Novel Method for the Evaluation of Ultra High Temperature CMCs applied in Orbital and Airbreathing Propulsion

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Abstract

One requirement on materials for combustion chambers is the ability to withstand high aerodynamic, thermo-mechanical and thermo-chemical loads during operation. For higher combustion efficiency, higher combustion temperatures (up to 1600 to 1900°C) have to be verified. Such demanding requirements limit the field of possible materials to high-temperature CMCs with suitable coating systems. Investigating and validating propulsion relevant materials is usually tedious and expensive. To minimize such costs, it's of utmost importance to have a fast, reliable and inexpensive way of material screening. Therefore the **E**nvironmental **R**elevant **Bu**rner **Rig**-**K**erosene (ERBURIG^K) facility is set up to investigate material behaviour in combustion chamber-like environments.

1. Introduction

Especially in the field of aeronautics and space exploration systems, Ceramic Matrix Composite (CMC) materials are being considered for applications in hot sections of jet engines e.g. for combustor liners, nozzle components, components for scramjets or dual-mode-ramjets, as well as leading edges, nose cones or similar TPS components of re-entry vehicles and furthermore in space propulsion components like nozzle extensions, gas-generator components, or orbital thrusters. They are made of high temperature materials, metallic and also more and more composites like C-C/SiC, C/SiC, or SiC/SiC in actively cooled or even pure radiation cooled structures.
Hypersonic as well as re-entry vehicles have to manage extremely high temperatures due to the aerodynamic heating during high velocity flight but even components of space- or air-breathing-propulsion systems have to operate at very elevated temperatures. Therefore combustion chambers of satellite engines (orbital thrusters) and hot section components of dual-mode ramjets require materials that can withstand the high aerodynamic, thermo-chemical and thermo-mechanical loads during operation [1].
By the combining of high-speed air-breathing propulsion with conventional rocket engines, it should be possible to improve the average specific impulse and thus the possibility for higher performing launchers, and eventually a fully reusability of such launchers can be established in the future [2].
Cost reductions but moreover increased performance is continuously placed as key element for development and application of advanced materials used in such propulsion systems. The need for higher combustion efficiency and/or performance leads to higher combustion temperatures and therefore to extreme material working temperatures reaching the range of 1600°C to 1900°C. In the field of high specific impulse (ISP) orbital propulsion systems current used materials are cost intensive high melting alloys based on Rhenium/Iridium, like Platinum-Iridium alloys or Iridium coated Rhenium. Besides this also (UHTC coated) ceramic- matrix composites based on C/SiC can be applied in the field of high performance propulsion components. Particularly the ability of carbon fibre-reinforced silicon carbide composites (C/SiC) to maintain its strength and its stiffness at extreme temperatures, as well as its low density make it an attractive candidate for such propulsion applications in future spacecraft. Most of the high temperature metallic or ceramic materials require an environmental barrier coating (EBC) system (e.g. Re + Ir coating, C/SiC + CVD SiC). These materials are strong contenders for high-temperature applications in engine hot sections, where oxidative degradation by aggressive ambient gases makes the durability of components an important issue [3]. Typical combustion gases composed of mainly steam, oxygen, carbon monoxide, carbon dioxide and hydrogen (which depends on the fuel-to-air ratios), leads to extreme harsh environment for the hot section materials with severe thermo-chemical interactions between the combustion products and the substrate. Chemical interactions like oxidation, carburetion or nitruration can appear. Typical hot gas compositions of different engine applications are shown in figure 1. For bipropellant satellite engines with hypergolic propellants like N_2O_4 + NO (MON)/ $CH_3N_2H_3$ (MMH) the combustion gases consists mainly of N_2, H_2O, O_2, CO_2 and H_2.The combustion environment

of kerosene with air is quite similar. In addition to the mentioned combustion products mainly CO, NO_X and C_{soot} will appear [4].

