EVOLUTION OF THE EXOMARS SAMPLE CRUSHING UNIT FROM BREADBOARD TO FLIGHT MODEL

Daniel Redlich (1), Robert Paul (1), Tim Tattusch (1), Christiane Bergemann (1), Samuel Senese (1), Fabio Musso (2), Stephen Durrant (3)

(1) OHB System AG, Manfred-Fuchs-Str. 1, D-82234 Weßling, Germany, E-mail: daniel.redlichl@ohb.de
(2) Thales Alenia Space Italia S.p.A., Strada Antica di Collegno 253, I-10146 Torino, Italy, fabio.musso@thalesaleniaspace.com
(3) European Space research and TEchnology Centre (ESTEC), Keplerlaan 1, PO Box 299, 2200 AG Noordwijk, The Netherlands, stephen.durrant@esa.int

ABSTRACT

This paper describes the development and testing of a jaw crusher (Crushing-Station). The sub-system is part of the Sample Preparation and Distribution System (SPDS) of the ExoMars Rosalind Franklin Rover. The ExoMars Rover and Surface Platform Mission, planned for launch in 2022, is a mission of international cooperation between ESA and ROSCOSMOS with a contribution from NASA. Thales Alenia Space is Prime Contractor to ESA. In the SPDS chain of sample preparation, the Crushing-Station has the task to pulverize the collected Martian subsoil sample to a powder with a defined grain-size distribution, minimizing possible cross-contamination between subsequent samples enabling scientific analysis.
The paper will focus on the design and its evolution through the different stages from Bread Board (BB) to Flight Model (FM). Special attention is given to the improvement of the crushing performance and crushing kinematic. Additionally it provides a detailed summary of the testing results from the qualification and acceptance phase.

INTRODUCTION

“Was or is there life on Mars” is one of the most intriguing questions in extraterrestrial science. To get one step closer to answering this question, ESA together with Roscosmos, decided to conduct the ExoMars program, which is divided into two missions: the first mission consisted of an Orbiter which was launched in 2016 whereas the second mission consists of a Lander with a Rover to be launched in 2022. The Rover is equipped with a Drill to take sub-soil samples down to a depth of 2 m, which will then be analyzed by several instruments located in the Analytical Laboratory Drawer (ALD) inside of the Rover.
To ensure an accurate analysis of the sample by the instruments, the Rover is equipped with the Sample Preparation and Distribution System (SPDS)[1]. It is developed by OHB System AG as subcontractor to the mission prime contractor Thales Alenia Space. To ensure the required sterility and cleanliness for the highly sensitive instruments, the ALD together with the SPDS form an enclosed volume, the so-called Ultra-Clean Zone (UCZ), which remains pressurized until first opening on Mars.

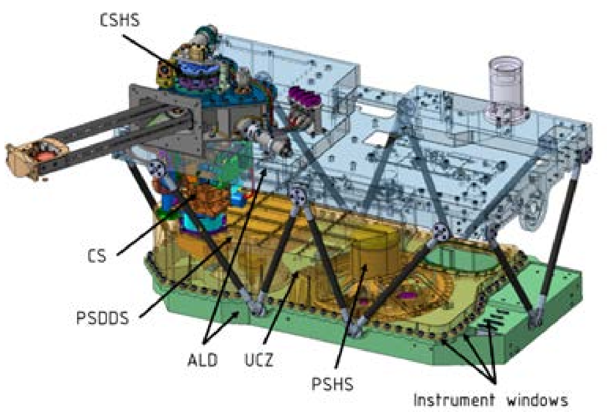

Figure 1. SPDS and ALD CAD models

The SPDS (see Fig. 1) consists of four separate sub-systems that interact with each other to transport the sample within the UCZ. The Core Sample Handling System (CSHS) [2] receives the sample from the drill and transfers it to the Crushing Station (CS) where it is crushed. The Powdered Sample Dosing and Distribution System (PSDDS) [3] receives the powdered sample, stores and doses it in defined quantities to different sample receptacles, which are subsequently brought to the instruments for analysis by the Powdered Sample Handling System (PSHS) [4].

