ONGOING EUROPEAN DEVELOPMENTS ON ENTRY HEATSHIELDS AND TPS MATERIALS

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ABSTRACT

The paper combines an overview on two elements of current European developments for heatshields of atmospheric entry probes and TPS materials. The first part describes the current status of the heatshield development for the European ExoMars EDL demonstrator module. In the second part the ongoing development of a European low-density ablative material for extreme heat flux applications is described.

PART 1: HEATSHIELD DEVELOPMENT FOR EXOMARS EDL DEMONSTRATOR MODULE (EDM)

1.1 Introduction – ExoMars Mission Overview

The revised joint ESA-NASA ExoMars program now includes two launches. In January 2016 a European composite spacecraft is planned to be launched consisting of an ESA-supplied Trace Gas Orbiter (TGO) and a European EDL Demonstrator Module (EDM). The composite will be launched by an Atlas V-431. In 2018 a NASA-supplied carrier-spacecraft, launched from an Atlas V-551, is planned to deliver a joint ESA-NASA rover module to the surface of Mars.

The EDM constitutes a technology platform whose main goal is to allow Europe to acquire a Mars landing capability and demonstrate the EDL technologies needed to carry large payloads to the Martian surface. These include heatshield, parachute system, Doppler radar system for ground relative altitude and relative velocity measurement, liquid propulsion system for attitude control and final braking, and crushable materials for impact loads attenuation.

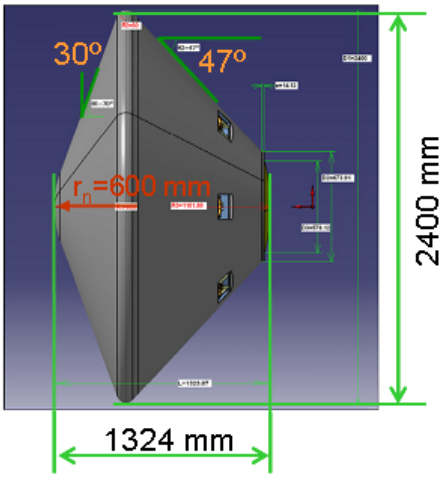

Figure 1-1: EDM aeroshape design

The EDM will have an entry mass of 600kg with a heatshield diameter of 2.4m. The aeroshape design is shown in figure 1-1. The heatshield will consist of a composite aeroshell covered by a lightweight cork-based ablator. It will be designed in order to withstand not only the aerothermodynamic entry loads with peak heat fluxes of about 2 MW/m^2 in CO_2 atmosphere, but also to survive the possibility of a severe dust storm during entry, thereby allowing an arrival during a global dust storm season.

1.2 TPS Material Selection

The thermal protection material selected for both, the frontshield and the backcover, is Norcoat Liège. This material has been developed by EADS Astrium and is made from cork powder impregnated with phenolic resin. It has flown on the European Atmospheric Re-entry Demonstrator (ARD) and is used for Ariane-5 and French ballistic missiles. Further, relevant

qualification for Martian entry was previously performed under the Beagle-2 and Netlander programs.

During an initial trade-off Norcoat Liège resulted in a simpler design, an easier implementation and a lower mass than alternative available materials, AQ60 and Picsil.

In order to comply with the planetary protection requirements, a dedicated outgassing and sterilization process is performed, resulting in the outgassed Norcoat Liège HPK FI. The material density is 450 kg/m^3.

The TPS tiles are individually machined on all six faces. The tiles are individually bonded to the structure with the silicone glue ESP 495 and the application of a vacuum bag. The glue material has been selected based on a dedicated trade-off and sample test campaign taking into account mechanical bonding performance, work time, availability and maturity. The same glue is used to fill the gaps between the tiles.

1.3 Frontshield Design

The preliminary frontshield TPS layout is shown in figure 1-2.

