Evaluation of Impact Craters on Thermal Multi-Layer-Insulation (MLI) Blankets

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List of Abbreviations

EDX  Energy-dispersive X-ray Analysis
MLI  Multi-Layer-Insulation
SE   Secondary Electrons
SEM  Scanning Electron Microscopy
WDX  Wavelength-dispersive X-ray Analysis

Summary

We studied and documented impact characteristics of perforation craters on thermal "Multi-Layer-Insulation" (MLI) blankets from 12 hypervelocity impacts, performed under controlled conditions. In addition, we examined impact residues of the projectiles on different layers of the MLI-samples. The objective of this study was to find correlations between impact parameters and crater characteristics including chemical residue analyses. These correlations could be used later as calibration for the analyses of impacts in space-exposed thermal MLI blankets. A number of correlation curves have been determined, giving information about impact parameters such as projectile size, impact angle, and kinetic energy.

The significance of chemical residue characterization was to show possibilities and problems with the analyses of the chemical compositions of projectiles hitting thermal blankets or similar satellite components. In spite of complex layer composition of the MLI-samples, qualitative chemical analyses of impact residues were successful in the case of different projectile and sample compositions.

Objective

Thermal Multi-Layer-Insulation blankets at the main-body of ESA’s "European Retrievable Carrier" ("EURECA") were subject to intense bombardment by natural and man-made debris particles during space exposure. These hypervelocity impacts by small pieces of debris and micro-meteoroids may indent or perforate the thermal blankets or other satellite components, e.g. EURECA’s solar cell samples, that were evaluated in part 1 of this project (Ref. 1). In order to evaluate particle impact history of retrieved material it is necessary to know the relationship between impact parameters and resulting crater morphology.
For this purpose particles were shot at MLI-samples under controlled conditions at the Ernst-Mach-Institut (Ref. 2) as part of an ESA/ESTEC project. Our objective in that collaboration was to determine to which extent it is possible to deduce impact parameters such as projectile’s size, impact angle, kinetic energy, and composition from the study of those impact craters. The analytical methods used included electron microprobe, optical and scanning electron microscopy. In addition, these investigations allow to compare the EURECA survey results with existing flux models for the low earth orbit particle environment.

Sample Description

We received 12 MLI-samples (type EU-262-EXP. 1, thick type 6), which were cut from an MLI-sheet, each held together with two staples and perforated by one impact from the top side, and accompanying data from the Ernst-Mach-Institut (Ref. 2). One of that samples is shown in Figure 1 in top side view.

Figure 1: Photograph of an MLI-sample as Received, Top Side View. The shown MLI-sample is 1959 sitting on an Al witness plate
The approximated sample dimensions are 85mm ¥ 60mm. The samples consist of 22 layers of varying compositions and thicknesses. Except for layer 1 and 2, all the other layers are separated by thin dacron nets. The layer configuration in an MLI-sample is shown in Figure 2. The schematic of the MLI-configuration without the dacron nets can be seen in Figure 8. There the composition and the thickness of each sample layer is described. Each layer surface is distinguished by its configuration number and a description like "top side" or "bottom side" as shown in Figure 8. For sample identification the original numbering system (Ref. 2) were used ranging from impact number 1952 to 1972.

In addition, the respective witness plates (e.g., Figure 1) used in the experiments (Ref. 2) were supplied with the MLI-samples. As they do not belong to EURECA we decided to neglect them in chemical residue analyses.

Figure 2: Side View Photograph of MLI-Sample 1959 showing the layer configuration.

The impact descriptions (Ref. 2) included information on the types of projectile used, their sizes, shot velocities and impact angles. The projectiles consisted of aluminum and plexiglass spheres and cylinders. In addition, there were an inclusion ("chondrule") from a meteorite, and an "olivine"-crystal as projectiles. Their exact compositions were unknown, but for the "olivine" it could be assumed that the main elements were Mg, Si, and Fe. The impact velocities ranged from 5.0 to 5.4 km/s and the impact angles 0° and 60° were used. The impact parameters are listed in detail in the tables in Appendix C.

Sample Handling and Documentation

The outer sample surfaces (layer 1, top side and layer 22, bottom side) were not suitable for determination of impact characteristics and for chemical residue analysis. It had to be assumed that the outer samples surfaces were contaminated by dust particles. Because of this
any chemical analysis of these sample surfaces would have been distorted. Additionally, the beta-cloth was not suitable to determine the size of a perforation hole because of its fibrous composition. Therefore the beta-cloth and the bottom side of layer 22 of each MLI-sample had to be excluded from chemical analyses.

