Rolls-Royce

FAA Continuous Lower Energy, Emissions, and Noise (CLEEN) Technologies Program

Ceramic Matrix Composite (CMC) Blade Track Public Report

OTA Number:
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Glossary of Acronyms and Terms

Designation	Definition
°C	Degrees Celsius
2-D	Two-dimensional
3-D	Three-dimensional
Al	Aluminum
Atm	Atmosphere (unit of pressure)
C	Carbon
CD	Conceptual Design
CDR	Critical Design Review
CMC	Ceramic matrix composite
Co	Cobalt
CO_2	Carbon dioxide
Cr	Chromium
CT	Computed tomography (abbreviated term for computerized axial tomography [CAT])
CTE	Coefficient of thermal expansion
CVI	Chemical vapor infiltration
DFM	Design for Manufacturing
DOD	Domestic object damage
DOE	Design of experiments
EBC	Environmental barrier coating
EFE	Environmentally Friendly Engine (Rolls-Royce demonstrator engine used to test SiC/SiC CMC blade track)
FAA	Federal Aviation Administration
FOD	Foreign object damage
HP	High pressure
hr	Hour
ILS	Interlaminar shear
ILT	Interlaminar tension
in.	Inch
IR	Infrared
K	Degrees Kelvin
kg	Kilograms
lb	Pound
LP	Low pressure
MI	Melt infiltration
min	Minute
mm	Millimeter
MPa	Megapascal
NASA	National Aeronautics and Space Administration
NDE	Nondestructive evaluation
NH	High speed rotor speed
Ni	Nickel
NOx	Nitrogen oxides
O	Oxygen

Designation	Definition
PL	Proportional limit
P41	Gas-path pressure
psi	Pounds per square inch
Pt	Platinum
RRHTC	Rolls-Royce High Temperature Composites
sec	Second
SEM	Scanning electron microscope
SI	Slurry infiltration
Si	Silicon
SiC	Silicon carbide
SMI	Slurry melt infiltration
S/N	Serial number
SS	Seal segment
TC	Thermocouple
TDC	Top dead center
TET	Turbine entry temperature
Ti	Titanium
TRL	Technology readiness level
UK	United Kingdom
U.S.	United States
V	Vanadium

Summary

This report has been prepared as part of the Rolls-Royce and FAA Continuous Lower Energy, Emissions and Noise (CLEEN) program to develop high temperature materials, namely ceramic matrix composites (CMC), for application in future civil aircraft engine applications. The objective of this program was the design, manufacture, and test of a silicon carbide (SiC)/SiC CMC high pressure (HP) turbine blade track. The development of high temperature blade tracks supports the CLEEN Program's goal of aircraft fuel burn reduction though improved thermal efficiency in the engine core. The blade track was intended for insertion and testing into the HP turbine section of the Rolls-Royce Environmentally Friendly Engine (EFE) demonstrator engine. This document will broadly discuss the design, manufacture, and testing of the CMC blade track components, and constitutes the Final Public Report for the CMC Blade Track program.

The desire to use a CMC material for an HP blade track application is motivated by its lighter weight and higher temperature capability relative to a corresponding metal blade track, reducing fuel burn relative to conventional technology. The parts developed under this program were tested in two builds of the EFE test engine in a rainbow arrangement (i.e., an assortment of metal and CMC components). This approach led to the design constraint that the CMC blade track be interchangeable with the baseline metallic component. As a result, the weight of the final CMC design was not a primary consideration to the demonstration hardware. However, demonstrating a reduction in cooling air was considered critical to a successful design. This cooling air reduction in combination with the primary blade track function of controlling blade tip clearance resulted in two key design drivers:

1. Working within a very tight space claim, the CMC blade track must transfer the pressure load acting on it back into the metal support structure.
2. The CMC blade track must manage the cooling airflow to demonstrate overall reduction relative to metal blade track design without overheating the metal support structure.

This report describes the design and analysis methodology used in evaluating the CMC component and layout against these two design goals. It provides the approach to validate the CMC blade track design for engine testing, and also provides a summary of the testing and performance of the blade tracks. Finally, a technology assessment of the HP CMC blade track is provided.

The FAA CLEEN program provided valuable experience and a number of lessons learned in the development of CMC HP turbine blade tracks. The program demonstrated the feasibility of a CMC blade track for a large civil engine with a proof of concept design. The blade tracks succeeded in running in the engine environment while using less cooling air than traditional blade tracks. Despite the unexpected events due to unrelated engine hardware that caused both tests to end prematurely, the CMC material did not suffer any ultimate failures. Based on the engine test experience, the CMC blade tracks have demonstrated Technology Readiness Level (TRL) 6, qualifying this technology as ready for use in full scale production engine development. The first CMC blade track production components are expected to enter into service by the end of the decade, in line with the CLEEN Program's targets for fuel burn reduction technologies like these to transition into the fleet. It is estimated that a 1% fuel burn benefit can be achieved in wide-body applications (engine specific) by implementing multiple stages of CMC components.

1. Program Overview

In support of the FAA CLEEN Program goals, reductions in fuel consumption will be achieved with the introduction of components in the turbine that require substantially lower levels of cooling airflow. These advances will not only serve to address the fuel burn directly but also indirectly assist in NOx and CO_2 reduction by reducing the total mass of NOx and CO_2 produced.

Rolls-Royce is addressing the achievement of reduced fuel consumption with low weight, long life, and affordability by combining high turbine pressure and temperature with low cooling flow. High turbine temperature requires that turbine blade tracks are either well cooled or have high temperature capability. Therefore, Rolls-Royce has developed a CMC turbine blade track comprising ceramic surfaces suspended from metal frames, which minimizes the need for cooling air.

The CMC blade track has higher temperature capability than a metal blade track, which permits significant cooling flow reductions for the CMC component. The lower material density of the CMC materials also enables weight savings, further reducing fuel-burn compared to conventional metal technology.

The CMC blade track technology was tested in the Rolls-Royce EFE demonstrator. The EFE was a technology demonstrator based upon the high bypass ratio Trent 1000, the engine powering Boeing’s 787 aircraft. This advanced cycle demonstrator was used by Rolls-Royce to develop, in an engine environment, near-term technologies slated for future products. The EFE operating conditions were beyond current state-of-the-art civil engines, providing an aggressive test environment. Piggybacking on an existing demonstrator program also minimized development cost and time.