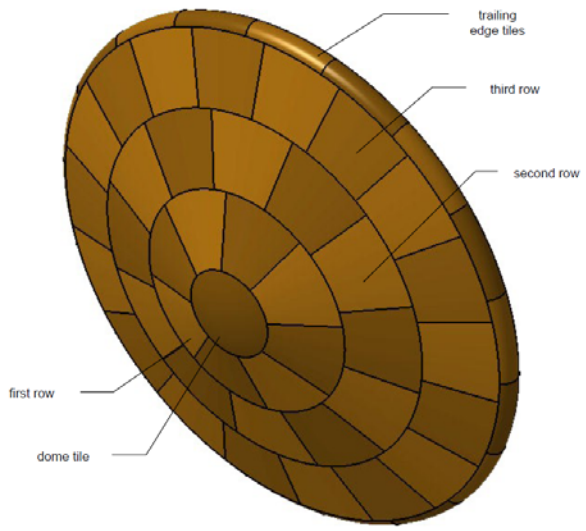

Figure 1-2: Frontshield TPS layout

The frontshield TPS is composed of 57 tiles, applying five different types of tiles. The tiles are bonded in staggered rows to avoid longitudinal flow. A trade-off is still ongoing on straight versus inclined joint lines at the tile-tile interfaces.

The frontshield structure is a 20mm sandwich composed of an aluminum honeycomb and CFRP skins. The design is based on the heritage from Huygens. The structure will be provided by EADS-CASA Espacio in Spain. The temperature limit specified at the frontshield shell is 180°C (qualification limit).

1.4 Backcover Design

The preliminary backcover TPS layout is shown in figure 1-3.

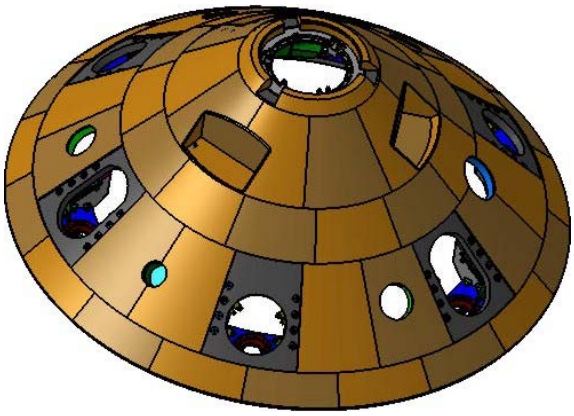

Figure 1-3: Backcover TPS layout

The backcover TPS is composed of 89 tiles made in Norcoat Liège. In addition two tiles made in the silicone-based Norcoat 4011 are applied over the antennas, which are integrated in two of the access doors. Norcoat 4011 is chosen here in order to limit the attenuation of the radio signal. 16 main shapes are applied, plus an additional 29 sub-tiles linked to specific cut-outs and interface points, including the parachute container and brake-out patch, three openings for the interface brackets to the orbiter module, and various circular and oval access doors dedicated to handling, access to the frontshield interface brackets and the fill-and-drain valves. Further openings are foreseen for the Sun sensor (used during cruise) and a venting filter. Figure 1-4 illustrates the closure of one of the access doors.

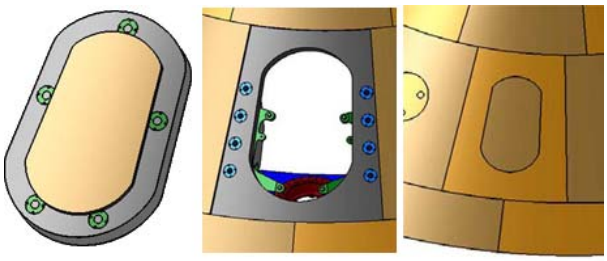

Figure 1-4: Closure of an access door

The backcover structure is provided by the prime TAS. It is made of a 25mm sandwich structure composed of

an aluminum honeycomb core and CFRP T300/M18 skins. The skin thickness varies from 0.6mm to 1.8mm at local reinforcements. The temperature limit specified at the backcover cone is 130°C, respectively 100°C in reinforced areas. For the base and the parachute break-out patch a limit of 70°C has been specified (qualification limit).

1.5 TPS Sizing

The TPS sizing is currently updated. The information provided below represents therefore a preliminary snapshot. TPS sizing is performed by Astrium using the Amaryllis ablation tool, which is part of the SAMCEF software suite. The sizing is based on elementary material characterization.

