Ablative thermal protection systems for entry in Mars atmosphere.
A presentation of materials solutions and testing capabilities

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ABSTRACT

EADS SPACE Transportation aims at providing the aeroshell, as part of the Entry Descent and Landing System (EDLS), for the ExoMars Descent Module. ExoMars is the first Aurora flagship mission to Mars for ESA in the continuation to Mars Express. With the aim to bring safely a rover and a Geophysical and Environmental Package (GEP) to the Martian surface in order to study biological environment, the aeroshell is a key element to guarantee mission success.

The reference material for the thermal protection system (TPS) of ExoMars is the Norcoat-Liege, a flight proven cork powder and phenolic resin based ablator. In addition to its original use for launchers, the Norcoat-Liege was previously used for two re-entry programs, namely the Atmospheric Re-entry Demonstrator (ARD) that performed a guided and controlled re-entry on Earth in 1998, and the Beagle 2 probe that entered Mars atmosphere in 2003. For the latter use, the material was for instance adapted to comply with stringent planetary protection requirements.

The paper will present an overview of the background on this material, including the most recent outcomes from R&D studies, aiming at a refinement of the material knowledge.

In addition to the material itself, most of the skills required to achieve the development of the whole TPS are available at EADS-ST. These key proficiencies are heat shield engineering and design, material fine modeling, high temperature testing capabilities that include plasma wind tunnel with dust injection and CO2 environment, and assembly facility with clean room conditions.

Finally, possible alternative uses for the material will be outlined (Titan, aft body thermal protection, assessment of growth potential). The Norcoat-Liege will be compared to other ablators such as the EADS-ST Picsil developed for LEO servicing missions, and the AQ60 used for the Huygens EDLS.

1. EXOMARS MISSION OVERVIEW

1.1 ExoMars mission objectives

The ExoMars mission is devoted to the outstanding scientific question of establishing the existence of life on Mars: it will thus search for traces of past and present life, characterize the Mars geochemistry and water distribution, and improve the knowledge of the Mars environment and geophysics.
ExoMars is the first flagship mission within the Aurora program of ESA, and will also by the way have a role of preparation for future robotic or human exploration missions. ExoMars will thus demonstrate the safe Entry, Descent and Landing of a large size spacecraft on Mars [1], the surface mobility and access to subsurface, forward Planetary Protection and identify possible surface hazards to future human exploration missions.

The spacecraft will be composed of a Carrier Module (CM) and a Descent Module (DM) (Fig. 1) that will be released in order to allow safe landing of two elements on the Martian surface, that will support the ExoMars scientific mission: a high-mobility Rover and a fixed station — the Geophysics / Environment Package (GEP).
The ExoMars Rover will carry the Pasteur Payload devoted to exobiology and geological research and will ensure a regional mobility (several kilometers) over its planned 6-months lifetime.
The Geophysics/Environment Package (GEP) will be accommodated on the DM and is designed to be in operation for more than 6 years. It will be the first item of a network aiming at the long-term study of Martian geophysics and ambient conditions.

In addition, sensors on the DM heatshield will provide an opportunity to perform vital "entry and descent science" measurements. Today, the only existing atmospheric sounding data sets for Mars stem from the twin 1976 Viking mission.

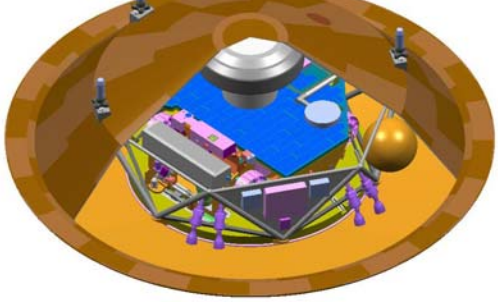


Fig. 1. ExoMars Descent Module architecture (as of phase A)

1.2 Programmatics and schedule

It is currently scheduled by ESA to launch the ExoMars mission in 2011, with a possible back-up launch date foreseen in 2013.

The project started in 2003 and three parallel phase A studies were conducted in the time-frame 2003/2005.
Following these studies, the ExoMars Phase B1 activities are expected to consolidate the mission and system requirements, design and interfaces, including the GEP and the Rover with the Pasteur Payload set of instruments, to a level of detail which will allow the start of the following phases B2 and C/D. As much as possible, available and proven technologies shall be selected in order to minimize uncertainties and project risks and thus to guarantee the success of the mission.
The ExoMars Phase B1 is planned to be finalized by March 2007.

