SPECTRAL MEASUREMENTS OF RETURNED SPACECRAFT SURFACES AND THE IMPLICATIONS FOR SPACE DEBRIS MATERIAL MEASUREMENTS

K. Jorgensen[1], R.D. Culp[2], and R.N. Clark[3]

[1]NASA/Johnson Space Center, Houston, TX 77058 USA
EMAIL: kira.jorgensen1@jsc.nasa.gov
[2]University of Colorado,Campus Box 431, Boulder, CO 80309 USA
EMAIL: robert.culp@colorado.edu
[3]U.S. Geological Survey, Mail Stop 964, Box 25046 Federal Center, Denver, CO 80225 USA
EMAIL: rclark@speclab.cr.usgs.gov

ABSTRACT

Knowledge of the physical properties of orbital debris is necessary for modeling the debris environment. Current methods determine the size and mass of orbital debris based on knowledge or assumption of the material type of the piece. By using spectroscopy, one can determine the material type of the piece by comparing the absorption features of its spectra to that of lab spectra for given materials. The goal of this research is not to improve the models themselves, but to improve the information others use to make the models.

In order to determine the effects of the space environment on the reflectance spectra of spacecraft materials, researchers measured materials from returned spacecraft. Measurements of material degradation for returned missions from the Long Duration Exposure Facility (LDEF) are documented herein. When the spectra of returned spacecraft materials were compared with the pre-flight laboratory spectra degradation in the samples were seen mostly in the visible wavelengths, while the samples showed similar features in the near-infrared. Overall, the results displayed less degradation on the spaceflight samples than anticipated. The spectral measurements of returned spacecraft materials lent credence to continuing the study of determining the material type of orbital debris using spectroscopy.

1. INTRODUCTION

Missions, like the Long Duration Exposure Facility (LDEF), have been flown specifically to determine material degradation due to the space environment. Studies on the returned spacecraft have aided researchers in gaining knowledge about the effects of thermal coatings and paints on the materials. However, spectral measurements of the returned materials are mainly in infrared and far-infrared wavelengths. Measuring the returned spacecraft reflectance spectra through the visible and near infrared would enable researchers to anticipate the altered reflectance of the [illegible] paper is to determine the effects of the space environment on the reflectance spectra in the regions: REG1, 0.5 – 1.0 µm; REG2, 1.5 – 1.8 µm; and REG3, 2.1 – 2.35 µm, and determine if the regions are valid areas to determine the material type of the piece. This paper will discuss the measurements of LDEF in the visible and near-infrared wavelength regimes. A comparison of materials pre- and post-flight will be discussed.

2. TESTING PROCEDURE AND SET-UP

The measurements of the returned spacecraft materials discussed in this paper were measured spectrally at NASA JSC in a 10,000 level clean room. The field spectrometer used for these tests was the United States Geological Survey (USGS) ASD-Spectrometer, with a range from 0.3 to 2.5 microns with a resolving power of approximately 200 (corresponding to a bandwidth of 10 nm at 2 µm) and 717 channels.

Measurements of a calibrated piece of mylar were used each day to test the wavelength stability of the spectrometer. One end of the fiber optic probe is used to take the actual measurements and can be placed at any distance from the material being measured, allowing researchers to obtain measurements of specific areas on the samples. Before each material is tested, a white reference is taken so that the measurements have common ground for comparison. For reasons of constancy and greater accuracy, the white reference and the material are placed at the same distance from the probe. The angles of incidences for the lamp as well as for the probe are noted. The field spectrometer is configured so that a spectrum is taken every tenth of a second. Every six seconds, the spectra are averaged and the result is graphed on the computer screen for the researcher to see near real-time spectra of the sample. Each sample's averaged spectra is recorded approximately three times and averaged again later into one spectrum.

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3. LDEF

3.1 Orbital and Design Characteristics

LDEF was deployed on April 7, 1984 by the Space Shuttle STS 41-C and was designed to determine the effects of the space environment on long-term spacecraft. Due to the Challenger explosion and other planning difficulties, the LDEF remained in space for approximately 5.7 years, rather than the originally-planned retrieval date sometime in March of 1985, just less than one year in orbit. The satellite was at a mean altitude of 465 km and an inclination of 28.5 degrees [1]. LDEF orbited Earth in a fixed position where the long side of the spacecraft was pointed away from Earth with specific rows (nine and ten) in the ram-facing direction. Dependent on the fixed geometry and the constant flight attitude of the LDEF, the angle of incidence for each experiment tray was fixed controlling the amount of atomic oxygen (AO) and estimated solar hours (ESH) on each row and bay of the spacecraft [2]. LDEF contained 57 exposure experiments and had 150 m^2 of exposed surface area. On this surface area were materials of interest to spacecraft designers such as aluminum, other metals, polymers, composites, ceramics and glasses, as well as various coatings and paints. Aluminum 6061 covered 75% of the exposed surface area, while the bolts, fasteners, trunnions, keel pin, and end-support beam spindle were made of nonmagnetic 303 stainless steel. The experiment trays housed a variety of material types some of which will be discussed in this paper.