The initial temperature of the TPS at the begin of the atmospheric entry phase is assumed to be at -40 ºC for the frontshield and at -20 ºC at the backshell. Radiation to the Mars sky has been considered with a radiative sink temperature of -80 ºC.

Temperature limits at the TPS-structure interfaces are described in chapter 1.3 and 1.4 above. A margin of 10 ºC is considered for the TPS sizing.

The following margins are taken into account on top of the computed minimum TPS thickness:

- Material and model uncertainties (~15-20%)
- Manufacturing thickness tolerance (0.2mm)
- Margin for dust erosion (3.5mm, frontshield only)

The latter margin for dust erosion is taken into account due to the arrival during a global dust storm season. The value has been derived from a series of dedicated plasma test campaigns in the L3K plasma wind tunnel at DLR with addition of dust particles of various materials, diameters and masses (see figure 1-5).

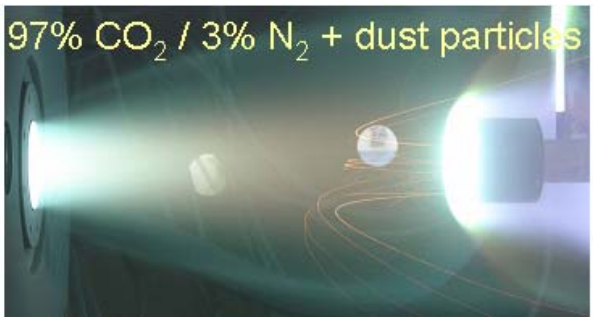

Figure 1-5: Plasma test with dust particles

Figure 1-6 shows the preliminary TPS sizing results. For the backshell results are omitted here due to a currently ongoing design iteration taking into account an updated sizing trajectory.

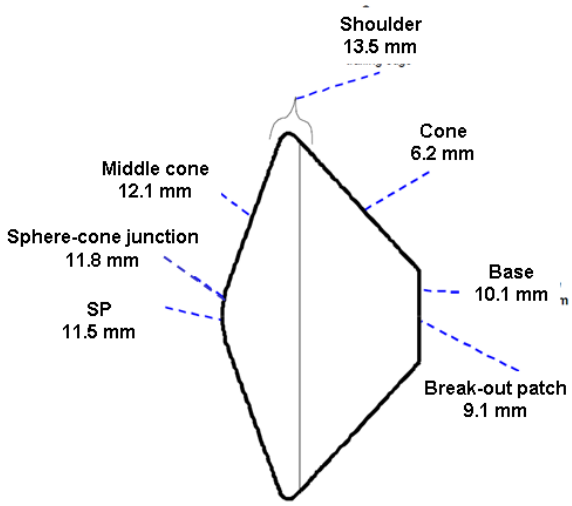

Figure 1-6: Preliminary TPS sizing results (including margins)

1.6 Verification Testing

The thermal justification for the TPS design is mainly done by analysis. Based on the heritage mentioned in chapter 1.2 the TPS material had already a high maturity at the begin of the ExoMars heatshield development.

Nevertheless, delta-qualification was required to verify the performance of the materials and the design under the expected heat fluxes of up to about 2 MW/m^2 at the stagnation point. In addition, delta-qualification of the TPS material was required after the specific sterilization process needed to cope with the ExoMars planetary protection requirements. Further, extension of material testing towards very low temperatures expected during the cruise phase (down to -110 ºC) is necessary.

The following test program was defined:

- Plasma tests (development and qualification) on representative assemblies based on sterilized and aged Norcoat Liège
- Mechancial and thermal characterization of sterilized and aged Norcoat Liège
- Mechanical characterization of TPS mounted on structure to check bonding performance and compatibility between TPS and structure

The plasma tests are performed in the Simoun facility at Astrium. In the following some main elements of the plasma test program are described.