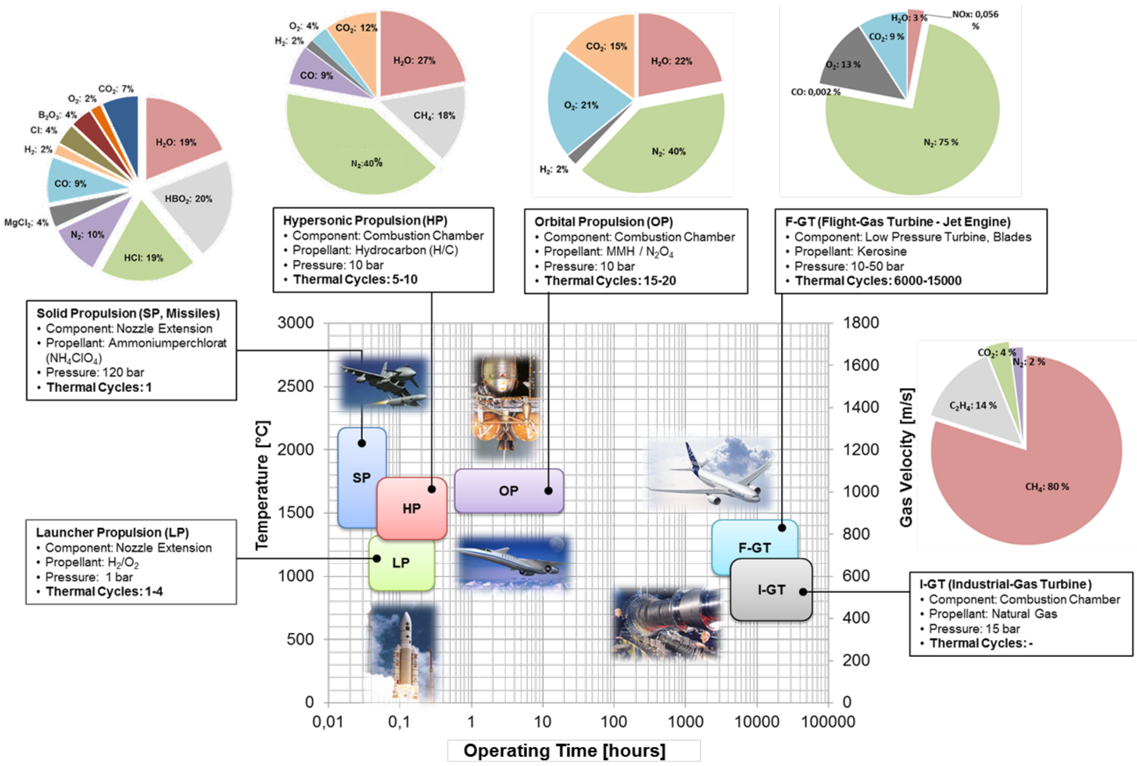

Figure 1: Typical combustion products of an orbital thruster

In addition to the combustion temperatures and the combustion gases with the resulting interactions the hot gas flow with extreme high gas velocity influences the stressing of the combustion chamber material.

2. Materials and Coatings

Ceramic matrix composite (CMC) materials have been developed with a more damage tolerant behaviour compared to ceramics, which are very sensitive to crack propagation because of their intrinsic brittleness. The mechanism of toughness, also called “quasi-ductile” behaviour, is possible only if the interface between fibre and matrix is low bonded. Very good mechanical performances can be obtained at room temperature as well as in high temperature environment in inert atmosphere. Critical issues for non-oxide CMCs like C/SiC-based composite materials are at high temperatures in oxidizing environments because of carbon oxidation when matrix cracks occur as well as SiC degradation based on corrosion mechanisms.

To protect the surface of C/SiC based components an efficient thermal stable environmental barrier coating system has to be applied. It could be a gradient multilayer system with an adapted chemical composition of each layer or even a mono-layer SiC coating where the intrinsic protection of SiC depends on the efficiency of silica sealant.

EADS/ Astrium Space Transportation is involved in the development and manufacturing of a particular class of ceramic matrix composite materials (CMCs) for space propulsion applications. This is realized by means of cost-effective process routes like rapid chemical vapour infiltration (r-CVI) for carbon/carbon (C/C) materials and liquid silicon infiltration (LSI) as well as the polymer-infiltration-pyrolysis Process (PIP) for carbon/silicon carbide (C/SiC) materials. At EADS/ Astrium different CMCs with Ultra-High-Temperature Coatings (UHTCs) are manufactured tested and evaluated in the temperature range from 1700°C to 2050°C and relevant propulsion environment.

The standard CMC material which is in use in development programs of high performance orbital thrusters, thermal protection systems (TPS) as well as thermo-stable structures [see EUCASS Paper: “BepiColombo HGA ARA C/SiC Struts: A thermo - mechanical challenge for support structures in harsh environments”. F. Wigger, S. Schmidt-Wimmer, S. Beyer, E. Sperlich. EUCASS 2013. Munich] is a C/SiC material named SICARBON®. The C/SiC is

fabricated via the filament winding and Polymer-Infiltration-Pyrolysis (PIP) process with or without an optional surface coating. The PIP manufacturing process is based on the wet-infiltration of a fibre roving or preformed fibre materials with liquid ceramic polymeric precursors with following heat treatments (pyrolysis) and re-infiltrations to obtain specific material quality. A detailed description of the SICARBON®-manufacturing process can be found in [5, 6].
SiC is also an integral part of the CARBOTEX$^{SI®}$ surface infiltrated (SI) material which is used for composite structures of hypersonic propulsion components. The C/C CARBOTEX® development was initiated with the objective of combining multidirectional (3D) textile structures with cost-effective infiltration methods. For active cooling systems several circuits have been compared to ensure good behaviour of the engine walls, with respect to the combustion-required environment and the fuel mass flow in a special manner. Many configurations of cooling are envisaged, such as series of channels of rectangular shape, or the so called pin-fin circuit, which was confirmed being more efficient than the machined-channels which resulted in the so called PTAH-Socar technology. The textile performs for typical applications were braided in a pre-defined fibre architecture (e.g. layer amount, fibre angle etc.) on a robot assisted circular braiding device and act as skin material for the components. To generate the typical sandwich structure of actively cooled components with the typical pin-fin structure a distance-tooling has to be applied and the 2D textile-perform has to be sewed/stitched with a robot assisted sewing (tufting) device in the orientation perpendicular to the layer orientation prior to the carbon infiltration. Even this process step acts as a 3D reinforcement of such material. The textile component gets densified via the r-CVI process, a special form of a CVI process, which has several advantages like cost and time savings as well as a tuneable process route concerning the material quality/performance. Finally the high temperature surface siliconization to get the final C-C/SiC state of the material (CARBOTEX$^{SI®}$) is performed. Depending on the application an optional diffusion barrier-coating can be applied. Detailed information to the manufacturing process of CARBOTEX$^{SI®}$ material can be found in [6].

