Demonstration of Coating Techniques for Reduced Engine Maintenance Costs – Phase I and II

AMENDED Final Report

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Acronyms and Abbreviations

Term	**Definition**
ATP	Acceptance Test Plan
CMAS	Calcium, Magnesium, Alumino-Silicate
CTMA	Commercial Technologies for Maintenance Activities
DOD	Department of Defense
EASMET	Environmental Accelerated Simulated Mission Endurance Test
EB-PVD	Electron Beam – Physical Vapor Deposition
GE	General Electric
GRC	Global Research Corporation
MVP	Minimum Viable Produce
NCMS	National Center for Manufacturing Sciences
ngTBC	next generation Thermal Barrier Coating
ODASD-MR	Office of the Deputy Assistant Secretary of Defense, Materiel Readiness
TBC	Thermal Barrier Coating
TRL	Technical Readiness Level

1. Executive Summary

Aircraft operation in austere environments present a significant challenge for engine durability and performance retention. Both military and commercial aircraft encounter such environments during various missions and/or regions of operation. Particularly significant challenges to engine durability and performance arise with sustained operation in environments with high concentrations of sand and dust as well as operations in salt-water environments. Sustained operation in environments such as these lead to erosion of airfoils, accumulation of sand/dust in cooling and flow path surfaces, corrosion, as well as degradation and spallation of thermal protection coatings. The resultant impact to the engine from operation in these environments include reduced time on wing, higher maintenance costs, degraded performance and in some instances reduced operability capabilities. Additionally, these negative impacts are typically further accelerated in engines that operate at higher temperature and pressure conditions.

Funding was secured for the collaborative initiative through the National Center for Manufacturing Sciences (NCMS) Commercial Technologies for Maintenance Activities (CTMA) Program and the Office of the Deputy Assistant Secretary of Defense, Materiel Readiness (ODASD-MR).

1.1 Results

Advanced coating technologies to mitigate the destructive effects of austere operation have been developed and applied to the high-pressure turbine components of a T408-GE-400 engine targeted for a sand and saltwater ingestion engine demonstration program. The coating technologies included: next generation Thermal Barrier Coating (ngTBC), Thermal Barrier Coating (TBC) Shield, and TBC Slotting. Development of the coatings for the requirements of the T408 engine and test program were successfully completed. The engine hardware was manufactured with the advanced coatings and affected parts assembled into the engine combined with baseline hardware for performance comparisons. The T408 engine assembled with the advanced coatings completed acceptance testing, were inspected with acceptable hardware and performance requirements, and shipped to NAVAIR for the engine demo testing.

The testing validated these technologies to Technical Readiness Level (TRL) 6 for this class of engines operating in austere environments.

1.2 Benefits

The T408-GE-400 engine test vehicle provides a unique opportunity to utilize a specific military application to demonstrate advanced coating technologies that will provide increased durability, performance retention, and cost reduction across multiple commercial applications. Such benefits include:

- Improved aircraft availability for operation
- Reduction in aircraft maintenance costs for aviation components
- Improved durability and performance retention for operation in austere environments

By demonstrating this technology on a Department of Defense (DOD) asset, the advanced coating technologies will be more easily deployed on DOD aircraft across all Services, as these coatings are compatible with the current hardware materials and coatings across all aircraft engines. Inclusion of advanced coatings will reduce lifecycle costs and increase DOD aircraft operational flexibility, protect time-on-wing, decrease engine downtime, and ultimately improve readiness. Additionally, the ability to mitigate dust buildup on nozzle and blade surfaces can protect engine performance and operability margins. This effort will also provide the data needed for future programs for the DOD; many different coating strategies and technologies were included in this effort.

1.3 Technology Transition

It is expected that these advanced coating technologies are easily transferred to various commercial and military applications.

1.4 Invention Disclosure

Invention Disclosure Report(s):

DD882 Invention Report sent to NCMS ☐

No Inventions – (DD882 Negative Report sent to NCMS) ☒

1.5 Project Partners

- NAVAIR
- Global Research Corporation (GRC)
- General Electric (GE)
- National Center for Manufacturing Sciences (NCMS)

2. Introduction

GE has developed multiple dust mitigation coating solutions to address sand/dust buildup and the subsequent damaging effects of continued operation in austere environments. The objective of this project was to prepare an engine test vehicle to allow for demonstration of these coating technologies in a military durability test. This durability test was a field mission-based test that simulated the various concentration levels of sand and salt-water ingestion encountered during fleet operations. The target demonstration engine selected for this project would exercise the applied coating technologies in these higher operating temperature environments which are typical of today's advanced technology engines. This demonstration extends the TRL 6 of the dust mitigation coatings to a broader range of applications, configurations and operating environments for military and commercial aircraft.