DESIGN DRIVER

The main design drivers can be divided into the following three groups:

- Design drivers derived from the milling of the sample material,

- Design drivers originating from Planetary Protection, Cleanliness and Contamination Control requirements for preserving the planet Mars and Martian samples from Earth contamination,
- Design drivers imposed by the planetary environment on Mars

For the SPDS a set of samples were defined to cover the complete range of possible Martian samples to be found during the ExoMars mission. These samples shall be processed by all four sub-systems. The first group of design drivers are related to sample materials which shall be milled by the CS to a powder where 90%vol. of the grains are between 50 and 500 μm in size. The above mentioned samples have a wide range of properties ranging from very hard over brittle to soft and sticky. The sub-system must be able to produce 2.5 ml of powder within 2 hours. In addition to the wide variation of different samples the CS must be able to crush sample with unconfined compressive strength up to 110 MPa.

The second group of major design drivers is imposed by Planetary Protection, Cleanliness and Contamination Control requirements. While searching for traces of extraterrestrial life on Mars, any kind of contamination originating from Earth could lead to false positive or false negative findings of the ALD Analytical Instruments during sample analysis. For this reason, an Ultra Clean Zone (UCZ) has been designed and implemented, within which the CS and the other SPDS sub-systems operate. A priority requirement is therefore to control and minimize the organic contamination (molecular, particulate and biological) to an extremely small extent, which allows in the end to arrive at a total organic contamination of the whole UCZ of very few tens of nano-grams (ng). Furthermore, for Planetary Protection reasons and to preserve UCZ sensitive items from microbial contamination, all UCZ parts are also treated with a rigorous bioburden reduction process (Dry Heat Microbial Reduction) which will bring the UCZ hardware bioburden to a level of 0.03spores per square meter maximum. To achieve these very challenging Planetary Protection, Cleanliness and Contamination Control requirements, all UCZ constituent parts are integrated in an ultra-clean environment (ISO3 AMC-9, glove boxes train), and to avoid risk of recontamination, the UCZ will be over-pressurized from the moment of its sealing after integration in the ultra-clean environment until the first opening on Mars. Since actuators as well as sensors and other electrical components are a high source of contamination, SPDS electro-mechanic components are not allowed inside the UCZ. This calls for the need of dynamic feed-throughs that, on the one hand need to be gas-tight and, on the other hand, need to avoid high parasitic torques to allow smooth motion and a low system mass. These are two challenging requirements that make the adoption of carefully balanced compromises necessary. Furthermore, all structural parts of the sub-system that enclose the UCZ need gas-tight seals on their interfaces, requiring a stiff structure with a minimum number of internal interfaces. Other origins of contamination are different types of materials or coatings. Basically, the only material group that is acceptable inside the UCZ are metals. When unavoidable, a very limited use of specific polymers and low temperature grease is allowed. Also the choice of coating is limited by several factors, such as their compatibility with the ultra-cleaning processes applied to the parts before entering the ultra-clean integration environment (which includes bake-outs, ultra-sonic baths with different solvents, bioburden reduction and CO² snow-cleaning), chemical compatibility with instruments analysis as well as the demanded small surface roughness (Ra = 0.1 / 0.2μm) for all surfaces in contact with the sample, to improve cleaning efficiency and reduce sample contamination by contact transfer.

The last group of design drivers are a result of the environmental conditions on Mars. The environmental conditions impose several restrictions on the design, such as the operative temperature range of -60°C to +40°C, and the dry low-pressure CO2 atmosphere. Contrary to the sterile vacuum in which most space mechanisms operate, the sample processing produces a very dusty environment, imposing many challenges for the mechanisms' tribological elements. The dry atmosphere causes additional triboelectric charging of the particles, which can cause them to adhere to all surfaces they come into contact with. The UCZ is thus converted into to an extremely dirty (but uncontaminated) environment during sample handling [4].

SHORT RETROSPECTION OF THE SYSTEM EVOLUTION

At the beginning of the ExoMars program not much experience in fully automated milling/crushing of Martian samples and information about the possible problems was available. Therefore, the principle of the existing laboratory jaw crushers has been adapted for the ExoMars mission and a first simplified BB was designed and built (see Fig. 2).

