# ADVANCED PENETRATORS AND HAMMERING SAMPLING DEVICES FOR PLANETARY BODY EXPLORATION

ESA/ESTEC, NOORDWIJK, THE NETHERLANDS / 12 – 14 APRIL 2011

**J. Grygorczuk(1), M. Banaszkiewicz(1), A. Cichocki(1), M. Ciesielska(1), M. Dobrowolski(1), B. Kędziora(1), J. Krasowski(1), T. Kuciński(1), M. Marczewski(1), M. Morawski(1), H. Rickman(1), T. Rybus(1), K. Seweryn(1), K. Skocki(1), T. Spohn(2), T. Szewczyk(1), R. Wawrzaszek(1), Ł. Wiśniewski(1)**

(1) Space Research Centre PAS, Bartycka 18A, 00-716 Warsaw, Poland, Email: jurekgry@cbk.waw.pl
(2) Deutsches Zentrum für Luft- und Raumfahrt, Rutherfordstr.2, Berlin, Germany

## ABSTRACT

The paper highlights the most recent achievements of the team in the field of penetrators and hammering devices: the development of the CHOMIK sampling device for the Phobos-Grunt mission, and the evaluation of KRET's ('mole' type penetrator) performance. The principle of operation of both devices is based on the MUPUS penetrator device for the Rosetta mission; however, the features of construction are significantly different.

## 1. INTRODUCTION

Spectacular space missions need outstanding solutions. It is particularly true in the case of planetary exploration missions, where mechanical devices have to operate in extreme, often uncertain environmental conditions, in micro-gravity and also have low power consumption. Penetrators that can meet above mentioned requirements must be technologically advanced devices. They are usually dedicated for geological investigation and sensor transportation.

In recent years, several penetrators have been designed and tested in laboratories. Some of them were prepared for space missions, e.g. PLUTO developed by DLR in Cologne for the Beagle 2 lander on ESA Mars Express mission [9]. Another interesting device is the HP$^3$ instrument proposed by DLR Berlin for the ExoMars mission [10]. Herein, we present all penetrators developed at Space Research Centre PAS, Warsaw.

The paper is organized as follows: in the two subsequent sections the basic information on the penetrators and its potential application areas are described. Then the penetrators MUPUS, mole KRET and CHOMIK are described in detail, especially in the context of future exploration. Finally, the last chapter summarizes the paper.

## 2. LOW VELOCITY PENETRATORS

The Space Research Centre PAS has been involved in the development of low speed, hammer-driven penetrators since 1996. It was strictly connected with the realization of the MUPUS project for the Rosetta mission and the invitation of our group to join the project given by Prof. Tilman Spohn (PI). The penetrator was necessary for conducting in-situ measurements, namely for insertion of thermal sensors into subsurface cometary nuclei layers. The SRC PAS proposed a unique solution that has not been applied before in space missions – a hammering insertion device with an electromagnetic drive.

The penetrators are used to insert sensors and sampling devices into a determined depth of the ground. In principle, they can efficiently work only in fragmented not compacted ground like sand, soil or porous regolith. There are three known methods for insertion of self-driven space penetrators:

(i) Driven by a pyro. An efficient method of insertion – instantaneous, non-problematic in microgravity space environment. Problems appear with explosive materials of the pyros, exhaust gases and the lack of insertion depth control in a not well defined ground.

(ii) Driven by a hammer. Single operation of the hammer is much less energetic than that of the pyro. Thus, that insertion scenario has to take into account a series of the hammer strokes with a typical depth progress of a few millimeters per stroke. The difference in principle of operation between the pyro and the hammer drive is shown in figure 1.

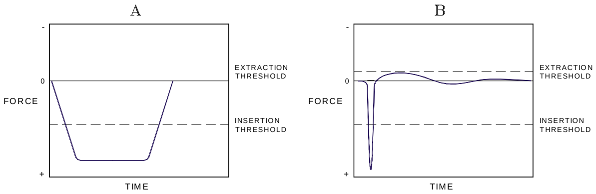

Figure 1. The force between the penetrator and the ground as a function of time.
A – for the pyro, B – for the hammer

All hammering insertion solutions are based on the mechanical interaction between three masses of the hammer, the rod and the counter-mass. The hammer and the rod are elastically suspended to the counter-mass, so that they can hit each other. The driving force is generated between the hammer and the counter-mass. Due to the unavoidable recoils of the counter-mass, the method is tricky to use in microgravity conditions. An important feature of the hammering drive is the accumulation of energy in the spring, spinning wheel or capacitor, shown schematically in figure 2.