Plasma tests for frontshield TPS

Plasma tests at assembly level for the frontshield TPS are performed in air atmosphere instead of CO_2. Since testing in CO_2 requires a considerably higher electrical power than in air, the achievable heat flux in Simoun under CO_2 is limited to about 1 MW/m^2. A dedicated campaign was therefore performed on identical wedge samples and under identical test conditions in order to compare the material behavior in air and CO_2. The results demonstrated that under air and CO_2 outgassed Norcoat Liège shows a very similar behavior in terms of material final aspect (including micrographic analyses), measured temperatures and thermal performance, and the final surface recession. It was therefore concluded that testing in air is representative for the frontshield TPS behavior under CO_2.

A dedicated test campaign was performed to verify the frontshield TPS design under a heat flux profile representative to the expected worst case entry. Two different configurations have been tested to assess the influence of the orientation of the inter-panel joints. One sample was realized with joints in the direction of the flow while on the second sample the joints were inclined by 20° (see figure 1-7).

The tiles of both test items were bonded with ESP495 as foreseen for flight. Also the inter-tile joints were filled with ESP495.

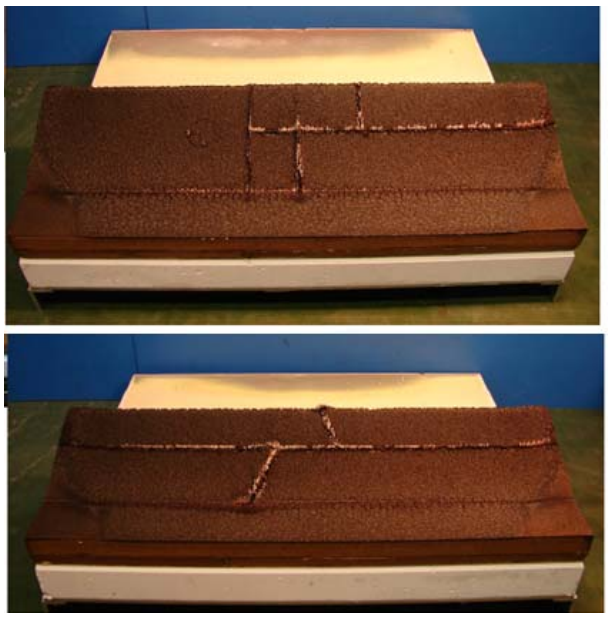

Figure 1-7: Plasma test samples after test with straight (top) respectively 20°-inclined (bottom) joint lines

A heat flux profile with a peak cold wall heat flux of about 1.8 MW/m^2, a total heat load of 58 MJ/m^2 and a wall pressure of about 200 mbar has been applied.

A relatively homogeneous recession was observed on both samples, with an identical total ablation. No significant loss of the inter-tile filler material occurred. However, a clearly visible crust formation has been observed along the inter-panel joints laying in flow direction. These crusts are very similar are very similar on both samples. Analytical evaluation of the influence of these crusts on the aerothermodynaic behavior is still ongoing. However, preliminarily it can be concluded that the test did not show any significant advantage or disadvantage for either of the two tested concepts.

A dedicated post-test thermo-ablative analysis campaign has been performed. The outcome showed conservatism with respect to previously predicted backface temperatures and recession. Based on the test results the thermal, pyrolisis and ablative response model has been correlated and eventually an improved model been developed. A comparison of results from the improved model with the test data is shown in figure 1-8. The mismatch in the onset of the outermost thermocouple reading is believed to be due to a slight uncertainty of the thermocouple position.

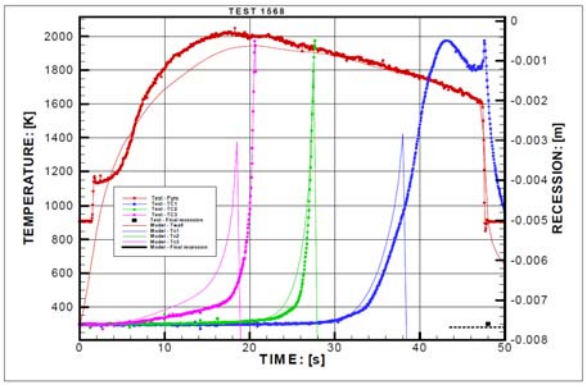

Figure 1-8: Measured and predicted temperatures after model correlation and improvement

Plasma tests for backcover TPS

Dedicated plasma tests are also performed on TPS samples representative for the backcover TPS. The objectives of these tests are to improve the knowledge on the material behavior at low heat fluxes (without ablation) and to verify and consolidate the design of the backcover tiles pattern, particularly the interface between Norcoat Liège and Norcoat 4011 as used for the antennas.