1.3 Descent Module Architecture

The study of the aeroshell was one of the contributions of EADS-ST during phase A. A Viking-like aeroshape was selected (Fig. 2).

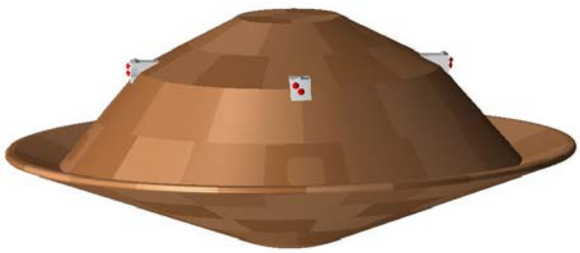


Fig. 2. Descent Module aeroshape
(as of phase A)

Both Frontshield and Back-Cover designs rely on a robust lightweight solution made of a sandwich structure (aluminium honeycomb + CFRP skins) covered with Norcoat-Liege thermal protection implemented under the form of panels or tiles (Fig. 3) glued onto the underlying structure.
It is worthwhile to highlight that Norcoat-Liege was selected as baseline solution independently by each of the three teams contracted for ExoMars phase A.
Table 1 summarizes the main characteristics of the ExoMars TPS and shows that Norcoat-Liege provides a mass effective solution, with limited TP mass fraction.

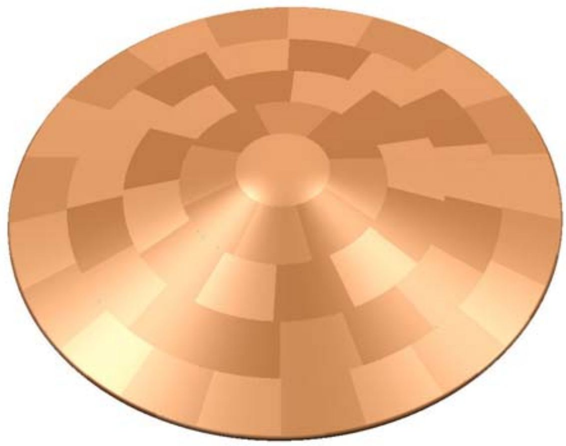


Fig. 3. ExoMars Frontshield TPS arrangement

Table 1 - Main characteristics of ExoMars TPS

Frontshield	T.P. material	Norcoat-Liege
	Density	d = 0.47
	Thickness	10 mm
	T.P. mass	90 kg (including glue and periphery on rear face)
	T.P. mass fraction	7.5 %
	T.P. arrangement	~ 60 large panels (4 rows) + 50 smaller tiles (shoulder area)
	Structure	CFRP honeycomb
Back-Cover	T.P. material	Norcoat-Liege
	Density	d = 0.47
	Thickness	6 mm
	T.P. mass	45 kg
	T.P. mass fraction	3.7 %
	T.P. arrangement	~ 80 panels
	Structure	CFRP honeycomb
Whole Entry Module	Max. diameter	3.80 m
	Total mass of the vehicle	1200 kg

1.4 TPS trade-off

For application on ExoMars, Norcoat-Liege was preferred to alternative solutions, such as AQ60 or Picsil.
AQ60 was the low density silica / phenolic material used for Huygens heatshield (Fig. 4) [9].
Norcoat-Liege allows a simpler design, an easier implementation and a slightly lower mass budget.

Fig. 4. AQ60 tiles on HUYGENS heat shield

Picsil (Fig. 5) is the low density silicone-based ablator developed in 1995-96 within ESA's MSTP program [10]. This material was finally selected as baseline for the European CTV studies.
It is however less optimized than Norcoat-Liege for a mission to Mars, for which the thermal solicitations are less severe. In addition, maturity of Norcoat-Liege was higher.

