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CMC KEY TECHNOLOGIES – BACKGROUND, STATUS, PRESENT AND FUTURE APPLICATIONS

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ABSTRACT

CMC key technologies enable design and manufacture of hot light weight structures. Such structures were required for rigid TPS, leading edges, fins , rudders and movable control surfaces and shall be applied for future space vehicles. CMC key technologies presented in this paper cover

- **CMC bearings** (to enable the realization of movable hot structures),
- **CMC tribology** (required for hot sliding applications),
- **Oxidation protection systems** (required to prevent oxidation of CMC materials),
- **CMC fasteners** (required for hot ceramic-to-ceramic joining),
- **Hot-cold-structure combinations** (required to attach hot CMC structures to cold metallic structures),
- **High temperature insulations** (to protect metallic structures),
- **High temperature static and dynamic seals** (required to limit hot gas ingestion or heat transfer and prevent overheating of structures and components).

The background of these key technologies is highlighted especially with respect to the lessons learned. The actual status of the art of such technologies (which have directly been applied for the body flaps of NASA´s 38 space vehicle 201) and their technical potential are described.

Further, the continuation of key technology development carried out in the frame of the CRV- and the ASTRA-program is described.

Key words:
Carbon re-enforced silicon carbide, ceramic high temperature components, space re-entry vehicles.

INTRODUCTION AND BACKGROUND

The design of European space vehicles focussed on advanced CMC key technologies which enable design and manufacture of hot light weight structures. Such structures were required for rigid TPS, leading edges, fins , rudders and movable control surfaces.

Ablative TPS systems and Shuttle tiles have been rejected mainly because of the following reasons:

- Ablative systems are mass consuming, not reusable and do not keep their geometrical shape;
- Shuttle tiles are limited in their size resulting in a high number of tiles/m^2 and in relative high maintenance costs. Their application is limited to operation temperatures lower than required for future vehicles.

Instead of tiles or ablators, C/SiC material has been selected. C/SiC shows better specific strength properties at highest temperatures than metallic alloys and their fracture toughness properties enable the realization of thin-walled structures – in contrast to monolithic ceramic materials which are too brittle to be applied for TPS or hot structures.

C/SiC-panels and C/SiC hot structures for different European programs and vehicles have been developed. In the course of these programs several CMC key technologies have been identified. Programs, vehicles and identified technologies are summarised in Table 1.

The development was mainly vehicle specific and therefore the development status of these key technologies was different. Different vehicles have been under development. None of them has been realised (with the exception of vehicles like ARD and CETEX used for CMC-TPS material qualification).

TPS and hot structure development has been continued for further vehicles (for example HOPE-X, X-33, X-34 etc.). Further vehicle-specific TPS and hot structures have been developed and successfully tested. But, the development status of key technologies has still not been equivalent and fundamental key technologies were missing.

According to this situation it has been decided by MAN Technologie to develop CMC key technologies which

- universally can be applied for most of TPS and hot structures,
- have an equivalent development status,
- are available in time,
- are reusable,
- are qualified on the base of a relevant reference vehicle.

This decision was mainly driven by the objective to be prepared in time for a participation in national and/or international space re-entry programs like X-38 for example.

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A fundamental pre-requisite for Europe's participation in the X-38 program was, that CMC key technologies had to be brought up to flight standard and that the X-38 space vehicle V201 was selected as reference vehicle for development. For this reason a comprehensive development program has been established which is summarised in Figure 1.

Key Technologies	Shuttle Type	Capsules	Hypersonic Vehicles	Lifting Bodies (Colibri)	**Development Status**
	HERMES	**CHA. ALSCAP**	**SÄNGER**	**HEISSE STRUKTUREN**	
CMC panels (small)	trapezoidal**	trapezoidal, corner edged, disk shaped**			**good** (tested, product)
CMC panels (large)					**missing**
CMC structures* (integral)	–	–	hot air intake ramp	small structural CMC element	**medium** (tested, feasible)
CMC structures* (integral, movable)	–	–	–	small body flap prototype	**medium** (tested, feasible)
HT insulations	Internal multiscreen insulation (IMI)**	Saffil			**good** (tested, product)
HT seals	Nextel envelope, Saffil core**	–	–	–	**poor** (no hot tests)
CMC fasteners (ceramic to ceramic joining)			C/SiC fasteners	C/SiC fasteners	**medium** (tested, feasible)
Hot-cold structure combinations***					**missing**
Oxidation protection	yes	yes	–	yes	**medium** (tested, feasible)
HT lubricants				Base experimental investigations	**medium** (tested, feasible)
HT bearings				bearing prototype	**poor** (tested, feasible)

*) Transfer of high mechanical loads on high temperature level
**) Rigid External Insulation (REI) concept
***) Ceramic-to metal-joinings and interfaces

Table 1 Identified CMC key technologies, applications and development status (1998)

