SAMPLING THE ORBITAL DEBRIS POPULATION USING A FOIL RESIDUE COLLECTOR IN A STANDARDISED CONTAINER FOR EXPERIMENTS (SCE)

A. T. Kearsley[1], G.A.Graham[2], M.J. Burchell[3], M. Cole[3], G. Drolshagen[4], R.J. Chater[5] and D.S.McPhail[5]

[1]Department of Mineralogy, Natural History Museum, London SW 7 5BD, UK; antk@nhm.ac.uk
[2]Institute for Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, Livermore, CA 94551, USA; graham42@llnl.gov
[3]School of Physical Sciences, University of Kent at Canterbury, CT2 7NR, UK, M.J.Burchell@ukc.ac.uk
[4]TOS-EMA, ESTEC-ESA, Keplerlaan 1, 2201 AZ Noordwijk, NL; G.Drolshagen@esa.int
[5] Department of Materials Science, Imperial College of Science, Technology and Medicine, London SW7 2AZ, UK; R.J.Chater@imperial.ac.uk; D.S.McPhail@imperial.ac.uk

ABSTRACT

Monitoring small particles responsible for hypervelocity impact damage in orbit may rely upon post-flight investigation of returned spacecraft components, or deployment of dedicated collectors and sensors. Returned surfaces do generate invaluable data as to the origin of particles, but provide time-averaged data, and require costly missions for successful return. The exposed material may also be a difficult substrate on which to locate and analyse residue from impacting particles. Preparation and analysis may be very time-consuming and require damage to large components. Sophisticated electronic sensors deployed upon spacecraft in a wide range of orbits may yield detailed information about impact timing and energy, and allow inferences as to velocity and chemical composition of the particle, but do not provide material for subsequent analysis in the laboratory. Even monitoring of particle fluxes in low Earth orbit, from which samples may be returned during service missions or crew changeover, requires substantial preparation for safe accommodation and transport of the returned hardware. It thus seems that there is great potential for a simple dedicated, reusable, modular, low-mass collector that requires no data or power services from its host spacecraft and which might be deployed and retrieved for analysis as opportunity arises. Careful appraisal of samples returned from space suggests that polymer foils will the most suitable collector material. In this paper we concentrate upon the design and fabrication of materials and container dedicated to collection of hypervelocity impact residues and their interpretation on return to Earth.

1. INTRODUCTION

Measurement of the number of small particle impacts on a spacecraft at a particular altitude and over a given length of time has been successfully performed by dedicated on-board experiments such as DEBIE (Kuitenen et al., 2001), SPADUS (Tuzzolino et al., 2001) and GORID (Drolshagen et al., 2001), and from post-flight investigations of returned spacecraft surfaces, e.g. Solar Max (Warren et al., 1989) the European Retrievable Carrier (Taylor et al., 1999), the Long Duration Exposure Facility (LDEF) (Bernhard et al., 1993) the Space Flyer Unit (SFU) (Yano et al., 2000) and the Hubble Space Telescope (HST) (Graham et al. 1999; Moussi et al., 2005).

Post-flight investigations have examined a wide range of spacecraft structural components, such as solar cells or multi-layer foil insulation, or more specialist materials deployed as dedicated collectors and sensors. Although returned surfaces generate invaluable data as to the origin of particles, they usually provide a data set from a long interval of exposure, without potential for the recognition of short-lived events. Retrieval of large spacecraft components also requires costly missions for successful return to Earth. Nevertheless, studies of HST solar array post-flight surveys (Moussi et al., 2005) have shown the value of repeated monitoring of particle fluxes in Earth orbit, with chemical analysis of impact residues on the same substrate type (solar cell glass) from effectively the same altitude and orientation (sun-facing) revealing temporal changes in the number of impacts by specific types of space debris, probably reflecting a complex interplay of human influence (changing numbers of orbital launches and hardware configurations) and variation in upper atmosphere density (due to timing within the eleven year solar activity cycle).