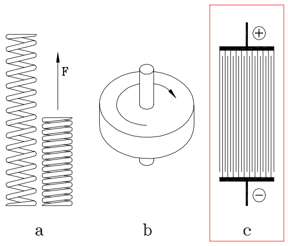

Figure 2. Three forms of possible energy storage: spring (a), spinning wheel (b), capacitor (c)

The source of the simplest transformation of the accumulated energy into kinetic energy of the hammer is the capacitor (e.g. MUPUS). The spring is widely applied in the mole penetrators; however, it is more complicated. The spinning wheel can accumulate utmost energy at high spin, but that method has not been applied yet due to unresolved problems with reliable energy transfer mechanism.

(iii) The wooden wasp method. This is a recently discovered und studied method [5], very different from the existing ones. It is a penetration action combining insertion with drilling. The penetrator rod consists of two halves with linear joint between them. If one half of the rod is pressed or hit forward, the second one provides resistance support to the ground. There are no similar recoils like in the hammering three masses drive and therefore this method could intrinsically work better in microgravity conditions. At a moment it is too early to say if that method will be successful. The serious mechanical problems are not sufficiently solved yet and a lot of additional research is needed.

## 3. POSSIBLE APPLICATIONS

The current and future applications of the low velocity penetrometers can show the growing interest of such devices in scientific community and its usefulness in planetary bodies' exploration. It is worth to indicate that some of the applications listed below are currently under realization which gives certain prospects for the future and more ambitious ones.

### 3.1. Thermo-physical and seismology research

The penetrometers are planned to be used in a close future in a series of space scientific mission as sensors carriers for subsurface investigations. For example, one of activities of International Lunar Network was to define the geophysical lander and appropriate payload for in-situ measurements of the lunar surface. Some of the geophysical investigations related to the Moon are listed below:

1. Determination of the size, composition, and state (solid/liquid) of the core of the Moon;
2. Characterization of the thermal state of the interior and elucidation of the workings of the planetary heat engine;
3. Determination of the thickness of the lunar crust (upper and lower) and characterization of its lateral variability on regional and global scales.

The penetrator types devices equipped with appropriate sensors are useful in accomplishing these science objectives by the following actions [11]:

- Making spatially distributed lunar geophysical measurements over a long period of time, covering at least one lunar tidal cycle (≥6 years);
- Making simultaneous measurements of seismic events – at least one from a location where waves pass from the origin through the Moon's core and at least one location where they do not;
- Making heat flow measurements below 1m depth over a long period of time
- Correlating surface magnetic measurements with seismic events.

Up until now the SRC PAS was involved in three different space missions, where different types of penetrators were used i.e. small penetrators for Cassini Hugens mission, MUPUS for Rosetta mission and CHOMIK for Phobos-Grunt mission. The data for the last two of them will be available in the next three years.

### 3.2 Determination of mechanical properties of the regolith

Mechanical properties determination of the regolith is a complicated task due to the heterogeneity of the space bodies materials and no information about them a priori. In principle the surface structure "accepted" by the penetrators are:

- loose material similar to sand on the Earth – for example the dune on the Mars,
- porous material, "foam glass material" alike – for example on the comet.

In addition, all our penetrator devices are driven by a hammer, which means that they are capable of working in the regolith in the dynamic range. This turn creates additional difficulties – it is crucial to correctly identify mechanical properties of the regolith. In principle, our effort goes in two, three different directions:

- attempting to correlate the experimental data obtained in the terrestrial conditions in various space regolith simulants with numerical model of regolith [12]. Based on that the typical properties of the regolith i.e. cohesion coefficient, different strength limits, shear strength can be determined;
- development of the database of analogues with measurements performed by our penetrators and different standard technique (e.g. static test for

tension or shear strength determination). Such database will be useful when the records from space experiments will be available;
- development of a universal, standard method which would allow determining “regolith strength for penetration.”

