68th International Astronautical Congress (IAC), Adelaide, Australia, 25-29 September 2017.

IAC-17-A3.4B.6

The D-MEN Sampling Device – Extracting and Collecting Asteroid Material for Sample Return

Martin Schimmerohn[a]*, Erkai Watson[a], Jan Hupfer[a], Aron Pfaff[a], Albert Falke[b], Frank Schäfer[a]

[a] *Fraunhofer Institute for High-Speed Dynamics, Ernst Mach-Institut, EMI, 79104 Freiburg, Germany*, martin.schimmerohn@emi.fraunhofer.de, erkai.watson@emi.fraunhofer.de , aron.pfaff@emi.fraunhofer.de , frank.schaefer@emi.fraunhofer.de
[b] *Airbus DS GmbH, 88090 Immenstaad, Germany,* albert.falke@airbus.com
*Corresponding Author

Abstract

We report about the development and the characteristics of a Device for Material Extraction from Near earth objects (D-MEN). The D-MEN sampling device was developed as part of the NEOShield-2 project and is optimized to collect at least 100 grams of asteroid material including up to 4 cm sized particles. The design drivers are a short static landing scenario and the required capability to not only collect loose particles, but also to extract material from solid surfaces having compressive strengths of up to 50 MPa. This performance is achieved by a combination of fluidizing loose regolith material and extracting solid material by pyrotechnically driven bolt actuators. The D-MEN is a highly integrated system including two bolt actuators, two self-closing material compartments and a pressure pipe system. 3D metal printing technologies have been applied to implement the system in a cylindrical volume of 150 mm diameter by 130 mm high. The performance of the system is demonstrated here by comprehensive tests on different target configurations.

Keywords: sample return, sampling mechanism, asteroid, near earth object, NEOShield-2

Acronyms/Abbreviations

D-MEN Device for Material Extraction on NEO
NEO/NEA Near Earth Object/Asteroid

1. Introduction

Sample return missions for small bodies are increasingly attracting attention in in recent years. Acquiring samples of unaffected asteroid or comet material allows for studying the nature and composition of early remnants from planetary formation processes. The return of the acquired material enables more precise and more detailed ground based post-flight analysis than achievable through in-situ analysis with spaceborne instruments. Providing several grams of intact NEO material including centimeter-sized particles allows analysis of the elemental and isotopic composition, the mineralogy as well as the geologic history of material that is unaffected by surface and cosmic ray effects.

The first autonomous sample return missions have been the Soviet Luna probes 16, 20 and 24 in the 1970ies. Using a rotary-percussive drill mechanism with cylindrical dimension of 69 cm (length) by 29 cm (diameter), Luna 24 sampled a mass of 170 grams from more than two meters depth of the moon surface [1],[2]. This marked the last successful autonomous sample return with masses in the gram range. The NASA Stardust mission captured ten hypervelocity particles >0.1 mm from the Coma of the comet Wild 2 using Aerogel collectors [3]. JAXA's Hayabusa mission returned micrograms of sub-millimeter particles from the S-type asteroid Itokawa [4]. These surface particles are deemed to having been ejected due to the thruster operation during the touch-and-go maneuver of the spacecraft. The actually intended sampling process, a 5 gram Aluminum projectile to be fired on the surface [5], failed. Like its precursor mission, the ongoing Hayabusa 2 mission also uses a kinetic impact for asteroid material extraction from a C-type asteroid. This time, the impactor is formed by an explosive shaped charge device [6]. The failed Russian Phobos-Grunt mission carried onboard an electromagnetic driven hammering device to penetrate packed surface material for sample return [7]. NASA's currently launched OSIRIS-Rex probe uses a high-pressure gas flow to fluidize and collect loose surface regolith material from Asteroid Bennu for return [8].

The D-MEN sampling tool was developed as part of the NEOShield-2 project, which addresses technologies for characterizing or deflecting hazardous NEOs. In the context of sample return missions, this includes the development of autonomous spacecraft control systems for landing on, and the D-MEN system for collecting of material from Near Earth Objects.