The tests for the backcover TPS are performed in CO_2 atmosphere. As an example one test is described below. The test sample design is shown in figure 1-9. It comprises typical tile to tile interfaces and includes one

tile made in Norcoat 4011 as used over the antennas. The sample was exposed to a heat flux profile corresponding to the shallow entry trajectory with a peak cold wall heat flux of about 72 kW/m^2 and a total heat load of about 5.5 MJ/m^2.

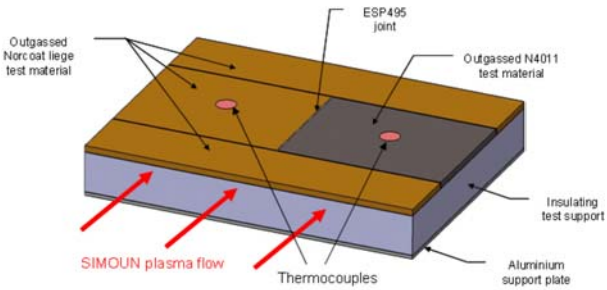

Figure 1-9: Backcover TPS test sample with Norcoat Liège tiles and one Norcoat 4011 tile

Figure 1-10 shows the sample after the test. The post-test appearance is very satisfactory. Surface charring with a typical periodic roughness pattern is visible, however no unexpected ablation occurred. A homogeneous light swelling over the Norcoat liege tiles is observed. No joint material has been lost. Also no unexpected behaviour was observed on the Norcoat 4011 tile.

The post-test analysis campaign confirmed that the material model for the outgassed Norcoat Liège, as refined after the frontshield plasma test campaign, can be applied without modifications also for the significantly lower heat fluxes expected for the backcover.

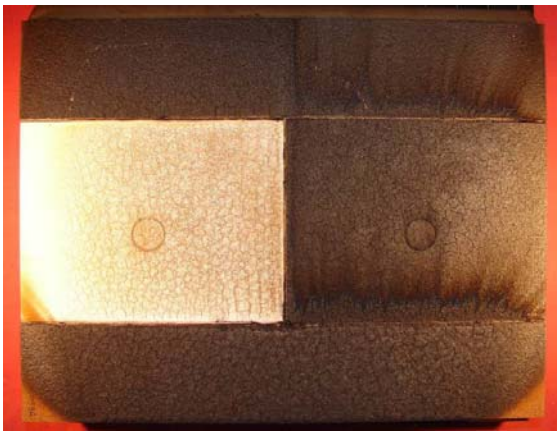

Figure 1-10: Backcover TPS test sample after test

1.7 Instrumentation

A set of entry system sensors will be integrated in the heatshield allowing to reconstruct part of the entry environment and the TPS response. The following sensors are currently foreseen:

On the frontshield:

- 7 thermal plugs including 3 thermocouples
- 7 thermistors
- 5 pressure sensors

On the backcover:

- 7 thermal plugs including 2 thermocouples
- 3 thermistors
- 5 pressure sensors

The implementation of potential further sensors is being assessed, but today not confirmed. This might include a combined aerothermal and calorimeter sensor unit (pressure, temperature and total heat flux), a radiometer sensors (radiative flux) and recession sensors.

PART 2: DEVELOPMENT OF A EUROPEAN LIGHTWEIGHT ABLATIVE MATERIAL FOR EXTREME HEAT FLUX APPLICATIONS

2.1 Introduction

Various sample return mission scenarios have been studied in recent years (e.g. Mars, comets, asteroids). Most recently the ESA Cosmic Vision program has selected a revised version of MarcoPolo as one of four candidates for a medium-class mission planned to launch in the period 2020-22. MarcoPolo-R is a mission to return a material sample from a primitive near-Earth asteroid (NEA) for detailed analysis in ground-based laboratories.