3. Thermo-Chemical Interactions of C/SiC

Fibre reinforced carbon silicon carbide (C-C/SiC or C/SiC) is an attractive candidate for the use in rocket or hypersonic propulsion engine components, as for example combustor liner materials. They enable the engines to operate at extreme wall temperature and to reduce the overall mass of such engines. One of the major constraints to the general use of C/SiC structures in propulsion systems of future launch vehicles is that the reinforcing carbon fibres oxidize at medium to high temperatures and the SiC matrix degradation can be initiated at high temperature in an environment in which water vapour (H_2O), oxygen (O_2) hydrogen (H_2) and carbon dioxide (CO_2) is present. But nevertheless this does not forbid the use of C/SiC with or without suitable coating systems in future launch vehicle applications, as long as it can be verified through testing and analysis that the component will maintain its strength and stiffness throughout its life time (including the demonstration of sufficient safety factors). Therefore a meaningful testing as well as an assessment of the oxidation behaviour of C/SiC composite structures must be included along with the usual design and analysis activities (like the thermal, dynamic and thermo-structural analysis) of the different components.
The typical combustion gases of orbital thrusters as well as hypersonic combustion are composed of mainly steam, oxygen, carbon monoxide, carbon dioxide and hydrogen, which depend on the respective fuel-to-air ratios. Therefore suchlike gas compositions have a significant influence on the lifetime of the C/SiC-material. In addition to that the component lifetime is also significantly depending on the nature of the SiC itself. Typical reactions and furthermore degradation of silicon carbide in presence of the severe propulsion gas composition depend significantly on temperature gas flow/velocity and total pressure [7].
Generally silicon carbide can oxidize by either an active (formation of gaseous SiO and CO or liquid Si) or passive (formation of protective silica layer SiO_2) oxidation mechanism. The transition from passive to active oxidation depends on temperature, pressure and gas flow. Oxygen or water vapour attacks the carbon in C/SiC composites both on the surface and in the interior of the composite. The oxygen gains access to the interior of the composite via an interconnected pore network, which is formed by the combination of matrix cracks, separation of fibres from interface or matrix and void spaces between adjacent fibre layers. In the typical combustion environment also the lifetime of the silicon carbide is strongly influenced by the combustion gases composed mainly of steam, oxygen, carbon monoxide, carbon dioxide and hydrogen (which depends on the fuel-to-air ratios). This lifetime is also depending on the nature of SiC. A detailed description of the potential appearing mechanisms can be found in [8, 9].
SiC reacts with O_2, CO_2 and H_2O to produce silica and gaseous products (passive oxidation). Relative to oxygen, water vapour has a lower effective diffusivity in amorphous silica but a higher solubility. Thus the rate constant for water vapour is generally 5-10 times higher compared to oxygen as oxidant [10].

T<1400K $SiC (s) + 2 H_2O (g) = 3 SiO_2(s) + CH_4 (g)$

T> 1400K $SiC (s) + 3 H_2O (g) = SiO_2(s) + CO (g) + 3 H_2 (g)$

$SiC (s) + 3 CO_2 (g) = SiO_2 (s) + 4CO (g)$

$SiC (s) + 3/2 O_2 (g) = SiO_2 (s) + CO (g)$

In combustion environments water vapour pressure is high and the created silica reacts with the high pressure steam to form volatile hydroxide species. It was observed that SiC containing substrates oxidize more rapidly in comparison to a non-steam environment [11].

$$SiO_2 (s) + H_2O (g) = SiO(OH)_2 (g)$$
$$SiO_2 (s) + 2 H_2O (g) = Si(OH)_4 (g)$$

Although other reactions are possible with steam but the main hydroxyl species remains the $Si(OH)_4$. As a consequence of the formation and vaporisation of silicon hydroxides, the protective silica layer is continuously destroyed during hot firing and testing. At extreme temperatures other mechanisms have to be considered At these temperatures transport rates are very important in the liquid phase which again accelerates SiC oxidation. CO(g) can be generated by the interaction of SiC with SiO_2 . This reaction can start at 2110K at atmospheric pressure [12, 13].

$$SiC (s) + 2 SiO2 (s) = 3 SiO (g) + CO (g)$$

All this different temperature based SiC-oxidation-/corrosion-mechanisms are summarized and illustrated in figure 2.