The CMC blade track technology maturation effort included component design, validation, development, and demonstration in an engine environment. The following report outlines the design activities, test results and conclusions, and the way-forward for CMC blade track technology in future Rolls-Royce products.

2. Concept and Preliminary Design

2.1 Design Requirements and Constraints

The CMC blade track was designed for physical and functional compatibility with the baseline EFE HP turbine architecture. This approach was defined to allow the CMC blade track to be interchangeable with the standard metallic design, thus enabling both configurations to be run simultaneously in the engine. The resulting CMC blade track configuration design constraints are summarized in Figure 1. Physical compatibility required that interfaces with surrounding components could not change from the standard metallic blade tracks. However, the cold build clearance of the CMC blade track was allowed to differ from the standard metallic blade tracks as required to ensure equal rotor tip clearance during engine operation. In addition to the physical interface requirements, the CMC blade track was required to use no more cooling air than the standard metallic blade track, and the abradable coating was required to be compatible with the cutting tip used on the EFE HP turbine blade.

In addition to the interface and cooling air usage requirements described above, the following requirements were mandated of the CMC blade track design:

- Required design life – 150 hr
- Required cyclical life – 600 cycles
- Weight limit of blade track assembly – 0.3 kg
- Must utilize existing metallic blade track hanger
- No external mating features modifications are allowable:
    - Flow-path surface must match at a high power cycle point
    - Flow-path chamfers
    - Hangers
    - Seal grooves to remain unchanged:
        - Piston ring
        - Butterfly strip seal

        - Steady-state analysis required at high power and maximum power cycle points
        - Transient thermal and mechanical analysis
        - The blade track should safely cope with a deep rub representative of civil large engine experience as a one-off unplanned event
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CMC design must incorporate the following EFE features:

1. Common flow path
2. Common blade track count
3. Same hanger arrangement
4. Include common piston ring grooves
5. Use same or less cooling air
6. Incorporate intersegment strip seals
7. Abradable flow-path coating

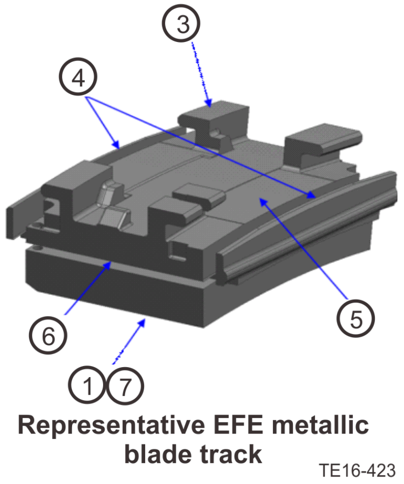


Figure 1. EFE design configuration requirements.

The required design and cyclical life came from the endurance test cycle shown in Figure 2.

The requirement to fit within the design space of an existing component provided several challenges. The space claim was smaller than the metallic blade tracks since the CMC and all seals had to fit within the existing metallic blade track. This limited the options for sealing as well as cooling. An optimized design would typically require more vertical space claim. This would allow for larger radii in the composite laminate as well as open up space to optimize the length versus diameter of the cooling holes providing cooling air and purge air to the CMC blade track.

2.2 Material Selection

2.2.1 SiC/SiC CMC Materials

Rolls-Royce selected a Hi-Nicalon fiber woven into a five-harness satin fabric ply as the preferred approach for this component. The plies were pre-formed to shape in a 2-D laminate stack. The laminate was then densified with a matrix by a combination of chemical vapor infiltration (CVI), followed by slurry infiltration (SI), and finally a melt infiltration (MI). Using the SI and MI process rather than a CVI-only process reduced processing time and improved material capability. These improvements included an increase in proportional limit, an increase in strain to failure, an increase in toughness, and a higher thermal conductivity. The material properties of the resultant SiC/SiC CMC were gathered experimentally via specimen testing with additional knockdowns for safety margin.

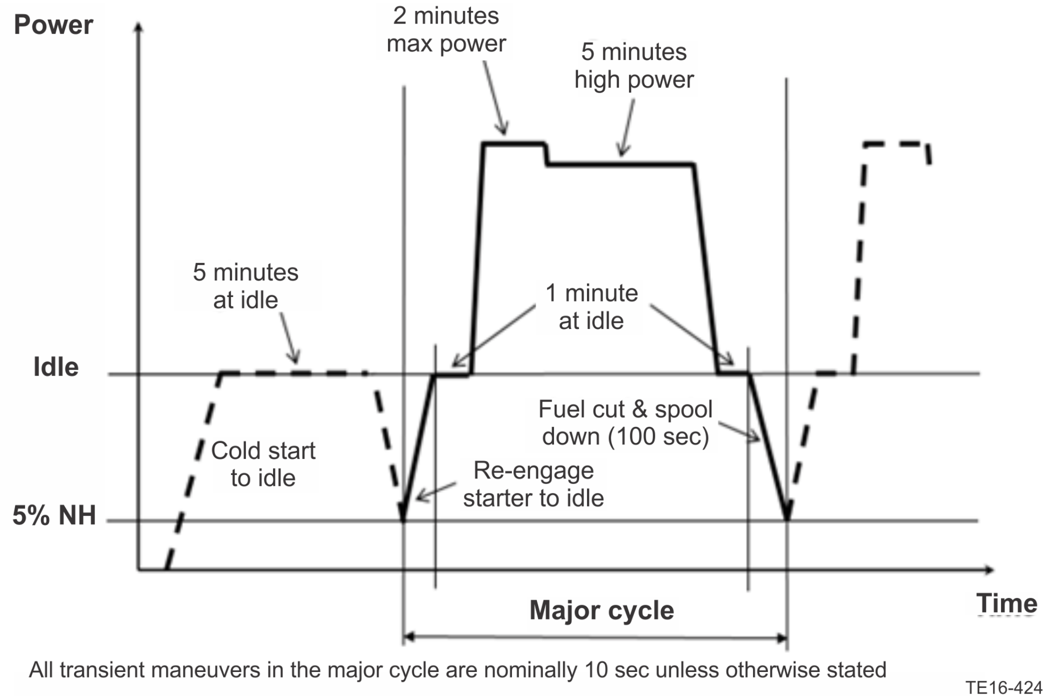


Figure 2. EFE endurance test cycle.