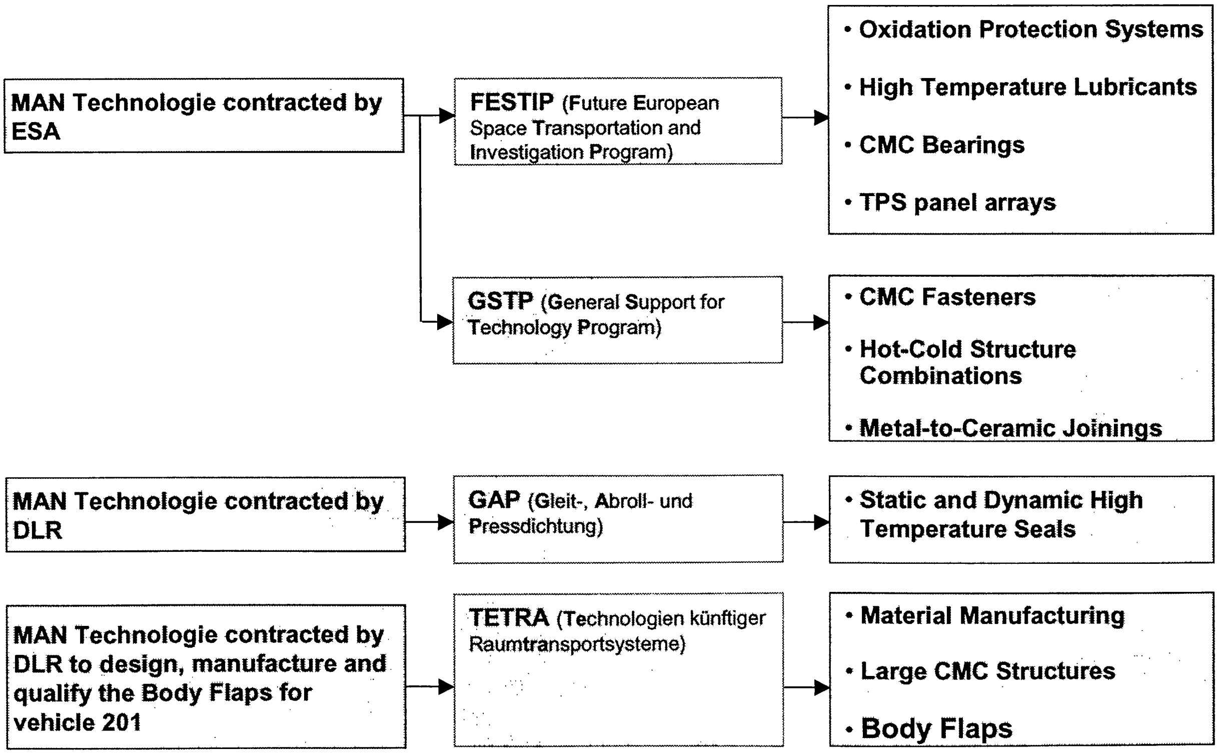


Figure 1 Development and qualification based on NASA's X-38 space vehicle V201 (Reference Vehicle)

In the frame of these programs, MAN Technologie has developed and qualified relevant key technologies which have directly been applied for the innovative X-38 body flaps shown in Figure 2 and 3 for example. It has to be pointed out that it would not have been possible to deliver the body flaps for X-38 in time without the pre-development and qualification of these CMC key technologies.

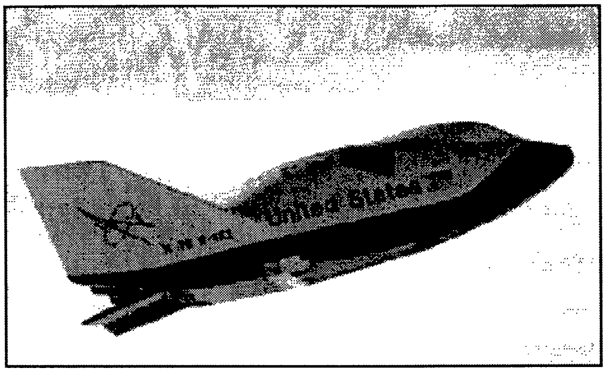


Figure 2 NASA's X-38 space vehicle V201 with two body flaps at the rear windward side of the vehicle to allow roll-, pitch and yaw manoeuvres during re-entry

APPLICATIONS

Figure 3 gives a good overview on CMC key technologies applied for the X-38 body flaps which are completely made of C/SiC materials. Such materials allow to transfer high mechanical loads on temperatures up to 1600 °C. The oxidation protection system applied for the body flaps allows to operate the flaps in oxidising atmosphere. The low density of the C/SiC materials allows light weight design resulting in a body flap mass which is approximately half of the mass of a conventionally designed flap. Innovative ceramic bearings allow to introduce mechanical loads into the flap, to attach the flap to the vehicle's aft structure and to move the flap individually. The complex structure of the flaps has been realised by 4 boxes per flap which are joined by innovative ceramic fasteners. Hot gas flow between the flap and the vehicle's aft structure is prevented by ceramic high temperature seals.

The next chapters will describe in detail the status of the art and how further development is continued by MAN Technologie.

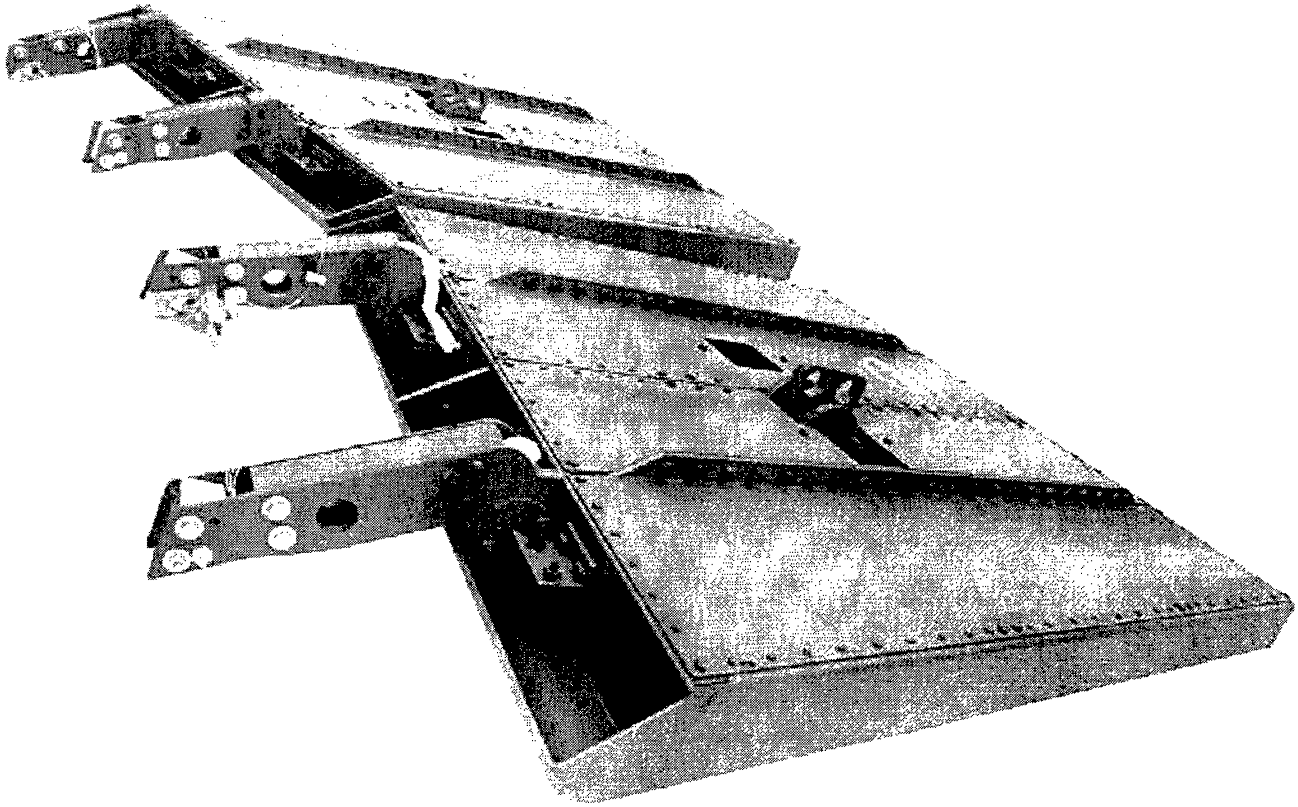


Figure 3 CMC key technology incorporating body flap qualified for 4 re-entries (Body flap size: 1.4 m x 1.6 m; Body flap mass: 68 kg)