2. Design requirements

The design drivers for the D-MEN material sampling are a short static landing scenario and the required capability to not only collect loose particles, but to also extract material from compact surfaces having compressive strengths up to 50 MPa.

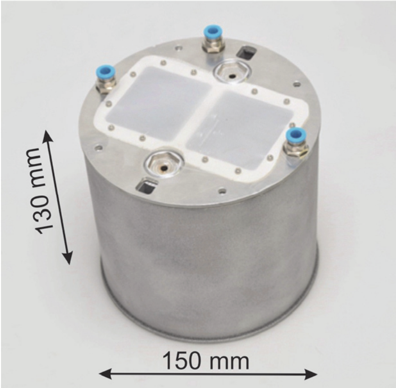

Fig. 1: Final D-MEN prototype.

2.1 Target definition

The target asteroid for the D-MEN development is the NEA 1996 FG_3., which is classified as C, X or B-type asteroid [9],[10],[11]. The surface of the asteroid is covered by a 5-20 mm deep regolith layer composed of fine dust, fragmentary rocky debris, sands or most likely a stuff of their mixture [12]. Individual pebbles and cemented parts of the surface are considered to have compressive strength of approximately 50 MPa. This is the strength of terrestrial carbonaceous chondrites and taken as the upper limit for the development of the D-MEN. The bulk density of the acquired samples is assumed to be in the range between 1-2.2 g/cm^3. The interparticle cohesion is defined to be in the range of 0.1 kPa to 5 kPa.

2.2 Sampling requirements

The performance requirements for the D-MEN are related to the amount of mass that is required for performing detailed ground analyses. A minimum mass of hundred gram of loose material including particles in the size range of <100 µm to 3 cm and any shape need to be acquired for this purpose. The sample need to be maintained free of contamination. The major impact on the sampling method comes from the requirement that the D-MEN shall be able to break through surface having 0.3-50 MPa compressive strength and extract centimeter-sized fragments for collection. This limits the application of scoop and brushing concepts since a quite high compressive force is needed to cause fracture in the compact material surface. Such material extraction need to be enabled in more than one sampling attempt.

2.3 System requirements

The system requirements for the D-MEN are derived from mission requirements of the European MarcoPolo-R and the Phootprint/Phobos Sample Return Mission studies. Most important for the mechanism design, a short static landing scenario is assumed, thus allowing for a sampling time of up to 30 minutes. The sampling operation is allowed to impose maximum 35 kN on the

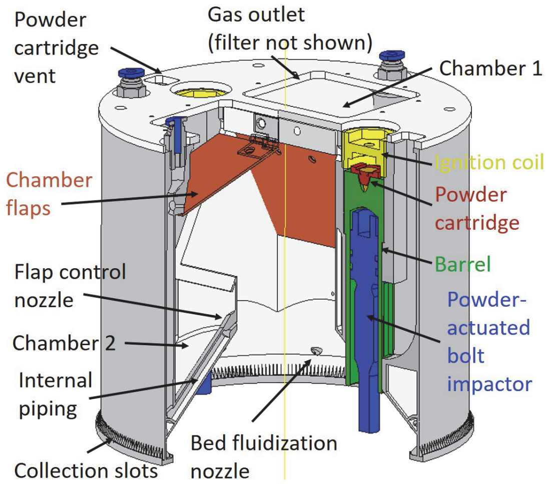

Fig. 2: Schematic (sectional view) of the D-MEN.

landed spacecraft during a timeframe of maximum 1.5 milliseconds. As a consequence, maximum lift-off of 5 cm is caused by this sampling dynamics on the low gravity body. The design goal for the sampling device is an overall mass of 3 kg including margins and collected soil material. The maximum cylindrical dimensions are 150 mm diameter by 130 mm high to fit in the Earth re-entry capsule.

3. D-MEN design

Based on the design requirements, we developed the Device for Material Extraction on NEO (D-MEN). The D-MEN is capable of breaking hard material (e.g. rock) and collecting loose material (e.g. dust particles, rock fragments). The goal is to collect the two different materials, regolith layer material on the surface of an asteroid and broken rock material, into separate chambers by a two-fold process.