As the samples were completely perforated we first checked the inclination of the perforation. This was done for every MLI-sample by carefully inserting a clean pin into the perforation of each sample and photographically documenting the orientation. With help of these photographs, the angles between the pin and the vertical were measured. These data can be found in Appendix C. The sample preparation with staples at the "Ernst-Mach-Institut" and the way the experiment was carried out (Ref. 2) led to an asymmetrical thickness of the MLI-sample after the shots (see Figure 2). As the MLI-samples were pressed in a special sample holder during the shots, the best way to simulate that compression of the sample without contaminating the sample surface was to temporarily squeeze the sample edges with clean paper clips. By doing that simulation the error of the measurement was minimized. As an example for that procedure see Figure 3.

![Figure 3: Photograph of the Determination of Perforation Inclination. The angle between the pin and the vertical was measured. The paper clip at the sample edge was used to simulate the pressed state during the shot. The MLI-sample shown is 1957.](image)

During all steps of sample handling, preparation, and analysis, special care was taken to avoid any unnecessary contamination or alteration. That includes sample handling with gloves and storage in a laminar-flow box between analyses. In all the preparation steps only clean tools were used.
For photographic documentation all the staples were removed and the individual layers were partially separated. For each MLI-sample different kinds of photographs were taken:
1) a microscopic picture of the perforation hole on layer 2, top side, with magnification 13.7, and 2) microscopic pictures of the perforation hole on layer 22, top side, and layer 21, bottom side, and the damage area on 1st witness plate with magnification 8.9. Additionally, a low magnification picture was taken in one single case where the perforation area was too big for a microscopic photograph.

For electron microprobe analyses the samples had to be cut to sizes below 25 mm in diameter. Four representative impacts were chosen for these measurements: 1955 (projectile: "plexiglass"), 1957 ("Al"), 1961 ("chondrule"), and 1972 ("olivine"). In each case the cuts were made with a clean knife around the impact areas on layers 2 and 22. In addition, another specimen was taken from layer 1 (beta-cloth) of MLI-sample 1972 to be able to compare material deposition on lower layers with the composition of layer 1. Figure 4 shows a cut out specimen with the impact area on top side of layer 2. This specimen is mounted on a sample holder for electron microprobe analysis.

*Figure 4: Photograph of a Cut Out Impact Area on Layer 2, Top Side. This specimen is mounted on a sample holder for electron microprobe analysis. For these measurements the MLI-sample had to be cut to sizes below 25 mm in diameter (size of Al sample holder in background). The different colors on the sample cut and its holder were caused by an inhomogeneous thickness of the carbon film coating them. The impact shown is 1972.*
Figure 5 shows the remaining part of layer 2 of MLI-sample 1972 after cut out. For the analyses the sample cuts were coated with a thin carbon film of about 40 nm to ensure electrical conductivity on their surface. Inhomogeneous thicknesses of that carbon film caused different colors on the sample cuts and their holders.

![Figure 5: Photograph of the Remaining Part of Layer 2 after Cut Out. The layer in the photograph belongs to MLI-sample 1972.](image)

**Determination of Impact Crater Characteristics**

The impact crater characteristics were determined with the help of the photographs in Appendix D in order to keep sample handling to an absolute minimum. The most important damage feature of each sample was the perforation hole. Examples for that can be seen in the figures of Appendix D. For each sample layer chosen the longest and shortest diameter of the perforation hole were measured, assuming a roughly elliptical shape. With these values the approximated area and the eccentricity were calculated. All of these data can be found in the tables in Appendix C.
On the top side of each layer besides the first one some kind of material deposition could be found around the perforation hole. Figure 6 shows a typical example for that.

![Figure 6: Microscopic Picture of a Part of the Impact Area on Layer 22, Top Side. Around the perforation hole in the upper right corner deposited material can be seen. As the area of the deposited material has no clear borders and decreases continuously with increasing distance to the perforation hole, its dimensions cannot easily be determined. The square bright lines are areas shaded by the dacron net originally located just above.](image)

Since this deposition film decreases continuously with increasing distance to the perforation hole its dimensions could not easily be determined. The deposited film appears to consist mainly of degraded material of the respective upper layers.