At this moment MUPUS and CHOMIK instruments are prepared to bring information about mechanical properties of the space bodies.

### 3.3. Sampling

Sampling process, in context of sample return missions, is simply an autonomous drawing of samples of surface or subsurface material. Autonomous sampling process in space bodies is complicated due to the microgravity conditions, huge uncertainties about the surface properties and very low temperature. Therefore, the requirements for sampling devices are hard to fulfill. In case of CHOMIK sampling device for Phobos-Grunt mission the following requirements were defined:

- sampling of friable and porous material,
- sampling of material for which static penetration occurs below 500 N force,
- <3N force transmission to the lander,
- <5W power budget,
- mass of the device less than 1.4 kg,
- sample size – several cubic centimeters,
- high reliability,
- capability to crush material in case of hard rock surface.

The CHOMIK device prepared for Russian Phobos-Grunt mission fulfilled all of these requirements.

### 3.4. Exploration

The real time information about thermophysical and mechanical properties of the regolith could provide technical assistance to future ESA exploration programs – both human and robotic. For example: the determination of the effectiveness of regolith for radiation shielding for astronauts; seismological data as an indicator of planetary bodies quake; information about ion concerning the concentration and extent of water in the water-rich regions. Penetrators can also play a significant role in future search of different specific minerals on asteroids like rare elements.

All of the above mentioned applications combining research and exploration are a promising sign of doing next step in the future planetary bodies’ exploitation.

## 4. MUPUS

The ESA cornerstone mission Rosetta comprises of two objects: the orbiter and the Philae lander. Landing on the surface of about few kilometers square, almost gravity free, cold and atmosphereless is one of the greatest challenges met so far in the history of space research, but one that can be also extremely benefiting in terms of scientific and technological outcome. Among the devices to record and monitor the physical state of the cometary nucleus is the MUPUS Instrument. The experiment was designed to measure temperature profile in subsurface layers, the thermal conductivity and mechanical properties (starting with strength) of the cometary soil.

The main technical challenges of the MUPUS experiment are the issues connected with how to transport the penetrator at a distance of about 1m away from the lander, and afterwards how to insert it into the nucleus. The first difficulty was solved by the lightweight manipulator, consisting of two parallel tubular booms rolled up on the reels and driven by a stepper motor (figure 3). The supporting role of the manipulator was crucial for the insertion of the penetrator in microgravity conditions.

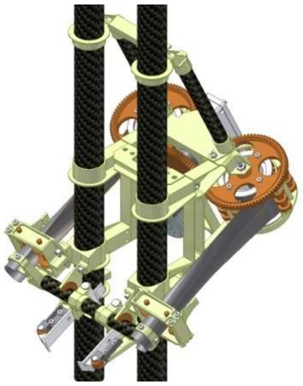

Figure 3. MUPUS manipulator (deployment device) in stowed configuration, CAD drawing

For the insertion of MUPUS into the surface a unique hammering device, which used an electromagnetic drive, was developed for the first time for space application. This novel insertion device was described in [1] and is presented in figure 4.

Figure 4. MUPUS hammering Insertion Device integrated on the EQM model

Insertion of the MUPUS penetrator in microgravity conditions was possible due to:

- High ratio of the counter-mass to the hammer (13:1) which provided relatively low energetic recoils of the counter-mass;
- In the insertion initiation phase the penetrator was supported by the tubular boom manipulator giving 1N friction force. The force was negligible during strokes but on the other hand was sufficient for damping the recoils;
- Anchoring properties of the tip (figure 5) which was designed with sharp and elastic barbs.

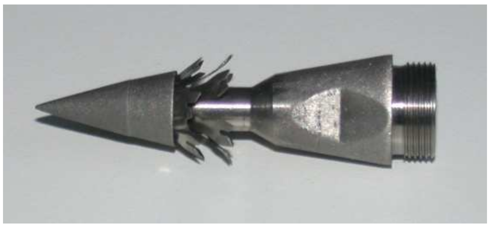

Figure 5. Titanium tip with two rows of barbs

The hammering process is monitored by a depth sensor which provides useful information not only about the insertion progress, but also about material properties, in particular its crushing strength and structure. As the crushing strength of the cometary surface layer is practically unknown (the possible range is estimated at 0.01÷10 MPa), the data to be obtained on the comet will certainly narrow this range and may help in evaluating other physical properties, e.g. thermal conductivity. The hammering tests that were performed on the foam glass material and porous ice showed very strong dependence of the insertion progress on the material properties of the penetrated medium [4]. For example, the insertion progress into the Foamglass T4 (0.85MPa) was 4.2mm and 8.0mm, when the power setting PS2 and PS3 respectively was used. The test in the same conditions but with the stronger material Foamglass F (1.70MPa) showed that the insertion progress was only 2.0mm and 3.8mm correspondingly per one hammer stroke.