Two main space environment factors discussed in this paper are the direct solar, calculated through the Estimated Solar Hours (ESH) and the Atomic Oxygen (AO) found in the residual atmosphere. The Earth's albedo is included in LDEF's calculation of ESH for the Earth-facing end. The fluences of atomic oxygen vary by 19 orders of magnitude from the leading edge to the trailing edge. The largest number of ESH was seen in the space end and the smallest number in the earth-facing end. Among the trays, rows nine and three were at opposing ends for total ESH [3]. As a note, rows twelve and six were most affected by the seasonal changes of the Sun and Earth orientation.

3.2 Spectral Measurements of LDEF

NASA JSC houses most of the LDEF structure and a few experiment trays. Measurements were taken of approximately 80 samples, including aluminums, other metals, composites, and paints. For each sample, exposed and unexposed measurements were taken when applicable, resulting in more than 180 spectra of LDEF materials. The measurements were conducted in a 10,000 level clean room at NASA JSC. The following sections discuss the specifics of the spectral

3.2.1 Experiment Trays

Under the category of experiment trays lay a vast number of material types. Any single material, grouping of materials, or sheet of material between the frames is considered an experiment tray. Because of the extensive number of materials in the experiment trays, only a few will be discussed in this section.

Fig. 1 displays the reflectance spectra for two different areas of experiment tray H12E00. This tray was part of an experiment testing heavy ions in space and was located closer to the ram direction than the anti-ram. The portion the author tested was composed of a lexan sheet covered by a Chemglaze II white painted Multi-layer Thermal Blanket (MTB). Chemglaze II is an inorganic paint held to the MTB with an organic-based binder. During the mission, the tape holding the MTB in place deteriorated allowing the MTB to curl back upon itself exposing the underside of the MTB and the lexan sheets to the space environment. The blankets that had not curled back were a medium-brown color, while the portions that had peeled back showed brown and white sections. The lexan sheets, due to the space environment exposure, also displayed discolorations. Fig. 1 shows a more exposed and less exposed section of the lexan sheet. The terms used were denoted by the visual color of the section seen while taking the measurements. The more exposed regions were browner than the less exposed regions. The color difference is seen in the visible section from 0.4 to 0.8 µm. Using the regions necessary to determine the material type through on-orbit measurements of debris pieces, the differences in the spectra are slight in this sample. The space environment does not affect the strength of the absorption features in REG2 and REG3, which are used to differentiate plastics and epoxies from the metals, for lexan sheets. Strong C-H (Carbon Hydrogen) bands are seen at 1.6 and 2.1 µm in both the more exposed and less exposed samples of lexan.

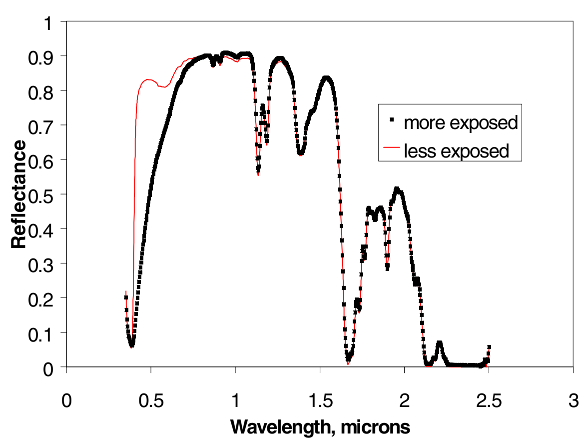

Fig. 1. Lexan Experiment Tray H12E00.