For all the MLI-samples, there is at least one perforation hole in each layer. In every case the perforation area increases with increasing layer number except for the last layer, which has a smaller perforation hole. This can readily be explained by the fact that the last layer (22) is thicker and the perforation resistance is larger than in upper layers. For MLI-sample 1954, all the layers were separated and the perforation dimensions were determined for each layer. A typical plot for the distribution of perforation hole areas inside an MLI-sample is shown in Figure 7.
Figure 7: Plot of Perforation Area vs. Layer Number. The perforation area increases with increasing layer number except for layer 22, which is thicker than the upper layers.

In Figure 8 all perforation holes of MLI-sample 1954 are displayed in a 3-dimensional way to visualize the concept of a perforation cone. Analogous figures could be created for each MLI-sample.
Figure 8: Schematic of the Perforation Cone created by perforation holes in the sample layers. As the first layer has a completely different composition, the shape of its perforation hole is different and cannot be compared with the other ones. This Figure also shows the MLI-sample configuration except for the first layer. The numbers indicate each layer’s composition and thickness.

Note: Layers 3 through 21 have identical compositions and thicknesses.

2 Kapton layer, 3.0 MIL

3 aluminized Kapton, 0.3 MIL

21 aluminized Kapton, 0.3 MIL

22 Kapton layer, 3.0 MIL, aluminized on top side, painted black on bottom side
Investigation of the Crater - Impact Relationship

The main objective of this study is to evaluate relationships between the crater characteristics and the impact parameters. For this purpose we searched the accumulated data for correlations between any two or more properties. In the following, the best correlations found are discussed in detail. Analogous to part 1 of this investigation program (Ref. 1) it is again obvious that the significance of the results is fundamentally limited by two factors:

1. The number of the impact experiments is relatively small for the number of parameters changed (such as projectile material, shape, size, and impact angle). No single experiment was performed twice under constant conditions, making it difficult to estimate the reproducibility and statistical variation of the crater characteristics observed.

2. All experiments have been performed with little variation in impact velocities ranging only between 5.0 and 5.4 km/s. This is unfortunate because the important parameter of kinetic energy of the projectile is now almost only a linear function of its mass. Any diagram shown below involving kinetic energy would give a similarly good correlation if energy were replaced by the projectile mass.

Despite these limitations it was possible to find some properties with clear correlations.

A perforation cone’s inclination indicates the projectile’s angle of incidence. Figure 9 shows the theoretical (open symbols) and the experimental data (filled symbols) of the perforation cone’s inclination plotted vs. the respective MLI-sample. Since the error of the experimental determination of the angle of incidence is about 5°, a good correspondence can be established for the 0°-impacts. Comparing the data for 60°-impacts a significant difference is noticed. The reason for that difference was the impossibility to simulate the pressed sample state around the impact area in an absolutely satisfactory way. Because of this, the pins were less inclined and the incidence angles seemed to be smaller for 60°-impacts. Taking that into account the difference between theoretical and empirical data diminishes and there is a similarly good correspondance for 60°-impacts as for 0°-impacts. In fact, it is possible to determine the impact angles even more accurately if it can be achieved that the sample thickness is approximately the same during the determination of the incidence angle and the impact.
There is still another way to determine a projectile’s impact angle. That way leads to larger errors of the measurement data than the way of incidence angle determination does which is described above. Calculating the eccentricities of the respective perforation holes and plotting them versus the impact angles results in the relationship shown in Figure 10. As expected, the eccentricity of the perforation hole increases when the impact angle becomes more oblique. In the diagram, related impacts (with the same material and size of the projectile) are connected with lines to better show the trends in the data. Unfortunately, for each group only two impacts can be compared, since only two angles were used. It is difficult
to construct a correlation curve and, therefore, impact angle determination with help of hole eccentricity will only be possible within a large margin of error.

Figure 10: Plot of Eccentricity of Perforation Hole on Layer 2 vs. Impact Angle. The impacts were only performed at angles 0° and 60°. Related impacts (with identical projectile material and size) are connected by lines.

The longest diameters of 60°-impact holes are much larger than those of 0°-impacts. That has to be expected because with larger angles of incidence the projectiles hit larger surface areas. Additionally, the projectiles pass longer distances through the sample and interact with more material (see Figure 11).
Figure 11: Schematic of Sample Configuration during 60°-Impacts. In these cases projectiles hit larger surface areas than in the cases of lower impact angles. In the MLI-sample the trajectory passes the distance "t = h / cos(60°)" which is twice the distance passed by 0°-impacts. The projected longest diameter of the perforation hole is "D_{max/proj} = D_{max} \cos(\theta)".