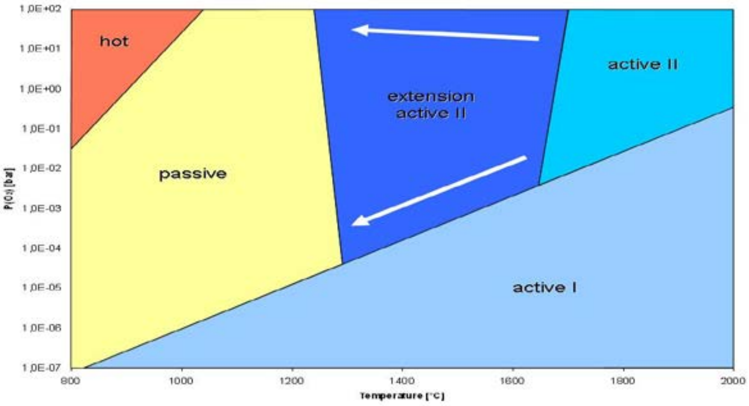

Figure 2: Areas of active and passive corrosion of SiC [13]

In addition to these general degradation effects of SiC the gas compositions in propulsion systems which depend on the fuel mixture ratio O/F show a significant influence on the SiC behaviour. In case of a fuel-lean mixture, the gas consists of mainly the oxidant. Under fuel-rich conditions oxidation is still possible but gas also contains a significant amount of hydrogen and carbon-monoxide. Therefore the fuel-rich environment in the existing boundary layer becomes an oxidizing/reducing mixture of H_2O/H_2 and CO_2/CO gases. In mixed oxidizing/reducing gases like H_2O/H_2 or CO_2/CO mixtures, the silica can be reduced by one of the following reactions to form volatile SiO(g)

$$SiO_2 (s) + H_2 (g) = SiO(g) + H_2O (g) \quad (1)$$
$$SiO_2 (s) + CO (g) = SiO(g) + CO_2 (g)$$
$$SiO_2 (s) + H_2O (g) = SiO(OH)_2 (g)$$
$$SiO_2 (s) + 2 H_2O (g) = Si(OH)_4 (g) \quad (2)$$

According to to E.J. Opila and co-workers, in steady state conditions of high pressure and high velocity, the oxidation/volatilization mechanism is achieved relatively quickly. A typical recession process is illustrated in figure 4 via the investigation of different specimens along a C/SiC CVD SiC coated combustion chamber [10].

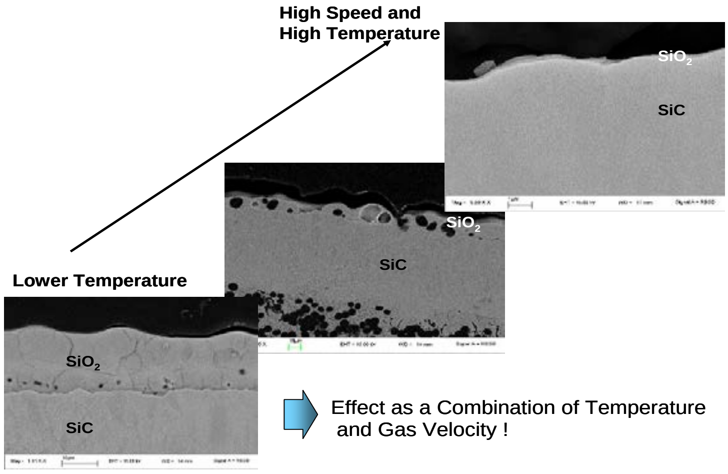

Figure 4: Observed SiC recession based on temperature and gas velocity

4. Testing and Evaluation

Accompanying to the material development itself the material quality as well as the material life-time has to be proven. In addition to that material or even more component life-time has to be investigated evaluated and finally validated in propulsion relevant environment [14].