If we are to continue to monitor the origin of impacting particles we should consider the most effective material that could be used. It needs to be able to catch particles across the nanometre to millimetre range, to record their size, and preserve a representative chemical composition. It should be made of a material that is easy to distinguish from all important types of impact residue. The structure should be robust and easy to disassemble, with components that can be handled easily without contamination and can be directly inserted into analytical instrumentation without need for preparation.

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2. SUITABLE ANALYSIS TECHNIQUES

Problems in analysis of impact residues on glass, metals, PTFE / glass fibre blankets and multi layer insulation have been extensively reviewed (Graham et al., 2001). Each material has limitations, primarily in distinguishing one or more important types of particle from the substrate. No single survey has been able to demonstrate all of the different types of micrometeoroid and space debris that might be expected to leave residue.

The speed, reliability and reproducibility of sample characterisation by analytical scanning electron microscopy (ASEM) using energy dispersive X-ray spectrometers (EDS) have made it the technique of first choice for impact residue analysis (Graham et al., 1997 and 2004). The relatively small volume of electron beam interaction, and X-ray generation limited to a shallow surface zone (both of micrometre scale), coupled with absence of sample ablation during analysis, allow repeated and long duration analyses of the same sample area. The relatively poor detection limit of EDS (c. 0.2 wt % for most elements) is not a substantial limitation for location of impact residue, demonstrated by the high percentage (c. 75%) of HST craters shown to have detectable residue (Kearsley et al., 2005). Recent advances (particularly low vacuum imagery, low dead-time electronics, and fully integrated stage movement, image acquisition and processing software) have made ASEM a very powerful tool for non-destructive mapping of large areas of uncoated surfaces. Rapid data acquisition, with count rates exceeding 10k s^{-1} even for low energy X-rays, permits micrometre scale mapping of centimetre-scale areas per hour. As a conductive surface coating is no longer required, there need be no contamination by carbon, and locations of organic materials can be determined readily.

For this study we employed three microscopes: a Jeol 840 scanning electron microscope (SEM) fitted with an Oxford Instruments exL EDS; a Jeol 5900 Low Vacuum SEM fitted with an Oxford Instruments INCA EDS; and a LEO 1455 Variable Pressure SEM, also fitted with INCA. A combination of back-scattered electron imaging (BEI) and EDS X-ray elemental mapping were used with typical working conditions of 10 mm working distance, 2 nA beam current, 20 kV accelerating voltage and 20 Pascal chamber pressure in low vacuum mode.

The main limitations lie in the complexity of the substrate chemical composition, rather than in analysis technique, so it is worth optimizing collector design for easy and rapid characterisation by ASEM.

3. THE IDEAL COLLECTOR SUBSTRATE

Is there a substrate composition upon which all of the important types of impact could be recognised? No spacecraft constructional material currently in use is immediately obvious as an outstanding candidate. Novel material is required for a dedicated collector, and must meet strict criteria regarding durability in the low Earth orbit (LEO) environment for it to be space qualified. It is highly desirable that it be made into a device that is cheap, lightweight, can be easily stored, quickly deployed and retrieved, for example from a manned station in space. Above all, it should provide a suitable substrate composition for recognition of impacts by all particles between nanometre and millimetre scales, and rapid analysis of their residues. The above criteria preclude use of most conventional spacecraft materials, such as glass and metals.

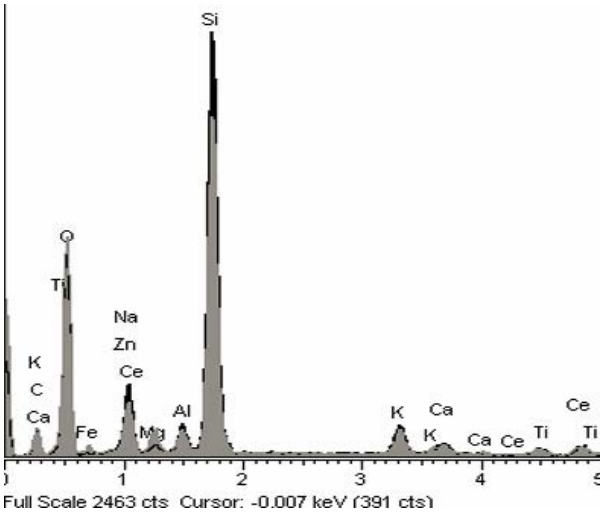

Figure 1. Energy dispersive X-ray spectra (EDS) of laboratory impact of hydrated mafic phyllosilicate grain from the meteorite Orgeuil (grey spectrum) onto HST solar cell glass (black spectrum). Note the complex glass composition including very high silicon.

