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Preface

The 25th Annual Cocoa Beach Conference and Exposition, an international meeting on engineering ceramics and structures, was held January 21-26, 2001. The conference attracted more than 525 attendees from 24 different countries. During the meeting, more than 350 technical papers covering a wide range of advanced ceramics topics were presented in eight topical focused areas and three symposia. One symposium on piezocomposite devices: design and utilization was held in honor of Professor Robert E. Newnham. The 2001 James Mueller Lecture, the highest award granted by the Engineering Ceramics Division of the American Ceramic Society, was presented by Professor R. Judd Diefendorf, McAlister Trustee Professor Emeritus of Clemson University, Clemson, SC.

We would like to thank the symposia and focused topical session organizers, session chairs, presenters, and conference attendees for their efforts and enthusiasm in planning and participating in a vibrant and leading edge conference. Once again, "Cocoa Beach" has demonstrated why it is the premier conference on advanced ceramics and composites in the world. A special thanks is extended to the ACerS staff for keeping things running smoothly.

The 156 technical presentations accepted for publication in the conference proceedings following a peer-review process are a tribute to this excellent meeting. These papers are included as issues 3 and 4 in Volume 22 of the Ceramic Engineering and Science Proceedings. Issue 3 includes papers under the broad topical headings of Product Development and Commercialization, Thermomechanical Property Characterization, and Ceramic Matrix Composites. Issue 4 covers Advanced Synthesis and Processing, Porous Materials, Wear Resistant and Protective Coatings, TBCs and EBCs, Piezocomposite Devices, Biomaterials and FGMs. Subtopics for each of the areas are included in the appropriate table of contents.

We hope you find these papers technically stimulating and look forward to seeing you at "Cocoa Beach 2002".

Todd Jessen
Mrityunjay Singh
Product Development and Commercialization
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ABSTRACT
ENCERATEC has developed high volume, commercial applications of structural ceramics in diesel engine systems. Ceramic implementation required a combination of factors which included: the improved tribological properties of the ceramic, dedication by the end-user to understand the ceramic capabilities, consideration of Total Life Cycle (TLC) costs, and the development of precision manufacturing technology. Several successful ceramic applications are described along with potential approaches for increasing the commercialization of ceramics.

CERAMICS IN DIESELS
In the early 1980’s there were predictions that advanced ceramic materials would, within 10 years, comprise a significant portion of the diesel engine. Low heat rejection (“adiabatic”) diesel engines used ceramic materials for cylinder head faces, piston caps, cylinder liners, exhaust ports and valves to provide a cleaner, more fuel efficient diesel engine.

Twenty years later, the predictions did not materialize due to a number of reasons. The initial fuel economy predictions were overly optimistic which was partially due to the state of engine combustion modeling at that time. The fuel economy benefits of low heat rejection engines were not as significant as originally projected and diesel fuel prices have remained relatively stable over the past 20 years. Also, the fuel consumption and emissions of engines using more conventional material technologies continued to improve while the total cost of the ceramic components remained high. In addition, fundamental technological barriers hindered ceramic implementation in-cylinder. The development of a high temperature lubricant while meeting low emissions was never fully realized and the strength of ceramic materials is still not sufficient for many applications.

However, advanced ceramic materials have been applied to a number of commercial diesel engine applications in the last 10 years. Most of these applications involve lower temperature oil or fuel lubricated components.

ENCERATEC FORMATION
Cummins Inc. sought out a ceramic partner that was committed to joint efforts to develop the diesel applications and ceramic manufacturing processes. Silicon nitride was initially selected as the ceramic material with the necessary strength and wear properties for the identified diesel engine applications. In searching for a partner, Toshiba Corporation exhibited the willingness to work in a long-term joint development arrangement and had world-class silicon nitride technology. A joint development agreement was entered into in 1984.
From 1984 until 1989, extensive rig and engine testing was performed to quantify the advantages that silicon nitride offered compared to traditional metallic materials. This effort concentrated on oil-lubricated components, primarily in the fuel injection and valve actuation systems. Dramatic reductions in wear were observed, especially in used oil contaminated with soot and diesel fuel.

The successful introduction of a silicon nitride injector link and optimism that additional opportunities for ceramic materials existed in diesel and other industrial applications led Cummins and Toshiba to form a separate joint venture company, ENCERATEC, in late 1989. The goal of ENCERATEC was to focus on the design and supply of advanced ceramic components. Table I shows the results of this work. The close alliance between a ceramic manufacturer and an end user for an extended period of time is perhaps unique in the world and was a key factor in the number of successful applications that have been developed.