4.1 Environmental Relevant Burner Rig - ERBURIG - testing facility

The ERBURIG-testing facility was developed to serve exactly as a fast, flexible and cost-effective way of material testing in combustion chamber-like environments for long term testing. Two different versions of the testing facility were established, one to investigate combustion chamber environments containing CO, CO_2, H_2O, O_2 etc. by using **k**erosene and oxygen as fuel (ERBURIG$^{\mathbf{K}}$) and the other, using **h**ydrogen and oxygen as fuels, to investigate combustion chamber atmospheres without carbon-containing combustion products (ERBURIG$^{\mathbf{H}}$) [for detailed information to ERBURIG^{H} please see EUCASS paper “ERBURIG^{H} Test Facility: The Next Step of Material Testing for H_2/O_2 Rocket Combustion Chambers”. K. Bubenheim, C. Wilhelmi, S. Beyer, S. Schmidt-Wimmer. EUCASS 2013. Munich]. Along with the novel established ERBURIG test facility, the combustion gas compositions, the combustion gas temperature, the combustion gas velocity and the testing/burning time is well suited for the investigation of the thermo-chemical and thermo-mechanical effects on the variety of materials used in current and future combustion chambers (e.g. CMCs, refractory metals, copper alloys etc.).
The development of the ERBURIG testing facility was based on a commercially available High-Velocity-Oxygen-Fuel (HVOF) gun, which is typically used for thermal spraying. The baseline HVOF gun was subjected to modifications and improvements to suit the needs in the ERBURIG testing facility but the working principle of the ERBURIG^{K} facility can still be described being adequate to the HVOF thermal spraying gun. At the face-plate, the injector distributes the kerosene and oxygen in a way that a homogeneous and reproducible combustion is achieved. The combustion gases are accelerated through a nozzle.
To get a good understanding of the operating mode of the test rig prior to the testing, a deep investigation including the full simulation of the combustion in terms of the entire gas flow parameters as gas composition, gas velocity and gas temperature was established. These calculations were performed inside along the combustion chamber as well as in the free jet at different mixture ratios of the kerosene and oxygen. All the numerical investigations (see exemplary illustration in figure 5) were performed in different operating points, meaning different gas velocities, gas compositions or different combustion temperatures.

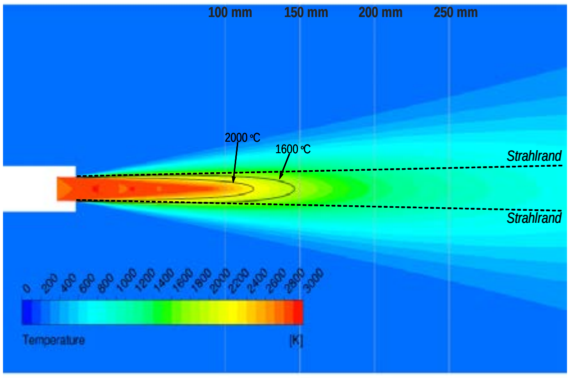

Figure 5: Exemplary temperature fields gained by numerical analysis of a free jet

In addition to that theoretical approach a multitude of measurements for validation was executed by means of thermocouples and pyrometers (on sample surface) as well as an enthalpy-probe and a Pitot pressure probe with accompanying spectroscopy measurements. The temperature was measured in the open gas jet depending on the O/F settings and distances to the nozzle-exit. Enthalpy probe technique was considered to be an appropriate method to measure all demanded variables, as gas temperature, velocity and gas composition. The open jet temperature was determined as a function of distance between the nozzle and measuring location as well as different O/F settings. The measured temperatures and the trend behaviour confirmed the measurement from the thermocouple and the pyrometric measurements. An operation range for the positioning of the samples could be defined with a temperature range from 1100°C to 2050°C. For various distances and O/F settings the corresponding gas velocity values were calculated and validated with the Pitot-probe measurements. The gas composition should be analyzed by extraction of the gas flow through the enthalpy-probe in the connected mass spectrometer. Clearly detectable peaks (mass numbers) are measurable. The height of the peaks varies depending on distance and the O/F setting. With the detectable compounds of the exhaust gas an analysing program calculated the element distribution in volume percent. The instrumentation set up is shown in figure 6.

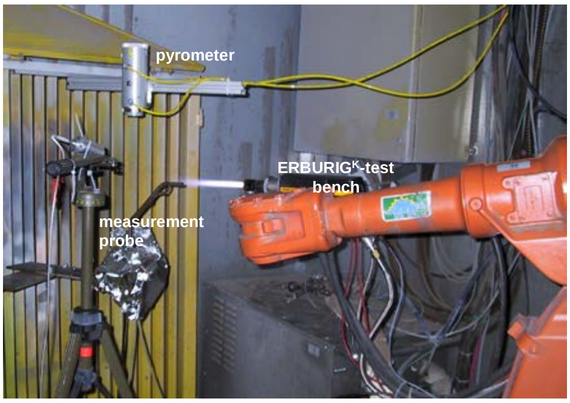

Figure 6: Measurement instruments for validation on ERBURIG^K test rig

The gas composition measurement has to be validated by further laser- and spectroscopic measurements inside the combustion chamber along with specific transparent measurement ports.
The currently performed experimental validation shows that simulation provides already a realistic temperature distribution in the gas jet. Additionally the performed simulations show close-to-reality conditions in terms of gas velocity.
The general testing is divided in two phases. Within both of them, flat test pieces and following micro combustion chambers with thermal and oxidation resistant diffusion protection systems as well as functional coatings, can be tested and evaluated (see figure 7). The flat specimen program (phase 1) is executed in the free jet, and during the micro-combustion chamber program (phase 2) parts of the original water cooled copper combustion chamber will be replaced by coated CMC chamber segments cooled and uncooled.