The D-MEN combines the functionality of 1) pyro-technically driven bolt actuators for the extraction of material from solid surfaces and 2) a collecting device based on the fluidization of regolith and loosed material.

3.1 Concept and sampling chain

The D-MEN, shown in Fig. 1 and Fig.2, consists of a cylinder with bed fluidization nozzles, two chambers for collecting samples and two powder-actuated bolt impactors for breaking hard material found beneath the regolith layer on the surface of the asteroid. Having two separate chambers allows a distinction between the samples collected from loose material, or regolith, on the surface of the asteroid and fragments of hard material collected after the bolt firing. This is of interest because it allows the separate analysis of the regolith layer from the hard underlying layer.

The collection process comprises six steps as shown in the sequence in Fig. 3.

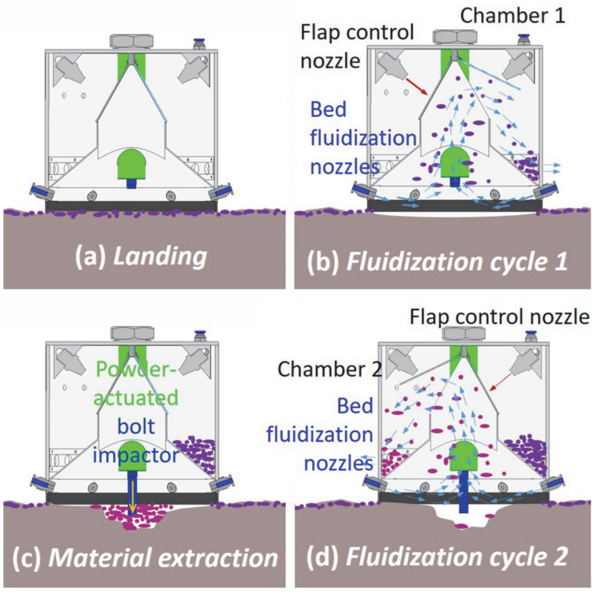

Fig. 3: D-MEN sampling sequence (one attempt).

(a) Landing on asteroid surface and positioning of the D-MEN by a robotic arm.
(b) Sampling starts with fluidizing the loose regolith material and smaller cm-sized particles from the surface the D-MEN stands on. The material is fluidized into collection chamber 1 by nitrogen gas flowing (from not shown storage vessel) through bottom lateral nozzles.
(c) Then bolt actuators are ignited to break up material from the now exposed surface or larger pebbles.
(d) Broken and loosened fragments are fluidized and collected into chamber 2.

Steps (c) and (d) can be repeated for redundancy by firing the second bolt actuator and fluidizing a second time, thus performing a second sampling attempt with material extraction. The complete sampling process has a duration of less than 2.5 minutes

3.2 Powder-actuated bolt system

The material extraction function is achieved through pyrotechnically actuated bolts, which are similar in design to a powder-actuated tool with the piston being used as the impactor. The advantages of this design is a relatively high compressive force and the avoidance of contamination as the bolt stays within the barrel, thus sealing the combustion gases from the sampling compartment. In the current stage of development we use standard powder cartridges with different amount of powders in the range 0.11-0.23 grams. We measured the average muzzle velocity of the bolt impactor to be 55 m/s. The cartridges are fired by resistive coils, which are used as reliable and compact ignition components. Gas vents in opposite direction to the kinetic impact

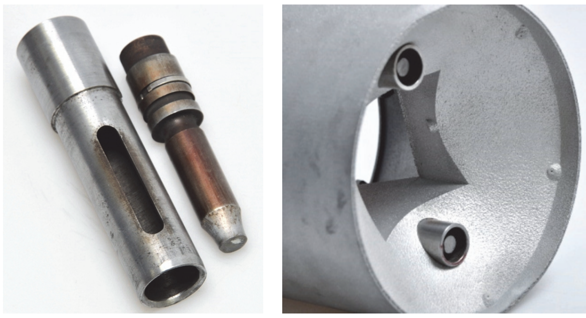
Fig. 4: D-MEN powder-actuated bolt impactor.

compensate a part of the recoil forces. The bolt mass is 67.3 grams. We investigated different bolt designs, in particular we analysed the fragmentation performance for different shapes of the bolt tips. We achieved the best performance on different materials using truncated flat bolt tips in vertical direction to the target surface. Fig. 4 shows the steel barrel and impactor bolt after testing. The long slot in the barrel allows the pressure to vent, decreasing the recoil from the bolt acceleration. Also shown are the bolts inside the D-MEN housing from the underside, showing the bolt tips.