## 5. MOLE PENETRATOR KRET

Following the successful MUPUS development, the idea of hammering penetrators was extended to mole type penetrators. KRET was developed between 2006 and 2008. Even though the idea of the operation of mole type penetrators have been already described at [6], the design and development of the mole penetrator KRET have brought some novel solutions that resulted in improvement of its performance in comparison to other penetrators of that kind. The most significant inventions were: implementation of a new latch system (that allowed for accumulating energy of even much higher value than 2J), improving mass ratio of the device's components and optimizing the shape of the tip of the cover [7].

The principle of operation in brief – the mole consists of three masses (components: hammer, counter-mass and cover) and the work cycle can be divided into four stages (figure 6): (1) accumulation of energy in the drive spring (by pulling the hammer to the counter-mass and compressing a driver spring between them), (2) releasing the energy (the hammer hits the bottom of the cover causing its displacement), (3) at the same time the counter-mass moves contrariwise, its kinetic energy is transformed into potential energy of gravity and of the return spring (the reaction force of the return spring is lower than the friction of the soil), (4) finally, the return of the counter-mass and the second hit to the casing [3].

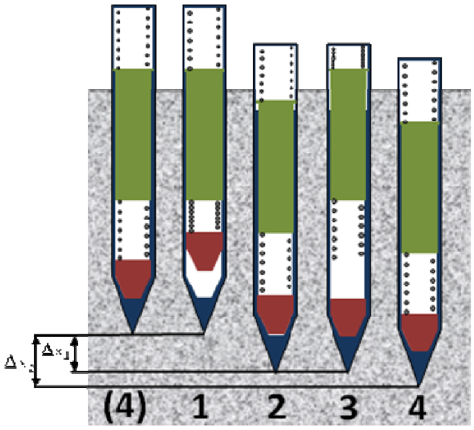

Figure 6. KRET's principle of operation

Using a linear magnetic encoder, a single stroke profile of movement was measured. The magnetic tape was connected to the cover of the mole penetrator. The figure (figure 7) below shows the displacement of the cover of the mole in reference to the fixed encoder head. The stages of a single work cycle can be clearly seen in the figure.

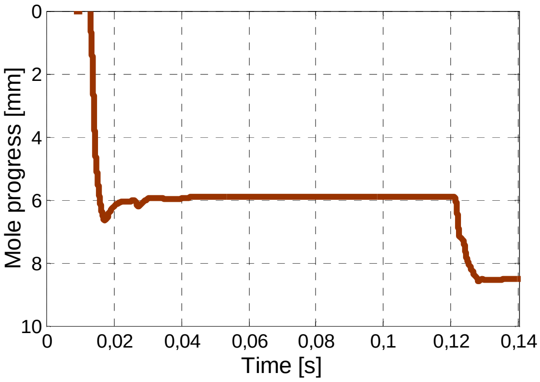

Figure 7. A single stroke displacement in time

Firstly, rapid and major displacement caused by the hit of the hammer occurs. Shortly after the hit, a compression and a kind of resilience of the soil can be seen (the slight movement back of the mole). Before the counter-mass hits the casing, there is a pause of about 0.1 second. During that time the counter-mass moves up, compressing return spring at the same time and then goes back stroking the casing. The energy of the second (smaller) stroke causes the second displacement of the mole. What was noticed during performance of the KRET in various materials is that at a high compression of the soil, the displacement of the penetrator caused by counter-mass is negligible or even not noticeable in comparison with the displacement caused by the first stroke of the hammer. It is one of the arguments that can lead us to the conclusion that there is a certain critical energy for soil with a certain compaction level (or a certain density level) at which the penetrator will not function at all. Therefore, high energy strokes (like in KRET) are not only satisfactory but even necessary to allow for an efficient performance.