The ability of polymer foil blankets to catch and retain substantial quantities has been demonstrated in several studies of LEO impacts upon multilayer insulation (MLI) (e.g. Graham et al. 2003; Kearsley et al., 2005a). Residue is abundant on foils, and includes compositional types not observed against silicate-dominated solar cell glass (figure 1). Some, such as patches on SFU foils (figure 2), may be contamination by fluid silicon-bearing polymers, but others from the Mir Trek experiment are demonstrably residue from solid particles. There is also better preservation when compared to solar cell or metal impacts, with discrete mineral grains (figure 3), as opposed to patches of melt blended with glass in solar cells, or tiny droplets of volatile-depleted melt on metal. The absence of silicon in the substrate allows determination of the divalent cation to silicon ratio, and hence mineral stoichiometry, indicative of the micrometeoroid origin.

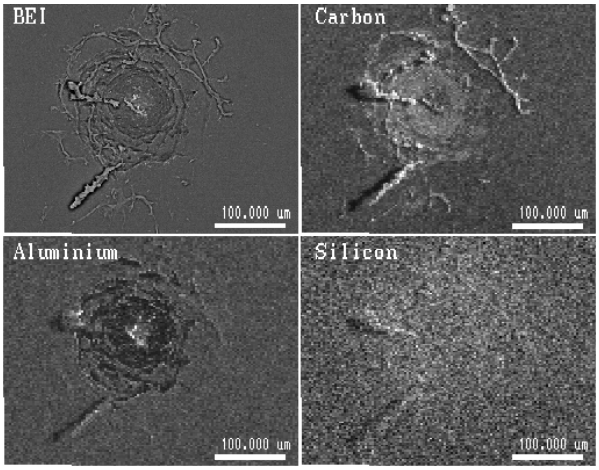

Figure 2. BEI and EDS maps of an impact onto SFU MLI, note the diffuse Si-bearing area and concentration of the Al coating into small granules.

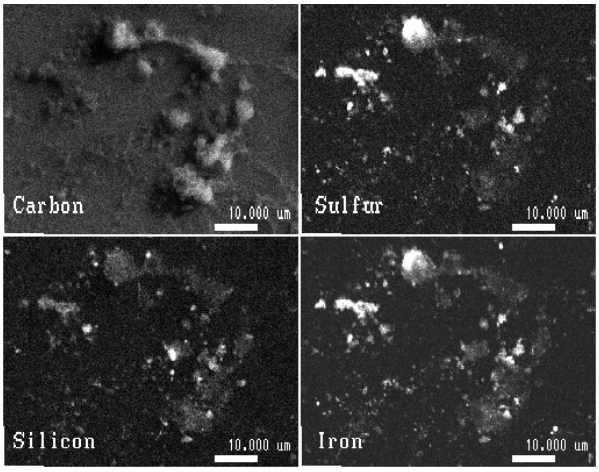

Figure 3. BEI and EDS maps of residue on SFU foil exposed to space, showing abundant particles of several discrete compositions.

However, although MLI type foils are co-operative substrates for micrometeoroid residue, their habit of fine aluminium granule formation during impact delamination of the metallic surface coating (figure 2) makes recognition of aluminous space debris residue almost impossible. Most metals interfere with analysis of residue, although a palladium-rhodium multilayer coating would provide adequate protection to the polymer, whilst avoiding confusion during rapid X-ray mapping of foil surfaces (Kearsley et al., 2005b). We therefore decided to test whether purpose-built foil devices might make effective collectors

4. LABORATORY IMPACT ANALOGUES

Three buckshot impact experiments used the two-stage light-gas-gun (LGG) at Canterbury (Burchell et al., 1999). From each experiment we were able to assess desirable parameters for an evolving orbital foil collector design. A detailed description of the target materials is given in Kearsley et al. (2005b).