**Table I: Ceramic Diesel Engine Components**

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<tr>
<th>Part</th>
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<th>Peak Volume</th>
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<tr>
<td>Injector Link</td>
<td>1989</td>
<td>30,000/month</td>
</tr>
<tr>
<td>EPC Bearing</td>
<td>1991</td>
<td>2,500/month</td>
</tr>
<tr>
<td>Injector Check Ball</td>
<td>1992</td>
<td>50,000/month</td>
</tr>
<tr>
<td>C-Brake Pad</td>
<td>1993</td>
<td>12,000/month</td>
</tr>
<tr>
<td>Timing Plunger</td>
<td>1995</td>
<td>50,000/month</td>
</tr>
<tr>
<td>Fuel Pump Roller</td>
<td>1996</td>
<td>48,000/month</td>
</tr>
<tr>
<td>Metering Plunger</td>
<td>1997</td>
<td>50,000/month</td>
</tr>
<tr>
<td>CAPS Pump Plunger</td>
<td>1998</td>
<td>5,000/month</td>
</tr>
<tr>
<td>Fuel Pump Check Ball</td>
<td>1998</td>
<td>480,000/month</td>
</tr>
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**PHILOSOPHY AND APPLICATIONS**

Another factor in the success of the Cummins/Toshiba alliance was the philosophy regarding the type of applications to develop. Historically, many research projects have been conducted on complex components such as turbine engine components, turbocharger rotors or valves. Complexity typically manifests itself in higher costs and manufacturing difficulty. Designing to the ultimate limits of ceramics using sophisticated finite element modeling and probabilistic design is a correct approach. But in many industrial applications the lack of accurate boundary condition information, limited ability to model dynamic effects, plus the cost involved, limits the usefulness to extremely challenging applications. Designing to a much lower stress threshold and using simple finite element analysis has allowed the successful use of ceramics in production.

The venture's application philosophy was to concentrate on relatively small parts with simple shapes that were wear surfaces in the diesel engine that experienced primarily compressive stresses. Near net shape forming was utilized to minimize the amount of material removal. Earlier rig and engine tests showed the benefits that silicon nitride provided in severe tribological conditions. Therefore, opportunities were sought out where a large improvement in durability or reliability was possible.

Common factors to the success of many applications included: definite and urgent need for improved tribological performance; ability and willingness to consider Total Life Cycle (TLC) costs, not just initial piece cost; dedication by the end-user to understand ceramic capabilities and limitations; development of precision machining capabilities; and the potential for cost reduction as the volumes increased. The following sections describe several successful applications.
STC Fuel Injector Link

In 1986, Cummins introduced the STC™ (Step Timing Control) fuel system. The injector incorporated a hydraulically actuated link that, when activated, advanced injection timing under low-load engine operation to improve emissions. The STC™ injector incorporated a steel link that is geometrically a cylindrical rod with tightly tolerated spherical ends.

The new emissions requirements resulted in more soot being generated in the combustion process and collecting in the lubricating oil. The soot accelerated the wear of the steel link as a result of the combination of high load and boundary lubrication. Therefore, the injectors had to be reset to maintain optimum engine performance and compliance with emissions regulations, a significant inconvenience to customers. The options were limited, as the injector could not be redesigned to provide larger contact areas at the high wear points. Cost of the silicon nitride link was several times more than the steel link. Consideration of TLC costs, including warranty and customer satisfaction, made the option an attractive one. Production of the ceramic link began in 1989. This ceramic link was the first known application of silicon nitride as a commercial structural component for diesel engines anywhere in the world. Figure 1 shows the silicon nitride link developed by Toshiba and used by Cummins, which replaced the steel link. The reduction in wear was significant. Wear of the entire injector train was reduced by 40% by replacing this one component.

![STC™ silicon nitride link and injector](image)

To date, about 2 million silicon nitride links have been produced in three sizes for various model fuel injectors. The ceramic injector link is an ideal application for ceramic as the loading is primarily all compressive with insignificant side loading. Axial loads are approximately 900 kg, which results in a Hertzian contact stress of approximately 1,000 MPa. The links are produced from a high-grade pressureless-sintered silicon nitride. Two forming methods have been used to produce the ceramic injector link, die pressing and injection molding.