The research on KRET penetrator was continued in a PECS project nr 98103 entitled “Mole penetrator optimization using the numerical model and operational tests.” The key goals of the project were as follows: (i) the construction of a 5m vertical test-bed and a 1.8m test-bed with variable inclination, (ii) the development of the numerical model of the mole dynamics coupled with the numerical model of the granular matter and correlated with macroscopic mechanical parameters of the soil, (iii) tests of the mole penetrator in various materials and comparison of test results with simulations, and (iv) determination of optimal parameters of the mole penetrator. The results of the tests are presented in this paper.

To perform further tests of KRET, two test-bed systems have been constructed: a vertical 5-meter test-bed (figure 8) and 1.8-meter test-bed with variable inclination (figure 10).

Figure 8. The top of the 5-meter test-bed with vacuum conveyor

The 5-meter test-bed is made of a polyethylene tube with an internal diameter of 0,74 m and concrete foundation in the ground. A special vacuum conveyor allows for filling the test-bed with any granular matter and, after the completion of the test, to empty it and pull out the penetrator. To provide relevant conditions of tests a new regolith analogue has been developed in cooperation with AGH University of Science and Technology in Krakow. The new analogue, named AGK-2010, has mechanical properties and particle size distribution corresponding to CHENOBI analogue, which is a simulant of Moon’s highlands. In autumn 2010 tests in quartz sand (particle size: 0.2-0.8mm) and AGK-2010 with various compaction level were performed [8]. Results of these tests can be seen in figure 9.

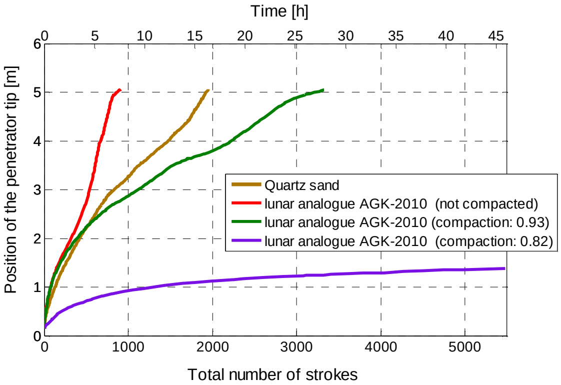

Figure 9. Results of mole tests in 5-meter test-bed system

The compaction level of the soil was defined as the ratio of the volume of loose material (stored in a container) which fully fills the test-bed system without compaction process, to the volume of loose material (stored in a container) which fully fills the test-bed system with compaction process. The tests were highly successful and have confirmed that KRET can penetrate soil up to the depth of 5 meters. Moreover a progress of the penetrator is stable at the end of the motion even in highly compacted lunar analogue. More detailed information on KRET’s performance is presented in table 1.

Table 1

| **Material** | **Av. progress [mm/stroke]** | **Av. velocity [mm/h]** | **Final velocity [mm/h]** |
|---|---|---|---|
| Quartz sand | 2.59 | 310.4 | 319.8 |
| AGK – 2010 (not compacted) | 5.72 | 665.9 | 528.2 |
| AGK – 2010 (0.93 compaction) | 1.59 | 180.8 | 48.9 |
| AGK – 2010 (0.82 compaction) | 0.26 | 30.2 | 6.8 |

One of the conclusions that can be derived from the tests is that for less compacted material, the mole progress decreases up to about 1.5m depth and then remains stable, as a result we can expect that mechanical resistance of the cable is negligible. Even though the mole's progress depends highly on the compaction level of the lunar analogue, KRET is able to work in subsurface layers of planetary bodies (made of regolith material). At the time of this publication, KRET has already made about 13500 strokes and traveled a distance of some 27 meters. The TRL of the penetrator was improved to a level of 4-5. To test the mole in Moon's gravity conditions, the second version of mole penetrator KRET is being developed at SRC PAS. Its performance will be improved by implementing a drive spring with higher energy (3,5J) and ability to work in microgravity conditions. The new mole is going to be tested in a 1.8-meter test-bed system with variable inclination (figure 10) that can be changed in range of 85-0 degrees to simulate different gravity conditions. The tests are scheduled for June 2011.