Fig. 5. PICSIL technological demonstrator

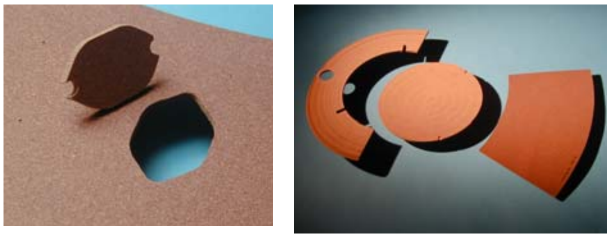
2. PRESENTATION OF NORCOAT-LIEGE

2.1 Composition and manufacturing

Norcoat-Liege is made of hot-pressed cork particles and phenolic resin. This material is a very good insulator with a density of 0.47.
Three types of Norcoat-Liege can be achieved:

- the standard material called Norcoat-Liege F,
- the fire proof material called Norcoat-Liege FI,
- the fire and water proof material called Norcoat-Liege FIH.

Large panels (1200x700 mm²) with a wide range of thicknesses (from 1 up to 150 mm) are industrially produced.
This material is easily machinable (boring, spotfacing, routing) in order to cope with the numerous geometrical constraints (access doors and hatches, dismountable covers over the back cover pyro nuts, back cover venting and break-out patch, antennae, etc…). It can also be easily formed to a desired simple geometric shape, if necessary.
It is then bonded onto various types of structure with a space-grade silicone based glue. The same glue is also used to seal the junction lines between panels.



BC cone tile and access door | Upper cone and Break out Patch tiles

Fig. 6. Norcoat-Liege Tiles for Beagle 2: various shapes obtained after forming and /or machining

2.2 Heritage

Norcoat-Liege was developed in the seventies for application on launchers. It was used first for deterrent force, then on Ariane 4.
Its first application on a re-entry vehicle was for the Atmospheric Reentry Demonstrator [2] that successfully flew on October 21st 1998.
Norcoat-Liege panels 19 mm thick protected the rear cone structure and the back cover of the ARD capsule. It must be highlighted that many singularities could easily be implemented in these areas (thrusters, TPS experiments, measurement devices, antennas, access doors, etc…)
The first analysis and inspection after recovery showed and demonstrated the perfect behavior of this kind of material after the atmospheric reentry (Fig. 7).

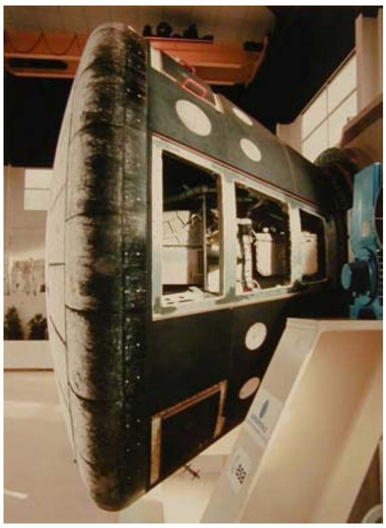


Fig. 7. ARD after flight

Norcoat-Liege also equipped the Frontshield and Back-Cover of the Beagle 2 probe (Fig. 8). This probe [3] aimed at delivering at the surface of Mars a scientific payload devoted to study chemical composition of soil and atmosphere. Unfortunately, the mission failed on December 25th 2003. However, the Beagle 2 ESA / UK Commission of Inquiry stated in April 2004 that 'the entry thermal protection is not a likely cause for the Beagle 2 loss'.

Fig. 8. Beagle 2 heat shield in assembly workshop

Beside its application on entry probes, the main use of Norcoat-Liege is for launchers (Ariane 5 and French deterrence force), and the material is regularly and continuously produced for these applications, with secured and perennial procurement source for raw materials.

2.3 Adaptation to space missions

In order to meet requirements specific to Mars entry missions, the standard Norcoat-Liege required some adaptations [4].

The first one was the thermal treatment devised to cope with outgassing requirements, after several evaluations with variation of the following parameters:

- A temperature level chosen to be in accordance with the maximum temperature seen by the material during the tiles fabrication process.
- A vacuum level imposed by the available vacuum pumps which are likely to be used during the fabrication process.
- A duration of the cycle fitted in order to meet the targeted outgassing properties.

After application of the abovementioned thermal treatment, the obtained outgassing properties for the Norcoat-Liege are given in Table 2.

Total Mass Loss (TML)	4.05%
Collected Volatile Condensable Material (CVCM)	0.09%
Recovered Mass Loss (RML)	0.72%
Water Vapor Released (WVR)	3.33%

Table 2 - outgassing properties of Norcoat-Liege FI after thermal treatment

Though a still high mass loss mainly due to water release, these properties were deemed acceptable for application on Mars entry heatshields.