In order to make the longest diameters of 0°- and 60°-impacts comparable the diameters of 60°-impacts were multiplied with the cosine of the impact angle:

\[ D_{max/proj} = D_{max} \cos(\theta) \]

with:

- $D_{max/proj}$: longest diameter of the respective perforation hole projected to one plane (mm)
- $D_{max}$: longest diameter of the respective perforation hole (mm)
- $\theta$: impact angle (°)
With this method the longest diameter of the perforation holes were projected onto one plane. Figure 12 shows the relationship between the projected longest diameter of the perforation hole on layer 2 and the projectile diameter for all impacts.

\[ \text{Figure 12: Plot of Projected Longest Diameter of Perforation Hole on Layer 2 vs. Diameter of Projectile. The straight line has the slope 2.13. The grey area indicates the straight line’s uncertainty caused by an error of ±0.15 mm for the measuring data.} \]

If it is assumed that the projectile’s energy is high enough to perforate the sample there will be clearly a linear relation between the damage feature and the impact parameter. A linear curve fit of the data through the point (0, 0) yields a slope of 2.13. The fit appears to be independent of other parameters such as projectile material, size and - because of the projection described above - impact angle, as can easily be seen from the labels of individual symbols in Figure 12.
In that Figure the grey area indicates the uncertainty of the straight line. This uncertainty is caused by an absolute error of ±0.15 mm which can be assumed for the measuring data.

Please note: That correlation may only be used in cases of adequate impact angle determination. Because of that a similar procedure to determine the projectile's size in solar cell samples as impact targets (Ref. 1) did not seem to be useful.

It was difficult to determine a correlation between any impact feature and the kinetic energy of the projectile. Each MLI-sample was completely perforated and, therefore, only a part of the projectile’s kinetic energy was lost during the interaction with the MLI-sample. After sample perforation the projectile’s remaining energy was absorbed by witness plates (Ref. 2). Obviously, in the case of strongly damaged plates, the projectile’s energy loss during the interaction with the MLI-sample was small. When the plates’ damage features are analyzed (see the Figures in Appendix D) it can be noticed that witness plates were hardly damaged for 60°-impacts (except for impact 1956). These hardly damaged plates indicate that the projectile’s kinetic energies must have been small after the projectile-sample-interaction. For a 60°-impact the distance passed by the projectile inside the sample was twice as large as for a 0°-impact (see Figure 11). So in this case the length of the projectile-sample-interaction was also twice as large as for a 0°-impact and, therefore, the projectile’s absolute energy loss during that interaction had to be larger than for a smaller interaction length. Therefore it can be assumed that four of the 60°-projectiles lost most of their kinetic energy during the interaction with the MLI-sample.

The following assumptions, which are independent of the impact angle, appeared to be helpful for the evaluation of the projectiles’ kinetic energies:

1) As shown in the tables in Appendix C, for different impacts the projectiles’ kinetic energies were different before the samples were hit. But for the four 60°-impacts, that were mentioned above, the projectiles’ kinetic energies had to be similar after the interaction with the samples because the projectiles caused similar damage features on the witness plates. Because of this, it can be concluded that the projectiles’ absolute energy losses were different during the projectile-sample-interactions. This results in the fact that the projectiles of higher kinetic energy before the impact lost more energy than the projectiles of lower kinetic energy.

2) A large perforation cone is caused by large perforation holes in the sample layers (see Figure 8). Additionally, large perforation holes indicate a large amount of degraded material and, consequently, a large extent of the projectile-sample-interaction can be assumed which points to high absolute energy loss of the projectile. Conversely, smaller perforation cones indicate less absolute energy loss of a projectile.
There are two points where the amount of energy is particularly important (the energy before and after the impact) and a resulting energy loss which is the difference of those two energies. The problem in the evaluation of the kinetic energy was the fact that each projectile did only lose a part of its kinetic energy during the interaction with the sample layers. Since the projectiles’ remaining kinetic energies after the impact and their energy loss during the projectile-sample interactions were unknown, a comparison of different impacts was impossible. Only for the four 60°-impacts - with similarly damaged witness plates as described above - the energies after the impacts appeared to be similar. So the two unknown parameters - projectile’s energy loss and energy after the interaction - are reduced to one, the projectile’s energy loss. Since the energy loss could be determined from the damage in the perforation cone as described above, for the four 60°-impacts a correlation between the perforation cone and the kinetic energy could be determined.

