ANALYSIS OF IMPACT RESIDUES ON SPACECRAFT: POSSILITIES AND PROBLEMS

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ABSTRACT

Determination of the frequency and importance of impacts by space debris and micrometeoroids of below 1mm in size is best achieved by examining spacecraft surfaces that have been exposed in the near-Earth orbital environment. Post-flight investigation of the returned surface not only allows the measurement of particle flux and the dimensions of individual impact features, but also the composition and origin of the impacting bodies. Impact residue analysis is inherently a difficult task, as a particle traveling at speeds of between 5 and 70 km s^{-1} leaves little chemical evidence following a hypervelocity collision. Notwithstanding this difficulty, returned surfaces from a range of spacecraft, including the Long Duration Exposure Facility (LDEF), the Space Flyer Unit (SFU), the Hubble Space Telescope (HST) and Salyut 7-Kosmos 1686 station, have enabled detailed studies on the chemistry of both micrometeoroids and space debris. The development of new dedicated capture cells, e.g. aerogel, should enable even more detailed studies of the micro-particle populations in Earth orbits, and beyond.

1. INTRODUCTION

Space debris in low Earth orbit (LEO) includes a very wide range of objects from µm- to m- scale. In addition to space debris, studies show there is a significant impact hazard from the continuing flux of natural micrometeoroids. Ground-based optical [1] and radar measurements [2] can be used to locate and track larger particles (cm to m size-range), and recent studies have demonstrated the potential of space-borne lidar investigations of the µm to mm population [3]. However, detailed studies of the smaller size particles have conventionally focussed upon materials collected in-situ in Earth orbit. Much of the space debris in this size regime has been determined as *mission-related*, that is the result of the deployment, activation and use of space hardware [4]. Significant mission-related debris includes aluminium oxide particles, formed and released during the burning of solid rocket motor (SRM) fuels, and also includes particles of human waste. The other source of small-sized debris has been defined as *fragmentation debris*, which has been considered as the largest contributor to the total population of catalogued space debris [4]. It is typically made up of particles generated by the break-up or deterioration of space hardware, e.g. solar cell glass shards released during impact events, fragments of embrittled polymer paint binder, and thermal blanket debris [4]. Space debris and micrometeoroids can be collected by active, dedicated impact experiments (e.g. DEBIE [5]), although their limited duration and surface area may not yield such statistically significant samples as detailed post-flight laboratory analysis of larger returned space-exposed surfaces. Previous studies have shown that various types of non-dedicated surfaces can be used for post-flight investigations. Micrometeoroid impact investigations were conducted on surfaces from Apollo spacecrafts [6] and the Skylab IV mission [7]. Detailed post-flight investigations of the recovered thermal blankets and the aluminium thermal control covers from the Solar Maximum satellite identified both micrometeoroid and space debris remnants in impact features [8].

One of the first attempts to use a dedicated collector was carried out using a microabrasion foil experiment (MFE), flown on a space shuttle Orbiter [9]. This experiment was particularly important as it identified that capture cell technologies could work, and relatively low cost in-situ sampling could be achieved in LEO. Other dedicated collector experiments have focussed on capturing specific particles e.g. from Earth encounters with the particles that create meteors. Such cometary particle streams have the potential to cause catastrophic failure to space hardware [10]. In 1985 during Earth's encounter with the Draconid meteor stream (related to comet Giacobini-Zinner), particles were captured by the COMET-1 experiment [11]. The collectors retained not only debris from the stream but also cosmic dust particles attributed to other origins (most likely asteroidal), and space debris. Recent dedicated in-situ sampling experiments in LEO, e.g. the Orbital Debris Collection (ODC) experiment on the *Mir* space station [12] have used new capture cell

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technologies that may preserve the impacting material without major disruption.

Herein we review a number of spacecraft materials as non-dedicated and dedicated capture substrates for the analysis of LEO particle populations. The range of compositions and structures of spacecraft surfaces available for investigation is extensive. However, most have important spacecraft functions as structural, insulation or power-generation components, and their value as collectors of well-preserved particles was rarely a major design consideration. They often have multi-element compositions and sophisticated laminate structures, and captured materials are often contained within complex impact features, mixed with the substrate materials, and may initially present little unambiguous chemical information to help determine their origin. We attempt to assess the potential of some commoner substrates as reliable repositories of information as to the origin of particulate impactors.

