Design and Breadboarding of the Sample Preparation and Distribution System of the ExoMars Mission

Wolfgang Schulte, Christoph Widani, Peter Hofmann, Tobias Bönke

Kayser-Threde GmbH, Munich, Germany
wolfgang.schulte@kayser-threde.com

Edoardo Re
Galileo Avionica S.p.A., Milano, Italy
eduardo.re@galileoavionica.it

Pietro Baglioni
ESA/ESTEC, Noordwijk, The Netherlands
pietro.baglioni@esa.int

Abstract

Europe is presently preparing for ExoMars: the first European Mars exploration rover mission. The aim of this mission is to search for traces of past and present life and to investigate the Mars environment and geophysical properties. The German company Kayser-Threde is carrying out design and breadboard activities for the ExoMars Sample Preparation and Distribution System (SPDS) under contract to Galileo Avionica of Italy who is subcontractor for the Drill and SPDS Subsystem to the mission prime, Thales Alenia Space, for this ESA exobiology mission.

The SPDS is a core element of the Pasteur Payload Module that is accommodated on the ExoMars Rover. It handles and processes the Martian rock and soil samples that are collected by the sample acquisition system – a surface and subsurface drill with sampling capability. It presents the sample cores acquired by the drill to instruments for optical inspection and spectroscopic analysis. A crushing station comminutes the drill cores to fine grained samples and distributes defined quantities of this material to another suite of analytical instruments. The SPDS transfers the samples to several stations/instruments, stores samples and handles sample waste and sample blanks.

This paper describes the current design status of the SPDS and the development of breadboards: mainly a jaw crusher and a dosing station for sample material.

1. Introduction

The ExoMars mission will deploy a Rover on the surface of Mars carrying a comprehensive suite of instruments dedicated to imaging, soil analysis and to exobiology research: the Pasteur Payload [1]. The Rover will be capable of traveling several kilometers searching for traces of past and present life. It will collect and analyze samples from surface rocks and from subsurface layers. The combination of rover mobility with the capability to access underground locations where organic molecules might be preserved is unique to this mission offering the opportunity to answer the question of whether life ever arose on Mars.

The ExoMars landing platform, as an option under study, will also host a fixed station dedicated to investigations of the environment and interior of the planet, the Geophysics and Environment Package (GEP).

Current baseline for the ExoMars mission is a launch with Ariane 5 ECA in 2013. This allows "full" science packages on this mission, including a 16.5 kg Pasteur Payload on the Rover. The Rover will be able to identify scientifically interesting places, travel to them and perform in situ analysis with the Pasteur instruments externally accommodated on the Rover mast and robotic arm. A drill with a capability to
penetrate down to a depth of 2 m will then retrieve and deliver Martian soil and rock samples which are distributed by a dedicated Sample Preparation and Distribution System (SPDS) to a Rover-internal suite of analytical instruments. The SPDS mechanisms and structures and the analytical laboratory instruments are accommodated in the so-called Analytical Laboratory Drawer (ALD), a subunit integrated in the Rover vehicle structure, in the Rover front part.

The Pasteur Payload instruments’ suite consist of

1. Rover-external instruments
   - Panoramic Camera (PanCam)
   - Infrared Spectrometer (Mima)
   - Ground Penetrating Radar (Wisdom)
   - Close-Up Imager (Clupi)
   - Mössbauer Spectrometer (Mimos II)
   - Raman-LIBS external optical heads.

2. Rover-internal instruments
   (Analytical Laboratory)
   - Microscope with visible and infrared channels (MicOmega)
   - Raman/Laser-Induced Breakdown Spectrometer (LIBS)
   - X-Ray Diffractometer (XRD)
   - Mars Organics Detector and Mars Oxidant Instrument (UREY)
   - Mass Organic Molecule Analyzer (MOMA) (a laser desorption mass spectrometer, LD-MS, and a gas chromatograph, GC)
   - Life Marker Chip (LMC) at present TBC.