3.3 Bed Fluidization

The operating principle of the bed fluidization and material collection is shown schematically in Fig. 3. Nozzles in the outer rim at the bottom of the D-MEN pointing at the asteroid surface to fluidize loose material and transport them into the appropriate chamber. Control of the chamber flaps is achieved by regulating the gas flow through the upper control nozzles pointed at the chamber flaps. During the first flushing sequence (b), pressurized nitrogen passes through the bottom nozzles and the left flap control nozzle. The gas flow opens the right flap while the left flap is kept in place by the control nozzle flow. Similarly, access to the second chamber (d) is achieved by routing gas through the bottom nozzles and the right control nozzle, thus carrying the broken fragments into the second chamber. The gas outlet is at the top side of the sampling device.

3.4 System design

The D-MEN is a highly integrated system including two bolt actuators with recoil compensation, two self-closing material chambers and a pressure pipe system. State of the art 3D printing technology has been applied to implement the system in the cylindrical volume of 150 mm diameter by 130 mm high. The final prototype, except for the bolt actuator system, lid, flaps, and fittings, is completely additively manufactured from aluminium. The nozzels and piping for the fluidiaztion are directly incorporated into the main body of the D-MEN. This allows for a highly integrated, lightweight device with a relatively large collection chambers. Fig. 5 shows the volume that is usable for collecting

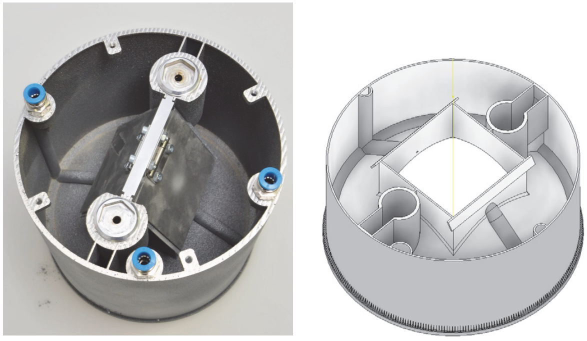

Fig. 5: D-MEN without lid and cutaway view showing the available volume for soil material storage.

sampled material. The volume of is region is 472 cm^3, which would theoretically allow to return between 472 and 1039 grams of material (assuming the density being 1 g/cm^3 and 2.2 g/cm^3 respectively).

Dust collector bins are integrated at the outer rim at the base of the D-MEN. These collectors are small slots that circumvent the edge of the sampling device on both the inside and outside of the cylinder. Stray particles that happen to get trapped in these slots will allow for a minimum science return in the worst case scenario where the D-MEN was placed on the asteroid surface but recovered without having carried out any sampling attempt. This feature may be increased by including a sticky material at the bottom inside of the D-MEN at a later development stage.

4. D-MEN performance testing

Comprehensive tests on different target materials and configurations have been conducted to evaluate the D-MEN sampling capabilities and to demonstrate the compliance with the sampling requirements.

4.1 Material extraction testing

Building upon comprehensive development testing of different bolt actuator system designs, we conducted performance tests using the completed D-MEN prototype. The breakup effectiveness was evaluated using three geological materials that most closely meet the target definition: sandstone, tuff and aerated concrete (see Table 1).