Large complex hot structures

The body flap is composed of 4 boxes. One of such a box is shown in Figure 4. Each box is integrally manufactured by C/SiC material which is oxidation protected. Each box incorporates integral stiffeners (T- and I-shaped), 3-dimensional corners and curved and plane surfaces. The 4 boxes are joined by ceramic fasteners as shown in Figure 5.

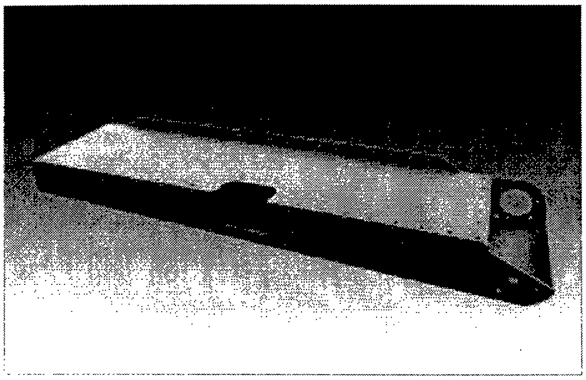


Figure 4 Large integral C/SiC structure (box) (length 1700 mm, width 400 mm, height 120 mm, wall thickness 2-3 mm)

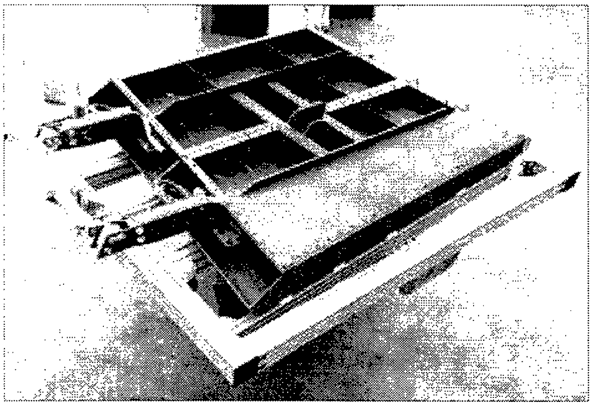


Figure 5 Body flap assembled of four boxes by C/SiC fasteners (right box with cover)

The technologies applied for the boxes can also be applied for any hot TPS structure or panel. The development actually is continued in the frame of the international CRV- program (Objective: Improvement of CFK preform manufacturing with respect to cost and time) and the national ASTRA-program (Objectives: Reduction of number of fixations, replacement of load introduction via external rod by load introduction via torque tubes in order to increase application spectrum and development of integrated and vehicle specific structures for potential vehicles like Pre-X, Sphynx, etc. [1]).

Oxidation Protection System

The application of carbon fibre reinforced Silicon carbide (C/SiC) in oxidising environment (air) is restricted to temperatures < 500 °C due to fibre burn-out at higher temperatures. For higher temperatures special oxidation protection systems in the form of **O**xidation **P**rotection **C**oatings (OPC) are required, which have to fulfil manifold technical and physical requirements such as:

- Prevention of oxygen diffusion to the C-fibres,
- Chemical compatibility between coating and C/SiC substrate,
- Thermal resistance in air over a wide temperature range (500 °C – 1700 °C),
- Good adherence to the C/SiC substrate,
- Resistance against damage and spall-off.

Furthermore the coating process must be applicable by industrial methods and economical and must not deteriorate the substrate properties. Last but not least the coating process has to be reproducible also in case of complex shaped parts and shall be suited for C/SiC-materials manufactured by different processes.

In the second phase of FESTIP the development of effective oxidation protection systems has been tailored to X-38 body flap requirements because such worldwide unique body flaps have to carry high mechanical loads at temperatures up to 1600 °C in oxidising atmosphere. All body flap components such as the large boxes, bearings and attachment elements have completely been made of C/SiC materials and protected by a multifunctional oxidation protection system which is tailored and adapted to the individual components of the body flap.

The development of the oxidation protection system was carried out by MAN Technologie in the frame of FESTIP-program not only in comprehensive sample and fixation tests but also in tests of large parts and assembled structures.

Sample tests: In former projects (like HERMES for example) OPC`s have been developed which are efficient at high temperatures (> 750 °C). For the X-38 body flap components the coatings have been improved especially with respect to lower temperatures (500 °C- 750 °C) and with respect to extreme hot air flow and plasma conditions at highest temperatures. Fur this purpose an improved multilayer OPC has been selected and investigated with respect to

- Properties of the improved oxidation protection,
- Influence of coating thickness on oxidation protection efficiency and velocity,
- Adaptation to the substrate material with respect to adhesion.

The sample tests covered

- Static oxidation tests,
- Bending tests after static oxidation,
- Cycling oxidation tests and
- Bending creep tests.

Assuming that the body flaps are exposed to high temperatures for overall 2 hours (equivalent to 4 re-entries), the physical properties of the C/SiC body flap material must remain unchanged after oxidation attack. This has been demonstrated in a comprehensive sample test campaign. In Figure 6 the results of bending strength values obtained in different tests (bending tests after static oxidation, bending creep tests and hot bending tests) carried out at different temperature levels (700 °C, 1200 °C and 1600 °C) are compared with bending strength values at **R**oom **T**emperature (RT). Even if oxidation protected samples are exposed to highest temperatures for more than 5 hours (equivalent to 10 re-entries) no significant effects on the residual bending strength can be observed.