Kayser-Threde (Germany) is responsible for the mechanical system of the SPDS acting as a subcontractor to Galileo Avionica Milano (GAM), Italy, who retains the responsibility for the overall Drill and SPDS electronics. Kayser-Threde, furthermore, supports ESA and the ExoMars mission Prime for the Pasteur payload (and GEP) analytical integration and interface definition [2].

The SPDS system configuration and the design of its mechanisms were studied within the ExoMars Phase B1 in the time frame 2006-2007. A breadboard of a jaw crusher was developed, built and tested. Subsequently a Bridging Phase (Phase B1 Extension) was initiated to last until March 2008 in order to follow on with the design studies adapting to the meanwhile changed boundary conditions and interfaces as the Rover and payload/instruments designs have progressed. Also SPDS breadboard activities are continuing in the Bridging Phase.

2. Pasteur Analytical Laboratory and Sample Preparation and Distribution Functions

The main requirements for the sample preparation and distribution functions are summarized below:
- To receive samples (repeatedly) as drill cores from the drill unit and present them to the optical instruments for non-destructive scientific analysis
- To transport the samples (drill cores) to a milling station
- To process the samples and distribute crushed sample material (≈100 µm grain size required) to the instruments of the Analytical Laboratory
- To save (crushed) sample material from up to three different samples for possible subsequent measurements runs of the analytical instruments; the volume of each saved sample shall allow serving each analytical instrument repeatedly with sample material.
- The failure of one of the Pasteur analytical instruments shall not endanger or block the sample preparation and distribution function and/or the measurement sequence
- Compatibility with Rover mass, volume and power resources
- Redundant functionalities (as feasible within resources constraints)
- Compatibility with ExoMars bioburden reduction and cleanliness requirements.

The SPDS is an assembly of mechanisms and devices that allows the handling, processing and scientific analysis of the acquired surface and subsurface samples. Its design and operational flow are driven by the requirements of the Pasteur Analytical Laboratory instruments and characteristics. Its main physical elements are:
- A core sample transport mechanism: to receive the samples (drill cores) from the drill, to allow the sample observation with the microscope and Raman/LIBS instrument, to transport the sample to the crushing station
- A crushing station: to reduce a (solid) drill core (diameter of 1cm, length of 2-3cm) to powder suitable for subsequent scientific analysis
- A dosing station (DS), consisting of three independent dosing devices: to store enough material from three different drill cores for a repeated analysis on these samples and to distribute the crushed material to UREY, XRD and MOMA, according to a pre-programmed sequence
- A distribution system holding a) re-usable (refillable) sample containers on a carousel to allow the sample presentation to MicrOmega (IR instrument), XRD and to the LD-MS of MOMA; b) a limited number of pyrolysis ovens used for the measurements of the MOMA GC instrument.

3. SPDS Concept

The SPDS processes, distributes and presents or hands over the samples according to requirements which are specific for each of the instruments of the Analytical Laboratory. It must also be designed to preserve the physical and chemical conditions of the samples and to avoid degradation as much as possible before the samples are transferred to the instruments.

Sophisticated and innovative solutions are necessary to develop the SPDS mechanisms satisfying the requirements of all Pasteur ALD instruments within the engineering constraints imposed by the allocated resources and cleanliness requirements.

Figure 1: SPDS design concept and payload layout currently under study (ExoMars Bridging Phase)

The physical configuration of the ALD and the SPDS elements layout is highly driven by the operational requirements of the instruments and by the nature of their mechanical and thermal interfaces with the Rover Module. The SPDS concept recently studied in the frame of the ExoMars Phase B1 is based on the layout of the Analytical Laboratory Drawer that has been defined by the mission prime, Thales Alenia Space of Italy (TAS-I). Updated instrument data were used to define the current Pasteur payload packaging concept. Data were taken from the ESA/Prime specifications contained in the Experiment Requirements Document (E-IRD) and from the instrument ICDs provided by the Instrument Teams. Several configurations and their impacts on the sample transfer chain were studied.