GE has developed Calcium, Magnesium, Alumino-Silicate (CMAS) resistant solutions compatible with electron beam – physical vapor deposition (EB-PVD) TBCs. The specific coatings and treatments to be included in the engine test were:

- ngTBC is the industry partner's CMAS resistant EB-PVD TBC coating system. ngTBC includes a treatment of the current standard EB-PVD TBC which provides the CMAS resistance without debiting the impact on erosion capability of the current standard EB-PVD TBC.
- TBC Shield is a method of applying CMAS reactive particles to either coating or deposit surfaces. The CMAS reactive particles react to change the properties of the deposits leading to decreased CMAS infiltration into the thermal barrier coatings. The TBC Shield modifies the dust chemistry to promote shedding of the deposits thereby reducing accretion.
- TBC Slotting is a method of machining the TBC to reduce strain within the coating and to stop propagation, thereby decreasing coating loss.

Additionally, two unique bond coat technologies were demonstrated with the advanced technology coatings and treatments. The efficacy of these advanced technologies on multiple base coating configurations will greatly expand the installed base where a retrofitted application could be considered.

The project included providing coated hardware as demonstrators for the sustainability technology to advance the current state-of-the-art and reduce maintenance burden for both commercial and military applications. Validation of the coating processes on the T408-GE-400 hardware will mature the technology implementation to facilitate faster technology transition to the customer. The provided hardware demonstrated the desired user objectives. Specific emphasis was placed on the following:

1. Procure Scrap Hardware for Processing Trials
2. Engine Modification Drawings for Advanced Coated Hardware
3. Validate Shop Coating Demo Processes
4. Manufacture Engine Demo Hardware
5. Engine Assembly and Acceptance Test
6. Ship Engine to NAVAIR for Demo Test

3. Project Narrative

Objectives

The primary objective of this project was to validate advanced coating technologies developed specifically to mitigate the impacts of sand/dust and salt-water on aircraft engines in an engine test environment. The test vehicle targeted for this demonstration was a T408-GE-400 military aircraft engine. The proposed demonstration test simulated sustained engine operation in environments with sand/dust and salt-water ingestion. This project extends the operating range, scope of components, and coating technologies relative to prior programs.

Scope/Solution Approach

The collaborative effort provided advanced coating technology hardware built into a T408-GE-400 engine. Development and validation of the coating treatment processes was completed by GE; the government supported by providing field hardware knowledge expertise. To adapt the application processes to the T408-GE-400 hardware, an agile approach was utilized, and scrap T408 hardware was used to quickly iterate and test minimum viable products (MVPs) of the process until process requirements were met.

Tasks

This project provided coated hardware as demonstrators for the sustainability technology to advance the current state-of-the-art and reduce maintenance burden for both commercial and military applications. T408-GE-400 hardware was coated with the advanced coatings and treatments. Validation of the coating processes on the T408-GE-400 hardware advanced maturation of the technology implementation to facilitate faster technology transition to the customer. The provided hardware also demonstrated the desired NAVAIR objectives. The following tasks were planned and completed to develop and implement the advanced coatings to the T408 test engine.

3.1 Procure Scrap Hardware for Processing

- Four (4) TBC Coated Stage 1 Turbine Blades procured for ngTBC qualification
- Four (4) TBC Coated Stage 1 Turbine Blades procured for TBC Shield qualification
- Four (4) Stage 1 Turbine Nozzles procured for TBC Shield qualification
- Four (4) Stage 1 Turbine Nozzles procured for TBC slotting qualification

Additional quantities of scrap hardware were requested as the coating validation process progressed for trials and iterations.

3.2 Engine Modification Drawings for Advanced Coated Hardware

Requirements for the coating applications were established per GE quality and engineering design intent. Such requirements included coating thicknesses, compositions, regions of coverage, uniformity, and quality checks to ensure no cooling passages were affected. These requirements were documented in updated baseline part drawings unique to the parts with advanced coatings.