Figure 10. The 1.8-meter test-bed system with variable inclination.

Similarly to the other presented penetrators, the mole devices allow determining the mechanical properties of the regolith through the information on its progress during insertion. The main advantage of the mole is that the measurements can take place even over 5m depth and therefore the differences of regolith properties vs. depth can be estimated.

## 6. CHOMIK

A unique geological penetrator CHOMIK (figure 11) dedicated for the Phobos–Grunt mission is being developing at the SRC PAS. One of the most important goals of the mission is to collect a soil sample from Phobos and deliver it to Earth. The sample will be collected from the surface of the satellite by the Polish penetrator and deposited in a container that is going to land in 2014 in Kazakhstan encased in the Russian re-entry capsule. Apart from sampling, CHOMIK will perform thermal and mechanical measurements of Phobos' regolith [13].

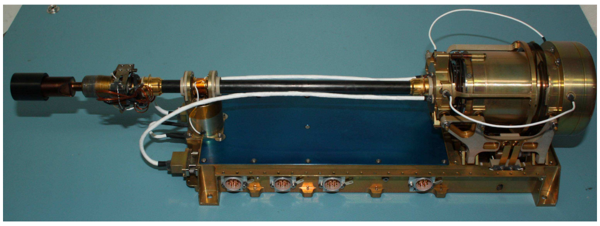

Figure 11. CHOMIK instrument

**Thermal investigations.** The CHOMIK experiment on the Phobos-Grunt mission provides an excellent opportunity to obtain a new kind of in-situ data, i.e., the temperature itself as a function of rotational phase - both at the surface and at some shallow depth. Device has been equipped with two sensors: Surface Temperature Sensor (TSS) and Thermal Conductivity Sensor (TCS).

**Mechanical properties of the Phobos regolith.** Future exploration of the Solar System bodies requires knowledge of the mechanical properties of the regolith. In many cases these properties are different than the Earth analogs due to the vacuum and microgravity environment. Depth sensor will collect progress data during insertion and give an estimation of these parameters which can be then compared with sample properties on the Earth.

CHOMIK instrument fulfills all the requirements defined in chapter 3.3. Its operation scenario was defined for two cases: sampling and thermo-mechanical measurements. The tasks in particular scenario are presented in the table below.

Table 2

| Task no. | Sampling scenario | Thermo-mechanical measurments |
|---|---|---|
| 1 | Sampling place selection | Measurments place selection |
| 2 | CHOMIK positioning by manipulator arm | CHOMIK positioning by manipulator arm |
| 3 | Surface detection | Surface detection |
| 4 | Sampling (first on the low power setting, if neccesery on high power setting) | Thermophysical measurements on surface |
| 5 | Sample break | Thermophysical measurements under the surface |
| 6 | CHOMIK retrack | CHOMIK retrack |
| 7 | CHOMIK movment to the return capsule | CHOMIK movment to the new measurement place |
| 8 | Sampling container separation | |

The results from the CHOMIK qualification tests confirm the CHOMIK's ability of sampling in vacuum environment and in microgravity conditions. Below the pictures from appropriate phases of the sampling scenario and figure with information about the sampling progress in air and vacuum conditions are presented.