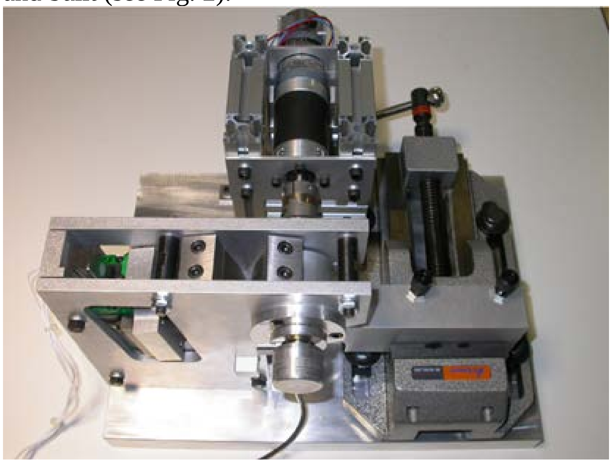

Figure 2. CS simplified BB

With this BB a set of samples was processed (Sandstone, Marble, Porous Basalt and Massive Basalt) which enabled the most basic parameters of the design to be determined, namely:

- Forces induced by the different samples into the jaws,
- Torque needed to crush the sample,
- Power needed to crush one sample

Based on these first results and the gathered design experience, the CS elegant BB (see Fig. 3) was developed and built. This BB was tested with the above mentioned samples and also with a set of samples that were defined by ESA.

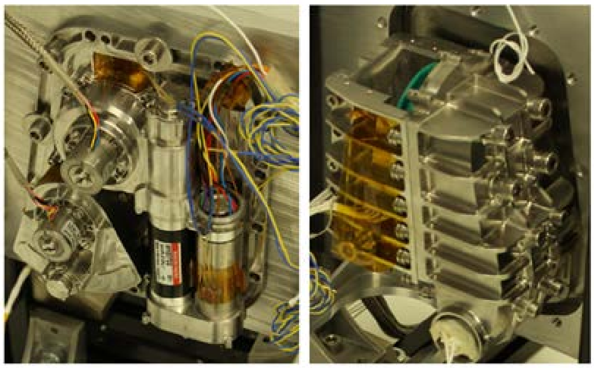

Figure 3. CS elegant BB

During this test campaign the following changes were implemented to meet the defined requirements.

- Changing the jaw profile to reduce high crushing loads at the beginning of a crushing phase,
- Introduction of a flexibility to the not-actuated jaw, to reduce the needed time for the crushing of samples which tend to stuck to the jaws
- Upgrading of the CS with a Vibration and Shock Mechanism (VSM) to clean the CS after the crushing of a sample. This is needed to reduce the cross-contamination of the different crushed samples. Different damping elements has been tested to avoid undesired shock propagation.

After the CS elegant BB proved that it can provide the needed sample processing performance, the CS QM were developed with the following additional improvements:

- Introduction of dynamic seals,
- CS became enclosure for the UCZ,
- Increasing of the drive train robustness,
- Change of the drive-train dust protection concept

Together with the CS QM an identical Life Test Model (LTM) was assembled. After the finalization of the qualification campaign, the QM was sent to the customer for further qualification on system level. With the LTM, the required life test campaign with subsequent disassembly and inspection was performed. The subsequently built FM (see Fig. 4) is a complete rebuild of CS QM and LTM and was also sent to the customer upon completion of the acceptance test campaign.

Figure 4. CS FM (upside down)

DESIGN OF THE CRUSHING STATION

The CS has the following main functions:

- Receiving the sample from the CSHS (filled in from top), crushing the sample (strength of up to 110MPa) to defined grain size and delivering it to the PSDDS,
- Ejecting unwanted or not processable sample,
- Minimizing cross-contamination between subsequent samples,
- Preservation of the UCZ to avoid sample contamination with rover (earth-) born particles

The CS sub-systems are composed of three mechanisms, namely the Crushing Mechanism, the Dejamming Mechanism and the Vibration and Shock Mechanism (VSM), which interact with each other to provide the required functionalities. They are all hosted in a common housing, which forms part of the UCZ barrier separating the drive trains from the end effectors via dynamic and static seals.