2.2.2 Coating Materials Selection

The coating system selected for this component was a multilayer system, as shown in Figure. It consisted of a silicon bond layer on the CMC, which also provided long-term oxidation resistance for the CMC. The next layer was an environmental barrier coating (EBC) that was intended to provide the CMC with water vapor protection. The final, thicker layer was the abradable coating that was meant to be cut into by the turbine blade tips to effectively reduce tip clearances. A number of tests were conducted to compare coatings, with ytterbium disilicate being the selected coating for both layers.

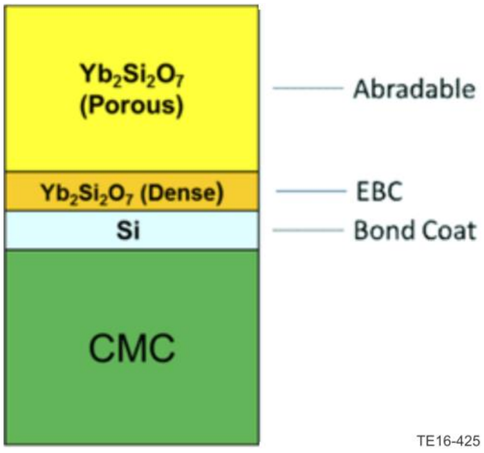


Figure 3. Coating system used on CMC blade tracks.

2.3 Conceptual Design Studies

A total of seven concepts were considered during the Conceptual Design (CD) phase. To allow timely evaluation of the merits of each design, a simplified analysis of each concept was utilized. This simplified analysis method, in addition to being sufficient for performing a relative comparison of the various concepts, also did a very good job of predicting in-plane tensile stresses, which are a key design parameter.

Various hanger designs were examined during the CD phase of the program. The configurations incorporated various attachment features such as hooks and dovetails. These designs were examined for peak stress levels, thermal growth, and manufacturability.

The final concept considered incorporated all the lessons learned from the various design concepts analyzed to that point. A single wide-dovetail hanger was implemented that had the low stress riser benefit of a dovetail, the bulk stiffness provided by the fill region, and accommodation of the thermal growth mismatch between the metal and the CMC.

Peak stresses for the wide-dovetail design were at the bearing location on the aft hanger face. It was believed that through closer study and refinement of both the design and the analysis, these stresses could be brought down to an acceptable level The wide-dovetail design was considered the best option coming out of the concept design phase.

2.4 Preliminary Design

The complexity of the analysis work increased significantly as the design effort transitioned into the Preliminary Design phase. Specific examples are provided in the following list:

- Isotropic analyses were eliminated in favor of full orthotropic models. This was necessary to the model each of the sublaminate regions of the blade track and to accurately characterize the full complement of stress components (i.e., σ_{11}, σ_{22}, σ_{33}, σ_{12}, σ_{13}, and σ_{23}).
- The full holder/blade track assembly, along with contact interactions, was modeled.
- A range of geometric parameters were studied through a design of experiments (DOE) process to minimize as many critical stresses as possible.

The blade track design selected from the CD phase was the single wide-dovetail design. The fabrication process utilized by the manufacturer was based on hand layup of 2-D dry fabric (0/90, 5-harness satin weave). After a Design for Manufacturing (DFM) workshop with the manufacturer, a lay-up architecture with a sublaminate structure was agreed upon.

3. Detailed Design

3.1 Final Design Configuration

The complete CMC seal segment assembly includes the wide-dovetail CMC blade track, the metallic holder, and the associated hardware required to complete the engine-ready assembly.

Figure 4 shows an exploded view of the CMC blade track assemblies:

- Part 1 is the modified holder, which provides the support structure for the CMC seal segment. This support structure was machined into a baseline metallic blade track casting and the radial height has been reduced. The split line edges show the cutout to accept the dovetail shape of the blade track and the cooling hole patterns. Using the original metallic blade track casting allowed the CMC blade track to work with the existing tip clearance system as-is. Due to configuration differences and differences in coefficient of thermal expansion (CTE) between the standard metal blade tracks and the CMC blade tracks, the cold build tip gap was made larger for the CMC blade tracks so the location and radii for all blade tracks would match at the high-power cycle condition.
- Part 2 is the CMC blade track. This is an isometric view of the CMC part with the coatings (Part 4) applied. It slides into the holder circumferentially.
- Part 3 is the shim/isolation layer. This part acts as a shim to account for manufacturing tolerance buildup, as well as to control the load points to three locations on the CMC. Additionally, this part serves as an isolation layer between the Si-based CMC and the holder.
- Part 4 is the CMC coating system, described in more detail in Section 3.2.
- Part 5 is shown in green and is a series of rope seals. The rope seals are installed into grooves in the holder after the shim is installed.
- Part 6 is the endcaps, which were made to circumferentially clock/anti-rotate the CMC blade track in space as well as provide the original butterfly strip seal interface. The pins, Part 6.b, are press fit into the end caps and welded to the holder.
- Parts 7.a and 7.b are the manifolds. They have cooling channels machined into them.
- Part 8 highlights the plugs for the top holes. The holes are drilled through the manifold and the holder. The plugs are installed and are tack welded in place.

1. Holder
2. Blade track
3. Shim/isolation layer
4. Coatings
5. Rope seal
6. End caps
1. End cap
2. Retention
7. Manifolds
1. Forward manifold
2. Center manifold
8. Plugs

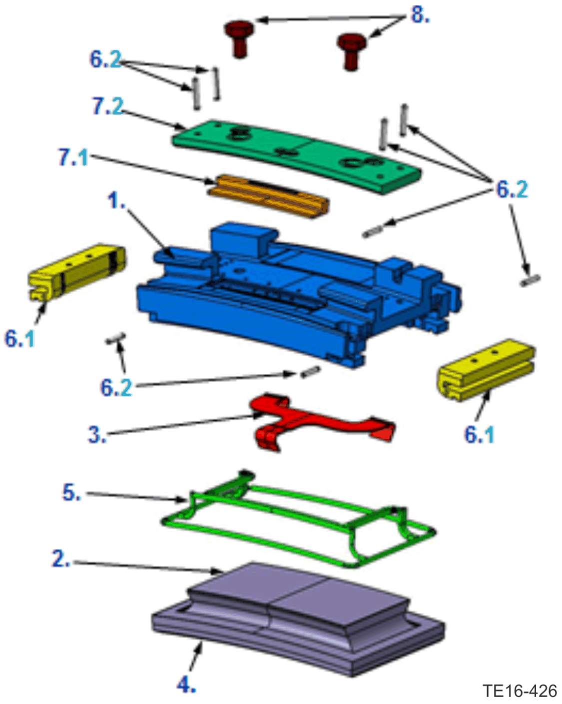


Figure 4. Exploded view of CMC assembly.