Table 1. Asteroid simulant material properties

Material	Density (g/cm^3)	UCS* (MPa)	Ref.
Seeberg sandstone	2.05 ± 0.04	67.3 ± 2.7	[13]
Weiben tuff	1.42 ± 0.01	12.3 ± 3.5	[13]
Aerated concrete	0.6	2.4± 1.2	[14],[15]

*uniaxial compressive strength

We started testing on bulk material with the D-MEN being placed in direct contact besides. This included test

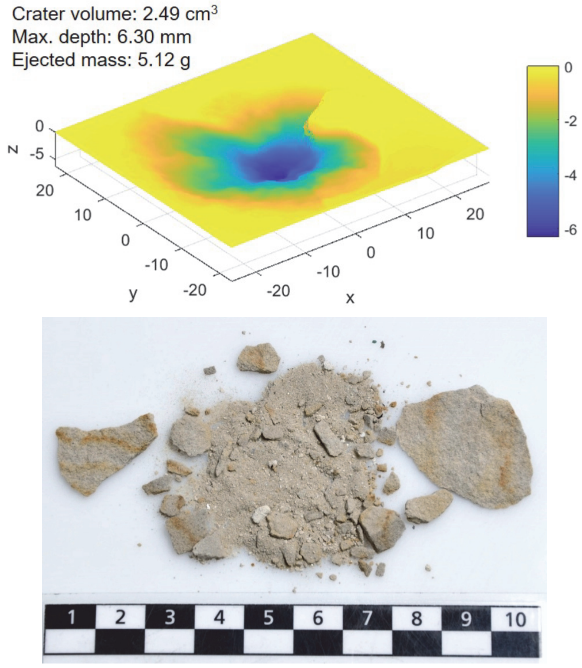

Fig. 6: Crater scan and broken fragments extracted from bulk sandstone.

with the D-MEN in oblique impact situations, i.e. the sampling device placed with an angle of up to 30 deg to the material surface. We analysed the extracted material by weighting, 3D scanning of impact craters and review of fragments. Fig. 6 shows the crater scan and the broken fragments from a sandstone target as an example.

We also determined the recoil force resulting from bolt firing by means of a rigidly mounted 3D force sensor. Fig. 7 shows the measured recoil force vs. crater depth and ejected mass. The positive correlation of these variables is reasonable. In addition, we found no correlation between material and recoil force, thus indicating that the recoil is a consequence of the bolt acceleration only.

We note that larger ejected masses tend to lead to larger fragments. This observation was made by measuring the largest fragment from the experiments and plotting them against the ejected mass as shown in Fig. 8.

The craters in oblique sampling situations show an evident asymmetry and a decreased ejected mass. Even in this suboptimal situation, we demonstrated that the D-MEN is able to break up sufficient material for collection with the fluidization cycle. We continued extraction testing with several centimeter-sized pebbles. Here again, the D-MEN proofed to be well suited to the task of breaking up fragments into pieces small enough to fluidized (see Fig. 9).

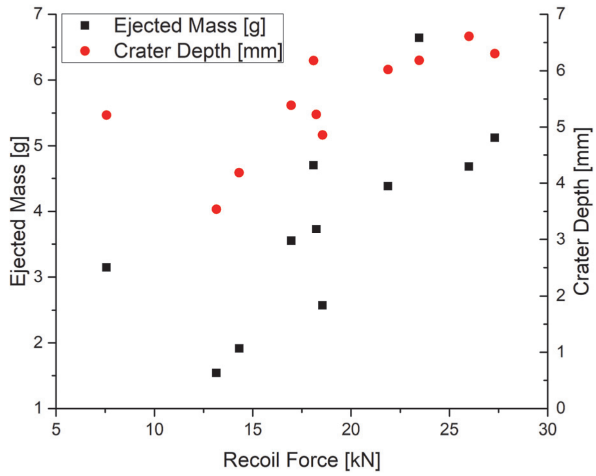

Fig. 7: Recoil force vs. and extracted fragment mass and crater depth from sandstone and tuff surfaces.

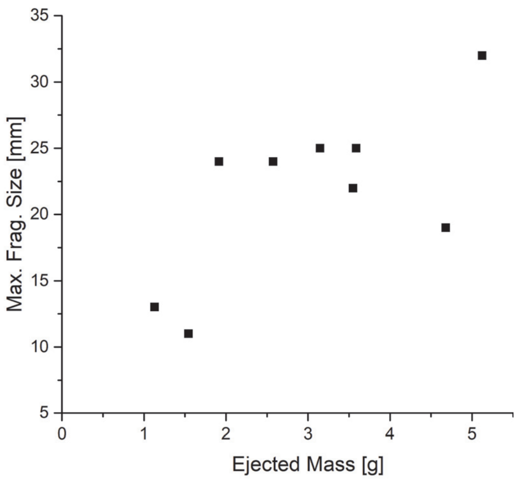

Fig. 8: Fragment size vs. ejected mass.