Fig. 2 shows another plastic, Polyetheretherketone (PEEK), flown as part of experiment number A0171 in experiment tray A8 (near the ram direction). This sample was obtained from Marshall Space Flight Center (MSFC); accompanying the sample was a control piece of PEEK. When compared to the control sample, the flown sample shows a decrease in the total reflectance as seen in Fig. 2. A slight discoloration is seen on the exposed sample near 0.55 µm and was noted visually while testing the sample. A comparison of the strengths of the absorption feature in REG2 (near 1.7 µm) shows the C-H band decreasing in the flight sample. The feature is still apparent and still strong enough to detect through on-orbit observations, but is definitely not as strong as it was prior to flight. The C-H features in REG3 (near 2.1 and 2.35 µm) are both the same strength in the control and flight samples. When the regions deemed necessary for determining the material type of orbital debris through on-orbit spectral measurements are examined, it appears that the space environment does not change significantly the absorption features seen in plastics in those regions.

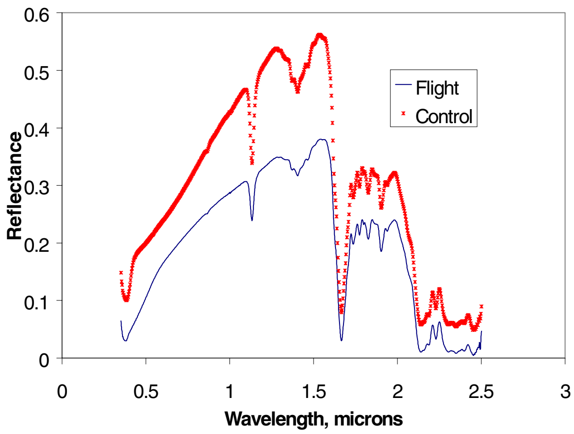

Fig. 2. PEEK, Control and Flight Sample.

3.2.2 <u>Clamps</u>

Clamp assemblies attached each tray to the LDEF structure. Some of the clamps had white discs painted on their surfaces as a visual aid for spacecraft motion. The discs were painted with Chemglaze A276 white paint on top of Chemglaze Z306 black paint. Fig. 3 shows the reflectance of four clamps with the white painted discs. Visually, the discs on the anti-ram direction (rows two through five) had turned a gold color, while the discs on the ram direction had appeared to remain white. However, curators of the LDEF samples told the author, the painted discs began white and then turned gold due to the environmental effects of space [2]. The samples in the ram direction were believed to have had all of the organics erode from the sample, returning the disc to its original white color solely due to the pigment in the paint. The initial researchers believed the samples in the anti-ram direction did not experience enough AO to see the cycle through completion. However, in Fig. 3, the organics are still present in the spectra for all of the samples, those visibly white (D11C03 and D10C03) as well as the samples those visibly gold (H11C02 and D06C03). One difference seen in the samples, other than the change in reflectance, is the drop in the visible region seen in the gold samples. The widths of the absorption features due to C-H, seen at 1.7225 and 2.3 µm, are very similar in all four samples, however, the banddepth of the features vary. The H11C02 sample received more ESH than the other three samples, while receiving one order magnitude less of AO than the two samples than remained white in color. This could be evidence that AO is more of a factor in changing the color of the paint than ESH. The absorption features found in REG2 and REG3 used to delineate the paints from the aluminums are still strong despite earlier notions that the organics were eroding in the ram direction. In three of the samples, the classic aluminum feature is present, and is strongest in the samples in the ram direction. If this feature was apparent in the on-orbit sample, researchers would be able to tell not only what color paint was being used, but what the substrate was as well. The structures of all four samples shown are encouragingly similar; strengthening the hypothesis that researchers can determine material composition from reflectance spectroscopy.

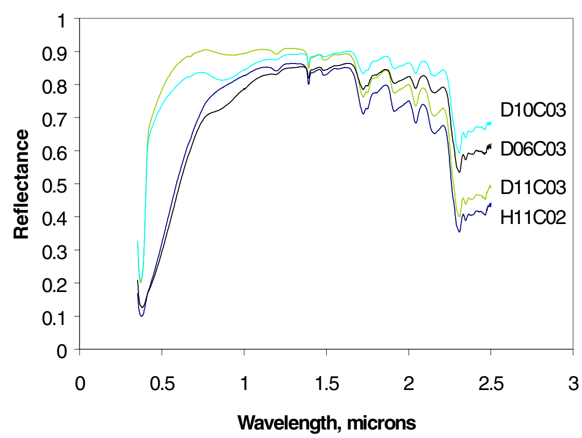

Fig. 3. White Paint on the Clamps on LDEF.