The second adaptation was required in order to comply with planetary protection constraints and regulations, established to avoid contamination:

- of the outer space planets with terrestrial organisms carried by spaceships,
- of the Earth with alien organisms brought back by return re-entry vehicles or samples

The manufacturing and the integration of the Beagle 2 Mars lander have required to work in stringent cleanliness conditions and therefore to set up appropriate decontamination / sterilisation methods.

The work began by screening different decontamination / sterilisation methods mainly based on medical experience, and then a trade-off allowed selection of the most appropriate method.

- For the frontshield, bonding operation in class 100 000 clean room (Fig. 9), then packing in double bio bags and sterilization

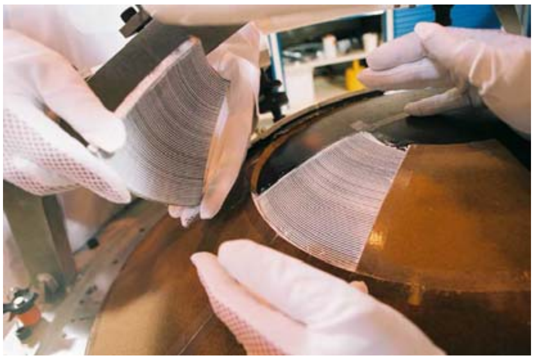


Fig. 9. Bonding of a FS tile in class 100000 clean room

- For the back cover, individual sterilization of structure and TP elements, then bonding operation in class 100 clean room (Fig. 10) and finally packing in double bio shields inside this room.

Fig. 10. Bonding of Back Cover tiles in class 100 clean room

3. THERMAL QUALIFICATION TESTS

Norcoat-Liege was extensively characterized and qualified for Mars entries including with CO2 environment during plasma testing. This was carried out in the framework of the abovementioned Beagle 2 program and also of CNES' NetLander EDLS project, for which phase B was completed in 2002, as well as in the framework of in-house R&D activities conducted in parallel to these two programs. COMETE and SIMOUN facilities of EADS-ST were upgraded [5] to allow simulation of anticipated aerothermal environment.

3.1 Synthesis of plasma tests results

Plasma tests were carried out in different test centers (EADS-ST, IPM in Russia, VKI in Belgium). The various following parameters were investigated:

- Plane board and stagnation point configurations
- Air and CO_2 atmospheres, with some tests allowing direct comparison
- Different heat flux missions on tangential flow tests: ~800kW/m² for Beagle2, up to ~1600kW/m² for Netlander plus some supplementary tests with a (not measured) value estimated to 1800 ± 100 kW/m².
- Heat flux up to 2000 kW/m² in stagnation point
- Validation of TPS architecture (including joints, steps and gaps)
- Instrumented samples, allowing detailed exploitation and elaboration of a thermal model

It must be highlighted that the experienced values of heat flux were the qualification levels required for the considered programs. The capability of the material is certainly significantly higher and further exploration is recommended to assess it more completely. Anyhow, the robustness for the ExoMars application is already ensured based on available results.

3.2 Stagnation point plasma tests

As mentioned above, Norcoat-Liege was tested up to 2000 kW/m² in stagnation point configuration. Numerous tests were performed in different test centers. Fig. 11 to Fig. 13 show pictures of Norcoat-Liege samples after the most severe tests carried out for each facility.

Fig. 11. COMETE sample (air - ~2000 kW/m²)

Fig. 12. sample tested at IPM (CO2 - ~1100 kW/m²)

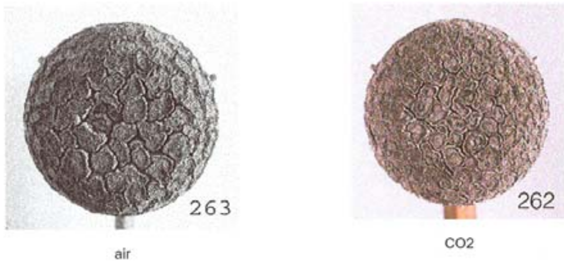


Fig. 13. samples tested at VKI
(comparison air-CO2 - ~2000 kW/m²)

These tests proved the good behaviour of the material both in air and CO_2 atmospheres. No influence of the atmosphere composition was noticeable during these tests. This contributed to validate the qualification approach on flat samples, for which the highest levels could be reached only in air.