2. LABORATORY METHODOLOGY

The returned spacecraft surfaces in this study were examined using a Jeol 840 scanning electron microscope (SEM) fitted with an Oxford Instruments eXL light element energy-dispersive spectrometer microanalyser (EDS). The analysis protocol used is described in detail in [13], but essentially uses a combination of back-scattered electron imaging (BEI) and X-ray elemental mapping. If necessary, the samples were carbon coated and the typical working conditions were a 32 mm working distance, 2 nA beam current and 20 kV accelerating voltage. High-resolution secondary electron imaging of selected samples were carried out using a Philips XL field-emission microscope (FEG-SEM) at the Natural History Museum, London. The typical working conditions for FEG-SEM were an accelerating voltage of 5-7 kV, with a working distance of 10mm.

In order to test our models for understanding the retention and fractionation of impact residues, experiments were carried out using a two-stage light-gas-gun (LGG) and a 2 MV Van de Graf accelerator (VGA). Details of the experimental working protocols for both are given comprehensively in [14].

3. DISCUSSION

The damage seen on returned surfaces of space hardware from LEO suggests that the impacting body experiences intense energy transfer when rapidly decelerating from a velocity of ca. 25 kms^{-1}. Such events alter the appearance and composition of remnants that are retained in and around the impact feature. The most obvious sign of alteration is seen in the grain morphology; only rarely are homogeneous and discrete near-intact particles identified on non-dedicated collector surfaces [15]. Instead, complex residues are frequently observed; these are usually composed of an intimate mixture of impactor remnant and the host substrate. Whilst it is clearly evident that both micrometeoroids and space debris particles are highly altered by hypervelocity impact events, characteristic residues can be routinely located by analytical electron microscopy.

One of the most significant difficulties to be overcome is the recognition and separation of analytical artifacts from the signal that is due to impact residue. A scanning electron microscope fitted with EDS is the analytical tool of choice for many post-flight investigations. Under normal conditions, microanalysis and imaging work would be carried out on specimens that have been specially prepared, with a polished and coated surface of minimal topographic relief. This type of preparation is rarely possible for the surfaces returned from LEO, as the sectioning usually removes much of the residue and prevents examination of the 3-dimensional distribution of residue, so important in complex substrates. Most EDS fitted to an SEM have a mounting and aperture design to provide an optimum geometry for quantitative analysis of polished surfaces at a 40° take-off angle, whilst still permitting high resolution electron imagery. The inclined position of the spectrometer, and the profile of many impact features that are uneven and have substantial depth, together create a partial topographic shadow-effect. As a result, no useful X-ray information is returned to the spectrometer from one half of the crater, and an area of darkness appears in an X-ray elemental map. It is then necessary to rotate the sample, and repeat the procedure in order to map residue that may be spread across the other side of the crater, a time consuming task. Surprisingly, the inclined detector position can substantially aid recognition of extremely thin residue layers on the melt pit of smaller craters.

3.1 Surfaces from the Long Duration Exposure Facility (LDEF)

LDEF spent 5.8 years in LEO (altitude approx. 470 km) [15] and has offered the most extensive and statistically reliable space impact dataset. LDEF consisted of a 12-sided cylinder (i.e. 14 faces in all) allowing sampling of different local viewing directions as the spacecraft was gravity gradient stabilized to maintain a fixed orientation with respect to Earth. The space-pointing face of LDEF had no Earth shielding and was essentially spinning with respect to interplanetary space (i.e. once per orbit), and over the entire lifetime of LDEF the exposure of the space face to interplanetary space was effectively randomized.

Exposure to meteoroids was therefore essentially random, whereas the orbital debris exposure was highly directional. LDEF surfaces were fitted with a wide range of experiments designed to investigate LEO [17], including both dedicated particle collectors [18-19] and non-dedicated surfaces [20-21] that also captured both cosmic dust and space debris. The alteration of impactor material during hypervelocity collision was emphasized by the relatively few individual remnant mineral components found in impact features. These showed evidence of intense shock metamorphism, planar deformation to crystal structure and recrystallisation (120^o grain intersections on remnant orthopyroxene material) [18]. In many cases, the impactor was believed completely vaporised [19]. The aluminium tray-clamps are in fact a good substrate for recognition of micrometeoroid impactors [20], and we are currently re-investigating clamp surfaces (Fig. 1.). The alloy composition is, however, a difficult material against which to recognize residues of some space debris compositions, e.g. fuel particles from solid rocket motor (SRM) operation.