A comparison of the perforation cones of these four impacts was possible by the determination of the ratio of the perforation areas of layer 22 and 2 of the MLI-samples:

\[
\text{Ratio } R = \frac{\text{Perforation Area on Layer 22 (mm$^2$)}}{\text{Perforation Area on Layer 2 (mm$^2$)}}
\]

This ratio allows to calibrate the respective perforation cones because any influence of other impact parameters (such as size, composition, etc.) is excluded. As described above, with the help of the perforation cones the determination of the kinetic energy before the impact is possible. This evaluation of the kinetic energy is shown in Figure 13. The best fit line does not go through the point (0, 0) because a certain minimum energy is required for a projectile to perforate each sample layer. The straight line is described by the equation:

\[
E = 0.72 + R \cdot 3.84 \quad (\text{J})
\]

E: (Kinetic Energy of Projectile in J)
R: Ratio (see above)

The grey area indicates the error in the measurement of the hole dimensions.
Figure 13: Plot of Projectiles’ Kinetic Energy vs. Ratio of Perforation Area on Layer 22 and Layer 2. Only impacts with significant energy loss during projectile-sample-interaction were considered. The central straight line shows the best linear curve fit with a slope of 3.84. The grey area indicates the error in the measurement of the hole dimensions.
Chemical Characterization of Impact Residues

We also tried to find out to which extent it is possible to determine the chemical composition of the projectile based solely on the debris found around the impact site. SEM (scanning electron microscopy) with EDX (energy-dispersive X-ray analysis) was used to characterize the morphological and chemical composition of the deposition film found at the impact site.

With this method accelerated electrons excite sample-atoms and their emitted X-rays are detected energy-dispersively for elements with ordinal numbers larger than 8 (oxygen). Since each element has characteristic X-ray energies, a qualitative determination of the sample composition is possible. The presence of elements with ordinal numbers lower than 9, e.g. organic material, results in a continuous X-ray (Bremsstrahlung) spectrum superimposed to the characteristic peaks in the lower energy range. Since the penetration depth of the electron beam is about 5 µm, the carbon coating of approx. 40 nm which was applied to ensure electrical conductivity does not influence the spectrum significantly.

First of all, the chemical compositions of the sample’s first layer ("beta-cloth") and of the dacron nets separating the aluminized Kapton layers were determined. That was important because degraded fragments of these materials were expected to be found in the deposition layer around the impact holes of the respective lower layers.

The dacron nets consist mainly of organic material and also contain titanium, which could be a component of the white paint. Thus degraded fragments of dacron nets could be identified by their Ti content.

In the following, these terms are being used: a) "degraded material", which describes the beta-cloth’s, the dacron nets’, and the aluminized Kapton layers’ degraded fragments which were found on MLI-layers after the impact, and b) "impact residues", which describes the projectiles’ remaining parts that could be found in some cases on MLI-layers after the impact.

Chemical composition analysis of the beta-cloth were made with EDX at spots without any particles around. The result of that beta-cloth analysis is shown in Figure 14 where the EDX-spectrum indicates a complex composition with F, Mg, Al, Si and Ca as important elements. Especially the Si-Ca correlation appeared to be significant for that material. In the EDX-spectrum the high background Bremsstrahlung’s spectrum compared to other EDX-spectra indicates that the main component of that sample is an organic material. The spectrum shown is only qualitative and does not allow the quantitative determination of the sample’s composition. It was found that both F and the organic component were heterogeneously distributed throughout the sample. Therefore, only the Si-Ca-Mg-Al-correlation was assumed to be significant for the beta-cloth.
Figure 14: Typical EDX-Spectrum of Beta-Cloth. This layer has a complex composition containing organic material as the main component and Si, Ca, Al, Mg and F as dominating elements. The peak heights are not calibrated and give no information about the quantitative composition. Here, the beta-cloth of MLI-sample 1972 was analyzed.