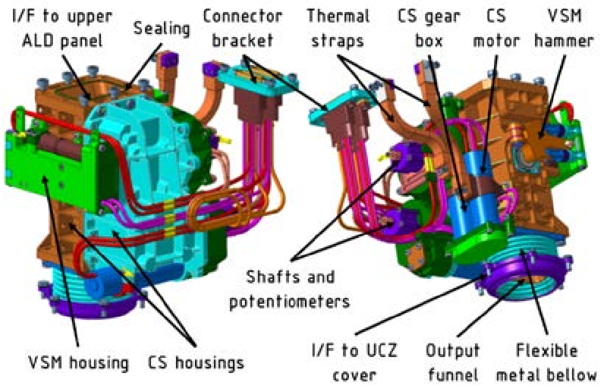

Figure 5. CS QM CAD design

4.1 Crushing Mechanism

The crushing motor drives a gear box which is oriented in parallel via a spur gear. At its output shaft the gearbox is equipped with a worm. The counterpart, a worm wheel, is supported by two hard-preloaded angular contact bearings. It is mounted on the drive shaft to which a potentiometer to measure the angular position, as well as the eccentric to drive the jaw are attached. The drive shaft of the crushing mechanism is coupled to the housing by two additional needle bearings to absorb the high crushing forces. The active jaw is connected at its upper end via a needle bearing to the eccentric, which provides the motion, and at its lower end via a friction bearing to the dejamming mechanism (see section 4.2). To protect the kinematic behind the moving jaw from dust, protection lids are being pressed against the lower and upper part of the jaw via springs. The rotation speed of the active jaw is 1.27 minutes for a cyclic motion of the jaw that is equivalent to a consecutive 360 deg motion of the eccentric shaft.. The actuator is a brushless motor that is qualified and delivered by Maxon Motor AG.

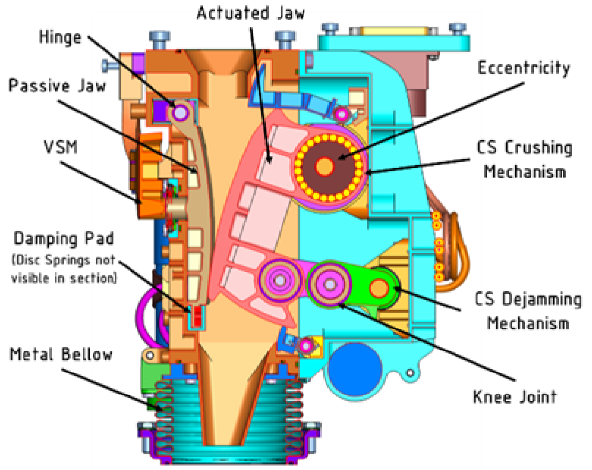

Figure 6. QM CAD model cross-section

Fig. 8 shows the simplified kinematic of the active jaw. The crushing movement is a superposition of the rotation of the eccentric on the crushing drive shaft and the upwards and downwards motion imposed by the dejamming knee. Both lead to a complex movement of the active jaw. During this movement the gap varies from 0.25 mm (smallest gap) to 0.5 mm (largest gap), with an up and down component of the movement during a complete turn of the crushing shaft (see Fig. 7). The size of the maximum crushing gap is a very important parameter for the crushing performance in terms of grain size and robustness. The robustness and the crushing efficiency are, however, largely influenced by the gap size. A maximum gap size smaller than 0.4 mm is to be avoided in order to have a robust crushing process. The CS design also provides the possibility to adapt the gap size if required.

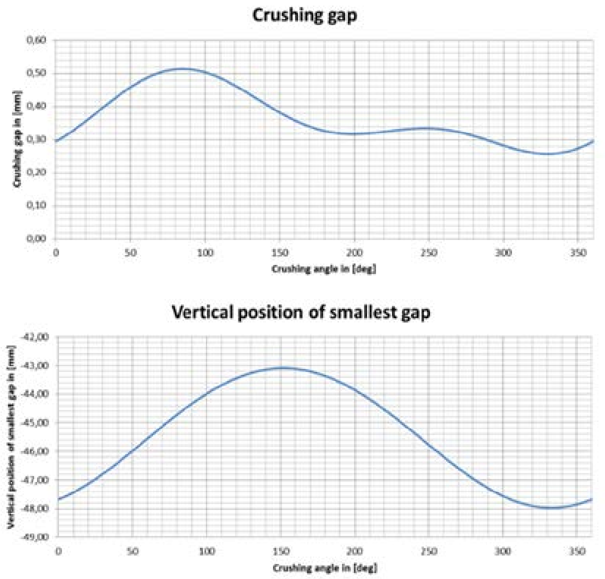

Figure 7. Crushing gap-size and its vertical position wrt the crushing shaft axis

Crushing can be performed in two directions: upwards and downwards. The downward crushing compresses the sample further during crushing. Therefore, the torque demand is much higher than for the upward motion which is to loosen the crushed material. The upward motion is the default crushing direction. The direction should switch during the crushing process to improve the crushing performance.
Due to the relatively high power and energy demands of the crushing process, which can take up to two hours and to protect the sample from mechanism induced heat, the necessity for a thermal strap was discovered in the thermal assessment of the CS.