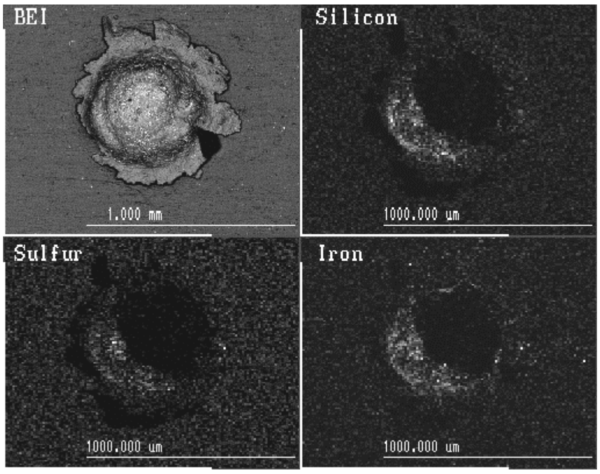

Fig. 1. BEI and X-ray maps of an impact crater on an Al-clamp from LDEF. The combined presence of Si, S and Fe strongly suggests a meteoroid impactor.

3.2 Solar Cells from the Hubble SpaceTelescope (HST)

The retrieval of one of the two solar array panels from the HST during the first service mission has proven to be particularly helpful. The HST array was in an operational orbit of approximately 600 km altitude, and thus experienced a similar environment to that sampled by LDEF (albeit with differing instantaneous exposure geometry [22). Using the analytical protocol described in [13] we carried out two extensive surveys of individual solar cells. We discovered that the complex cover-glass composition made an excellent substrate for residue recognition. The initial survey of craters with conchoidal diameter (D_{co}) between 100 - 1000µm showed micrometeoroid remnants to be dominant [23]. Residues were composed of remnants from silicate minerals, calcite, metal sulfides and metals. Residues often appeared as complex poly-mineralic melts within the melt pit (Fig. 2). The second survey, of 10-100µm D_{co} craters, identified the most common impactor as space debris. Aluminium and aluminium oxide residues (Fig. 3.) were most abundant, dominating craters below 30µm in diameter [24]. The results from the residue chemistry surveys have now been compared with a prediction derived from LDEF data and meteoroid modelling [25], and there is general agreement between the models and observations of residues from LEO [24].

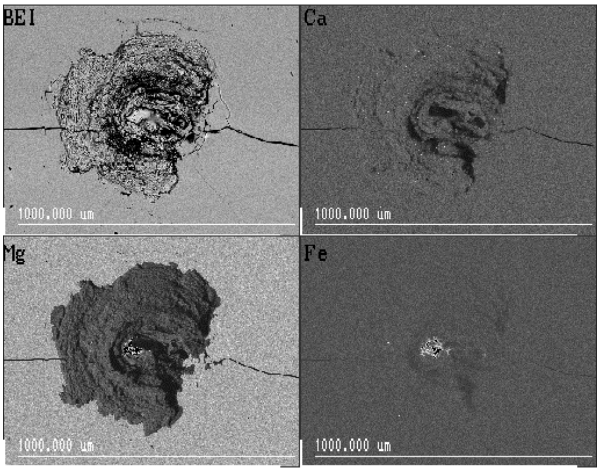

Fig. 2. BEI of an impact crater on a solar cell from HST. X-ray elemental maps for Mg and Fe show a micrometeoroid residue.