Because this was a critical breakthrough application for silicon nitride, material quality control was paramount. Any ceramic link failures would seriously jeopardize future ceramic applications
in the diesel engine industry. As a result, the level of inspection conducted was high. The geometry of the critical spherical ends is measured on every link by a special automatic measuring machine designed and developed by Toshiba. The links are 100% visually examined and inspected with fluorescent penetrant inspection. Each link is X-ray inspected for internal defects.

The result has been a perfect reliability record for the close to 2 million links produced. The wear resistance of the ceramic exceeded expectations and links are typically reused when fuel injectors are returned for refurbishment.

EFC Governor Hybrid Bearing

Cummins' larger displacement engines used for electrical power generation applications are typically equipped with an EFC (Electronic Fuel Control) governor. This governor includes a rotary solenoid valve that controls a throttle shaft, which is supported by two bearings. In electrical power generation, the control of engine speed within a few percent as load changes is a basic requirement for acceptable performance. When in steady-state conditions, the rotary valve is fed a "dither" signal that causes the valve to oscillate over a very small angle of rotation so that initial torque is reduced when response to a change in load is required. This improves the ability to control the speed of the engine within a tight band.

However, this small angle of rotation leads to a condition referred to as "false brinelling" of the races. As the balls in the bearing move back and forth a small amount, the grease lubrication is locally depleted. This depletion results in metal-on-metal contact and adhesive wear. A pocket is worn into the race at each ball location. This increases the torque required to turn the bearing when a larger movement is required, resulting in engine speed control issues.

A hybrid bearing (silicon nitride balls, steel races) was specified for this application due to the lack of cold-welding that occurs between ceramic and steel in conditions of marginal lubrication. The false brinelling condition was eliminated, increasing the reliability and durability of the control valve. No design changes were required to the system. The higher cost of the hybrid bearing was justified by reduced warranty costs and improved system reliability and durability.

Injector Check Ball

The Cummins CELECT™ electronically controlled unit fuel injector incorporates a check ball, Figure 2, in the high-pressure portion of the fuel supply path to allow fuel flow in one direction. The ball seals against the seat with considerable force and at high frequency, equal to

![Figure 2. Silicon nitride check balls](image)

the injection frequency. The original steel check ball was wearing the seat resulting in fuel leakage and affecting the performance of the injector.

A silicon nitride check ball was recommended for evaluation. The Hot Isostatic Pressed silicon nitride material was selected based on the capability of withstanding high stresses, proven corrosion resistance, lower mass, and lack of adhesive wear against steel. Also, the silicon nitride balls were readily available due to their extensive use in the precision bearing industry.
The results were successful with the seat wear problem solved. In service, the silicon nitride ball reliability has been excellent. The use of silicon nitride as a check ball in diesel and also gasoline fuel systems has increased. Several major fuel system manufacturers now use them.

C-Brake™ Master Piston Pad

Cummins began manufacturing its C-Brake™ engine compression brake in 1992. The master piston is part of the mechanical-hydraulic circuit which times the opening of the exhaust valves at the point of injection, thus effectively turning the engine into an air compressor, absorbing energy from the vehicle and reducing the use of the wheel brakes. When the brake is activated, the wear pad of the master piston contacts the head of the injector rocker arm adjusting screw resulting in a contact stress of 1,000 MPa. The pad is inverted with lubrication provided by splash from the valve train. There is a small amount of sliding motion between the adjusting screw head and master piston pad as the brake operates.

The combination of high contact stress, marginal lubrication, and sliding motion led to unacceptable wear of the components which caused the overhead to be adjusted more frequently than desired. The challenge with this application was developing a cost-effective ceramic design to replace the D4 tool steel master piston.

The result was a patented mechanical attachment method that allowed the use of a relaxed tolerance as-sintered silicon nitride pad, Figure 3, and a less expensive 52100 steel body. The ability to design for the use of an as-sintered ceramic component was critical for the acceptance of the ceramic master piston pad. The reduction in wear was dramatic, an average 80% reduction.

![Figure 3. Master piston pad](image)

Fuel Pump Roller

ENCERATEC teamed with Stanadyne, a major fuel systems manufacturer, to assist Stanadyne in meeting the application requirements for its DS50 pump (Figure 4), including the requirement to operate on the new fuel federally mandated in 1993, which reduced sulfur and aromatics and also reduced diesel fuel lubricity. The previously used steel rollers, which were diesel fuel lubricated, experienced scuffing and seizing in this new application environment. The roller experiences a combination of rolling motion against the internal cam ring and sliding motion against the roller shoe, Figure 5, in a boundary lubrication condition. A variety of steel materials and improved geometry and finish of the rollers did not result in the desired improvements. Stanadyne had, several years earlier, successfully tested silicon nitride rollers supplied by ENCERATEC for low lubricity fuel applications. A pressureless sintered material was proposed for this application since the contact stresses were relatively low and cost was a major consideration.