3.2.3 <u>Frame</u>

Thirteen pieces of the LDEF frame were measured for specular reflectance from various locations on the spacecraft. No measurements were made of pieces from the Earth or the Space end on the spacecraft, because none was available at JSC. The frame of LDEF was composed of 6061-T6 chromic anodize aluminum similar to the composition of the clamps. Measurements were taken of the exposed and unexposed portions of each piece of frame. Some of the exposed samples had stronger "nicotine" stains visually, apparently due to outgassing of the experiment it surrounded. One those samples, measurements of the brownest sections and the clearer sections were taken as seen in Fig. 4.

The unexposed frame as well as the exposed sample but to a lesser extent, show spectral features from 0.3 – 0.6 µm. Since 6061 Aluminum not associated with LDEF showed no such features, the author believed the absorptions were due to the coating on the LDEF frame. However, upon examination of the coating on a piece of 6061 aluminum not part of the LDEF materials, the author noted that the specular features were not present in that spectrum. Therefore, the features in the short wavelengths of the visible region are not due to the coating the literature claims was on the clamps and the frames [4]. It is possible that the pieces were treated with something other than what was documented, which might be the cause of the features. In the samples where the "nicotine" stain was visibly darker, the specular features are virtually nonexistent as seen in Fig. 4. Therefore, the author believes that the outgassing from the experiment tray surrounding these pieces of frame not only stained the pieces but also eliminated the product causing the absorption features. Unfortunately, the clamps surrounding the experiment trays in question were not measured and therefore the belief remains an assumption based on the facts available. Although these features are not within REG1, this researcher believes noting the feature is necessary.

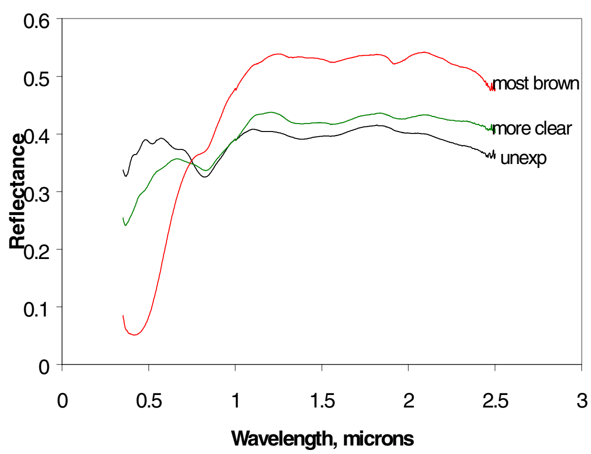

Fig. 4. "Nicotine" Stained Frame Sample.

Also seen in the samples is the feature at 2.3 µm, which is a classic feature due to aluminum hydroxyl (AL-OH) [5,6]. This feature is seen most strongly in the sample with the most degradation and should be used to further delinate aluminum from metals and plastics.

A shift in the aluminum feature normally found near 0.8 µm is from the exposed to the unexposed sample seen in Fig. 4. In this sample, the shift is slight. Some of the samples show longer and shorter shifts.

Prior to looking at the frame samples, the author postulated three hypotheses, one dealing with amounts of AO and ESH, another was outgassing of the experiment trays, and the final dealing with an undocumented coating. Although more testing should be done to clarify the reasons for the shifts, the author is more inclined to believe that the unknown coating thought to be causing the features in the visible spectral region is the cause of the shift in the aluminum features also.

4. CONCLUSION

General conclusions of all the LDEF materials are difficult because of the varying responses observed in the reflectance spectra. It is impossible to select only one element of the space environment and test its effect on the materials unless the study is conducted in a laboratory. Although laboratory studies would lend insight into the individual aspects, the implications are not strong because of the possible synergistic effects of ESH and AO. Overall, ESH and AO do not affect the strength of absorption features appearing at wavelengths longer than one µm. In general, if changes in the features are seen it was occurring in wavelengths shorter than one µm. The paints and plastics were more affected by the space environment than by the metals, as far as strengths of absorption features are concerned. Some of the paint samples had a visible change in color; the author speculates that the organics in the paints were eroding away due to the AO; however, the author saw no change in the organics absorption features of the paint samples that would confirm this speculation. On some paint samples the aluminum substrate becomes apparent in the spectra, leading the author to believe that layers of the paint were eroding off as more time was spent in space. According to the measurements of the LDEF samples, REG2 and REG3 prove to be valid regions to delineate the plastics and paints from the metals. Any major changes observed in the strength of absorption features was seen in wavelengths less than one µm, which means the basic chemical bonds are not broken.