4.2 Dejamming Mechanism

The function of the dejamming mechanism is to provide the possibility to remove jammed material or to discard sample that shall not be investigated by the instruments. The jaws shall then open to enable an uncrushed core sample to fall through. It is also used to reduce the cross contamination of the CS by introducing shocks via the VSM to remove residue when the dejamming mechanism is open. The dejamming mechanism for opening and closing the CS respectively is located at the bottom part of the active jaw. The de-jamming mechanism is a knee-joint with a knee angle that varies in closed position with the crushing shaft position. To open it, the mechanism drives 55deg between its two hard stops. It is in contact with the lower hard stop when the jaws are closed for crushing, and with the other one when the jaws are fully open for ejecting a sample or for cleaning the jaws (see Fig. 8). The lower hard stop also intakes the crushing force.

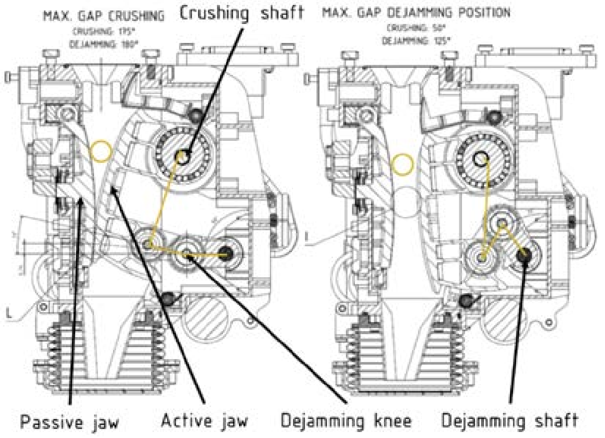

Figure 8. CS dejamming mechanism (left: closed, right: open)

During the normal crushing process, only the bearing directly attached to the movable jaw and the bearing in the dejamming knee are to move. This means the dejamming shaft does not rotate during nominal operation. To prevent this the high crushing forces are transferred to the shaft a hard stop is attached to it which prevents the shaft from turning during nominal crushing operation.
The dejamming rack and pinion system maximize the possible torque available for the dejamming shaft within the allowable envelope.

4.3 Vibration Shock Mechanism

To decrease the cross contamination of the CS caused by material stuck on the jaws and to increase the material flow during the crushing process, a VSM (see Fig. 9) was added to the CS design that introduces a single shock to the passive jaw (to which most of the material sticks) when it is commanded to do so. Since only one actuator can be in operation at a time, the other CS actuators have to be stopped. The VSM is a self-driven additional mechanism to the CS that is entirely outside the UCZ.

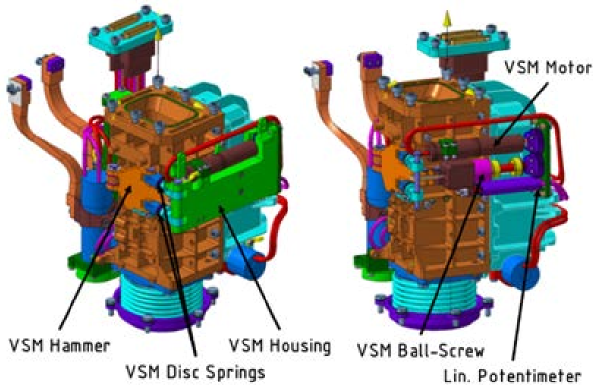

Figure 9. CS with and without VSM housing

A ball screw transfers the rotation of the VSM Motor into a translational motion that tensions the hammer. The ball screw position (and therefore the hammer status) is measured by a linear potentiometer. When extending, the ball screw compresses a stack of disc springs until the hammer rests in its fully tensioned position. When it is retracted, it pulls the hammer out of this position and the hammer hits the passive jaw (see Fig. 10). By choosing different springs or spring arrangements the resulting impact load is adaptable. The hammer hits the passive jaw, which has a contact surface that protrudes out of the CS housing.