4.1 First test shot onto Multi-Layer Insulation foil.

This shot of relatively coarse olivine grains (38 – 53 micrometres) at 5.1 km s^{-1} was performed to see if laboratory impact features and residues would resemble those from MLI exposed in LEO on SFU. Similar morphology was observed, despite the lower velocity regime compared to that encountered in orbit. Very similar top foil penetrations were found, but some residue on lower foil layers had undergone less shock modification than in LEO examples (Kearsley and Graham, 2004), with good Raman spectra from olivine residue.

We have not determined the precise particle size and velocity threshold for penetration through the very thick external foil of SFU MLI (80 micrometres). However, it seems likely that micrometre scale particles such as solid rocket motor (SRM) debris will not reach underlying foils. They will also be difficult to find and analyse on an eroded Kapton exposed surface, with inevitable external contamination. For these reasons we chose thinner foils for subsequent designs.

4.2 Second test shot onto thin aluminised foils

The target for this shot was created by separation of thin (approx. 8 micrometre thickness) aluminised foils from a sample of MLI, and their reassembly as sheets supported and spaced by 2mm polymer. Although the foils had been pre-perforated for venting, it was easy to distinguish impact penetrations. Projectiles were fine alumina (3 micrometer) to simulate SRM debris, and olivine grains (38-53 micrometres) as micrometeoroid analogue, held within the buckshot sabot by a 1mm steel ball. Abundant full thickness holes through the top foil showed a bi-modal size range, implying that both projectile types had penetrated. However, local aluminium delamination and concentration was extensive on lower layers, confirming that such metallised foils are not suitable for location and analysis of residues.

4.3 Third test shot onto a gold-coated thin top foil.

This shot used similar projectiles to the second shot, but the foils were prepared from clean Kapton samples provided by DuPont, without aluminium coating. The top foil (8 micrometres) was sputter-coated with a thin layer of gold, providing an easy contrast for location of impact features in both light and electron microscopes (figure 4). Again, two size populations of top film penetrations were observed, and abundant residue was

found on the second and third foil layers (figure 5). The absence of aluminium coating allowed recognition of alumina residue. A faint trace of iron was also found in the area around the steel ball penetration on the third and subsequent foils, indicating that even large particles leave a distinctive residue signature. Delamination of gold on the top foil allowed location of very small impact features, but gold would make it difficult to recognise sulphur-bearing residue rapidly.

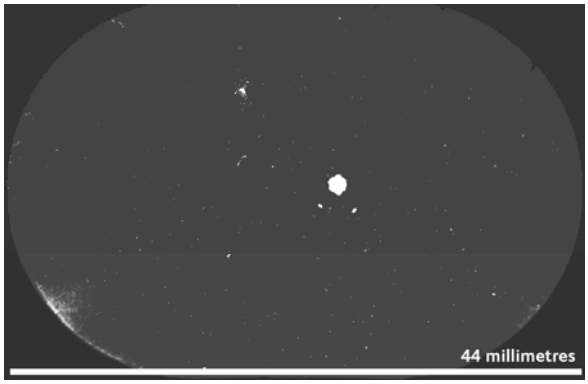

Figure 4. Optical scan of gold-coated top Kapton foil (8 micrometres) from second experimental shot, with perforations from the steel ball and mineral projectiles.

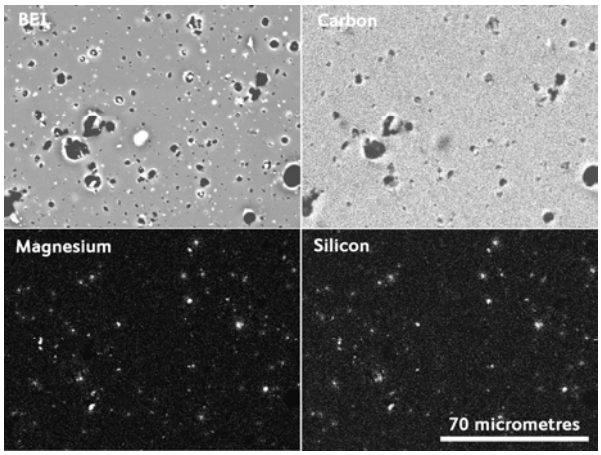

Figure 5. BEI and EDS maps of C, Mg and Si demonstrate abundant residue on the third Kapton foil layer of the third experimental shot.