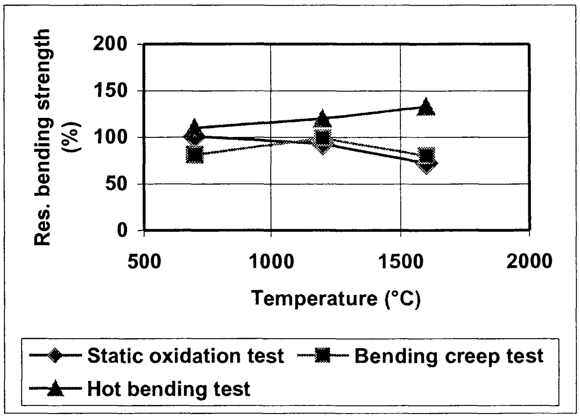


Figure 6 Relative residual bending strength of oxidation protected C/SiC samples (exposure time 5 hours at each temperature in each test type; 100% correspond to results obtained at room temperature)

The development of OPC`s has to take into account that different coating thickness are required for the individual components of hot C/SiC structures. In principle the coating thickness can be classified according Table 2.

Components	**Thickness**
Screws, nuts and washers	Thin coatings
Large components (e.g. BF boxes)	Medium coatings
Mechanically high loaded components (e.g. bearings)	Thick coatings

Table 2 Classification of coating thickness with respect to components to be protected

Sample tests carried out with different coating thickness indicate that the improved OPC thickness shall be ≥ 50 µm if material strength properties comparable to RT shall be maintained during the required life time.

Fixation tests: The oxidation protection test campaign has been extended with respect to CMC fixations. Table 3 summarises the individual tests and objectives.

Test	**Investigation on**	**Verification of**
A	effects of different slurry coatings	material
B	effects of different bolt/boring gaps	manufacturing process
C	effects of different screw types and assembly processes	design
D	effects of oxidation protection reliability on joined parts	analysis
E	large component test	repair of damaged coatings

Table 3 Test program overview for oxidation protected fixations

Test A: If the assembly concept for structural parts requires boreholes for ceramic fasteners which were drilled into the already completely coated (oxidation protected) parts, the boring will be unprotected afterwards. Therefore a special repair method mainly represented by a special oxidation protection slurry was developed which is able to seal the flank of the borehole and prevent oxygen attack of the C-fibres of the C/SiC material. Different kind of oxidation protection slurries have been investigated with respect to their protection efficiency at temperatures of 800 °C, 1300 °C and 1600 °C.

Boreholes have been protected with the most promising slurry and tested in static oxidation tests. The experimental results show that oxidation can be suppressed effectively if boreholes are oxidation protected by slurries after machining or drilling respectively. The effect is shown in Figure 7 for example.

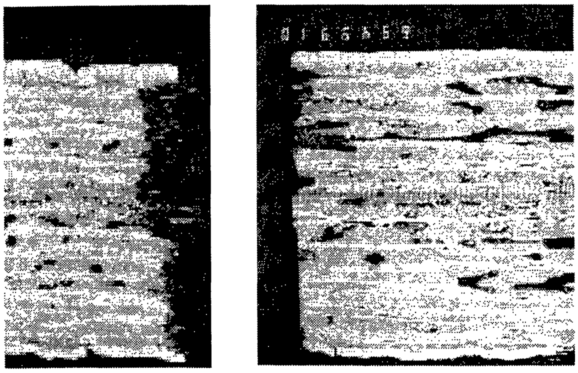
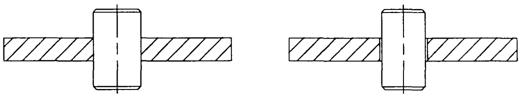


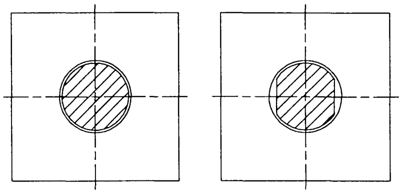
Figure 7 Effect of oxidation protection slurries in boreholes (20 min at 1200 °C; left figure not protected, right figure protected)

Test B: Another method to prevent or respectively to reduce access of oxygen to the C-fibres in boreholes is to design the gap (clearance) between the bolt and the borehole as tight as possible and/or to design the fasteners in such a way that head and nut contact surfaces tighten the boring.

Samples which simulate clearance (between borehole and pin) and shaft geometries (cylindrical or flat pin) have been manufactured (Figure 8) and exposed to 800 °C, 1200 °C and 1600 °C in air. The flanks of the bore holes were coated with the slurry selected in test A. The effect of oxidation attacks has been determined by weight loss measurements and ceramographical investigations. The best results have been obtained for cylindrical pins with tightest clearance. The worst results have been obtained for flat pins with higher clearance.



no clearance *small clearance*



cylidrical shaft *flat shaft*

Figure 8 Clearances and pin shaft geometry

Test C: In order to evaluate also manufacturing and assembly aspects, different fixation configurations have been manufactured. In a first step oxidation protection reliability of overall C/SiC fixations under thermal loads have been investigated. In the tests main fixation elements (head geometry of screw, C/SiC plates to be assembled, type and number of washers and nuts) have been varied. A fixation typical for the body flap is shown in Figure 9.

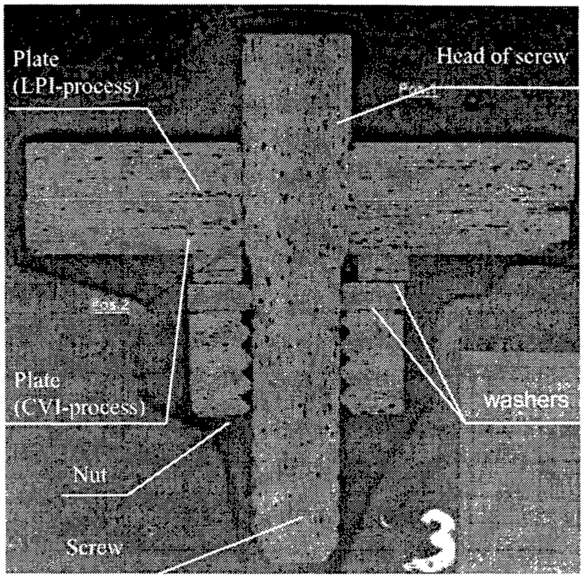


Figure 9 Section view of fixation typical for body flap

The samples have been exposed to temperature cycles shown in Figure 10 which are representative for the thermal body flap re-entry profile and which has been repeated up to max. 4 times.