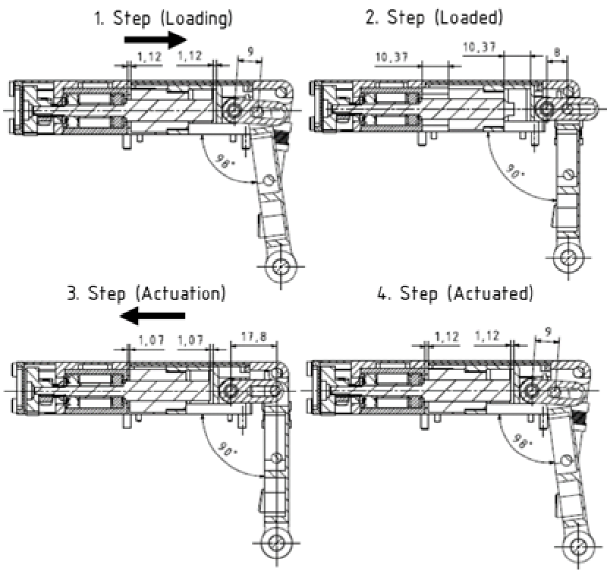

Figure 10. VSM actuation sequence

4.4 Sealing Concept

Both crushing and dejamming shafts enter the UCZ via a dynamic sealing (see Fig. 12). The sealing function is realized by Braycote 601EF grease that is placed in a grease reservoir between the shaft and the housing. It is kept in position by two PTFE sealing rings, to avoid that the grease be pushed out of the sealing when the differential pressure of 0.1 bar is applied for a long period, or 0.2 bar for a short period (0.22 bar proof pressure). The sealing has a very low stiffness to minimize its resistive torque. This is possible because it does not need to fulfil any sealing function itself.

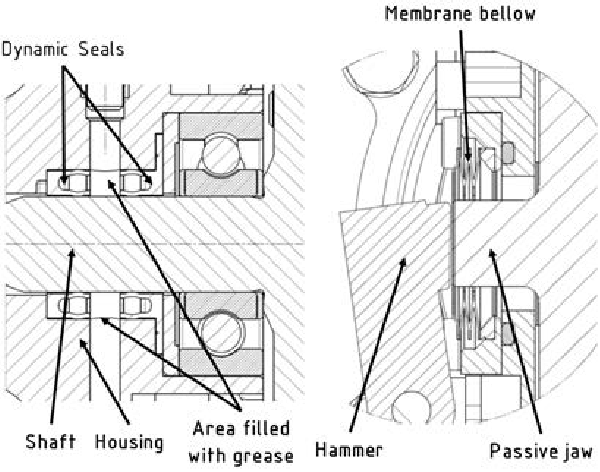

Figure 11. (left) Dynamic sealing, (right) Membrane bellow

All static sealings inside of the CS are metal sealings. The transport of the shock from the outside of the CS induced by the VSM to the passive jaw inside of the UCZ, is done by a membrane bellow that is always in contact with the jaw contact surface (to perfectly transfer the energy in the jaw). The membrane bellow can also compensate the motion of the passive jaw allowed by the disk springs providing the necessary flexibility (see section 4.5).

4.5 Optimizations of the crushing performance

As described earlier, it was found that during the first BB tests the crushing performance was not sufficient enough. The performance was improved with the measures listed below:

- Changing the jaw profile to reduce high crushing loads at the beginning of a crushing phase,
- Introduction of a flexible jaw to reduce the needed time for the crushing of some samples

During the development of the CS, a test program was established in which the influence of different jaw geometries on the crushing performance were investigated.

The jaw shape shown in Fig. 12 resulted in being the best option and was implemented in the CS design. It has only 2 striations to reduce the cross contamination caused by material stuck in between the jaws. The passive jaw has the negative of the profile of the moving jaw. Both jaws are made of hardened steel.

To improve dust protection of the mechanism kinematic and to reduce the friction on the side walls, the moving jaw has in its sides sharp edges so as to minimize the contact surfaces, which reduces the friction caused by the dust between jaw and housing. Dust channel behind the edges are leading the powder downwards to the CS outlet.

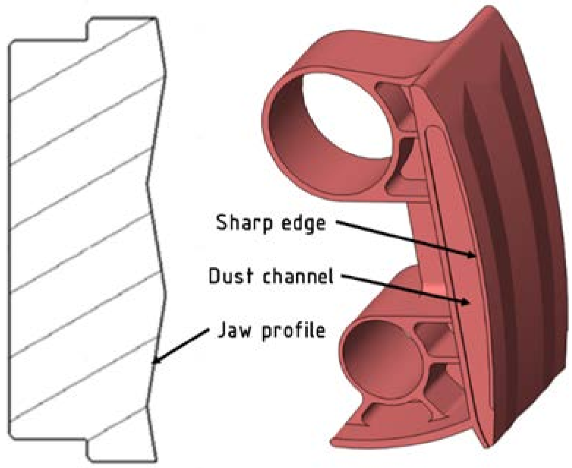

Figure 12. Shape of CS jaws

During the development of the elegant BB it was shown that the crushing performance was improved if one of the jaws is slightly flexible. This was implemented into the passive jaw by using disc springs. These springs are pre-stressed with a specific force. If the pushing force of the sample on the passive jaw is higher than the pre-stress of the disc springs these are compressed and the passive jaw moves slightly.