4.4 Palladium- and rhodium-coated top foils

We have now produced sheets of palladium-coated thin Kapton, ready for rhodium electroplating. These sheets will be used as the top foil in a series of LGG shots with soda-lime glass sphere projectiles of very well characterised size range, from about 10 microns upwards. From these shots we shall generate a calibration plot of top-foil penetration diameter dependence upon impacting particle size. We also intend to calibrate full-thickness penetration and top-foil crater diameter for smaller particles by Van der Graaff shots of small metallic iron particles.

5. ASSEMBLING COLLECTOR MATERIALS

Our experience of space-exposed blankets and the suite of laboratory experiments has enabled design of a flight model collector. The MULPEX (MULti-layer Polymer EXperiment) collector (figure 6) consists of thin poly(imide) foils, held apart by PTFE (poly(tetrafluoroethylene)) frames, and with the top surface exposed to space (Kearsley et al., 2005b). Each foil and frame layer is a resilient and uniform substrate, enabling rapid analysis and classification of impact residues by automated analytical scanning electron microscopy, without serious interference from the collector composition. The topmost foil is metallised providing necessary resistance to UV and atomic oxygen attack, and also charge dispersal. During fabrication, initial coating of palladium is performed using high temperature droplet evaporation on a heated tungsten wire under vacuum. Coating of large foil areas is possible by this technique, certainly in excess of 50cm x 10cm in each batch, sufficient for the creation of 5 MULPEX foils. This is more efficient and reproducible than the limited area palladium coating achievable by the sputter coating equipment available in most SEMpreparation laboratories. Deposition of the top layer of rhodium may be performed using acidic bath electro-plating, with the palladium coating treated as the cathode. The properties of rhodium significant for performance as an external protective layer are comparable to those of aluminium (Emsley, 1989).

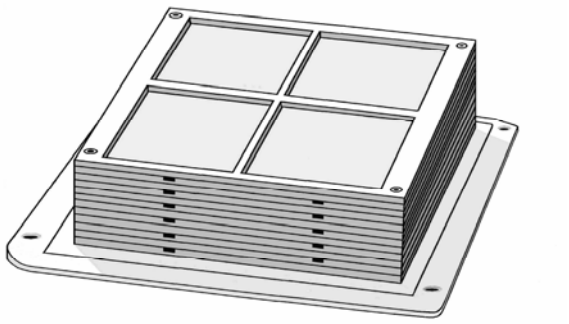

Figure 6. MULPEX foils and frames without cover.

We have found that during impact, local delamination and ‘roll-back’ of a thin metallic coating also reveals the location of penetrations in both optical and electron microscopes. Optical scans on a high-resolution flat bed digital scanner (>2400 pixels per inch) have proven particularly useful). In BEI, the increased metal thickness in the ‘roll-back’ produces a bright halo marking the site of delamination (figure 7).

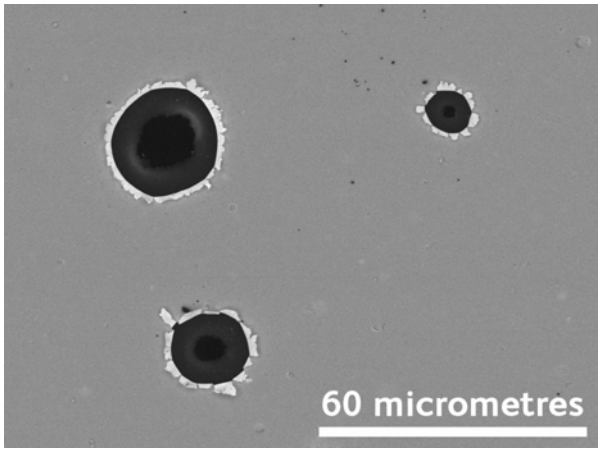

Figure 7. BEI of impact features on the top foil of the second experimental shot. Note 'roll-back' of the thin gold coating around the penetrations.