The Earth return from extraterrestrial bodies involves a hyperbolic trajectory resulting in atmospheric entry velocities of typically around or above 12 km/s and resulting peak heat fluxes in the order of 10-20 MW/m^2 with dynamic pressure loads up to around 800-1000 mbar. In addition, since the Earth return capsule is subject to a “double” delta-V (to the object and back to Earth), the return capsule and its heatshield have to conform to a very stringent mass budget.

The capability to design and manufacture the heatshield for future sample return missions is considered of high importance allowing Europe to play a significant role in potential international cooperation’s. ESA has therefore initiated a dedicated activity aiming at the development of a European lightweight ablative material for extreme heat flux applications. Following an initial review, technological

development has been initiated for two candidate materials, ASTERM (EADS-Astrium, F) and MonA (Lockheed Martin UK Ampthill). The development is coordinated by HPS, Portugal.

2.2 Load Assumptions and Requirements

The current material development is targeted towards sample return missions. Other applications, like a Venus exploration mission or a manned crew space transportation system, might later be considered depending on the material characteristics achieved.

The main technical driver for the material development is its capability to withstand the expected entry environment while keeping the heatshield mass at a minimum. Resulting from relevant mission studies (MSR, MarcoPolo), a peak heat flux of 14 MW/m^2 at a dynamic pressure up to 800 mbar in air have been specified for the current development phase. Depending on the mission design and resulting entry velocity, both values could eventually be higher. The above requirements therefore represent a compromise such to allow relevant material testing in existing facilities.

In terms of performance an area mass target of 15 kg/m^2 was defined for a given entry heat flux profile (total heat load ~250 MJ/m^2) while providing adequate thermal protection for the underlying structure (considering a structure temperature limit of 250°C).

In order to guarantee an unrestricted use of the final material by ESA, the availability of all base materials and manufacturing processes inside ESA member states as well as the non-restricted use of fabricated products is considered as an important criterion.

During the initial selection of potential development approaches only those options were considered which indicated that TRL 5 could be reached until 2011.

The complete set of requirements further comprises ablation performance, mechanical, material, interface, environmental, physical, PA and design requirements.

2.3 History and Development Approach

Within an ESA-Aurora study back in 2004-5 led by Astrium it was evidenced that none of the existing European ablator materials was able to cope with the expected severe entry environment while simultaneously fulfilling the stringent mass requirement of a sample return mission. A dedicated Development of a European Ablative Material (DEAM) has therefore been initiated by ESA in 2008.

Figure 1-1 shows the initially foreseen development logic within DEAM. An initial development was performed on two materials, ASTERM and MonA. As indicated in figure 2-1 it was then foreseen to continue the development for only one material. However, after a common plasma test campaign and a subsequent trade-off both materials were found to have high potential but also involving specific risks. It was therefore decided to continue the development and characterization for both materials.

At the time of writing the characterization test campaign is in preparation. In parallel a demonstrator design has been defined. The demonstrator manufacturing will only be done with the ASTERM material.