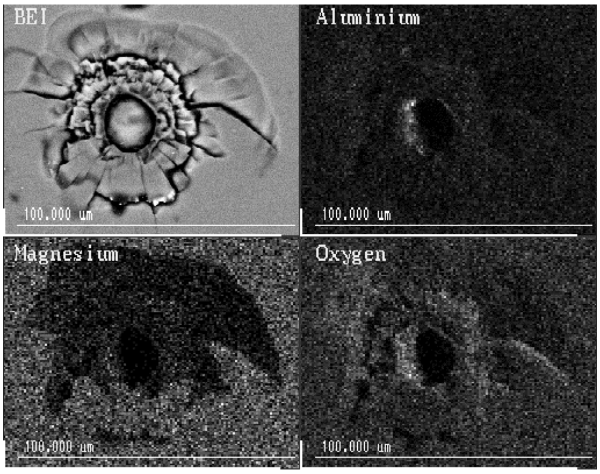

Fig. 3. BEI of an impact crater on a solar cell from HST. X-ray maps for Al and O indicate that the impactor was space debris in origin (an SRM particle).

3.3 Multi-Layer Insulation Foils from the Space Flyer Unit (SFU)

The Japanese Space Flyer Unit (SFU) was, like LDEF, designed to investigate LEO, and was retrieved after 301 days of exposure in an operational orbit of ~480km. The SFU carried a range of experiments and surfaces that enabled *in-situ* sampling of micrometeoroids and space debris. These surfaces were extensively examined as part of a detailed post-flight investigation [26-27]. We have examined the multi-layer insulation (MLI) foils, which consist of 12 layers of aluminised Kapton films and Dacron nets; a full description of MLI is given in [27]. Our experience suggests that MLI-foils may prove to be one of the most useful surfaces for particle capture that has yet been deployed. As the deceleration and fragmentation within the layers appears to give less damage to the particle fine structure than is seen on thicker brittle (glass) or ductile (metal) surfaces. However, whilst the foils are particularly good for recognition of micrometeoroid remnants (Fig. 4), they are not an ideal substrate for recognition of some types of space debris. It is extremely difficult to distinguish between fine aluminium particles generated by the degradation of the foil coatings during hypervelocity impact, and space debris particles such as SRM aluminium oxide. However other space debris remnants can be identified, e.g. components of steels and other metallic alloys.

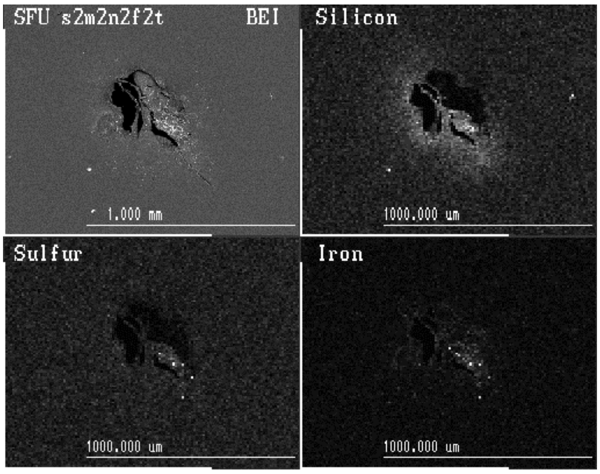

Fig. 4. BEI of the surface of an MLI foil layer, containing an impact feature. X-ray maps for S and Fe suggest that the residue is micrometeoroid in origin.

3.4 Pressure Tank from the Salyut 7-Kosmos 1686 Spacecraft

The potential, and also the difficulty of interpreting *in-situ* samples, is further exemplified by our investigation of micro-craters preserved on a titanium-alloy pressure-tank from the Russian Salyut 7-Kosmos 1686 spacecraft. The spacecraft assembly re-entered Earth's atmosphere early in 1991, and the tank was later collected from a debris strew-field in Argentina, having survived re-entry and landing. Whilst the surface shows a large number of craters (Fig. 5), some irregular forms may not have been generated by micrometeoroid and space debris particles in LEO, but by ablation debris from the rest of the spacecraft during re-entry. The tank is a complex and non-standard Ti alloy, with Cr and Fe, as well as Ti, Al and Mo. To further complicate analysis, there is strong oxidation of the complex alloy surface (probably from both prolonged LEO and from re-entry) and evidence of terrestrial contamination. Notwithstanding these problems, our preliminary investigation of the impact features has identified residue material of space debris origin in at least one of the craters.