Figure 7: ERBURIG^K test set-up for flat sample material and with integrated micro-combustion-chamber

4.2 ERBURIG Testing Procedure and Results

During flat sample testing, the material is fixed in the free jet. Flat sample tests are the most convenient way of material screening. These tests are fast and inexpensive. Only flat samples of a size between 40mm x 40mm and 100mm x 100mm are needed, depending on the distance to the ERBURIG^K gun. Figure 8 shows a typical flat sample test in progress. The Mach discs and the incidence of the free jet are clearly detectable.

Figure 8: Flat material sample during testing in ERBURIG^K facility

During flat sample testing hot gas temperatures of 800°C – 2500°C and velocities of 1100m/s – 2000m/s can be achieved depending on the adjusted operation point. The gas composition can be influenced by varying the oxidizer-to-fuel-ratio (O/F). The change of O/F-ratio again has an effect on the combustion temperature (so that for equal temperatures, with varying gas compositions, different distances of the material sample to the ERBURIG^K gun might appear). With the baseline of a known emission coefficient in the range of the testing temperature the sample temperature can be measured using a pyrometer.
After initial testing of flat material samples, **m**icro **c**ombustion **c**hambers (MCCs) can be used as a substitute for the original ERBURIG combustion chamber. With the micro combustion chambers it is possible to evaluate the additional effect of higher pressure on the behaviour of the material as well as the geometrical influence on the substrate material. The MCCs can be stressed in an uncooled as well as in an active (water) cooled manner with only minor modifications in the test set up. In the current running phase II of the ERBURIG^K investigation program a replacement of the standard water cooled copper chamber of the test facility by water cooled coated ceramic as well as different metallic alloy micro combustion chambers is executed. Further hot tests on the ERBURIG facility in different development programs on pure radiation cooled combustion chambers are performed. The following figure shows the original copper chamber and current design approach with water cooled half shell micro combustion chambers (MCCs).

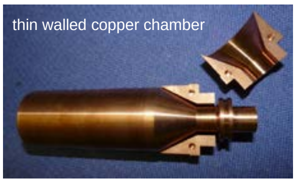

Figure 9: Copper combustion chamber with CMC combustion chamber inserts to be implemented

In addition to the active cooled MCCs radiation cooled combustion chambers can be tested with only minor modifications of the test rig.

Aim of the executed flat-test-series is the investigation of the feasibility and applicability of different protection coating systems like UHTCs on CMC substrate materials. Suchlike coatings have to encompass almost all required properties with respect to high performance propulsion conditions, such as:

- Good adhesion on substrate material
- Chemical combined with thermal resistance (thermo-chemical effects)
- High wear (erosion) resistance
- Thermal expansion comparable to substrate materials (no mismatch in thermal expansion)
- Applicability on complex rotation-symmetric components

Prior to the test the initial recording of the sample dimensions and weight is performed. Than the specimen is inserted in the ERBURIG^{K} test facility depending on the test parameters with the regarding distance to the jet exhaust via a robot assisted positioning mechanism. Subsequently, the pyrometer for the on-line non-contact temperature measurement and the point of incidence of the hot gas are adjusted to coincide in the middle of the sample, both using positioning lasers. Depending on the testing conditions (temperature, gas velocity, gas composition etc.) the test is divided in several single segments with according inspection steps in between. During the tests, different test settings and test conditions are realized. The temperature is measured via pyrometer along each test and the weight loss or weight gain of the material is measured after every test sequence.
The post-test analytical investigations include surface screening, metallographic cross-sections for the microstructure, X-ray Photoelectron Spectroscopy (XPS) for surface composition and layer thickness, Scanning Electron Microscope (SEM) for morphology and fracture behaviour and Energy Dispersive X-ray Spectroscopy (EDX) for element mapping.
The test-sequence is concluded when the maximum (accumulated) testing time which is specified is achieved or major deterioration is visible upon optical investigation. The post-test documentation includes temperature profiles, weight change, results of macroscopic and microscopic investigation to determine material degradation and formation of possible protective layers. An overview is given in figure 10.