3.2 Coating Configuration

A breakdown of the coatings is shown in Figure 5.

As shown in Figure 5, the Si bond coat (Item 2) is applied to the gas-path surface (Item 1). Next, there is a dense EBC applied (Item 3). Finally, a porous abradable coating (Item 4) is applied. The thickness of the abradable is driven by the rub requirement as well as the manufacturing tolerances expected.

A cross section of the assembly shows in more detail the location of the coating (Figure 6).

3.3 Cooling/Secondary Air System Design

The cooling design for the CMC blade track is similar to the baseline metallic blade track.

1. Blade track (CMC SiC/SiC)
2. Bond coat
3. EBC
4. Abradable

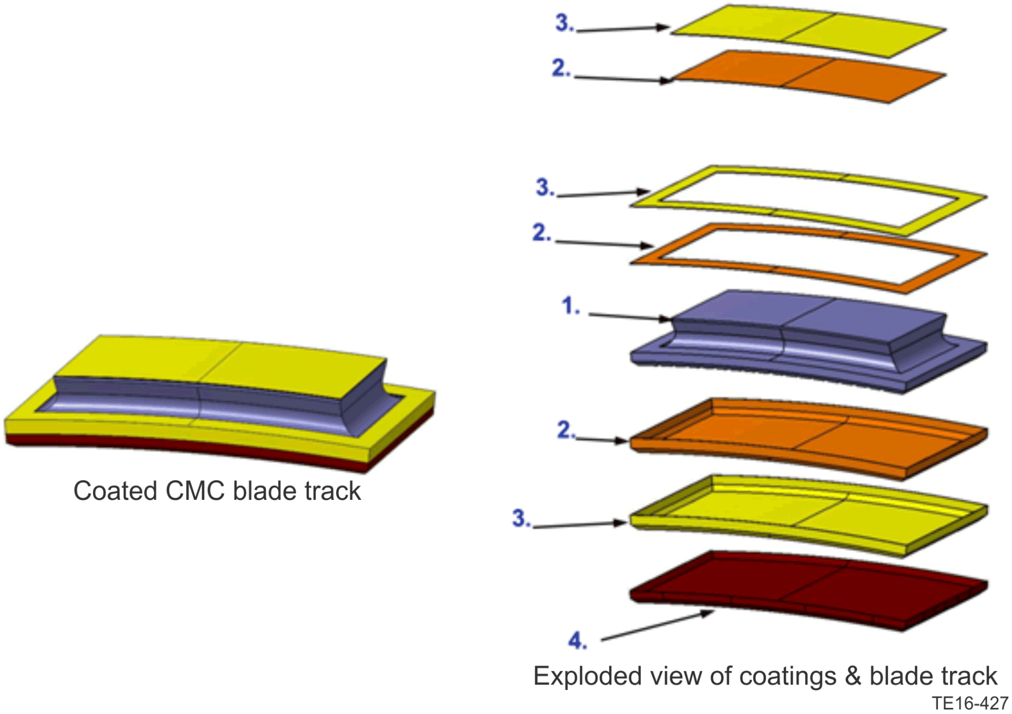


Figure 5. Exploded view of coatings on CMC blade track.

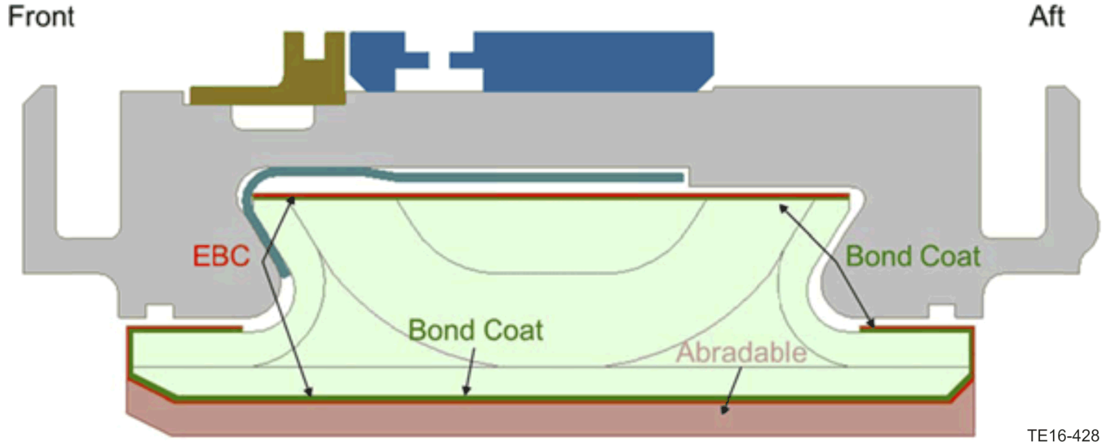


Figure 6. Cross section (center) of coatings definition.

The internal cooling design was uniquely configured to optimize the CMC design solution. To achieve an acceptable mechanical stress condition on the CMC blade track, a compartmentalized cooling solution was required. The secondary flow was separated into separate compartments above the CMC blade track, which allowed for an HP secondary flow over the leading edge to maintain a positive pressure margin. The positive pressure margin was required to prevent hot air ingress and ensure there was some cooling air that was purged along that edge. The compartmentalized flow also allowed for a lower pressure load on the top of the dovetail as well as on the aft edge of the blade track. The compartments allowed for more control over the flow, which minimized the thermal gradients in the part.