The ceramic roller was basically the same as the original steel roller with minimal changes to account for processing differences between the steel and the silicon nitride rollers. The steel roller form tolerances, which had been previously tightened in a series of steps in an attempt to solve the basic tribological problems, were relaxed for the silicon nitride roller with no reduction in
performance. This approach was proven through rigorous testing. Rollers produced to the extreme range of tolerance of several critical features and tested in pumps validated the selection of the production tolerances.

The robustness of the rollers was proven through a series of abuse tests. Roller spalling occurred only in very severe pump overspeed tests. The spalling was limited to the formation of shallow spalls on the surface originating at a location of high edge loading of the cam ring on the overhanging roller. However, this spalling never caused a reduction in pump performance and was only found upon inspection of the pump components at the scheduled end of test. The progression of spalling was followed in tests and was found to proceed at a relatively low rate. This experience provided a high degree of confidence in the capability of the silicon nitride material.

This application has completely eliminated the scuffing and seizing mode of failure and with no reported pump failures due to roller seizing in over four years of high volume production.

**Injector Timing Plunger**

Initial research into ceramic materials for tightly tolerated fuel systems components began in the early 1990's with the Cummins CELECT™ fuel system. Ceramic materials had been shown to have excellent wear properties and it was confirmed that ceramic-based materials had improved tolerance to marginal lubrication. Cummins conducted extensive test evaluations on silicon nitride and zirconia for these applications. Testing confirmed the superior performance of the ceramics, however the match clearances were not maintained as a function of temperature with the silicon nitride and zirconia was selected for this application. Figure 6 shows the location of the ceramic plungers in this system. Additional engine and rig tests proved the ability of the zirconia plungers to withstand scuffing and seizing even with water introduced into the fuel. The superior scuff resistance of the zirconia eliminated the necessity for a spherical radius at the end of the plunger, thus reducing the cost of the ceramic component. The ability to consider Total Life Cycle cost was key to acceptance of the zirconia plunger.

One significant barrier to timing plunger implementation was the lack of high volume centerless grinding capability to grind the outer diameter of the plungers to sub-micron tolerance levels. Cummins developed this capability and performs the final outer diameter grinding operations. Today, reductions in material and manufacturing costs have eliminated the cost premium of the zirconia plunger.
Injector Metering Plunger

Following the success of the timing plunger, a zirconia metering plunger was introduced in 1997, Figure 7. This component had an increased level of complexity with a drain hole through the diameter and intersecting a blind hole through the center of the plunger. Sharp metering edges in two locations were also a necessary part of the design. Preventing chipping of the edges during the grinding and handling operations has necessitated the development of improved manufacturing techniques. Materials with improved strength will further improve the abuse tolerance of the edges.

Zirconia plungers have significantly improved the Cummins CELECT™ injectors. CELECT™ fuel injectors have been instrumental in meeting current emission regulations and improving engine fuel economy in Cummins heavy-duty diesel engines.

CAPSTM Pumping Plunger

In 1998, Cummins introduced the CAPSTM common rail fuel system for mid-range engines with a zirconia pumping plunger, Figure 8. This marked a breakthrough as it was the first system at Cummins to be introduced into production with a ceramic component. The decision was made to use zirconia early in the development process. This enabled the plunger design to be modified for ceramic to reduce the total cost.
Figure 8. Cummins CAPSTM high pressure pump section with zirconia pumping plungers

With this application, ceramics are now considered as a material choice at the design stage rather than after a system has been introduced. Improvements in material and machining costs have made ceramic components cost competitive with other potential material choices, such as wear resistant coatings or surface-treated high alloy steels.

FUTURE

During the last 10 years, the use of structural ceramics in diesel engines has evolved. Initially ceramic applications were justified based on solutions to complex tribological problems in order to justify the use of the ceramic, essentially a last resort. Now ceramic components are being evaluated during the development stages of new systems due to their excellent track record in specific applications. Furthermore, improvements in the ceramic material cost and grinding cost allow many geometries to be competitive on a per piece basis with coated hardened steels.