A revised baseline concept of the SPDS is currently being worked out jointly by GAM and KT to be presented to ESA and TAS-I at a review at the end of 2007. A general view of the studied design concept is given in Figure 1 and 2. The hand-over of the core sample from the drill to the SPDS is external to the ALD envelope, shown in Figure 1 as a protruding rail shaped structure. The protruding elements shall be retractable and are stored inside the ALD envelope when not in operation.

Figure 2: SPDS design concept and payload layout as in Figure 1, rear side allowing a view onto the sample distribution carousel

Figure 3: SPDS and ALD payload layout top view
4. Crushing Station

The crushing station concept selected for ExoMars is based on a jaw crusher principle. A jaw crusher design for a planetary application was studied and developed previously by NASA [3]. In the initial ExoMars study phase existing laboratory and industrial milling devices were evaluated and the jaw crusher technique was identified to be the only one that can fulfill the ExoMars requirements to mill the drill core sample in a one-step process. The simple and robust principle that is used to crush the stones is shown in Figure 4. The material is comminuted between a fixed (1) and a moving (2) metal plate (jaw) actuated by an eccentric drive shaft. Due to the special provoked jaw movement the milling charge is drawn into the crusher until it falls out by passing the small gap between the two jaws at the lower end of the crusher.

![Figure 4: Jaw crusher schematics](image)

When the crushing station breadboard was designed in early 2007 it was decided that it should contain sensors to gather valuable data for the design and dimensioning of the later flight model. This prohibited a small and light-weight design close to a flight model. The only part of the test setup that was intended to be as close as possible to a flight model design was the crushing chamber in which the core sample is comminuted. For the breadboard it was also intended that certain geometrical parameters could be adjusted in order to test different geometries. Thus, the mass of the breadboard became substantially higher than the mass envisaged for flight hardware. Yet all results gained with the breadboard tests are comparable to those expected for the flight model. Figure 5 shows a photograph of the breadboard recently built.

![Figure 5: Crushing station breadboard](image)

4.1. Breadboard Objectives

The objective of the breadboard was to realize a prototype of the crushing tool to achieve the following goals:
- Showing the feasibility of crushing a core sample of various characteristics with a jaw crusher
- Measuring the required actuation torque and appearing loads
- Determining the output material characteristics such as grain sizes and grain size distribution
- Gather data for a first estimation of mass, geometry, power consumption and operations time for the flight model.

4.2. Breadboard Design

The setup of the jaw crusher breadboard is shown in Figure 6 with its main components: 1. crushing chamber, 2. electric motor, 3. structural elements, 4. vice as adjustable clamping device for fine adjustment of the geometrical parameters of the crushing chamber, 5. force sensor, 6. position encoder (sensor).

The core sample is inserted from top into the crushing chamber and crushed between the two jaws. The powdered material falls into a small interception tank underneath the crushing chamber. The dimensions of this part of the crushing chamber (Figure 7) have been designed for core samples of cylindrical shape (∅10mm, length 20-30mm), but the design could easily be adapted for larger or smaller test samples. The torque required at the eccentric drive shaft to crush the sample material is measured using the motors’ power consumption and motor characteristics. Three load cells allow the determination of the forces
applied to the crusher structure. The angular transmitter relates the gathered data to the drive shafts angular position.

The breadboard is actuated by a 24V DC motor and a 450:1 gear stage. The power consumption during the test runs was below 9W (Figure 8). Only about 2W were used for crushing the sample, the greater part of the used energy was lost inside the gear stage and bearings. The rotational speed of the eccentric drive shaft was 0.13Hz. The test runs to completely comminute a core sample of the given size had typical durations of 30 to 50 minutes.

The breadboard was tested with four different types of materials: sandstone, marble, porous basalt and massive basalt. To find a good presetting for the adjustable breadboard parameters several test runs were performed with the result that the smallest possible gap between the two jaws is about 400µm. This value also represents the largest particle size after crushing. Smaller max. grain sizes seem not to be feasible with a jaw crusher. All tests were performed under laboratory conditions. Low temperature tests and tests with other sample materials or water (ice) inclusions have not yet been performed, but they are envisaged for 2008.