Figure 15 is an SE image showing the morphology of the beta-cloth’s surface. The visible perforation hole is a second one beside the larger main perforation hole, both caused by the impact. The fibrous structure of the beta-cloth and a large number of particles can be seen on the surface. The particles labelled A) and B) have compositions as shown in Figure 14, which indicates that they belong to the beta-cloth. The fibers labelled D) have a completely organic composition.
Another important result of beta-cloth analysis is the observation of small iron-spheres like Particle C) in Figure 15. These spheres could be found on every analyzed sample layer of each MLI-sample and have sizes between 2 and 20 µm. The number of Fe-spheres decreases with increasing layer number. Because of this it can be assumed that the Fe-spheres are contaminants which were possibly produced during the impact shots. That assumption is supported by the fact that Fe-spheres were also found at the solar cell samples which were shot the same way with similar projectiles (see Ref. 1, pages 28-29). Figure 16 shows the largest Fe-sphere found on the examined beta-cloth.
The result of the beta-cloth analysis reveals the existing problems in residue analysis. In the deposited material of any lower layer degraded fragments of beta-cloth and dacron net as well as contaminants like Fe-spheres were found. This means that it was difficult to distinguish between degraded material and projectile residues because the projectiles are composed of organic material (plexiglass), Al, Si-Mg-Fe ("olivine") or "chondrule" with unknown composition. More detailed information about these problems can be found in the description of the respective residue analyses.

In order to investigate element correlations more deeply, "EDX-Element-Mappings" were made. With this method, a defined microscopic area is scanned by the exciting electron beam and an EDX-spectrum is acquired at each point of that area. Thus detailed information about the local chemical composition of the sample's surface is received. The local information of sample composition of all points taken together can be used to show the distribution of single elements in form of an "element map". In an element map different
colors indicate the element’s abundance at the respective locations. A color legend beside the element map assigns the element’s relative abundance to each color. The comparison of different element maps in a chosen area makes it possible to determine local element correlations. The same way, particles with different chemical composition are discernible.

In the upper left corner of each Figure showing element maps an SE-image of the respective area can be seen. These SE-images show the surface morphology at the same locations as the respective element maps. Generally, there are two kinds of X-ray detection, EDX and WDX. The element maps shown in Figures 17 and 18 with analyzed areas of 1 cm__ in size were made by WDX and in the "stage scan mode" which means that the sample surface was scanned by moving the sample stage under the fixed electron beam. The element maps shown in Figures 20 and 25 were made of microscopic areas of sizes in the µm-range. For these measurements EDX was used in the "beam mode" which means that the sample stage was fixed and the electron beam was scanned over the sample surface. For microscopic areas the beam mode is better than the stage scan mode because in µm-ranges the electron beam can be stepped more exactly than the stage.

The study of the SE-image and the element maps in Figures 17 and 18 led to the conclusions that the best way to find possible impact residues was to investigate the areas around the impact holes. With help of these Figures, it can be explained why the sample layers 2 and 22 were more suited for chemical impact residue analyses than other layers:

a) The perforation area of the last layer is smaller than the perforation area of layer 21 above (see Figure 8). Because of this, on top side of layer 22 the area of deposited material is larger than on upper layers. As shown in Figure 17 it is possible to find impact residues there. Additionally, since layer 22 is aluminized the Bremsstrahlung which is caused by the Kapton and superimposes the characteristic peaks in the lower energy range is mimimized.

b) Except for layer 22, the second layer is more covered by degraded material than the lower layers. That is due to the fact that this layer was occasionally hit by some material without being perforated as shown in Figure 18 for MLI-sample 1972. Since layer 2 consists of Kapton, which is an organic material, it is easy to distinguish between layer composition and any inorganic impact residue.
Figure 17: Element Mapping of the Impact Area on Layer 22, Top Side, of MLI-Sample 1972. Three element maps are shown and labelled at the bottom. In the upper left part of the Figure the SE-image of the analyzed area can be seen. The element maps prove the assumption that most of degraded material is found around the perforation hole. The color legend beside the images indicate the relative abundance of the respective elements. The length of the scale bar is 2 mm. Here, a good correlation of Si and Mg can be seen indicating the presence of olivine impact residues. The
missing correlation of Si and Ca excludes the possibility that these particles could be beta-cloth fragments.

**Figure 18:** Element Mapping of the Impact Area on Layer 2, Top Side, of MLI-Sample 1972. Three element maps are shown and labelled at the bottom. In the upper left part of the Figure the SE-image of the analyzed area can be seen. The element maps prove the assumption that most of degraded material is found around the perforation hole. The color legend beside the images indicate the relative abundance of the respective elements. The length of the scale bar is 2 mm. Here, a good correlation of Si and Ca can be seen indicating the presence of many beta-cloth fragments. The correlation of Si and Mg that can be assumed because of the bright
location in the upper right part of each element map may point to an olivine impact residue. At that point the layer was hit by some material but not perforated.