What can be done to improve the acceptance and use of ceramics in diesel engines in the future? Certainly, an important factor is that potential users must become knowledgeable about the advantages and limitations of ceramic materials. There is no substitute for learning by experience. In the engine technologies, applications continue to develop as the emission requirements become more stringent and the fuel and oil lubricated components become more highly stressed. Material and grinding costs continue to be reduced and materials with improved strength and fracture toughness are being developed. This increases the number of potential applications for ceramics. In addition to the production components described, many ceramic components have been prototyped and manufacturing-friendly designs developed. These components can be introduced when a favorable cost versus benefit point has been reached.

SUMMARY

The increased use of ceramics for fuel and oil lubricated components is very likely. Development engineers at Cummins, Toshiba and other companies are evaluating and designing ceramics into new systems. Previously, the introduction of the ceramic was limited to a copy of an existing steel component for an existing system. Designing for the ceramic manufacturing process and material capability enables more cost effective and robust designs. The examples of successful components demonstrate that a sustained, focused effort results in effective application of advanced materials. In each case, a tribological problem was solved resulting in significant savings and improved customer satisfaction. This experience can be used as a basis for other industrial applications where similar challenges are present.
ABSTRACT
Ceramic matrix composite materials (CMC) were originally developed for high temperature applications such as heat shields or thermal protection for spacecraft. Different processing techniques are currently in use for the manufacture of continuous fibre reinforced ceramic matrix composites, which result in low weight materials (~2 g/cm³) with outstanding properties. A novel technology to produce CMC structures with lower costs and shorter manufacturing times has been developed at DLR. The Liquid Silicon Infiltration (LSI) process is based on the infiltration of economically manufactured carbon / carbon with molten silicon and leads to so-called C/C-SiC materials. These represent a new class of high performance ceramic materials, not only suitable for space applications, but also as braking materials for new generations of high speed cars, trains and emergency brakes in the fields of mechanical engineering and conveying.

Due to their multiphase matrix composition and the internal SiC layers, C/C-SiC brakes offer advantages to state-of-the-art carbon/carbon brakes. In general, the coefficient of friction for C/C-SiC is higher, wear rates are lower and ambient conditions such as humidity have practically no deleterious effect on material characteristics.

INTRODUCTION
Fibre reinforced ceramics can be defined as composite materials, which on the one hand demonstrate the typical material characteristics of high temperature ceramics, and on the other open up the technical manufacturing possibilities for the construction of large, thin walled, complex structures. For these reasons, the possibilities of short fibre and whisker reinforcements as well as the reinforcement of glasses and vitreous ceramics, whose strengths decrease in the temperature range of 800 °C – 1000 °C, will not be discussed here.

The most important continuous fibre reinforced ceramics are:
- C/C carbon fibre reinforced carbon,
- C/C-SiC carbon fibre reinforced carbon with SiC constituents,
- C/SiC carbon fibre reinforced silicon carbide,
- SiC/SiC silicon carbide fibre reinforced silicon carbide.

The carbon fibre reinforced carbon matrix composites (C/C) have been in use the longest and represent the current technological state-of-the-art for particular high temperature applications, such as: brake disks, rocket nozzles, furnace heating. A well known example for the practical application of C/C composites is within the five American space shuttles, where the fuselage nose
and the leading edges of the wings are manufactured from coated C/C and have successfully withstood a total of 100 missions under the extreme re-entry conditions. C/C brake disks for both military and civil aircraft as well as Formula 1 racing cars are also in service.

In order to improve the oxidation resistance and thus the application lifetime of these composites, research has been exerted over more than two decades on using non-oxide ceramics instead of carbon as the matrix material. Silicon carbide is particularly suitable as a matrix material due to its high oxidation and thermal shock resistance and is, as carbon fibre reinforced silicon carbide (C/SiC) and silicon carbide fibre reinforced silicon carbide (SiC/SiC), the currently furthest developed ceramic composite. Practically the same manufacturing techniques can be used here as for the manufacture of C/C. By the development of both C/SiC and SiC/SiC, most experience has been with materials which have been manufactured using the chemical vapour infiltration (CVI) method. The French company SEP is leader in this technology and provides licenses, amongst others, to American manufacturers.

The typical field of application for CMC lies where metals (super alloys), due to their insufficient mechanical strength at elevated temperatures, can no longer be considered and encompasses all areas of lightweight construction. Thus, all projects concerning future space transportation systems and hypersonic aircraft foresee the extensive use of these materials, in particular for engine intake flaps, nozzles, thermal protection systems (TPS) or so-called hot, load bearing structures in the wings and fuselage, in order to fulfill the extreme lightweight construction demands.