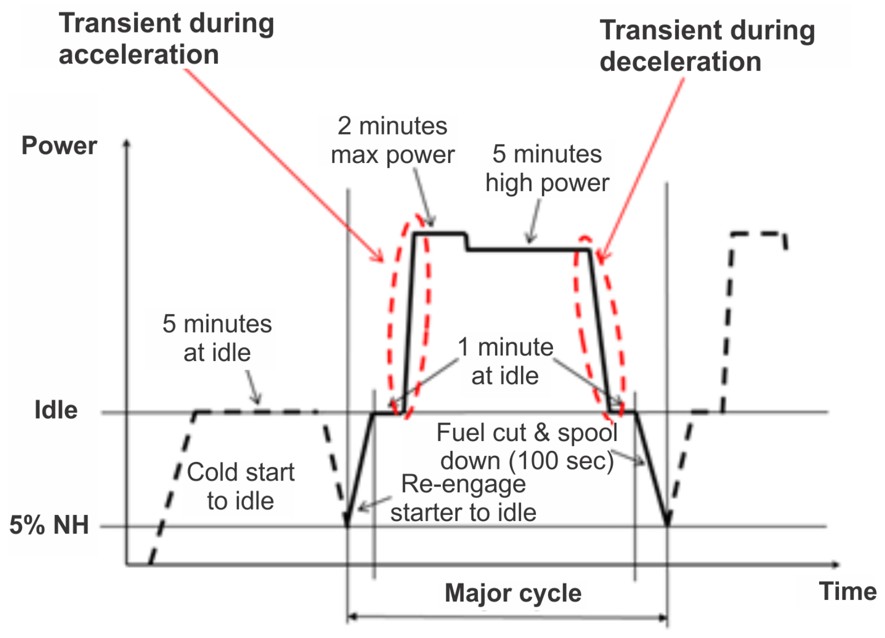
The SiC/SiC CMC material system is capable of running at higher temperatures than other turbine, metallic alloys. This allows the CMC blade track to use less cooling air than the metallic blade tracks. The air flowing through the cavities amounted to <50% of that required for a metal part.

Complex cooling channels guide the air from the cooling air supply (compressor discharge) through the metallic holder to the compartments between the metallic holder and CMC blade track.

A series of tests were used to validate the rope seal solution for compartmentalizing the cooling flow. Room temperature flow tests were run to measure flow through a length of rope seal at different pressure ratios. Those data were used to understand the seal effectiveness at different cycle points. It was found that the sealing effectiveness of the rope seals was dependent not only on the pressure delta, but on the pressure delta over the operating pressure ($\Delta P/P$). Due to thermal expansion of the different components, the gaps between the blade track and the holder would not remain constant through the test cycle. The gaps will grow as temperature ramps up.

3.4 Design Analysis

The test cycle for the EFE Endurance Engine Test is shown in Figure 2 and again in Figure 7. Evaluation of three steady-state cyclic points corresponding to a low power point, maximum power acceleration, and cruise was required to analyze the blade track. In addition, analysis of the acceleration and deceleration transients was required. Within the analysis, structural and thermal loads were applied in separate steps – a mechanical load step followed by supplementary thermal load step – to allow discernment as to what was driving the final stress state.



All transient maneuvers in the major cycle are nominally 10 sec unless otherwise stated

TE16-429

Figure 7. Transient points analyzed.

The most severe thermal gradients were present on the blade track in the post blade tip rub-in state (i.e., the abraded coating state) as a result of the limited insulating capability of the thinner coating. Therefore, only the abraded state was considered in all of the analyses.

Additionally, more effort was focused on the transient deceleration stage than the acceleration stage of the test cycle. This was due to the belief the thermal stresses generated during acceleration would be tempered by the bulk of the part lagging behind the edges. That is to say, as the edges of the part heated up preferentially relative to the core of the part, there would be a compressive component to the thermal stresses in these regions, thereby reducing their overall concern. Worst-case condition during acceleration would be steady-state maximum power. The conditions are inverted during transient deceleration with the bulk temperature of the part being hotter than the part edges, which begin to cool preferentially.

The stress analysis of the CMC blade track played a critical role in the evolution of the final design. Finite element analysis was able to identify critical stresses, and key design features were influenced. In the end, the feature-based testing proved the material was sufficient for engine testing.

4. Test Hardware Fabrication

The images in Figures 8 and 9 show the final design of the SiC/SiC CMC blade tracks used in engine testing. In both figures, the top image shows the flow-path surface, and the bottom image shows the backside surfaces. Note in Figure 8, the flow-path surface shown is the as-sprayed abradable coating. In Figure 9, the coating on the flow-path surface has been machined.

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Figure 8. Representative coated (EBC and abradable) SiC/SiC CMC hardware.

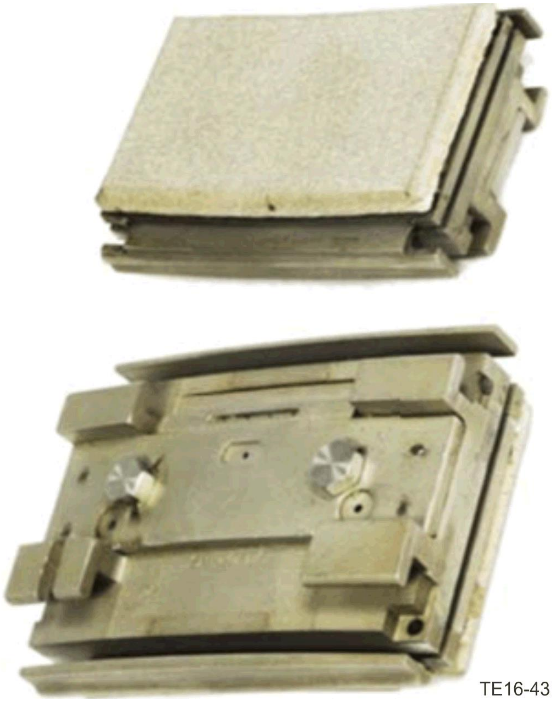

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Figure 9. Representative blade track assembly.

The SiC/SiC CMC blade tracks were manufactured by Hyper-Therm High Temperature Composites, Inc. (now Rolls-Royce High Temperature Composites [RRHTC]). Due to the novelty of this material system, there was no quality acceptance criterion in place at the time. A number of blade tracks were fabricated and inspected via infrared (IR) and 2-D computed tomography (CT) scans.

Each blade track was ranked for quality purposes. This ranking was based on the number of voids and the size of the voids. Blade tracks with varied quality rankings (more bad than good) were selected for validation testing. All blade tracks chosen for engine testing were from the top half of the quality ranking. Since specimens with bad rankings passed the validation test, the hardware with good rankings was assumed fit for engine testing.