4.2 Material collection testing

The nozzle design and configuration for the fluidization functionality was optimized using four different materials for development testing: Styrofoam balls (extruded polystyrene foam), sponge fragments, sand, and sandstone fragments. We chose the first two lower density materials to approximate some aspects of a micro-gravity environment under standard laboratory conditions. The collection tests included compacted sand, different material distribution configurations as well as oblique sample situations.

We demonstrate the D-MEN's sampling capability in an Earth gravity environment with a series of test involving sampling sand and sandstone fragments. The ability to sample sandstone fragment up to 2 cm in size and over 1 gram in mass with Earth's gravity lead us to believe that the D-MEN will easily be able to collect greater samples in a micro-gravity environment. Fig. 10 shows the opened sampling device after collection tests

Fig. 9: Before (left) and after (right) images of a sandstone pebble fragmented by the D-MEN.

with (a) sandstone fragments, (b) fragments and sand, (c) Styrofoam balls, and (d) sponge material.

The tests with the low-density materials mimic the effect of micro-gravity to some extent while having similar shape characteristics. These test yield to 98% of the material was successfully collected. Apart from the gravitational effects, the inertial effects caused by the difference in mass and friction differences due to the materials could lead to a slightly decreased performance on a low gravity body. However, based on many tests where useful amount of sand and sandstone fragments were sampled, even in Earth's gravity, we are confident that the D-MEN will be able to sample minimum 100 gram of asteroid material. Tests in a microgravity environment (which are out of scope for the D-MEN development within the NEOShield-2 project), should give further evidence. These tests are also needed to optimize the used fluidization cycle time and gas pressure.

5. Conclusions

In conclusion, we have developed the D-MEN prototype, a Device for Material Extraction on NEO in a sample return mission. The presented sampling system meet all defined development criteria. It is aimed for a short static landing scenario and tested for the assumed material characteristics of the C-type NEA 1996 FG_3.

The specific sampling feature of the D-MEN is the combination of a bed fluidization system with powder-actuated bolts for extraction of bulk material having a compressive strength of 50 MPa and more. The loose regolith layers and broken fragments are fluidized and collected in separate chambers by a two-step procedure.

The D-MEN is a highly integrated system. Besides two bolt actuators, it contains two self-closing material chambers and the bed fluidization system in an additively manufactured device. It has a cylindrical volume of ø 150 mm by 130 mm (height) for insertion into a re-entry capsule. At least 100 grams of NEO material including larger fragments can be received for ground-based analysis.

Comprehensive tests on different materials in different target configurations have been performed to bring the D-MEN to Technology Readiness Level of 4 to 5 (we state this range as we consider micro-g tests necessary to fully satisfy TRL 5 criteria). Besides space

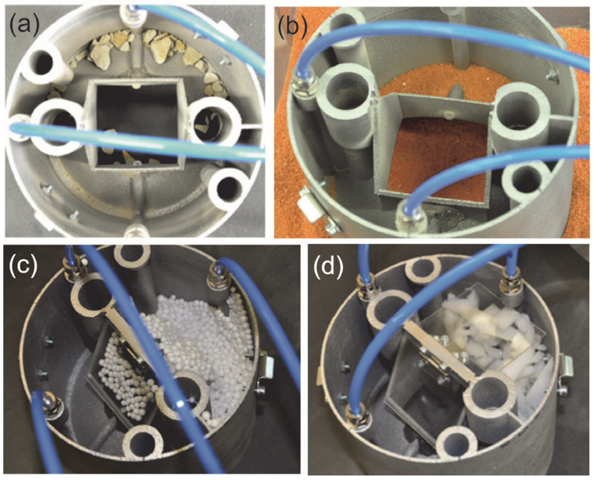

Fig. 10: Collected material after D-MEN collection tests under lab conditions.

qualification testing and full device integration, we identified further development activities to mature the D-MEN design. In particular, the issue of igniting the powder cartridges after long space exposure should be addressed in follow-on development activities.