3.3 SIMOUN plasma tests

In parallel, several tests were carried out in tangential flow configuration on the SIMOUN facility of EADS-ST (Fig. 20). This plasma arc heater allows good heat flow homogeneity on large samples of ~150 x 300 mm, together with a simulation of shear loads. The tests were performed either in air, or in CO_2.
Fig. 14 to Fig. 16 show pictures of Norcoat-Liege specimens after tests in different conditions.

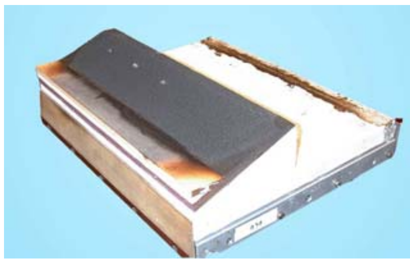


Fig. 14. SIMOUN sample after test
(Netlander – air – 1600 kW/m²)

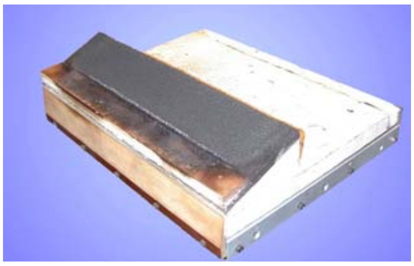


Fig. 15. Sample after test (Netlander complement - air – ~1800 kW/m²)

Fig. 16. A SIMOUN sample before and after test (Beagle 2 – CO2 – 700 kW/m²)

These tests allowed demonstrating the good behavior of the material itself, when submitted both to heat flux and aerodynamic shear. They also permitted to qualify some particular points simulating potential manufacturing defects, such as empty or wide joints, steps or local repairs.

Furthermore, these tests proved the satisfactory thermal performance of the material. Thanks to the quite complete instrumentation implemented for those qualification tests, good quality thermocouple data were obtained, which were then used for detailed exploitation and elaboration of thermal model (cf § 3.4).

3.4 Characterization and thermal model

Based on a combination of elementary characterization tests as well as on the exploitation of instrumented arc jet tests, a complete thermal model including pyrolysis and ablation effects has been established for Norcoat-Liege. This model is operated at EADS-ST for accurate and reliable design and mass-effective dimensioning (Fig. 17).

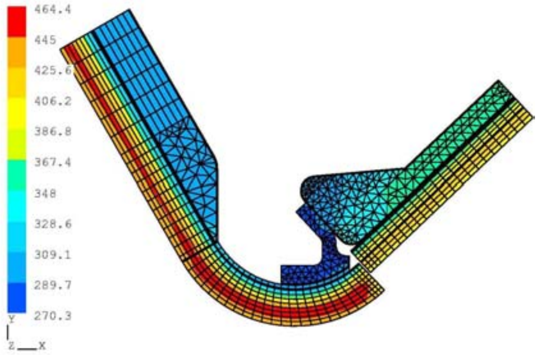


Fig. 17. 2D results for Beagle2 using Norcoat-Liege thermal model.

4. DUST EROSION

4.1 Overview

Due to periodical dust storms in Mars atmosphere, solid particles can remain in suspension for a long time. According to their high velocities, when reentry vehicles cross such dust clouds, even small particles can induce significant damage to the TPS, due to the high kinetic energies involved. Various effects can be encountered by the TPS and need modelling for a comprehensive assessment of dusty flows.

- Shock layer / particle interaction
- Particle / TPS interaction
- TPS charred layer erosion
- Increased heat flux

Ref [6] details the theoretical aspects of this theoretical and experimental combined approach defined jointly by CEA/CESTA and EADS-ST.

4.2 Test facilities

Ref [7] presents the test facilities used for experimental side.

The first step of the approach was based on the adaptation of an existing torch so-called AQTIL (Fig. 18). This Huels-type arc jet facility can be used with different gas mixtures (air, N2, N2+H2). The stagnation point heat flux level can reach 2.5 MW/m² on a standard ESA shape model (Φ50mm) with a working pressure equal to 1 atm.

The first experimentations were dedicated to the study of alumina particles impact effects on TPS in the framework of distancing rockets used on Ariane 5 boosters. Many difficult points have been solved during this AQTIL seeded plasma generator development in 2003.