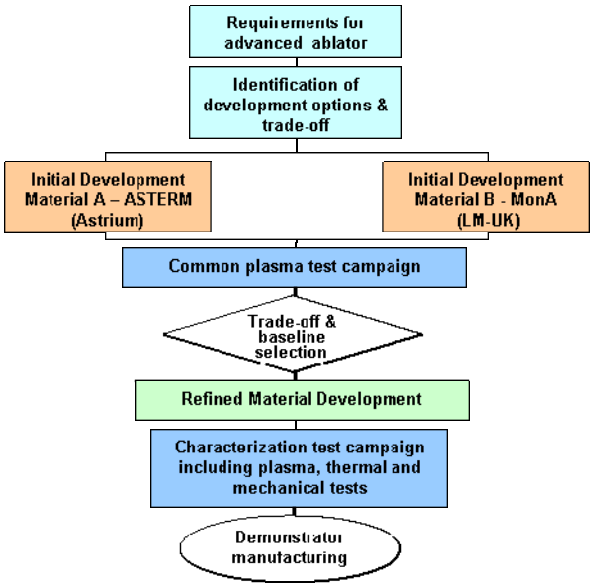

Figure 2-1: DEAM Initial Development Logic

2.4 ASTERM Development by Astrium

Following the above mentioned Aurora-study, Astrium initiated an internal R&D for an Ablator for Rapid Earth Re-entry (ARER). Following successful first plasma tests, the ARER development is continued under the support of internal R&D and in parallel within the ESA-DEAM activity. The material is in the meantime referred to under the trademark ASTERM. The development is based on the heritage from the AQ61 material (previously developed by Astrium), which represents a low density carbon-phenolic material manufactured by impregnating large pieces of carbon felts compressed to the right density during the impregnation process.

Opposed to this, the ASTERM material is manufactured by impregnating a rigid graphite felt

with phenolic resin, which is followed by a polymerisation process and final machining. This approach significantly reduces the manufacturing effort compared to AQ61 and allows a large scale production. The ASTERM material is entirely using standard European raw materials and available Astrium facilities.

An ASTERM material sample is shown in figure 2-2. The manufacturing approach allows a large range of final material densities, from 240 kg/m^3 to 550 kg/m^3. Successful plasma tests have been performed for samples with 350 kg/m^3 (see chapter 2.7), while the material manufacturing at 280 and 420 kg/m3 has also been demonstrated at sample level. Currently efforts are continued to improve the maturity of the material. This focuses in particular on an improved homogeneity of the graphite felt.

Figure 2-2: Large ASTERM material sample

2.5 Mon-A Development by LMUK Ampthill

The MonA (Monolithic Ablator) material has previously been developed and partially qualified by Lockheed Martin Space Systems (LMUS Denver) for potential use on the NASA aeroentry missions, including the Orion Manned Capsule. LMUK Ampthill has been granted the opportunity to transition the material into Europe. A TAA (Technical Assistance Agreement) and an MLA (Manufacturing License Agreement) have been placed allowing LMUS Denver and LMUK Ampthill to exchange information concerning the material composition and the manufacturing process.

MonA is a carbon-phenolic material that is structurally reinforced by packing it into a phenolic honeycomb (Flex-Core ©), see figure 2-3. The overall density can be adapted in a range of 280 to 320 kg/m^3.

In a first step arc jet tests were performed on coupons which were manufactured out of MonA panels manufactured by LMUS Denver (see chapter 2.7). In parallel, European suppliers have been identified and selected for adequate constituent raw materials. The processes and methodologies to manufacture a EuMonA out of the European raw materials have been established at LMUK Ampthill. MonA sample material has been manufactured by LMUK Ampthill using the European sourced raw materials, and the physical similarity to the US MonA been demonstrated by laboratory tests.

Currently the processing methods at LMUK Ampthill are refined to produce a homogeneous material. Coupon and plate samples are planned to be produced and submitted to the test campaign described in chapter 2.7.

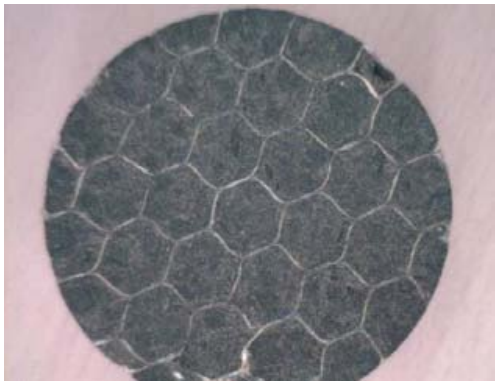

Figure 2-3: MonA material sample

2.6 Mathematical Modelling

Mathematical modelling of both materials has been initiated by FGE (Fluid Gravity Engineering, UK) using FABL (Fluid Gravity's ABLation code), based on implicit final difference models. The code uses a multi-component Arrhenius decomposition model and allows to model the in-depth response and the surface recession of the material. The intention is to perform pre- and post-test analysis of the planned arc heater test campaign (see chapter 2.7), and to support further improvement of the materials by numerical results. In addition, in case of ASTERM, it is planned to compare the material performance to the one of the American PICA material.