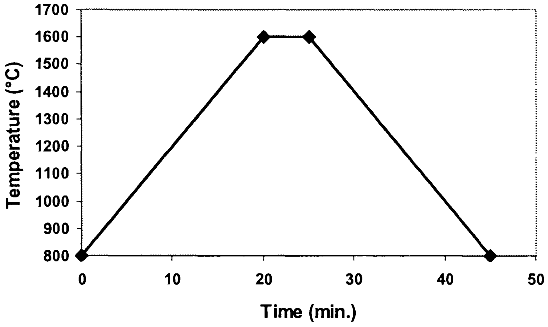


Figure 10 Thermal ageing cycle for fixation tests

In spite of the relative low number of samples the test results are in line with previous investigations: Geometrical measures (e.g. clearance between screw shaft and borehole, geometry of screw shaft and washers) may reduce oxidation and therefore improve the oxidation behaviour of fixations. Promising fixation combinations have been selected.

Test D: In a second step the effect of oxidation protection reliability of fixed plates under mechanical and thermal loads has been investigated. Fixations representative for X-38 body flaps have been tested in lap joint shear and two angle pull tests. The test sample configurations are shown in Figure 11 and 12 while their design took into account the results and know how already obtained in proceeding tests.

The temperature cycle shown in Figure 10 has also been applied for test D. During the dwell time the mechanical loads have been increased up to max. 10 kN (shear tests) and to 4 kN (two angle pull tests). The results confirmed that the fixations are able to withstand the thermal and mechanical loads expected for the X-38 body flaps during 4 re -entries.

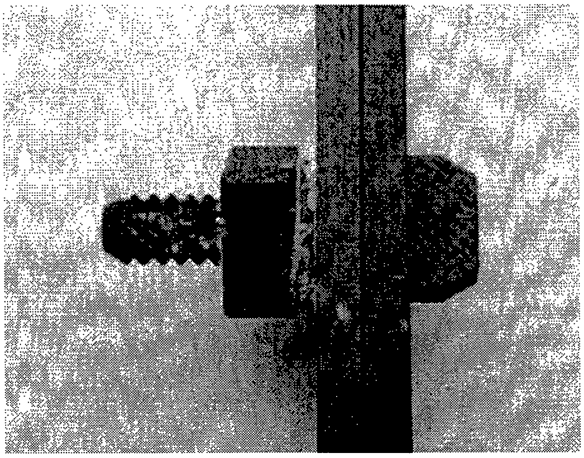


Figure 11 Test sample after lap joint shear tests

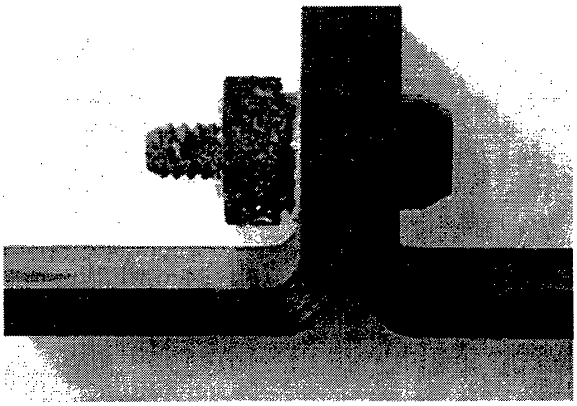


Figure 12 Test sample after two angle pull tests

Large part test: The main objective of the large part test was to demonstrate the reliability of the complete Oxidation Protection System consisting of different coatings, slurries, geometrical aspects and repair methods with a component which is most representative for the body flap and which is characterised by the following properties:

- Critical design element of the body flap,
- Exposed to lowest and highest temperatures during mission,
- Incorporates movable parts,
- Incorporates different CMC materials,
- Is composed of parts with different coating thickness,
- Incorporates boreholes oxidation protected by slurries during assembly,
- Incorporates areas which are machined after coating,
- Mechanically high loaded component,
- Large area to be oxidation protected by the (improved) multiplayer oxidation protection system.

Especially the body flap bearings, the body flap box-assemblies and the body flap attachment structures (all described below in more detail) incorporate the above mentioned properties. Their successful qualification tests impressively demonstrated the effectiveness of the developed oxidation protection system.

In case of the body flap attachment structure (compare Figure 19) it is pointed out that a coating defect shown in Figure 13 has also been successfully repaired by the selected slurry. Further it is pointed out that the OPC did not spall-off in spite of the relative high deformation of the attachment structure especially during the rupture test.

Figure 13 Flap bridge tube for the body flap attachment structure (compare Figure 19) with damaged OPC before repair

The oxidation protection activities are continued in the frame of the national ASTRA-program especially with respect to refurbishment and repair of components which have been attacked by salt, rain and hail.

DYNAMIC AND STATIC SEALS AND IMI

Static and dynamic seals developed for X-38 flight vehicle V201 mainly have to fulfil the following main requirements:

- Oxidative environment & temperatures up to 1700°C,
- Combined convective and radiation heating,
- Different thermal expansion of seal parts,

- Wear resistant with coefficients of friction between 1.07 and 1.17,
- Component movement and rotation,
- Low pressure – high differential pressure,
- Low permeability to minimize leakage
- ($1x10^{-10} - 1x10^{-11} m^2$).

Static seals have been applied for the nose, the rudders and the leading edges of the vehicle. Dynamic seals have been applied for the two movable body flaps mainly in order to prevent hot gas flow though the gap between the flaps and the aft structure of the vehicle as shown in Figure 14.

The development of dynamic seals has been supported by a comprehensive test program which covered flow characteristic, compression forces, temperature effects, seal resiliency and wear resistance [2].

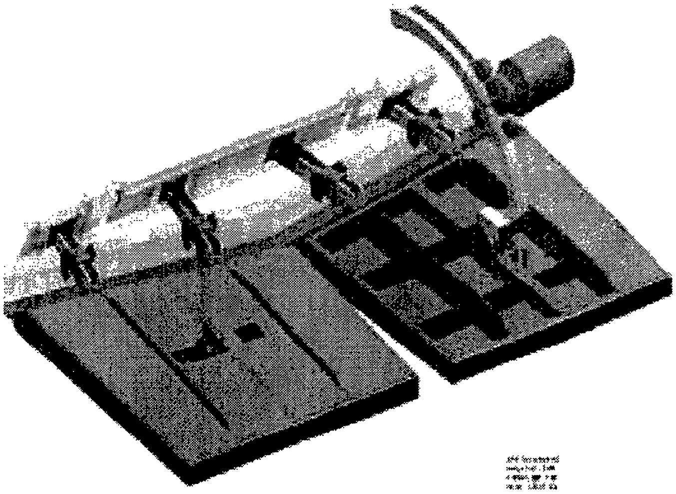


Figure 14 Body flaps sealed in the hinge lines by dynamic seals which allow movement and prevent hot gas flow at the same time

Dynamic as well as static seals were developed on the basis of stuffed ceramic fabric core. The material and components have successfully been qualified. Thermal & mechanical loads of X-38 mission requirements did not damage the seals. 20% seal pre-compression resulted in high effectiveness in blocking flow through gap with less than 1% leakage. Seals survived up to 1000 cycles scrub tests and remained securely attached. Seals did not influence movements or rotations of ceramic components. Seals act as effective thermal barriers to limit heat convection through seal gaps.