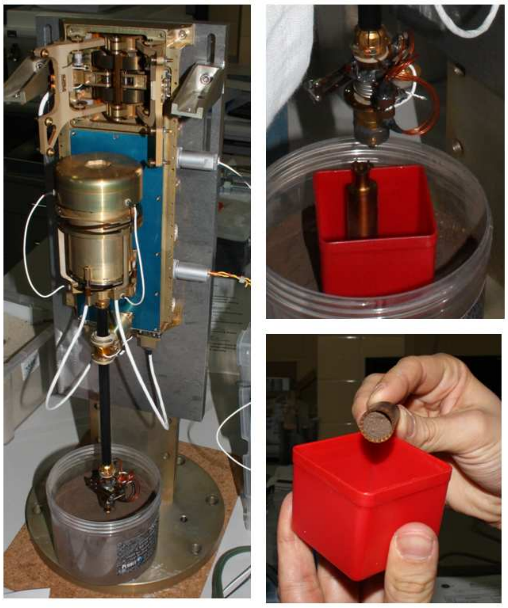

Figure 12. Sampling scenario of the CHOMIK device

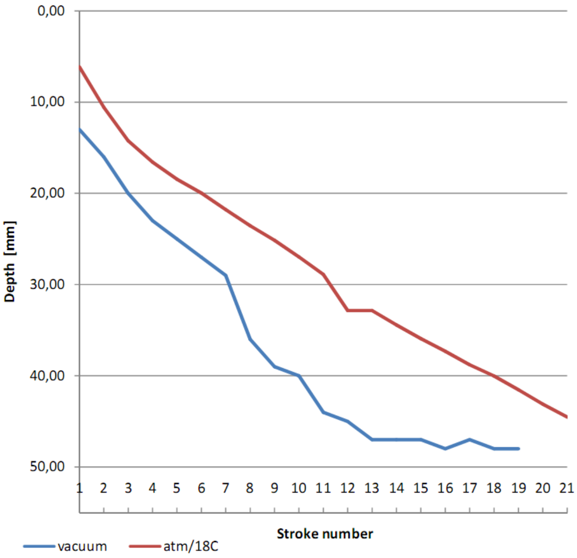

Figure 13. Progress of the CHOMIK device in foamglass material in function of number of strokes

One of the tasks of the project is to develop a new model of the insertion device similar to MUPUS, but with several times higher energy of the stroke. A new penetrator preliminary is named HEEP (High Energy and Efficiency Penetrator).The ability of insertion of the specified penetrator can be determined using several methods. One of them, a very practical one, is related to the value of the static force necessary to insert a penetrator as opposed to achieving it through hammering. For example, for the MUPUS penetrator the value was estimated at 500N. On the other hand, it could be said that if the 500N force was able to insert the MUPUS penetrator in a particular type of surface, then it is almost certain that its hammering drive would also be able to achieve it. For the newly developed penetrator, the static force is determined at 2500N (0.25T). The preliminary feasibility study shows that the development of this innovative and ambitious HEEP requires an improvement, in comparison to the MUPUS insertion device, of the following parameters:

- Mass – 3.3 times (1.0kg)
- Energy stored in the capacitor – 4 times (16J)
- Efficiency of the electromagnetic drive – 1.25 times (33%)

One of the HEEP design priorities is to provide a linear motion of the hammer and the counter-mass on the frictionless, specially shaped, flat springs' suspension. The lesson learned from the MUPUS shows that, particularly in case of the hammer, the frictionless linear motion is very beneficial at least for two reasons. Firstly, the HEEP's hummer will run at high speed, i.e. over 10m/s. Secondly, there is an unavoidable practical asymmetry of the electromagnetic forces acting on the hammer, which causes side friction and disturb the free axial movement. However, such solution has also a minor disadvantage – it must be locked, because the proposed solution for the flat spring suspensions are not sufficiently resistant to perpendicular forces occurring during vibrations test. In one of the MUPUS prototype models (No.2), the spring suspension of the hammer was applied and yet the device was still in a good working condition after tens of thousands of strokes. Nevertheless, it is certain that most laborious design and analysis challenges are connected with the more efficient electromagnetic drive.

## 7. FINAL REMARKS

The comets, asteroids and other planetary bodies in the Solar System are potential targets for the future exploration programs. The use of penetrators in such missions is highly expected. They are important tools for sampling and searching for minerals, water and whatever else (forms of life?) might lie in the underground layers.

During the last decade the number of scientific space missions developed by ESA together with international partners was dedicated for in situ investigations of space bodies. In most of them space instruments for subsurface investigations were used in order to get more information about the nature of subsurface materials, physical phenomena occurring under surface, and thermal and mechanical regolith parameters. The results that will be obtained as a result of MUPUS and CHOMIK operation, and also from Apollo missions, should be used to identify the 'geotechnical' parameters of space bodies, and as a result create the opportunity to formulate common civil engineering standards useful for building the International Lunar Base.

The penetrators (figure 14) properties are summarized in the table below.