To determine the grain size distribution of the crushed core samples the material obtained by the tests was wet sieved using four different mesh sizes: 200µm, 125µm, 100µm and 63µm. The sieving results are shown in Figure 9. Since the maximum gap width of the jaws at the output was set to a value of ca. 400µm for these test runs the largest particles are believed to have this grain size.
4.4. Conclusions from Breadboard Test

The crushing station breadboard tests have demonstrated the following capabilities of the jaw crusher:

- Low power crushing is possible (< 9W) with a jaw crusher
- Achievable grain sizes are smaller than ca. 400µm (mean grain size depends on sample material and condition)
- Crushing time is about 30 to 50 minutes (also depending on actuation, power consumption and sample material).
- The crusher is capable of crushing even hard materials like basalt
- The system allows miniaturization as compared to commercial industrial and laboratory milling devices (goal: to achieve a milling station flight mass of about 2kg).

For a flight model (Figure 10) it is envisaged to add a release and de-jamming mechanism to the crusher that allows opening of the crusher jaws at the lower end to release a stuck sample or to let a scientifically uninteresting sample fall through the mechanism without crushing it into a waste container underneath the crusher.

A triple dosing station is mounted at the end of a rotating arm (Figure 11). It can, thus, reach different positions inside the payload and SPDS envelope: under the crushing station to receive milled sample material and above the inlet funnels of UREY and the sample carousel to fill the sample containers. The dosing function uses a revolving cylinder with pockets of defined volume which determine the amount of milled sample material that is delivered by this mechanism.

5. Dosing Station

Currently a dosing station breadboard is being designed. It shall be manufactured and tested before the end of the ExoMars Bridging Phase.

The purpose of the dosing station is

- to distribute and dose known amounts of the milled sample material received from the crushing station to the UREY instrument which has two funnel inlets
- to distribute, dose and fill the milled sample material in a defined way (e.g. with a flattened sample surface) into a re-usable sample container that presents the sample material to three instruments (XRD, MicrOmega IR instrument, MOMA LD-MS) and into the pyrolysis ovens of MOMA GC located on the distribution carousel
- to enable dumping of unprocessed or waste material from the crusher into a disposal container.

Figure 11: Illustration of dosing station principle

6. Other Breadboarding Activities

In the ExoMars B1 Bridging Phase additional breadboard activities are planned to qualify technical solutions for other key SPDS devices:

- The core sample transport mechanism, that receives the acquired subsurface core sample from the Drill Unit, presents it under the optical instruments and carries it to the input port of the crushing station; this mechanism includes also fine positioning to move the sample container under the optical heads with a defined precision.
- Re-usable sample containers (i.e. with a capability of being emptied from sample material) for powder samples on the carousel
- A sample flattening mechanism able to produce a flat sample surface as required for XRD analysis.
The re-usable sample container and the flattening mechanisms are linked to the carousel concept (Figure 12). A breadboard design for these mechanisms will be elaborated in the ExoMars Bridging Phase lasting until early 2008.

Figure 12: Carousel with re-usable sample container (rectangular shape) and pyrolysis ovens (round shape) for the MOMA GC instrument

The above mentioned breadboards of the SPDS mechanisms will also undergo specific tests in Mars environment representative conditions. The tests results and the validated design solutions will be used to support the Engineering Models activities, foreseen for both the Drill and the SPDS at subsystem level and for the integrated assemblies.

7. Summary and Outlook

It has been shown that the design activities related to the ExoMars Sample Preparation and Distribution System of the Pasteur Analytical Laboratory and related breadboard activities are well proceeding paving the way for ExoMars Phase B2/C/D activities expected to commence in 2008. Special emphasis has to be devoted to planetary protection requirements which put demanding constraints on the SPDS and the Pasteur Payload instruments to be kept inside a bioshield of the Rover.

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9. References