Beyond the assessment of the SiC/SiC CMC hardware itself, a quality check was performed on the coatings applied to the CMC blade tracks. A quality check was also performed on the metallic parts in the blade track assembly. A final quality assessment was written against each assembly for historical and tracking purposes.

5. Technology Demonstration – Bench Testing

A series of bench tests was performed for proving the capabilities of various aspects of the CMC blade track design, including coating validation testing, thermal gradient testing, and various mechanical and seal testing.

5.1 Coating Validation

One of the tests to validate the coatings was the Sulzer rub test. In the test, a blade was spun against a coated specimen while it was heated by a high velocity, heated gas stream. A diagram of the test setup is shown in Figure 10.

The incursion rates tested on the Sulzer rig were varied. The requirement for incursion depth is to handle a deep rub representative of civil large engine experience.

The amount of blade transfer/blade wear was within the acceptable range. Ytterbium disilicate was the selected coating for this design. A picture of the rubbed test specimen is shown in the right half of Figure 11. This specimen is flat and does not have the curvature of the EFE blade track, which is why the rubbing only occurred at the center of the specimen. Figure 11 shows the as-coated CMC on the gas-path surface and the test specimen after the rub test.

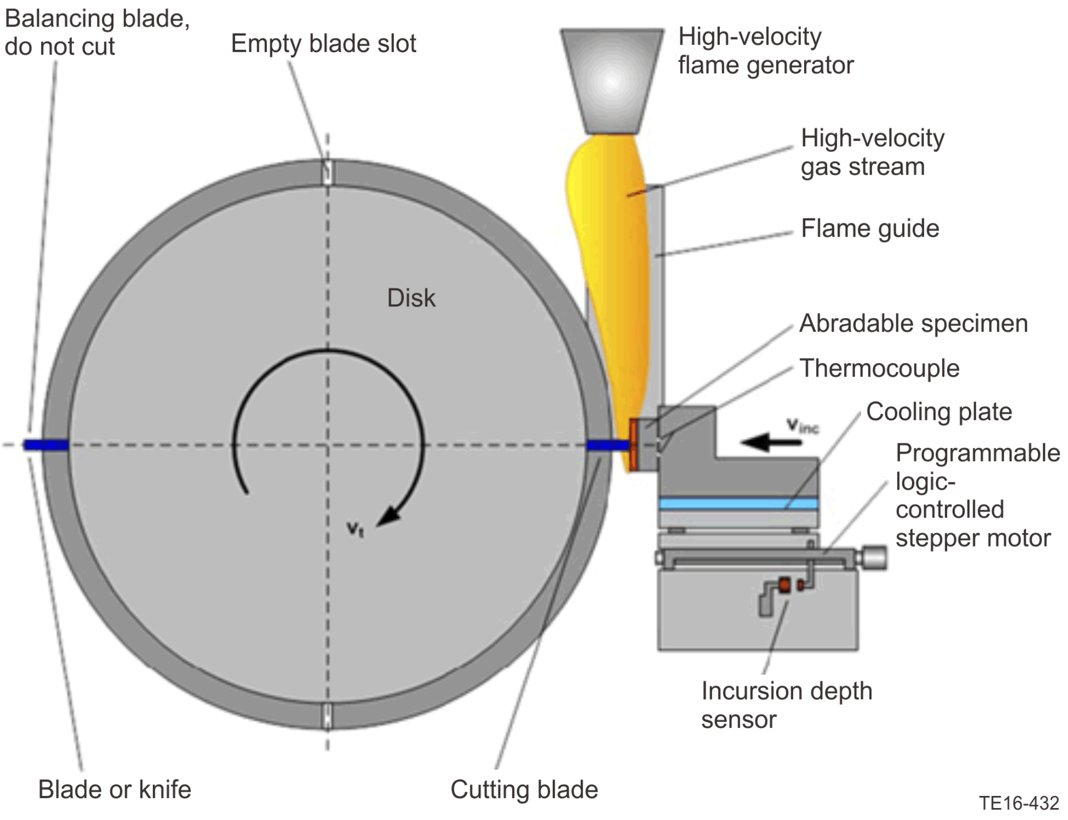

Figure 10. Sulzer rub test diagram.

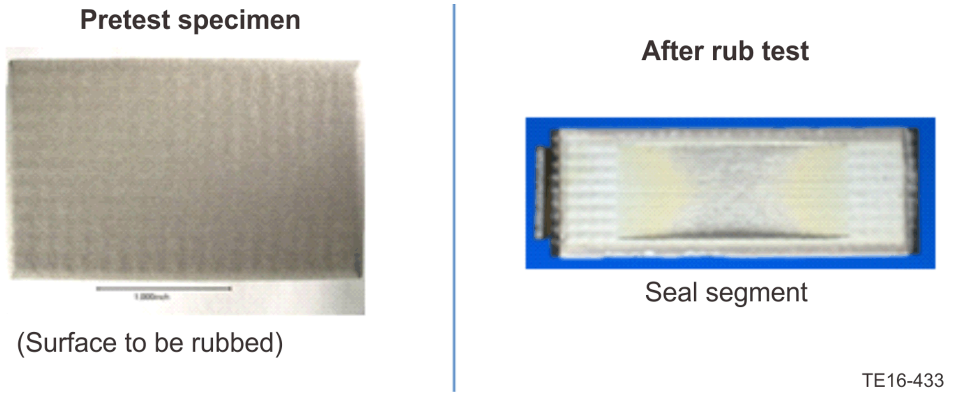

Figure 11. Representative coated blade track (left) and post-rub blade track.

5.2 Thermal Gradient Testing

CMC specimens were validated using a combination of thermal gradient testing and mechanical pull tests. The parts were first subjected to 1000 cycles of thermal gradient tests and then put through 1200 cycles of mechanical testing. The temperature on the gas-path side was achieved by placing the component in close proximity to a series of quartz lamps. Then two cooling blocks were placed against the back side of the CMC blade track to control the temperatures along the forward edge and the aft dovetail edge. The actual test setup is shown in Figure 12. The goal of this test was to match the thermal strains.

After the test, the CMC had no visible damage. Since the hardware survived the test without any visible damage, it was considered to have passed the test.