The metallic coating also acts as a clean surface seal to distinguish pre-flight construction contamination from particulate material accreted during space exposure. Residue from particles less than one micrometre in diameter can be sought in pits on the surface. Larger particles (>3 micrometres) penetrate through the thickness of the uppermost foil, and are disrupted into finer particles, subsequently emplaced upon the lower foil layers, or they may leave diffuse traces around the penetration holes. MULPEX type foil blankets can be made in a wide variety of sizes, with the advantage that a larger surface area will give a larger total number of impacts, an important consideration if space exposure is for a short time. Recent flux measurements (Moussi et al., 2005) suggest that 100 cm^2 of foil, exposed to space in a sun-facing orientation for a year at an altitude of approximately 600km, would accumulate only about 15 impacts of particles greater than 1 micrometre in diameter. Nevertheless, a ram-facing collector of this size, mounted on the International Space Station would be an effective sampler of smaller space debris particles. A small modular version will be available as exchangeable cartridges that fit within the dimensions of the standard experiment containers.

6. STANDARDISED CONTAINERS FOR EXPERIMENTS (SCE)

The small MULPEX models have no moving parts or need for electrical or data relay facilities, and they are designed to sit passively on the spacecraft exterior, oriented in whichever direction is desired for sampling the desired flux components, until retrieved for analysis on Earth. Carriage, attachment and external protection during deployment are provided by the Standardised Container for Experiments (SCE) (figure 8), with the foil cartridge bolted within the square base plate of 12 cm width.

The top to the thin-walled aluminium box housing has a square aperture of 10 cm width for exposure of the experimental surface. During storage before and after exposure, the aperture should be covered to prevent accumulation of dust on the collector upper surface. Due to the standardised box design and durable components, the SCE modules can be stored economically within a small space to await launch, or following exposure in space, pending return to Earth for analysis. The robust design is intended for repeated refilling of cartridges, possibly of many different collector materials (e.g. the calorimetric aerogel of Dominguez et al., 2005), and re-use on the spacecraft exterior.

A suite of standardised containers are to be manufactured by computer controlled water jet- and lathe-cutting in the workshops of Imperial College, London.

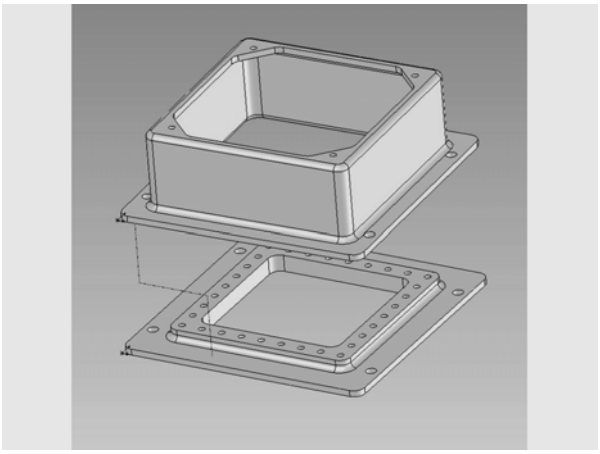

Figure 8. Schematic perspective view of the prototype Standard Container for Experiments (SCE). Base frame is 12cm across.

7. SUMMARY

A dedicated, simple, low mass collector that requires no data or power services from its host spacecraft can be a valuable source of information from opportunistic deployment. Results from LEO and light gas gun shots show the suitability of polymer foils. A small MULPEX collector uses the aluminium box housing of Standardised Container for Experiments (SCE), with an internal cartridge of Kapton foils supported on poly-tetrafluoroethylene window-frames in a square aperture of 10 cm width exposing the uppermost foil to space. The topmost foil is palladium/rhodium coated, a surface composition suitable for very rapid characterisation of impact features by automated analytical scanning electron microscopy.

8. ACKNOWLEDGEMENTS

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