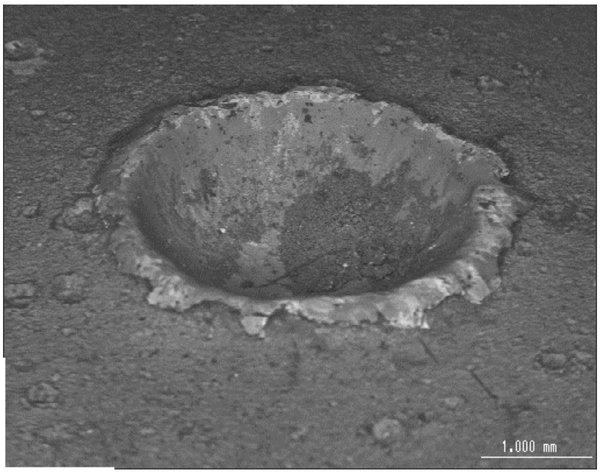

Fig. 5. BEI of a typical impact feature preserved on the surface of the fuel tank from Salyut 7-Kosmos1686.

3.5 Aerogel Capture Cells

Non-dedicated capture surfaces can provide large numbers of particle residues, but with severe degradation of the impactor structure and chemistry. The collection of material using dedicated capture cell technology has centered around the development of low-density aerogel cells [28] for dedicated space missions (e.g. STARDUST [29]). These also present an opportunity to sample the LEO environment, e.g. the ODC experiment [12]. In order to assess the degree of particle alteration and ease of extraction for analysis, we have carried out laboratory capture of projectiles in aerogel (Fig. 6), with impact velocities of 5.1 kms^{-1} [30-31]. Our experience suggests that a wide range of analytical techniques may be needed to characterize *in situ* particles in aerogel, and that delicate particle structures such as cluster interplanetary dust particles (IDP) may be severely disrupted during emplacement.

Fig. 6. An optical image of impact tracks generated in aerogel (density 96 kg m^{-3}) by accelerating (impact velocity ca. 5.1 kms^{-1}) crushed matrix material from the Allende meteorite (38 – 125 µm in diameter).

3.6 Particle Impact beyond LEO.

Space debris impacts are currently limited to relatively near-Earth orbits, however micrometeoroids range beyond. The NASA GENESIS spacecraft [32], that will be deployed in a Lagrangian orbit, will use numerous collector cells including silicon wafers, to trap samples from the solar wind. As collectors may experience micrometeoroid hypervelocity collision, we have simulated such impacts, to evaluate potential for residue retention and surface contamination. Silicon wafers were impacted with 38-53µm projectiles, at ca. 5.1 kms^{-1}, using the LGG. Most craters lost the central melt pit, due to extensive fracturing in the crystalline silicon substrate. However, some craters generated by 1 µm metal particles at velocities up to 100 kms^{-1} (using a Van de Graaff accelerator, VGA) did retain residue (Fig. 7).

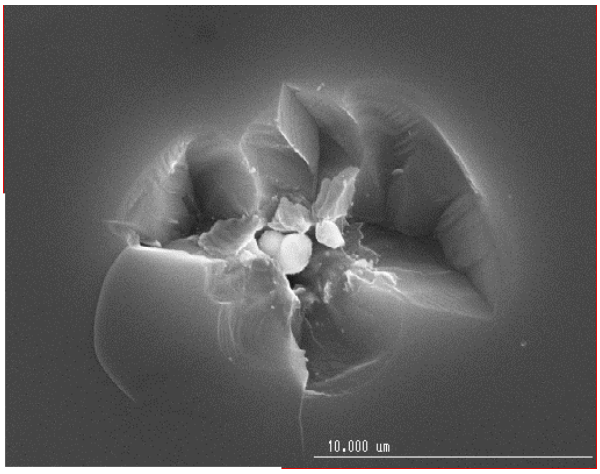

Fig. 7. SEI of a crater in a silicon wafer. The spherical object in the central pit is the iron projectile, apparently almost intact. Particle velocity not determined, VGA.

4. SUMMARY

All spacecraft surfaces probably have some potential as valuable records of hypervelocity impact, especially if analytical electron microscopy is employed in their analysis, and we encourage spacecraft operators to examine even the most unlikely-looking materials. Large surface area collectors, such as solar cells, offer large numbers of impact features, with poor particle preservation, but easy distinction between MM and SD. Foils provide better preservation, but less opportunity to recognize SD. The use of aerogel capture cells in LEO now offers the potential to sample space debris in a less damaged state, although some micrometeoroids may still suffer disruption.

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