A) Plexiglass Residue Analysis at MLI-Impact 1955

As described above, the characteristic X-rays of organic material like plexiglass cannot be measured with EDX. So the easiest way to get any information about plexiglass impact residues was to find small particles, that only cause Bremsstrahlung in EDX-spectra without any characteristic peak, and to analyze these particles then with WDX or secondary ion mass spectrometry (SIMS).

Nevertheless, no such organic particles could be found on layer 22. Any analyzed particle or cluster could be determined as an Fe-sphere or had a composition shown in the EDX-spectrum in Figure 19. That EDX-spectrum indicates beta-cloth particles. Layer 2 could not be analyzed since it also has an organic composition.

Figure 19: Typical EDX-Spectrum of Particles Found on Layer 22, Top Side, of MLI-Sample 1955. The measurement indicates beta-cloth particles.
B) Olivine Residue Analysis at MLI-Impact 1972

The exact chemical composition of the olivine projectile was not known. So the presence of the following typical element composition of olivine crystals was assumed:

1) O: approx. 43%
2) Si: approx. 19%
3) Mg: approx. 29%
4) Fe: approx. 7%

Although both olivine and beta-cloth contain large amounts of Si, it is possible to clearly distinguish the contributions of either material to Si found in particles on the MLI-samples due to the fact that it is correlated with Mg in olivine and with Ca in beta-cloth. With the assumption of the olivine composition as described above the deposited material on layer 2 and 22 of MLI-sample 1972 were examined.

Figure 17 shows element maps of Si, Ca, and Mg around the impact hole on layer 22. Si and Mg are present at the same locations indicating their correlation. Otherwise, only traces of Ca can be noticed at these places. It can be concluded that the observed material is a fraction of the olivine impact residues.

Figure 18 shows analogous element maps of layer 2 of MLI-sample 1972. In this case a good correlation for Si and Ca can be found while the X-ray signals of Mg are low at the same locations. There is one exception to that correlation which is localized in the upper right part of the maps. There, for both Si and Mg high relative abundances compared to Ca are found. A comparison with the SE-image shows that layer 2 was hit by some kind of material at that location, but not perforated. Again the presence of olivine impact residues can be assumed.

To verify the results described above, additional analyses of individual particles and fragments were made. Impact residue analysis on layer 22 shows better Si-Mg-correlations than the impact residue analysis on layer 2. For layer 22, Figure 20 shows the result of an element mapping of a microscopic area at a location with high Si- and Mg-abundances. There is again a fraction of particles with clear Si-Mg-correlations. EDX-analyses of the respective particles prove these interpretations because these analyses show typical olivine compositions with dominant Mg- and Si-peaks and low peaks for Fe. Figure 21 shows a typical EDX-spectrum of these Si-Mg-correlated particles. The low Al-peak is caused by the aluminized layer 22 which is also excited since the electron beam’s penetration depth is larger than the particle sizes. In fact, it can be concluded that olivine residues have been found. In addition to these impact residues, beta-cloth-fragments and Fe-spheres were found on both analyzed layers. Dacron net fragments were only found on layer 22.
Figure 20: Element Mapping of a Microscopic Area Next to the Impact Hole on Layer 22 of MLI-Sample 1972. Three element maps are shown and labelled at the bottom. In the upper left part of the Figure the SE-image of the analyzed area can be seen. The color legend beside the maps indicates the relative abundances of the respective elements. The length of the scale bar is 50 µm. The high abundances of Si and Mg in the same particles without a Ca-correlation prove the presence of olivine impact residues.
**Figure 21: Typical EDX-Spectrum of a Fraction of Particles Found on Layer 22, Top Side, of MLI-Sample 1972.** The analyzed particles are those with Si-Mg-correlations shown in Figure 20. The measurement indicates olivine impact residues that yield dominant Si- and Mg-peaks and a low Fe-peak. The low Al-peak is caused by the aluminized layer that is also excited.

**C) Chondrule Residue Analysis at MLI-Impact 1961**

The chondrule’s exact chemical composition was not known and, therefore, attempts to find impact residues appeared to be more difficult than in the cases of well-known projectile compositions. Any particle analysis on layer 22 of MLI-sample 1961 resulted in the identification of beta-cloth or dacron net fragments, Fe-spheres or loose particles yielding EDX-spectra with solely an Al-peak. These spectra were identical to the EDX-spectrum of aluminized Kapton.