HIGH TEMPERATURE INSULATIONS (IMI)

A special type of a light weight high temperature insulation is the so-called **I**nternal **M**ulti-Screen-**I**nsulation **(IMI)** shown in Figure 15, a package which consists of extremely thin ceramic composite foils with high reflectance gold or platinum coatings, separated by fibrous insulation spacers.

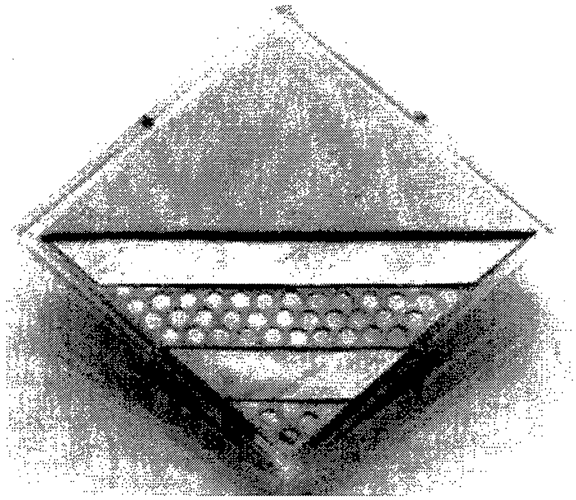


*Figure 15 Segment of a **I**nternal **M**ulti-Screen **I**nsulation **(IMI)** package*

The IMI is tailor-able according to insulation requirements, specifications, height & density. It allows insulation-design with up to 25% lower weight in comparison with conventional fibrous insulation. The IMI has been developed during the HERMES-program, applied for X33/X34 studies, tested at different NASA centres and successfully manufactured & qualified as "chin panel" insulation for the nose of the X-38 vehicle V201.

CERAMIC-TO-CERAMIC JOINING

Ceramic fasteners have been developed for the joining of ceramic parts and structures to be used at temperatures of 1600 °C in air [3]. Due to the dimensions and loads of the considered hot structures, screws of nominal diameters 6 mm < ∅ < 10 mm have been designed, manufactured (Figure 16), tested and applied to several space applications the most remarkable of which certainly was the X-38 body flap. In order to fulfil the high-temperature requirements, a multilayer oxidation protection of defined thickness was applied on the surfaces of screws, nuts and washers before assembly.

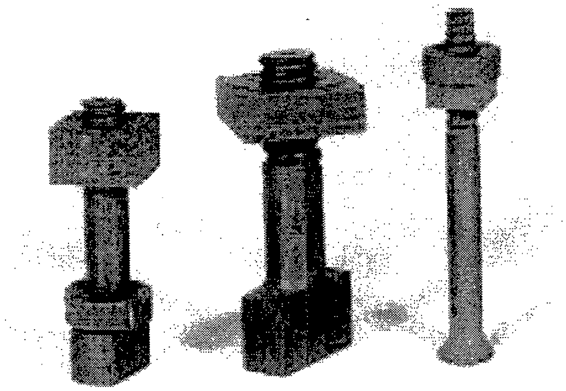


Figure 16 Different types of ceramic (C/SiC) fasteners

The technical features of the C/SiC fasteners have been determined experimentally and are summarised in Table 4. Mainly tensile and shear tests were carried out in order to characterise the deformation and strength properties of the fastener under typical load conditions. Further, wrench torque tests were carried to describe the preloading capability of such fasteners.

Diameter in mm	**min. tensile strength in kN**	**min. shear strength in kN**
6	3,5	2,6
8	6,5	4,7
10	10,0	7,3

Table 4 Main physical properties of different type C/SiC fasteners at 1600 °C.

The main advantages of C/SiC fasteners can be summarised as following:

- C/SiC has about 4 to 8 times lower mass than the considered refractory alloys,
- In opposite to refractory alloys the strength properties of C/SiC do not degrade significantly at elevated temperatures,
- Similar to refractory alloys, C/SiC must be protected against oxidation but damage of the oxidation protection coating does (normally) not lead to catastrophic failures.

A special fastener design has been carried out which allows joining even in case of "one-side access" joining (e.g. for the attachment of body flap covers as shown in Figure 17). The joining has been carried out via nut-strips which have been pre-qualified experimentally (Figure 18). Discrepancies to the behaviour of single nuts during/after vibration and thermal exposure have not been identified, but the similar fastener pre-load reduction has to be taken into account for flap design. Thus, the nut strip is considered to be a feasible solution for the X-38 body flap assembly and similar designed hot structures.

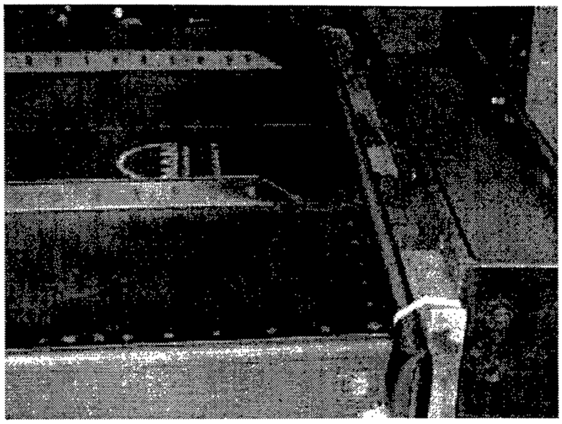


Figure 17 Assembly of body flap covers with nut strips

The box segment used in this test campaign contained both connection concepts applied on the Body flap boxes and was also geometrically representative for a cross section of these boxes. Thus, in parallel to the nut strip qualification, a pre-qualification of the boxes building up the body flap could be achieved with the test campaign.