In addition to the above mentioned flexibility, the passive jaw also accommodates the four damping elements to attenuate the induced shock by the VSM; two on the top and two on the bottom side of the passive jaw. As these elements are placed inside the UCZ, metallic isolators manufactured from stainless steel are used as dampers. These dampers consist of closely interwoven wires and provide isolation as well as damping. Compatibility with the Ultra-Cleaning was demonstrated.

TESTING OF THE CRUSHING STATION

All requirements have been qualified with the CS QM and LTM. The FM then was built as a replica of the QM and proved its function/performance within an acceptance test campaign.

With the QM the following qualification tests were performed:

- Functional test,
- Leak test,
- Vibration/shock test,
- Thermal Vacuum Cycling test with leak test (TVAC),
- Crushing test

In addition to the QM tests, the LTM performed a life test campaign with the crushing of 132 samples (includes ECSS margins) and a subsequent disassembly and inspection of the complete sub-system.

The FM was tested like the QM, with the following exceptions: The applied loads and temperatures were reduced from qualification level to acceptance level and no sample was crushed because a contamination of the sub-system which will fly to Mars has to be avoided.

During the above described test campaigns, all tests were passed successfully. For the discussion of the test results only the non-standard tests will be discussed. Tests like Vibration/shock or functional tests will not be further elaborated.

5.1 Results of the Leak and Thermal Vacuum Tests

During the CS test campaigns, the leakage of the sub-system was measured with a Helium leak detector. This test was performed before and after the Vibration/Shock test. The leak test after the vibration/leak test was performed in the frame of the TVAC test.
As the CS end-effector reaches into the UCZ, the pressure (100mbar) must be applied on the inside of the sub-system while maintaining vacuum outside of it to be able to operate the helium detector. To achieve this, the setup was built in a way that the chamber and the outside of the CS were connected with each other with a valve while the ALD interface of the CS was closed with a lid. Through this it was possible to evacuate both the CS and the test chamber at the same time without running the risk of creating a significant delta pressure between both. After this, the connection needed to be separated and the CS was filled with 100-mbar Helium. When this condition was reached, the leakage measurement instrument was switched on and the measurement started. Tab. 1 is showing all the leak results gathered during the CS test campaigns.

Table 1. CS leak measurement results

Model	Temperatur [°C]	Leak rate before vibration [mbar·l/s]	Leak rate in 1st TVAC Cycle [mbar·l/s]	Leak rate in the last TVAC Cycle [mbar·l/s]
QM	-60	4,00E-07	1,80E-07	4,00E-07
	20	3,00E-07	2,20E-07	3,00E-07
	70	-	4,00E-07	5,00E-07
LTM	-60	3,00E-08	4,00E-08	2,20E-08
	20	1,50E-07	1,60E-07	1,50E-07
	70	-	2,00E-07	2,50E-07
FM	-55	3,20E-08	4,30E-08	4,20E-08
	20	2,50E-07	2,40E-07	2,50E-07
	65	-	2,90E-07	3,20E-07

Additionally the leak rate was measured at 200mbar to characterize the leak, and at 220mbar to perform the proof pressure test.
The CS QM performed 8 thermal vacuum cycles whereas the LTM and FM only performed 4 cycles

5.2 Results of the Sample Crushing Test

In early project phases, e.g. phase A & B, CS design was focused on processing certain types of sample, which were assumed to be the most critical ones. As an example, the CS was originally tested with very hard materials assuming that the initial breaking force is the limiting factor for the crushing performance. After the first CS BB were designed to process hard samples, CS performance in processing soft samples was then investigated. It turned out that this type of sample, e.g. gypsum and geyserite, can be very critical as well, due to their tendency to adhere to the crushing jaws, causing jams and high actuation forces. Several small design improvements were able to solve these problems, clearly demonstrating the importance of an early definition/specification of the reference samples and/or simulants, with adequate and intensive early testing. As a result, a minimum set of reference samples and range of their key parameters to be considered for the SPDS verification has been defined:

- Sandstone High Quartz content,
- Sandstone Low Quartz content,
- Claystone High Calcium content,
- Claystone Low Calcium content,
- Weathered Basement (Gumbo Shale),
- Gypsum,
- Geyserite,
- Clay/Salts simulant,
    - 67% Montmorillonite,
    - 30% Magnesium sulfate heptahydrate,
    - 3% Magnesium perchlorate hexahydrate
- Very fine sand,
    - 50% Clay/Salts simulant,
    - 50% Based upon very fine Siliceous/quartz sand
- Medium-coarse sand,
- Fused silica FS120,
- 110MPa simulant (Staffs Blue)