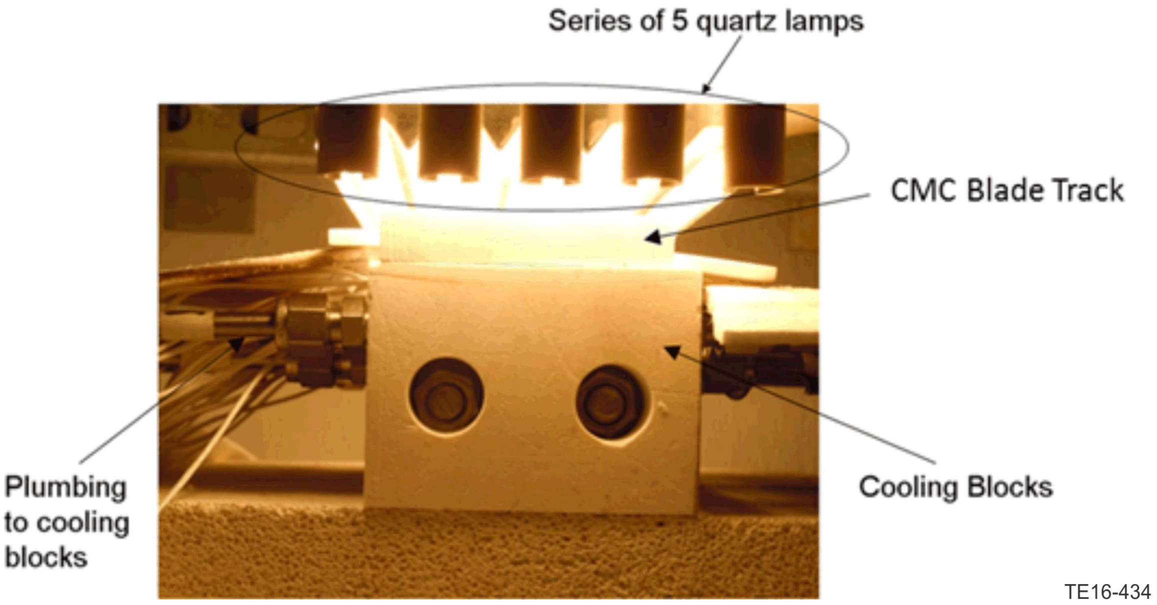

Figure 12. Thermal gradient test setup.

5.3 Mechanical Testing

All CMC parts manufactured were evaluated through nondestructive evaluation (NDE) to assess the quality of each component. The parts were also validated through monotonic and cyclic pull testing after thermal conditioning at temperature gradients simulating expected engine conditions. Specimens that were half the arc length were used for the monotonic testing. The lowest quality parts were selected for validation testing, while the best quality parts were selected for the engine tests.

The specimens performed much better than expected. In monotonic pull testing, the specimens exceeded 9x the anticipated engine load prior to ultimate failure. Each of the cyclic tests that were performed achieved 2x the number of cycles expected from the engine testing when cycled to the expected engine load. Upon completion of these tests, the parts were inspected and no damage was detected.

Testing of the specimens that were first subjected to thermal gradient cycling produced the same result. Those specimens were mechanically cycled to expected engine load, and upon completion no detectable damage was noticed.

5.4 Seal Testing

The compartmentalization design that was implemented to regulate the flow utilized two key features. Manifolds were added to the holder to reduce the feed pressure, and compressible rope seals were introduced to create the necessary partitioning.

A special test rig was designed and run to calibrate the seal leakage as a function of compression, absolute pressure difference, and pressure ratio. This information was used in the secondary flow model. A second test fixture was designed to measure the compressive stiffness of the seals as a function of percent compressed. These test data would characterize the seal’s nonlinear stiffness response. An exponential curve fit to the data was used to generate stress-strain data as supplied to ABAQUS.

5.5 Flow Testing

Once the CMC blade track was assembled to the metallic holder and other parts, a flow test was performed on the final assembly to ensure each could meet the flow requirements.

In addition to the high pressure flow rig, there were also low pressure bench tests performed to verify the flows through each compartment were behaving as expected. Each flow circuit was successfully tested individually on the bench tests to verify the flow split amongst the cavities.

6. Technology Demonstration – Engine Testing

Engine testing of the CMC seal segments was conducted in the Rolls-Royce EFE demonstrator vehicle in Bristol, UK. The CMC blade tracks were tested in Build 3 and Build 4 of the EFE test program. The engine configuration for these engine builds were identical except for the differences noted in the following subsections.

6.1 EFE Build 3

The EFE Build 3 demonstrator was planned to be the endurance testing vehicle. Events related to other components in the engine resulted in a shortened test. Nevertheless, the demonstrator provided value in a number of ways from testing that consisted largely of steady-state operation at moderate TET values:

i. The four SiC/SiC CMC blade tracks survived all testing in EFE Build 3 without any degradation of the SiC/SiC material.
ii. The test results highlighted the need for an improved abradable coating system.
iii. Data from instrumentation on three of the four CMC blade tracks showed some correlation between the analysis and actual engine conditions. It also verified that the compartmentalization of pressures was achieved in the CMC system to a degree.

In EFE Build 3, there were four total CMC blade tracks. Three of the blade tracks were equipped with pressure tubes and thermocouples to record the environment in and around the blade tracks as well as to act as a health monitoring system.

6.1.1 Engine Testing

EFE Build 3 was intended to conduct cyclic endurance testing, with a total accumulation of 500 cycles, or approximately 150 hr of runtime. However, due to engine problems unrelated to the SiC-SiC CMC seal segments, engine testing was halted after 8 hr 43 min.

During the initial borescope inspection on 21 March 2013, following a thermal paint test and performance run, evidence of coating degradation was witnessed on the CMC seal segments. As this was the first time borescope images were taken of the HP turbine blade tracks, the exact time the coating spallation occurred is not known. A risk assessment was conducted to determine if the CMC blade tracks should continue running in the engine despite the coating damage witnessed in borescope. Given the temperatures analyzed and the relatively short time at temperature versus the design capability, it was agreed to continue with the CMC blade tracks in the endurance test.

6.1.2 Comparison of Data to Predictions

The purpose of the instrumentation was to monitor the environment throughout the test and to assist in comparing analyzed predictions to what was actually achieved on the engine. In short, the instrumentation was successful in accomplishing both tasks.

Generally, the pressures and temperatures measured were lower than predicted based on the boundary conditions analyzed.