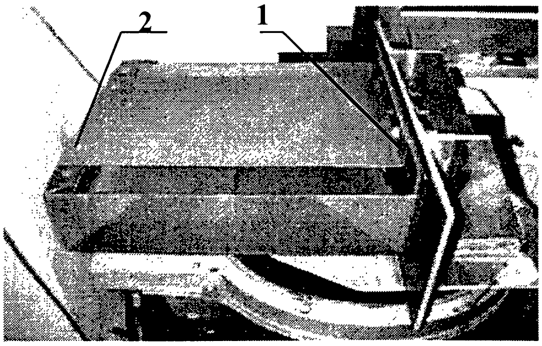


Figure 18 Box assembly for nut strip qualification testing (e.g. vibration); 1=centre line, where two boxes and one cover plate are attached, 2=attachment with nut strip (not visible) placed below the cover plate.

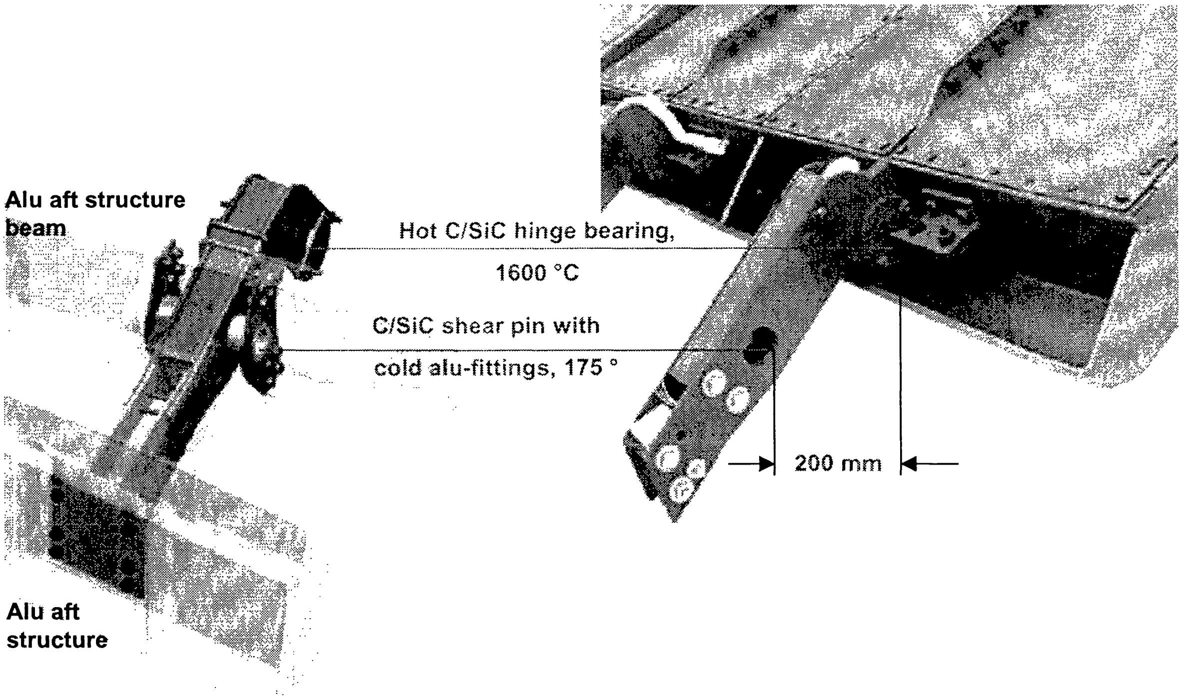
After the body flap qualification tests some fasteners have been selected, disassembled and tension-stress-tested. A comparison with test results obtained with "fresh" fasteners demonstrated that the mechanical properties of the body flap fasteners remained unchanged after the complete X-38 re-entry test campaign which was mainly characterised by **vibration loads** at launch (random Vibration 6.4 grms (20-2000Hz), by **thermal loads** (heat + actuation), by **mechanical pressure** 77 kN (ultimate load), and by

vibration load at re-entry (random vibration 11.0 grms (16-2000Hz)).

The fastener activities are continued in the frame of the CRV- and ASTRA-program especially with respect to the development and qualification of ceramic shear elements, fatigue load characterisation and exposure of fastener assemblies to CRV mission steps, in particular the repeated re-entry under oxidation attack.

CERAMIC-TO-METAL JOINING

Special design solutions have been developed for the joining of hot ceramic parts to cold metallic parts and are presented in the following. Figure 19 shows the attachment structure design of the hot ceramic body flap to the cold metallic structure elements (alu aft structure beam and alu aft structure). The main attachment elements are the C/SiC hinge bearing, the C/SiC square-shaped structure itself and the C/SiC shear pin which fits into the cold alu-fittings.



Body flap attachment structure design

The metal-to-ceramic joining had to be carried out in such a way that hinge bearing temperatures of 1600 °C are decreased down to the limiting temperature of the alu-fittings (175 °C) on a temperature path length of only 200 mm at mechanical loads of 4 tons and body flap movements at the same time. The attachment design has been qualified in a ground test in which 4 complete successfully have been simulated [4].

The load introduction for body flap activation is carried out by a metallic rod which is fixed to the ceramic bearing located in the centre of the body flap as shown in Figure 20. This hot metal-to-ceramic interface has been designed for temperatures up to 1100 °C and mechanical loads up to max. 40 kN (dynamic) and 70 kN (static). The reliable function of this interface has been demonstrated in the hot ceramic bearing qualification test in which also 4 complete re-entries have successfully been simulated [5].

Another example for ceramic-to-metal joining is shown in Figure 21. The joining has been developed by DASA subcontracted by MAN Technologie in the frame of the GSTP program. According to Figure 21 two C/SiC plates were connected to a metallic plate in such way that the assembly can be deflected and transfer high mechanical loads (27 kN) up to 1150 °C in air at the same time. The metal-to-ceramic joint successfully has been tested at the Austrian Research Centre (Seibersdorf, Austria).