Sample properties that are interesting for the CS are the following:

- Hardness (bulk and particle) → Crushing performance and impact on tribological contacts,
- Tendency to stick to surfaces → cross contamination,
- Uncrushed state (core / broken core / granular) → crushing and dejamming performance

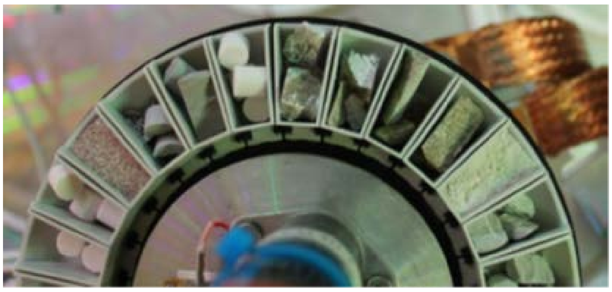

Figure 13. Different test samples

During the first test of the BB it became obvious that the time needed to crush one sample and the received grain size are directly coupled to each other. This means that the larger the grain size, the less time is needed to crush a sample, and vice versa. Together with the improvements described in chapter 4.5 and the tuning of the available parameters, it was possible to fulfil the requirements for almost all defined samples.

Fig. 13 shows the crushing process for the first sample which was crushed by the CS QM. This sample consists of Sandstone with high quartz content. The sample was crushed within 30 minutes

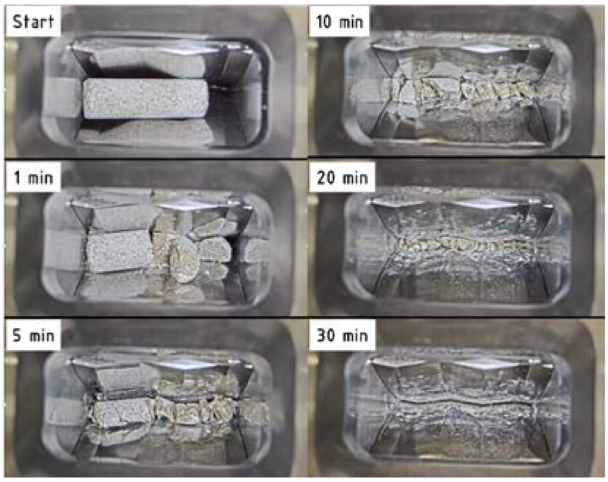

Figure 13. CS QM crushing progress

Tab. 2 shows the measured results of the grain size from all crushed samples. The chosen analyses value, Dv(90), indicates that 90%vol of the grains have a smaller diameter than the given value.

Table 2. CS grain size measurements

Sample	Model	Temperatur [°C]	Dv(90) [µm]
Sandstone High Quartz content	QM	-60	491
	QM	20	524
Sandstone Low Quartz content	LTM	-60	426
	LTM	20	560
Claystone High Calcium content	LTM	-60	459
	LTM	20	594
Claystone Low Calcium content	LTM	-60	418
	LTM	20	533
Weathered Basement (Gumbo Shale)	LTM	-60	560
	-	20	-
Geyserite	LTM	-60	272
	LTM	20	629
Gypsum	LTM	-60	582
	LTM	20	530
Clay/Salts simulant	LTM	-60	235
	LTM	20	255
Very fine sand	QM	-60	319
	LTM	20	336
Medium-coarse sand	LTM	-60	492
	LTM	20	646
Fused silica FS120	QM	-60	544
	LTM	20	515
110MPa simulant (Staffs Blue)	LTM	-60	560
	-	20	-

CONCLUSIONS

The Crushing Station showed during the qualification and acceptance campaign that it provides the needed performance with all required margins for the ExoMars 2022 Mission. The FM was delivered as the first SPDS sub-system to the customer (TAS in I) and waits now together with the other 3 SPDS sub-system for the Launch which is planned in 2022. The Qualification Model is integrated in the Ground Test Model where SPDS related system testing was successfully performed. All lessons learned from the BB could be implemented and therefore the performance of the CS could be continuously improved throughout the development phases up until the Flight Model. The result of this continued improvement led to the successful completion of the acceptance campaign and fulfilment of all necessary requirements.

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