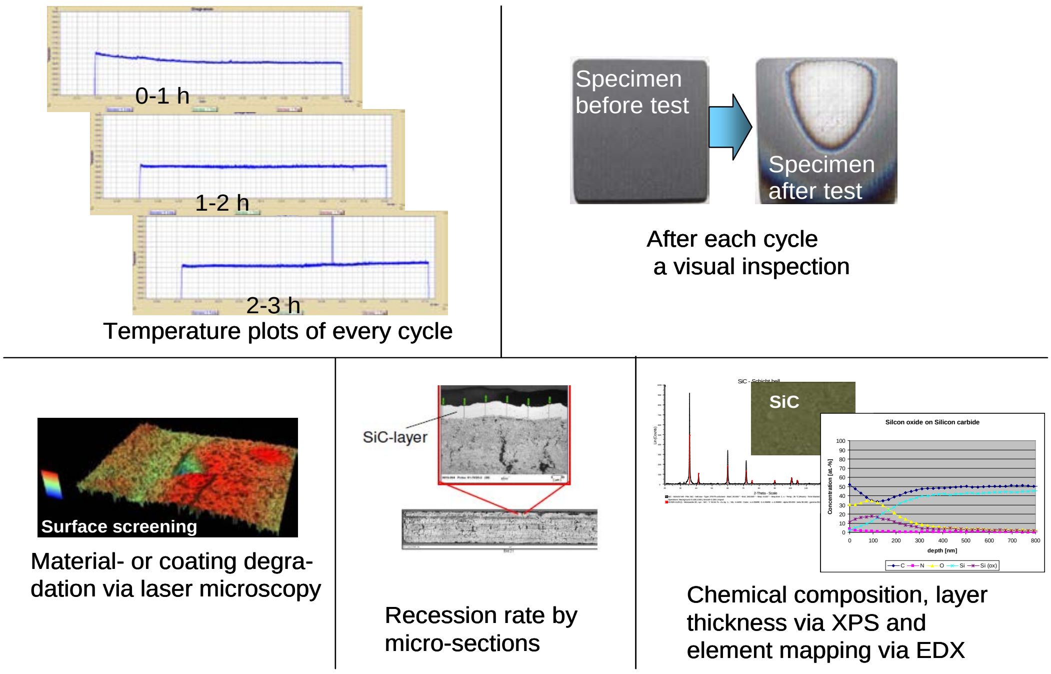

Figure 10: Typical documentation of test evaluation of ERBURIG^{K} testing on flat sample specimens

In several testing campaigns a variety of different CMC materials with and without coating systems have been assessed on their suitability for combustion applications. Therefore typical space propulsion conditions have to be simulated and applied with the special designed ERBURIG^{K}-test facility which allows an easy varying of influence parameters like combustion temperature, velocity of the combustion gas flow and composition of the combustion

gases. Currently the materials investigated were C/SiC without thermal and environmental barrier coating (EBC), C/SiC with different thicknesses of CVD-SiC coating, C/SiC with a multilayer UHTC, C-C/SiC, C/C and C/SiC material with a multilayer coating of CVD-HfC and CVD-SiC [15].
Figure 11 shows as a typical result the average coating recession of different tests based on different combustion temperatures. The yellow bars represent tests with a higher gas temperature and gas velocity compared with the blue bar. The brackets following the type of coating indicate the different coating thicknesses for CVD-SiC coatings and if so additional gasses added to the combustion while keeping O/F and overall mass flow constant.

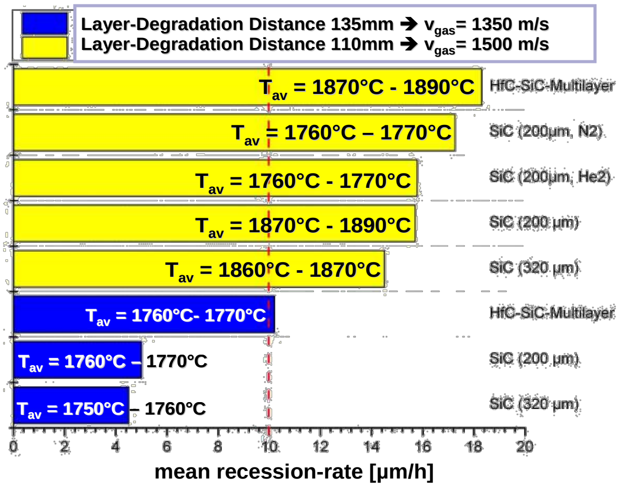

Figure 11: Comparison of averaged coating recession for different testing conditions

It can be seen, that the coating recession of the tested CVD-SiC coatings is superior to the coating recession of the benchmark multilayer system of CVD-HfC and CVD-SiC. Additional the tests revealed a strong influence of the gas velocity on the coating recession of CVD-SiC.
Objective of the previous test series was the investigation of the temperature-material interaction in a combustion relevant atmosphere. In addition the influence of the hot gas jet speed was investigated based on two test sequences. With approximately equal average temperature as well as equal volumetric flow rate the jet velocity was determined by distance variation of specimen/ ERBURIG-exit and the addition of nitrogen or helium. These investigations were executed on the "standard" CVD SiC system (200nm SiC) applied on C/SiC flat samples. It is remarkable that the test duration till a visible degradation of the material-coating system of these tests was reduced compared to the test duration with similar average temperature, however lower jet speed. This suggests a significant influence of jet speed to the degradation mechanisms on the materials which can be described currently via an exponential fit. As there was no detectable variation between the helium and the nitrogen admixture to the hot gas flow, a catalytic influence of the nitrogen on the degradation mechanism of the material at current test conditions is to be excluded.
Therefore the accelerated coating recession due to the gas velocity can even have a bigger impact on the maximum life-time than a pure temperature increase can have.