SPACE CAPSULE MISSIONS

For the development of re-entry technology, it is essential that the knowledge gained from ground test facilities and numerical analysis is tested under real re-entry conditions. One of such projects was the German-Japanese capsule EXPRESS which was launched in January 1995 (Fig. 1).

![Figure 1: The EXPRESS capsule with CETEX in the stagnation point (left); CETEX experiment (rear view) with PYREX and RAFLEX for the EXPRESS capsule (right)\textsuperscript{6,6}.](image)

Unfortunately the mission failed due to a malfunction of the launcher and the capsule missed the nominal orbit. After two orbits, the capsule was classified as lost. However, in December 1995,
the capsule was discovered in Ghana, by chance, and shipped back to Germany enabling interesting investigations.

The heat shield experiment, CETEX, is a hot structure comprising of the CMC material C/C-SiC. It was manufactured using the liquid silicon infiltration process, which has been developed at the Institute of Structures and Design within the German Aerospace Center (DLR). CETEX, as a key experiment, was integrated in the ablator of the capsule in the region of the stagnation point. It served as a non-ablative basis for three other experiments, namely PYREX, RAFLEX and the Japanese spectroscopic experiment RTEX.

The tile (Fig. 1, right) consists of a shell with constant thickness, stiffened by six radial and one circumferential rib. Load introduction is done by six local stand-offs, integrally manufactured with the circumferential rib. Shaping of the load introduction was conducted using wire erosion in the ceramic state of manufacture. The shape of the stand-offs was designed such that radial movement of the tile was feasible without creating thermally induced stresses in the load introduction area. This was realised by clamping the stand-offs with metallic interfaces using a castable ceramic both as a thermal insulation and to scope with tolerances. The metallic interfaces are screwed to the cold structure by bolts which are fixed on the back side of the nose cap of the capsule.

Since the beginning of the C/C-SiC material development, tests in various arc jet test facilities (IRS-Stuttgart University, ISAS Japan, LBK DLR Cologne) in the temperature range of 1150 °C up to approximately 3000 °C were conducted at different pressures and mass flow rates. Taking into account the different material degradation mechanisms which occur during the specific re-entry trajectory (time, temperature, pressure history), the weight loss or material recession measured in plasma tunnels corresponds quite satisfactorily with the values which were measured either flying two missions with Russian re-entry capsules (FOTON 6 and 9) or in the case of the EXPRESS mission.

THERMAL PROTECTION SYSTEM FOR CRYOGENIC TANK STRUCTURES

In the FESTIP (Future European Space Transportation Investigation Program) project under the direction of ESA, a new TPS (Thermal Protection System) concept for the cryogenic tank of a future single-stage-to-orbit reusable launch vehicle was developed in close co-operation with industrial partners (Alenia Spazio, CASA, DASA (EADS) and MAN-Technologie). Two test samples were manufactured and tested. The work share of the Institute was the concept development including the detailed design, a transient thermal analysis of the concept under re-entry loads and finally the integration and assembly of the components for the test samples. Alenia Spazio and CASA were responsible for manufacturing representative samples of the tank structures, MAN-T and DASA (EADS) were manufacturing the CMC panels plus stand-offs and fasteners and the high temperature insulation. The thermal and mechanical tests were carried out at the Institute of Structural Mechanics of DLR in Braunschweig.

The concept developed in FESTIP (Fig. 2) is a so-called rigid-surface TPS. The mechanical aerodynamic loads act upon a CMC surface skin and are transmitted to the load bearing substructure via stand-offs. The substructure is at the same time a conformal cryogenic tank, which means that good thermal insulation is necessary. In order to resist the re-entry thermal loads a flexible high-temperature insulation is packed between the CMC skin and the tank structure. The technical challenge in this design is to balance the thermal expansion behaviour of the hot CMC skin against the cold tank structure. The solution was to attach the CMC skin panels with CMC stand-offs that are flexible in the direction of the skin panel expansion and do not inhibit the expansion mismatch whilst fixing each panel to a central post. To prevent possible ingress of hot gas in the gap between panels, a seal is located underneath those gaps fixed in position by a CMC rigid seal support. The TPS concept also incorporates advanced CMC fasteners which can
bear the high temperatures at the vehicle skin. This is an essential aspect of the design since it facilitates the attachment of the TPS components from the outside of the vehicle with no internal access to the vehicle.

Figure 2: FESTIP CMC TPS design configuration for the test set-up

Figure 3: Schematic cross-section of the central post as a peg or blind rivet design