Acknowledgements

The research leading to these results has received funding from the European Union's Horizon 2020 Programme under grant agreement no. 640351 (NEOShield-2 Project).

References

[1] K. Zacny et al., Extraterrestrial Drilling and Excavation, Chapter 6, Drilling in Extreme Environments - Penetration and Sampling on Earth and Other Planets, (Y. Bar-Cohen, K. Zacny (ed.), Wiley, 2009, pp. 347-558.

[2] V.L. Barsukov, Preliminary Data for the Regolith Core Brought to Earth by the Automatic Lunar Station Luna 24, Proc. Lunar Sci. Conf. 8th (1977), pp. 3303-3318.

[3] F. Hörz, R. Bastien, J. Borg et al., Impact Features on Stardust: Implications for Comet 81P/Wild 2 Dust, Science 314 (2006), pp. 1716-1719.

[4] A. Tsuchiyama, M. Uesugi, T. Matsushima et al., Three-Dimensional Structure of Hayabusa Samples: Origin and Evolution of Itokawa Regolith, Science 222 (2011), pp. 1125-1128.

[5] H. Yano, S. Hasegawa, M. Abe, A. Fujiwara, Asteroidal Surface Sampling by the MUSES-C Spacecraft. Proc. Asteroids, Comets, Meteors (ACM 2002), ESA-SP-500, pp. 103-106.

[6] T. Saki, H. Sawada, C. Okamoto et al., Small Carry-on Impactor of Hayabusa 2 Mission, Acta Astronautica 84 (2013), pp. 227-236.

[7] J. Grygorczuk, M. Dobrowolski, L. Wisniewski et al., Advanced Mechanism and Tribological Tests of the Hammering Sampling Device CHOMIK, Proc. ESMATS 2011, pp. 271-278.

[8] T. Ajluni, T. Linn, W. Willcockson et al., OSIRIS-REx. Returning the Asteroid Sample, Proc. IEEE Aerospace Conference 2015.

[9] R.P. Binzel, A.S. Rivkin, J.S. Stuart, et al, Observed Spectral Properties of Near-Earth Objects: Results for Population Distribution, Source Regions, and Space Weathering Processes. Icarus 170 (2014), pp. 259-294.

[10] J. De Léon, T. Mothé-Diniz, J. Licandro, et al, New Observations of Asteroid (175706) 1996 FG3, Primary Target of the ESA Marco Polo-R Mission, Astronomy & Astrophysics 530 (2011), L12.

[11] D. Perna, E. Dotto, M.A. Barucci, et al, Ultraviolet to Near-Infrared Spectroscopy of the potentially hazardous, low delta-V Asteroid (175706) 1996 FG3. Astronomy & Astrophysics 555 (2014), A62.

[12] L. Yu, J. Ji, S. Wang, Shape, Thermal and Surface Properties Determination of a Candidate Spacecraft Target Asteroid (175706) 1996 FG3. Mon. Not. R. Astron. Soc., stu164 (2014).

[13] M. Poelchau, T. Kenkmann, T. Hoerth, F. Schäfer, M. Rudolf, K. Thoma, Impact Cratering Experiments into Quartzite, Sandstone and Tuff: The Effects of Projectile Size and Target Properties on Spallation, Icarus 242 (2014), pp. 211-224.

[14] T. Prakash, B. Naresh-Kumar, Karisddappa, Strength and Elastic Properties of Aerated Concrete Blocks (ACBs), Int. J. Chem., Environm. & Biol. Sci. 1 (2013), pp. 304-307.

[15] B. Na Ayudhya, Compressive and Splitting Tensile Strength of Autoclaved Aerated Concrete (AAC) containing Perlite Aggregate and Polypropylene Fiber subjected to High Temperatures. Songklanakarin J. Sci. Technol. 33 (2011), pp. 555-563.