On layer 2 there are two areas beside the perforation hole that were hit but not perforated by any kind of material (see Figure D33 in Appendix D). An SE-image of the larger one of those two imprints is shown in Figure 22. There the perforation hole’s edge can be seen at the left side of the figure.
At magnifications of more than a factor of ten higher than used in Figure 22 small particles with blurred shapes have been noticed in the imprinted area. These particles appeared to have a "melt texture" and are partially bonded together. Although the morphologies of both imprinted areas are similar, the EDX-analyses yield some differences. For the smaller imprinted area, that is not shown here, the EDX-spectra of particles or of the whole area indicate beta-cloth fragments, Al-particles or Fe-spheres. Since no material containing Al is located above layer 2 in the MLI-setup, it appears that the Al-particles found are either fragments introduced during the shots, analogous to the Fe-spheres, or are contaminants of unknown origin.

EDX-analyses of the larger one of the two imprints also indicate beta-cloth fragments, but more Fe-spheres and Al-particles than for the smaller imprint. Some particles contain both Fe and Al and others are composed solely of organic material. In addition, particles were found which yield EDX-spectra like that one shown in Figure 23. The dominant elements are Si, Fe, Mg, and S. These elements and the presence of Ni match a possible composition of the chondrule. Since similar element composition were not found on any other MLI-sample the analyzed particles can be identified as chondrule impact residues. So in this case, too, impact residues could be determined.
Figure 23: Typical EDX-Spectrum of a Small Fraction of Particles Found on Layer 2 of MLI-Sample 1961. The chemical composition (Si, Mg, S, and Ni) of the analyzed particles identifies them as chondrule impact residues because similar compositions were not found on any other MLI-sample.

D) Aluminum Residue Analysis at MLI-Impact 1957

Al impact residue analyses on layer 2 of MLI-sample 1957 were successful. On layer 2 a large fraction of particles were found that are composed of Al as shown in the EDX-spectrum in Figure 24. Like on each other MLI-sample, again beta-cloth fragments and Fe-spheres were found. On layers 2 of other MLI-samples pure Al-particles could not be found except for MLI-sample 1961, which was shot with the chondrule, where Al-particles of unknown origin were determined. The Al-particles on MLI-sample 1957 can be assumed to be Al impact residues because similarly large abundances of these particles were not observed on MLI-samples that were shot with other projectiles than Al.
Figure 24: Typical EDX-Spectrum of a Large Fraction of Particles Found on Layer 2 of MLI-Sample 1957. The chemical composition points to Al-particles. The analyzed particles can be assigned to the Al-projectile because Al-particles in similarly large abundances were not found on MLI-samples which were shot with other projectiles than Al.

Figure 25 shows the result of an element mapping of a microscopic area on layer 2. This element mapping is representative for the whole impact area on layer 2. The SE-image in the upper left part of Figure 25 shows several particles with sizes of more than 2 µm. The other 3 images show the element maps of the interesting elements. By comparing these element maps most of those particles could be determined. Five particles could be identified as Al-particles and two particles as Fe-spheres.

On layer 22 of MLI-sample 1957 particle analyses were also made. There, beta-cloth fragments and Fe-spheres could be determined. EDX-spectra like that in Figure 24 could be measured for a fraction of particles but the particles’ origin could not be determined since these particles could be aluminum impact residues as well as belong to layer 22, which is aluminized. Of course, the Al-particles could also be fragments of aluminized Kaptonlayers above layer 22.
Figure 25: Element Mapping of a Microscopic Area on Layer 2 of MLI-Sample 1957. Three element maps are shown and labelled at the bottom. In the upper left part of the Figure the SE-image of the analyzed area can be seen. The SE-image shows particles with sizes of about several µm. By comparing these maps five particles can be identified as Al-particles and two particles as Fe-spheres. The color legend beside the images indicates the relative abundance of the respective elements. The length of the scale bar is 20 µm.
Conclusions

It was shown that it is possible to determine some of the parameters of a hypervelocity impact onto thermal Multi-Layer-Insulation blankets by studying crater characteristics like its dimensions or inclination. For several relationships, correlation curves have been found which can be used for calibration. Thus, it is possible to determine important characteristics of the particle environment in space by the study of impact features on satellite components retrieved from low earth orbit.

The chemical composition of particle residues can be determined on retrieved satellite components that consist of similar thermal MLI blankets. Additionally, with the knowledge of the particles’ chemical compositions, their origin - whether micro-meteoroid or man-made debris - can be determined. Consequently, by analyzing all the impact residues the relative fluxes of micro-meteoroids and man-made debris in low earth orbit can be evaluated.

References