2.7 Material Testing

As shown in figure 2-1 a common plasma test campaign was performed on both materials after completion of the initial development phase. Tests were performed in two different plasma test facilities, the L3K facility at DLR Cologne and the PWK-RD5 at

IRS in Stuttgart. The PWK-RD5 is a magnetoplasmadynamic (MPD) plasma wind tunnel and can be operated at the specified 14 MW/m^2. However, related pressure levels are only around 40 mbar and therefore significantly lower than the expected levels during the Earth re-entry of a sample return capsule. On the other side, the L3K facility at the time could operate at the specified pressure level of 800 mbar, but only reaching heat flux levels of around 8-10 MW/m^2. Also slightly higher heat flux levels were reached, but at too high pressure levels.

The tested condition are summarised in figure 2-4. Images of test samples after test are shown in figure 2-5 for ASTERM and 2-6 for MonA. The density of the tested ASTERM samples was 350 kg/m^3, the one of the MonA samples was 300 kg/m^3. As can be seen both materials showed a good performance and a rather homogeneous ablation behaviour. Some small damage can be seen on the perimeter of the MonA sample tested at 10 MW/m^2, which however is considered to be fully related to the test approach, due to the exposed open honeycomb cell.

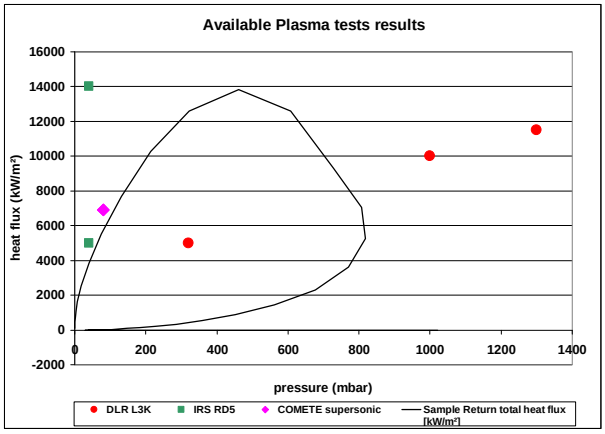

Figure 2-4: Conditions of first plasma test campaign

Figure 2-5: ASTERM samples after test
(left: 14MW/m^2/40mbar; right: 10MW/m^2/1000mbar)

Figure 2-6: MonA samples after test
(left: 14MW/m^2/40mbar; right: 10MW/m^2/1000mbar)

After the completion of the currently ongoing refined development phase, an additional plasma test campaign is foreseen. A modification of the L3K facility is currently performed to improve the representativeness of the test conditions with respect to the expected re-entry condition. It is expected that 14 MW/m^2 at 1000mbar respectively 11 MW/m^2 at 800mbar can be achieved.

In addition to the plasma campaign, a first material characterisation will be performed including thermal conductivity, specific heat and mechanical strength properties on both virgin and charred material. Some first ablation characteristics are intended to be derived from DSC test results.

2.8 Further Steps

The development logic of the currently ongoing activity DEAM was shown in figure 2-1. The refined development is almost completed and the characterisation and plasma test campaign (as described in chapter 2.6) are planned within summer 2011. Thereafter the activity will be completed with the production of a scaled one-piece heat shield demonstrator manufactured with the ASTERM material with a diameter of about 450mm.

Continuation of the development is planned to be initiated in the near future, which will include a fine-tuning of the material composition to match the refined technical requirements derived from ongoing mission studies (e.g. MarcoPolo-R, Mars Sample Return), an extensive characterisation and pre-qualification campaign, the manufacturing of tile assemblies with interfaces and the transition to relevant large scale manufacturing.

In parallel to this a further activity is planned aiming to determine the limits of the material as function of key parameters (e.g. density), and to derive semi-empirical models for the optimisation towards requirements coming from new mission applications.