Although the aluminum did not see a change in the strength of specific absorption features, some of the aluminum samples displayed a shift in the main aluminum absorption feature normally found near 0.8 µm. Sometimes the feature was found at a shorter wavelength and sometimes at a longer one, but no dependence on the amount of AO or ESH nor a combination of the two could be determined. Observations of the Al-OH stretch located near 2.2 µm furnished another reason to use REG3 as a delineator of material types. Coatings placed on the metals affect the total reflectance and the strength of the aluminum feature seen in REG1. However, the database compiled includes these coatings on various types of aluminum and therefore, the darkening of the materials will be anticipated.

Overall, a change in total reflectance was noted in most of the samples, but again a clear connection of changing the amount of AO or ESH or a combination of the two could not be determined. The change in reflectance was not as strong as researchers have seen in on-orbit measurements of debris pieces [7]. The debris pieces measured were fragmentation pieces, with varying angles believed to be causing shadows and thereby darkening the overall reflectance of the pieces. This darkening effect due to shadows has been seen in many observations of asteroids [8] and could be a reason for the darker measurements. Also, the debris pieces were measured at nonoptimal angles, which could also cause the decrease in reflectance. However, the discrepancy lends credence to the plan to conduct a study of remotely sensed orbital debris reflectances. The debris objects may in fact be less reflective, near 0.1, in orbit, but the reflectances of the LDEF materials tend to be much higher.

Using the three wavelengths regions REG1 (0.5 – 1 μm), REG2 (1.5 - 1.8 μm), and REG3 (2.1 - 2.35 μm) material type of orbital debris can be determined. The materials can be placed into at least three categories based on the absorption features present. Depending on the resolution of the system used to detect the spectra, further separation of materials within the three categories is possible. Degradation of spacecraft materials changes the materials' spectrum slightly. These changes are documented in the author's database and will be anticipated when on-orbit observations begin.

Due to the large number of LDEF samples measured, not all of the samples' spectra were shown in this paper. The database in entirety is available in paper form [9,10] and will be made available eventually on the USGS web site (http://speclab.cr.usgs.gov/).

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Drolshagen, G., McDonnell, J.A.M., Stevenson, T.J., Deshpande, S., Kay, L., Tanner, W.G., Manderville, J.C., Carey, W.C., Maag, C.R., Griffiths, A.D., Shrine, N.G., and Aceti, R.: 1996, Optical survey of micrometeoroid and space debris impact features on EURECA, in *Planetary and Space Sciences*, Vol. 44, no. 4, pp. 317-340.

2. See, T.H., Zolensky, M.E., Hörz, F., Bernard, R.P., Leago, K.S., Warren, J.L., Sapp, C.A., Foster, T.R., and Kinard, W.H.: 1994, The LEO Particle Environment as Determined by LDEF, in *Proceedings of Space 94 Conference, Engineering, Construction, and Operations in Space IV*, 1994.

3. Bourassa, R.J., Gillis, J.R., and Rousslang, K.W.: 1991, Atomic Oxygen and Ultraviolet Radiation Mission Total Exposures for LDEF Experiments, in *Proceedings of LDEF--69 Months in Space, First Post-Retrieval Symposium*, NASACP 3134, Kissimee, FL, 2-8 June 1991.

4. See, T., Allbrooks, M., Atkinson, D., Simon, C., and Zolensky, M.: 1990, Meteroid and Debris Impact Features Documented on the Long Duration Exposure Facility: A Preliminary Report, NASA Johnson Space Center publication #24608.

5. Clark, R.N., King, T.V.V., Klejwa, M, and Swayze, G.A.: 1990, High Spectral Resolution Reflectance Spectroscopy of Minerals, *Journal of Geophysical Research*, Vol. **95**, no. B8, 10 August 1990, pp. 12,653-12,680.

6. Clark, R.: 1999, *Manual of Remote Sensing,* A. Rencz, ed., John Wiley and Sons, Inc.

7. Henize, K.G., O'Neill, C.A., Mulrooney, M.K., and Anz-Meador, P.: 1994, Optical Properties of Orbital Debris, in *Journal of Spacecraft and Rockets*, Vol. **11**, July – August, pp. 671-677.

8. Lambert, J.V.: 2000, Private Communication.

9. Jorgensen, K.: 2000, Reflectance Spectra for Common Spacecraft Materials and Returned Spacecraft Materials, Technical Report, University of Colorado, Boulder, Colorado Center for Astrodynamics Research, April 2000, Interim Research Report no. SD-04.00-01KJ.

10. Jorgensen, K: 2000, Using Reflectance Spectroscopy to Determine Material Type of Orbital Debris, Ph.D. dissertation, University of Colorado, Boulder, Colorado.