Some parameters such as, carrier gas mass flow rate, number of injectors, their location and injection angle have been defined thanks to theoretical and experimental results.

Fig. 18. AQTIL Huels plasma torch

A specific injection device (Fig. 19) has been designed, based on four injectors settled up on a ring and located at the exit of the downstream electrode.
This allows a precise control of the mass flow rate of both particles and carrier gas.

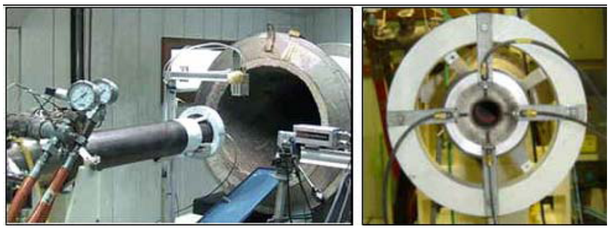


Fig. 19. AQTIL particle injection adaptation

Once the seeded plasma flow obtained, several diagnostic techniques have been implemented to obtain a precise control of the test conditions such as the homogeneity of the seeded flow, the particle velocity and status (solid, melt,...).
This injection technique with its adjustment was patented in year 2005. The AQTIL facility is now available and fully qualified for TPS characterisation under particle impingement, including simulation of dust particles erosion encountered during Mars atmospheric entry.

The second step of the development of seeded plasma test facilities has been initiated (as an internal R&D development) and a validation test campaign is scheduled in 3rd quarter of 2006.
The power injection will be implemented on SIMOUN (Fig. 20), based on the experience gained during former AQTIL development. The same injection method and diagnostic techniques will be used and validated in hypersonic flow.

As a first approach, the stagnation point configuration will be used with the 50 mm diameter ESA standard sample combined to axisymetric injection particles at nozzle exit.

The foreseen next step is to evaluate the use of SIMOUN facility in flat plate configuration, thus with combination of shear stress and particles erosion effects. This will be the last point to fully complete the excellent simulation capability of SIMOUN for Mars atmospheric entries.

Fig. 20. SIMOUN plasma test facility

5. R & D results and growth potential

Norcoat-Liege has been proven to be a TPS material with outstanding properties. As its main component is natural cork, it induces a relatively complex composition. In order to get a better understanding of the behavior of the material, thorough analyses and characterization work [12] were performed during the past last years in cooperation with universities and labs, particularly CRPP from CNRS.

Two main points were analysed:
- Influence of main organic (families of) molecules constituting the material
- Analysis of degradation process

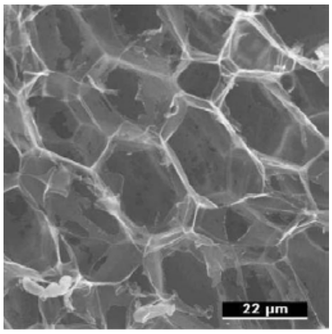


Fig. 21. Norcoat-Liege after carbonization @ 2000°C

This produced very interesting results, showing among others a very good stability of the carboneous cells at high temperature (Fig. 21).
Moreover, the better understanding of the role of each constitutive type of molecules provides a basis for a more detailed theoretical modeling, as well as for future tailored improvements of the material.
The two following perspectives are deemed quite attractive, and should enable to enlarge the use of this type of material to a wider domain:
- Inclusion of a mechanical reinforcement in the material, in order to strengthen the char layer. This is expected to allow use for more demanding missions, with higher heat fluxes than those encountered during Mars entries.

- Search for a lightened material, in view of application on aft body of entry probes, where the low density is a key parameter

6. CONCLUSION

EADS-ST is ready to bring a significant contribution to ExoMars development and future success, in particular through the different following topics, among which those mentioned in this paper:

- Thermal protection design and assembly
- High temperature testing facilities
- All the disciplines required for atmospheric entry (Aerodynamics, Aerothermodynamics,…)

These technologies and techniques can obviously also serve any future scientific mission with atmospheric entry probe [11, 13].

7. ABBREVIATIONS

CM	Carrier Module
CNRS	Centre National Recherche Scientifique
CRPP	Centre de Recherche Paul Pascal
CTV	Crew Transportation Vehicle
DM	Descent Module
EDLS	Entry Descent and Landing System
MSTP	Manned Space Transportation Programme
TP	Thermal Protection
TPS	Thermal Protection System

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