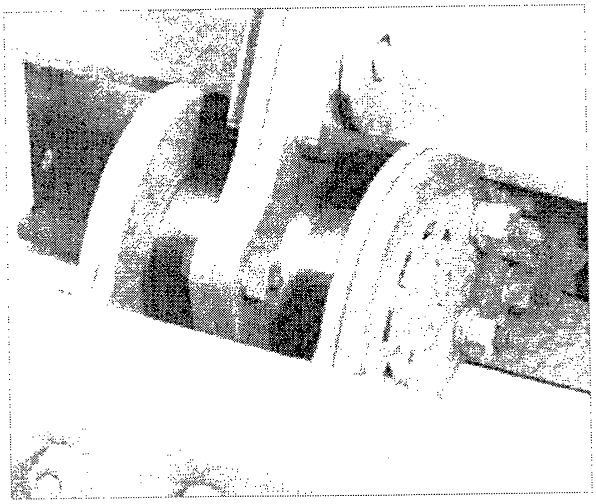


Fig 20 C/SiC Body flap bearing with metallic rod for load introduction

CERAMIC HIGH TEMPERATURE BEARINGS

Worldwide new high temperature bearings have been developed, manufactured and successfully been qualified for space flight [5]. Loads being equivalent to more than 4 complete re-entries from space have been simulated in a special test facility. The bearing for qualification testing shown in Figure 22 always operated reliable during testing. Such new bearings have revolutionised hot control surface design especially with respect to temperature resistance and light weight design. They have been installed into the two body flaps of the X-38 space vehicle 201 and are an inalienable prerequisite to allow movements and enable load introductions. Because of the high-temperature resistance of such bearings, re-entry temperature profiles are less constrained by control surface temperature limits compared with metallic-based control surfaces.

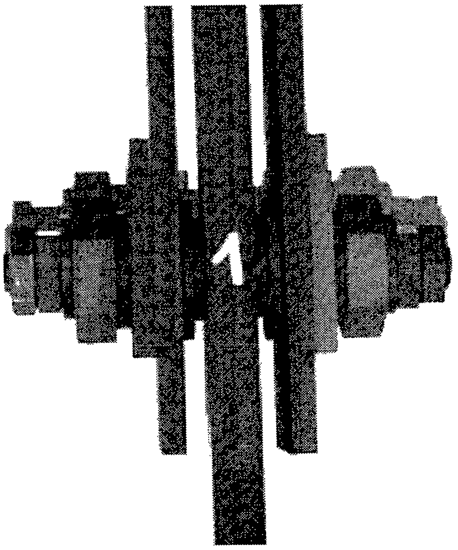


Figure 21 Ceramic-to-metal joining for high temperature hinge (1= metallic plate)

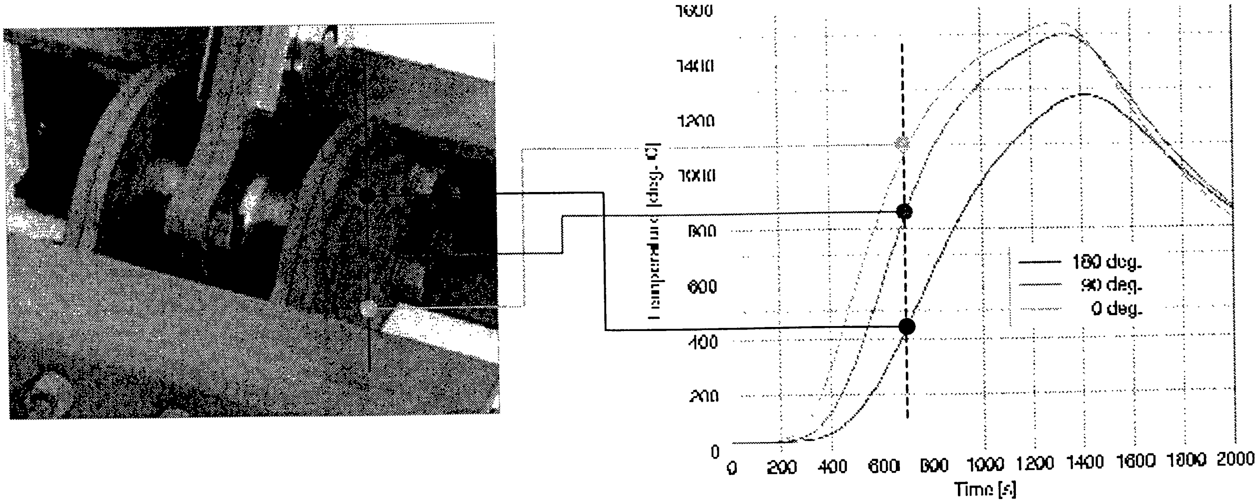


Figure 22 C/SiC bearing for qualification testing and analysed temperature histories for the bearing

Design of such innovative ceramic bearings mainly had to take into account the following challenges:

- Enable sliding from RT to max. 1600 °C in air,
- Keep clearance at local temp. differences up to 600 K,
- Allow operation temperatures > 1400 °C for 10 min. per re-entry,
- Allow heating up speeds of more than 300 °C /min.,
- Operate reliable during 4 complete re-entries in which more than 4000 movements are carried out under thermal and mechanical loads at the same time),
- Resist mechanical loads of 4 t (dynamic) and 7 t (static).

Figure 23 shows the bearing after the comprehensive and successful qualification test campaign demonstrating proper function, reliable operation and last but not least a reliable oxidation protection system.

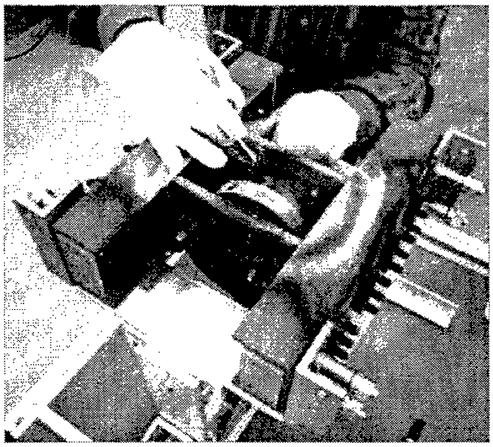


Figure 23 Body flap bearing after the successful simulation of 5 complete re-entries

CONCLUSIONS

CMC key technologies have successfully been qualified for orbital flight readiness on the base of a realistic reference vehicle (NASA's X-38 re-entry vehicle V201) [6].

CMC key technologies enable design and manufacture of hot light weight structures which are able to transfer high mechanical loads on temperature levels which exceed limiting temperatures of metallic materials. This has impressively been demonstrated by the application of these key technologies for the X-38 body flap and the successful qualification of the flaps [4,7].

Rigid TPS, leading edges, rudders, fins and control surfaces shall preferably designed as hot light weight structures as it is planned for future applications. If loads comparable to X-38 or less are required, CMC key technologies can directly be applied for Pre-X, EXPERT, SPHYNX, ...) [1]. CMC key technologies are actually further developed in the ASTRA- and CRV-program to reduce costs, increase reusability and to enlarge their application spectrum, reliability and availability.

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