured.

Once commissioning was complete the facility was equipped with the various instruments specified for the experimental work. These were all tested along with the heated gas thruster to establish the various modes of operation required. Regolith simulants were also introduced during the later stages to establish that this aspect also worked. These tests were quite extensive and took some time to complete. Most of them were successful but several aspects could benefit from some further investigation and alternative approaches. Nonetheless, the facility has been proved to be an effective tool for the study of the interaction between thruster plumes and regolith as well as various other types of experiments that need a reasonably sized vacuum facility.

The design and construction of the facility and the development of the modelling capabilities has been a challenging project given the aim to move a difficult subject forward. On the whole it has been successful despite many practical barriers, some of which have been difficult and time-consuming to overcome.

The objectives were refined leading to a new list of specific requirements and most of these have been met by the facility. Some aspects required some compromises due to practical limits encountered. These could usefully be the subject of further study to improve performance. In brief, the following are key areas that would benefit from further work:

- The gas supply system should be redesigned to reduce the gas flow delays and allow faster pulsing.

- The target temperature for inflow gas was 1000 K but this has been reduced to 800 K to ensure a sustainable and reliable system. Redesign of the heater system based on what has been learnt may improve performance.

- The calibration of the chosen Kulite pressure transducers is too dependent on temperature so this needs to be fixed. This is particularly obvious with the low thermal conductivity permeable plates.

- In addition, there have been a number of recommendations arising from the Acceptance Testing for changes that would be desirable:

- Automatic or manual traverse mechanism to adjust the height of nozzle assembly and impingement plates. This would avoid the need for much of the pump up and pump down time which is significant. Any such system will need to be vacuum rated as well as being able to cope with the regolith simulants which is a significant engineering challenge.

- Gimbal mounts for the nozzle and impingement plates would increase the inclination accuracy. Alignment of the various items was a constant challenge during the experiments.

- Access ports to facilitate the utilization of additional pressure transducers beyond the current limit of three transducers per experiment. This would again reduce the amount of pump up and pump down cycles per experiment programme.

- Increased size of permeability plates for better heat transfer capability. The differing heat transfer characteristics of the two types of plates makes interpretation of the results more difficult.

- Despite several hours of baking inside an oven, it has been observed that walnut shells exhibit a tendency to boil once the chamber pressure falls below 10 mbar. Although an innovative approach to remove the moisture from the walnut particles has been employed, the process remains one that requires a significant investment of time. Therefore, it is imperative that a substitute for walnut shell simulant in the context of Martian regolith is identified.

- Certain individuals may experience an allergic reaction to nuts. The process of outgassing emanating from walnut shells under low pressure conditions results in spreading of particles in the surrounding vicinity of the establishment via vacuum pump discharge points. Consequently, it is imperative to notify all individuals utilising the communal space near the facility.

- More sensor data is required within the vacuum chamber. Radio wave reflection and diffraction occurs at sudden changes in atmospheric pressure/density. At this time there is insufficient sensing within the chamber to detect and/or track gas flow or confirm/identify any pockets of high and low pressure/density. It is recommended that installing a large array of pressure sensors will be very beneficial in terms of diagnostics and removing uncertainties. High-speed IR photography will independently confirm the hot gas flow.

Engineering simulation tools have been developed and the fidelity of the results has been improved via several developments. These still have limitations but these are understood and the codes can still be run quickly. Further work may deliver better performance but the flow is intrinsically complicated so it may be necessary to use high-fidelity codes for the detailed modelling work.

The focus of the modelling development work was to introduce an erosion routine coupled with a moving mesh capability to the PLCO tool. To further augment these capabilities, a CFD tuning routine has been implemented to permit calibration of the flow-field pressures against those from a high-fidelity code. PLCO is now capable of providing a rapid assessment of surface alteration of the regolith based on a specified thruster configuration, thrust level history and approach trajectory.

Viscous erosion has been the focus of these developments. Modelling of this mechanism has led to the use of an annular region of peak shear stress to determine erosion. Conclusions of interest concerning observed erosion behaviour include:

- The distance of the peak in surface fluxes appears to obey a sublinear scaling with thruster altitude.
- Although the peak dynamic pressure decreases at higher thruster altitudes, the erosion area increases because the exhaust plume footprint size also increases.

The upgraded implementation of PLCO, calibrated to FGE’s ANITA high-fidelity CFD results, shows favourable agreement to the simulations performed. This agreement improves with increasing nozzle altitude as would be expected, owing to the reduced complexity of the flow-field and erosion dynamics. Concerning surface pressures, at the locations of peak dynamic pressure for the two highest nozzle altitude cases considered, $7.5\ R_N$ and $10\ R_N$, PLCO underpredicts the pressures by approximately 5-15 % compared to those computed by ANITA across the plume impingement durations considered (0s, 0.25s and 0.5 s). For peak erosion, again for the two highest nozzle altitude cases considered, the absolute delta between PLCO and ANITA results is approximately 5-10 % across the plume impingement durations considered (0.25 s and 0.5 s).

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