Table 3

| | MUPUS | KRET | CHOMIK |
|---|---|---|---|
| Power [W] | 1,5 | 0,3 | 1,7 |
| Energy per stroke [J] | 0,8 | 2,2 | 1,0 |
| Dimensions [mm] | Ø70 x 520 | Ø20,4 x 336 | Ø 70 x 418,6 |
| Mass [kg] | 0,48 | 0,50 | 0,62 |
| Main objectives | Thermal and mechanical measurements of the comet | Sensors transportation up to 5 meters under the surface, thermal and mechanical measurements of the soil | Soil sampling, rocks hammering, thermal and mechanical measurements |

Figure 14. MUPUS, KRET and CHOMIK devices

## 8. ACKNOWLEDGMENTS

The paper was supported from projects: national grants no. 2 PO3C 009 12p02; N522 003 31/1166; 791/N-ROSJA/2010/0 and the ESA PECS project no. 98103

## 9. REFERENCES

1. Grygorczuk, J. Banaszkiewicz, M. Seweryn, K. Spohn, T.( 2007). MUPUS Insertion device for the Rosetta mission. *Journal of Telecommunications and Information Technology*, pp 50-53, 1/2007.
2. Grygorczuk J., Seweryn K., Wawrzaszek R., Banaszkiewicz M. (2008) Insertion of a Mole Penetrator - Experimantal Result, 39th Lunar and Planetary Science Conference, League City, Texas.
3. Grygorczuk, J. Seweryn, K. Wawrzaszek, R. Banaszkiewicz, M. Rybus, T. (2009). Eksploracja warstw podpowierzchniowych Księżyca z wykorzystaniem penetratora „KRET”. *Wiertnictwo Nafta Gaz*, tom 26, zeszyt 1-2, 173-184
4. Grygorczuk, J. Banaszkiewicz, M. Kargl, G. Kömle, N. Ball, A. J., Seweryn, K.. (2009) Use of hammering to determine cometary nucleus mechanical properties. Penetrometry in the Solar System II, Eds: Günter Kargl, Norbert I. Kömle, Andrew J. Ball, Ralph Lorenz, Proceedings of the 2nd International Workshop on Penetrometry in the Solar System, Graz, September 25-28, 2006, Austrian Academy of Sciences Press, pp.93-107
5. Kömle, N. I. Hueter, E. S. Kargl, G. Ju, H. Gao, Y. Grygorczuk J. (2008). Development of Thermal Sensors and Drilling System for Application on Lunar Lander Mission. Earth Moon Planet 103: 119-141.
6. Gromov, V.V., Misckevich, A.V., Yudkin, E.N., Kochan, H., Coste, P., Re, E. (1997). The mobile penetrometer, a “mole“ for sub-surface soil investigation, proceedings 7th European Space Mechanisms & Tribology Symposium, ESTEC, Noordwijk, The Netherlands.
7. Grygorczuk, J., Seweryn, K., Wawrzaszek, R., Banaszkiewicz, M. (2009). Technological Features in the new mole penetrator „KRET“, Proceedings of the 13th European Space Mechanisms & Tribology Symposium, Vienna, Austria.
8. Seweryn, K., Banaszkiewicz, M., Bednarz, S., Gonet, A., Grygorczuk, J., Rybus, T., Rzyczniak, M., Wawrzaszek, R., Wiśniewski, Ł., Wojcikowski, M. (2011). Mole penetrator KRET for lunar exploration, Proceedings of 42nd Lunar and Planetary Science Conference, The Woodlands, Texas, USA.
9. Richter, L., Coste, P. Gromov, V., Kochan, H., Pinna S., Richter, H.-E. (2001). Development of the ‘Planetary Underground Tool’ subsurface soil sampler for the Mars Express ‘Beagle 2’ lander. COSPAR, Adv. Space Res. Vol.28, No. 8, pp.1225-1230.
10. Knollenberg, J. et al.(2007) *EGU.*
11. Weinberg, J. D.. et al. (2008) *LPSC XXXIX*
12. Seweryn K. Grygorczuk J Banaszkiewicz M. (2009). The micro scale modeling of the interaction of a penetrator with granular medium, Penetrometry in the Solar System II Eds: Günter Kargl, Norbert I. Kömle, Andrew J. Ball, Ralph Lorenz, Austrian Academy of Sciences Press
13. Seweryn, K. et al. 2010, 38th COSPAR Scientific Assembly