6.1.3 Post Test Hardware Assessment

The coating had three different types of damage: abradable spalling, erosion, and particle impact.

It is important to note that while the abradable was spalling off, the EBC remained intact. The weak link in the coating stack was the interface between the abradable and the EBC layers. This mechanism was witnessed on all the engine components.

Several parts had areas of erosion. The surface roughness of the flow-path surface was increased. These areas of erosion indicate the coating is too soft.

The coating also had evidence of small particle impacts. These impacts were likely a result of small domestic object damage (DOD) or foreign object damage (FOD). The CMC blade tracks (and adjacent metallic tracks) did not show any evidence of a rub. Improvements to the spray parameters and possibly a chemistry change will be required to produce a better abradable coating from the standpoint of coating retention.

6.2 EFE Build 4 Test Results

The EFE Build 4 demonstrator was planned to have two phases of testing. The first phase of the EFE Build 4 test was planned to run 50 hr. After completion of this early low temperature running, the test would enter a second phase that would create tip rub into the abradable, and would be followed by as many hours as possible at the high and maximum power points. The first phase of this testing was never completed due to failure of non-CLEEN components in the engine. The shortened EFE Build 4 test achieved approximately 17 hr of running and never began the higher temperature testing in phase 2.

6.2.1 Test Hardware

EFE Build 4 featured CMC segments. The EFE Build 4 hardware was manufactured at the same time as the EFE Build 3 hardware with one part being used from the Build 3 run.

6.2.2 Engine Testing

The first and only borescope inspection of the CMC components was performed on 4 May 2014 after approximately 14 hours of operation. At this point EFE Build 4 had been running up to approximately 90% of the high power point for combustion tests as well as other experiments.

The borescope inspection showed the abradable remained intact after a number of cycles, with no indications of the coating spallation seen during Build 3. Borescope views of the abradable coating are shown in Figure 13.

Figure 13. EFE Build 4 borescope images of abradable coating intact after ~14 hr of testing.

6.2.3 Comparison of Data to Predictions

The purpose of the instrumentation was to monitor the environment throughout the test and to assist in comparing the analyzed predictions to what actually occurred in the engine. EFE Build 4 was not run at a condition that was analyzed since all running was at relatively low temperature conditions. Thus no comparison was performed.

6.2.4 Post Test Hardware Assessment

The abradable coating had spalled off of the forward and center sections of each of the blade tracks. The dense layer of EBC and the Si bond coat remained in place at all locations.

6.2.5 Test Conclusions

Borescope inspection after 14 hours of engine testing showed the CMC blade tracks were in excellent condition, with no indications of the coating spallation seen during Build 3. The subsequent engine test event resulted in termination of the testing and removal of the engine. Post-test inspection showed significant loss of the abradable coating, but the EBC and silicon bond coating remained intact with no bare CMC exposed or damage to the CMC blade track structure.

The parts appeared to take on damage and survive the running in EFE Build 4. While the coating tensile bond strength could be improved, the coating survived the planned test conditions based upon the borescope results. It is highly likely the coating spalled during the engine failure event, which was unrelated to the CLEEN CMC components. Even though coating spallation was observed, the component stayed in place and continued to perform the function of a blade track.

7. Technology Assessment

7.1 Coatings

The multilayer coating system selected consisted of a silicon bond layer on the CMC, which provided long-term oxidation resistance for the CMC, an EBC that was intended to provide the CMC with water vapor protection, and an abradable coating that was meant to be cut into by the turbine blade tips to effectively reduce tip clearances. While the coating system performed well in validation tests, including rub, rig, and bench tests, the engine test results indicated the need for further development going forward for improved adhesion and erosion characteristics.

The location of the coating spallation between the dense EBC layer and the abradable layer is a desirable attribute of this coating system. All instances of coating loss during engine testing were limited to the thick abradable sections. The dense EBC layer stayed in place and continued to provide both environmental and thermal protection to the CMC component. Maintaining this failure mode will be sought as improvements are made to the abradable coating system in the future.

7.2 Assembly

The CMC blade track was designed for physical and functional compatibility with the baseline EFE HP turbine architecture. This approach was defined to allow the CMC blade track to be interchangeable with the standard metallic design, thus enabling both configurations to be run simultaneously in the engine. While this did not allow for the CMC design to be fully optimized, a suitable configuration was defined and produced for engine testing.

The physical interface requirements dictated the CMC blade track be installed circumferentially into the metallic holder, making assembly difficult. Due to higher dimensional tolerances of the as-fabricated CMC, shims and coatings were used to establish a proper fit with the metallic holder. In some instances, a very thick shim was necessary to get the correct assembly gap, resulting in interferences with the load pads. Future designs should incorporate modifications to the assembly direction and design features to make the assembly process easier.

Finally, future design will examine alternative sealing methods. The application of only rope seals, while suitable for the demonstrator configuration, did not provide the robustness required for a product configuration.

7.3 Cooling Design

Using a more robust seal versus a rope seal would improve the cooling system robustness. The expected pressures were not achieved in each compartment, most likely due to leakage past the seals.

7.4 Conclusions and Way Forward

The FAA CLEEN program provided valuable experience and a number of lessons learned in the development of CMC HP turbine blade tracks that support the CLEEN Program’s aircraft fuel burn reduction goal. It is estimated that a 1% fuel burn benefit can be achieved in wide-body applications (engine specific) by implementing multiple stages of CMC components. The program demonstrated the feasibility of a CMC blade track for a large civil engine with a proof-of-concept design. The blade tracks succeeded in running in the engine environment while using less cooling air than traditional blade tracks. Despite the unexpected events unrelated to the CLEEN hardware that caused both tests to end prematurely, the CMC material did not suffer any ultimate failures. Based on the engine test experience, the CMC blade tracks have demonstrated TRL6 per the U.S. Government/NASA definition, qualifying this technology as ready for use in full-scale production engine development.

Going forward, Rolls-Royce is continuing to pursue CMC blade tracks as part of our overall CMC technology development initiative. The design, manufacturing, and test experience, and the lessons learned from this program will provide a basis for a product CMC blade track configuration for future wide-body civil aircraft application. As part of the ongoing development of this technology, next-generation CMC blade track designs will also be incorporated into future Rolls-Royce technology demonstrator engines. This work will build upon the results of the EFE project to mature the design, material, and coating systems in preparation for production implementation.

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