5. Conclusion

To increase the performance of orbital thrusters and to realize hypersonic flight at high Mach numbers respectively combustion chamber materials are one of the key issues. Due to the harsh environment in such combustion environments noble or refractory metals as well as CMCs and the corresponding processes are required. Thus the number of applicable candidate materials is limited. Therefore the research in the field of advanced material systems like CMCs (e.g. C/SiC) which combine high temperature and high chemical resistance, with robust processes at acceptable production costs is very demanding. To use metals or ceramic matrix composites (CMCs) at extreme temperatures (> 1600°C) possibly adapted environmental barrier coatings (EBCs) like UHTCs are necessary to resist the extreme conditions. For the testing of suchlike materials a flexible, representative and cost effective test method has to be established. Within such testing material limits as well as effects in appropriate environment have to be investigated and assessed prior to execution of very costly hot tests in rocket-engine and hypersonic-flow test facilities respectively.
With the ERBURIG^{K} test facility it is possible to screen the material and coating behaviour of CMCs with specific UHTCs in very harsh environment under typical combustion chamber-like conditions, especially during long

operating times. It can be assessed, that the described innovative ERBURIG^{K} test facility provides a fast and cost effective test method for high temperature loaded material development.
During test operation a first mapping for C/SiC flat samples with different EBC‘s / UHTC‘s was established
The determination of an optimized coating system to be applied in micro-combustion-chambers (to be tested in the test rig) seems to be feasible.

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References

[1] J. Douglas Kiser, Dr. Ramakrishna T. Bhatt, Dr. Gregory N. Morscher, Dr. Hee Mann Yun, Dr. James A. DiCarlo, and Jeanne F. Petko. SiC/SiC Ceramic Matrix Composites Developed for High-Temperature Space Transportation Applications. *NGLT, Propulsion Research and Technology.* Glenn IR&D

[2] F. Falempin, L. Serre. “French Flight Testing Program LEA - Status in 2011. *17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*. San Francisco, California. 11 - 14 April 2011

[3] R. M. Sullivan. A Model for the Oxidation of C/SiC Composite Structures. *NASA/TM—2003-212720*. Glenn Research Center. Cleveland, Ohio. 2003

[4] J. L. Smialek, Raymond C. Robinson. SiC Recession Caused by SiO_2 Scale Volatility under Combustion Conditions: I, Experimental Results and Empirical Model. *J. Am. Ceram. Soc*. 82 [7] 1817–25. 1999

[5] W. Krenkel (Hrsg.), Motz, G., Schmidt, S., Beyer, S. The PIP-process: Precursor Properties and Applications. *Ceramic Matrix Composite.* 165-186. Wiley-VCH. Weinheim. 2003. ISBN 3-527-30529-7

[6] Schmidt-Wimmer, S., S. Beyer, F. Wigger, K. Quering, K. Bubenheim and C. Wilhelmi. 2012. Evaluation of Ultra High Temperature Ceramics and Coating-Systems for their Application in Orbital and Air-Breathing Propulsion. In: *18th International Space Planes and Hypersonic Systems and Technologies Conference*. AIAA 2012-5908

[7] E.J. Opila. Integrated High Payoff Rocket Propulsion Technology (IHPRPT) SiC Recession Model. *NASA/TM—2009-215650*. Glenn Research Center. Cleveland, Ohio. 2009

[8] F. Lamouroux, X. Bourrat, and R. Nasalain. Structure/Oxidation Behaviour Relationship in the Carbonaceous Constituents of 2D–C/PyC/SiC Composites. *Carbon, Vol. 31, No. 8*. pp. 1273–1288. 1993

[9] T. A. Parthasarathy, R. A. Rapp, M. Opeka and M. K. Cinibulk. Modeling Oxidation Kinetics of SiC-Containing Refractory Diborides. *J. Am. Ceram. Soc.,* 95 [1] 338–349. 2012

[10] R. C. Robinson. SiC Recession Due to SiO_2 Scale volatility under combustor conditions. *NASA Contractor Report 202331*. March 1997

[11] P. F. Tortorelli and K. L. More. Effects of high Water -Vapour Pressure on Oxidation of SiC at 1200°C. accepted for publ. in *J. Am. Ceram. Soc. Revised*. March 2003. manuscript 186661

[12] N. J. Jacobson, Kang N. Lee, Dennis S. Fox. Reactions of Silicon Carbide and Silicon(IV) Oxide at Elevated Temperatures. *J.Am.Ceram. Soc :75(6)* 1603-11. 1992

[13] E. Nestle. Charakterisierung des Schädigungsverhaltens von Siliciumcarbiden für den Einsatz in Gasturbinen unter komplexen Beanspruchungsbedingungen. *Dr. Ing. Dissertation.* Dept. Mechanical Engineering University of Karlsruhe. 2000

[14] R. C. Robinson. NASA GRC’s; High Pressure Burner Rig Facility and Materials Test Capabilities. *NASA/CR*-1999-209411

[15] W.J.Lackey, A W. Smith, D.J. Twait. Chemical vapour deposition of oxidation resistant HfB_2+SiC composite coatings. *Ceram. Eng. Sci. Proc.*, 9(9-10), 1223. 1988