3.3 Validate Shop Coating Demo Processes

This task involved transferring GE's advanced coating processes to the T408-GE-400 hardware selected; spray trials and evaluations of the transferred process on T408-GE-400 scrap hardware were completed to meet Engineering class hardware quality requirements.

For demo process transfer to spray the T408-GE-400 Stage 1 Turbine Blade with TBC Shield at piece part application, modeling and spray trials were performed to down-select spray parameters such as the spray angles, distances and motions. Scrap hardware evaluations were performed to confirm that the down-selected parameters met requirements such as thickness and coverage.

For demo process transfer to coat the T408-GE-400 Stage 1 Turbine Blade with ngTBC, first tooling was designed and manufactured. Application trials were performed to demonstrate that the coating requirements such as chemistry and coverage were met.

For demo process transfer to spray the T408-GE-400 Stage 1 Turbine Nozzle with TBC Shield at piece part application, modeling and spray trials were performed to down-select spray parameters such as the spray angles, distances and motions. Scrap hardware evaluations were performed to confirm that the down-selected parameters met requirements such as thickness and coverage.

For demo process transfer to perform TBC Slotting on the T408-GE-400 Stage 1 Turbine Nozzle, several slotting designs were first developed and tested on coupons. Slotting trials were then performed on the hardware using the down-selected slotting pattern, and the slotting process iterated until down-selected parameters met requirements such as depth and width of slots.

3.4 Manufacture Engine Demo Hardware

A plan was established to coat selected engine component hardware in a "rainbow" configuration, which assembled rotor and nozzle assemblies with an array of the advanced coated parts with baseline hardware for comparison. The approach was to fabricate the advanced coated hardware per the updated drawing specifications, then assemble the subassemblies per the planned arrangements. In each case, the baseline hardware was fabricated per original specifications with changes only in the coatings.

The following hardware was procured based on the rainbow arrangement designed for the engine assembly and test:

- Procure engine test hardware
  - Stage 1 Turbine Blades – Baseline bond coat #1 (Qty = 25) –bond coat #1 using alternative manufacturing process (Qty = 25). Have available
  - Stage 2 Turbine Blades –Bond coat #2 (Qty = 18).
  - Stage 1 Nozzle – Bond coat #2 (Qty = 7)
  - Stage 2 Nozzle – Bond coat #2 (Qty = 12)
- Process hardware for engine test
  - Stage 1 Turbine Blades
    - Nine (9) blades were coated with ngTBC and Engineering class quality requirements were documented and approved
    - Eight (8) blades were coated with TBC Shield at piece part and Engineering class quality requirements were documented and approved
  - Stage 1 Turbine Nozzles
    - Seven (7) nozzles were coated with TBC Shield and Slotted; Engineering class quality requirements were documented and approved

Perfection reviews of the received hardware were conducted. These engineering and quality reviews were intended to document the condition of the new hardware and confirm acceptable conditions. Some parts were rejected or returned for rework in order to meet quality requirements and engineering intent.

3.5 Engine Assembly and Acceptance Test

A government-owned flight test engine was selected for the demonstration test. An inbound performance test was conducted, then the engine was disassembled and inspected prior to rebuild with the advanced coated hardware. The assembly configuration was controlled using configuration management and test plan documentation for the planned rainbow assembly configurations.

Teardown and Inbound Inspection

An inbound acceptance test was completed to establish a baseline performance and identify any potential hardware or system issues. No significant findings were determined. After run wear was evaluated to be acceptable for test.

Rebuild

The rebuild of the engine implemented the mixed “rainbow” configurations of advanced coatings and baseline hardware for the assemblies of the high-pressure turbine Stage 1 Nozzle, Stage 1 Blades, Stage 2 Nozzles, and Stage 2 Blades. Placement of the S1 and S2 nozzles were set to place baseline hardware approximately in the vicinities of the hottest regions of the combustor exit.

Acceptance Test (ATP)

After assembly, an acceptance test was conducted to verify the engine performance met shipping requirements, and to document the performance as a baseline to the sand/dust/salt-water demo tests. Additionally, the hardware was visually inspected to verify acceptable condition of the advanced coatings and establish an on-engine baseline photo documentation prior to the austere environment tests.

The post acceptance test photos indicated no infant mortality of the advanced coatings.

3.6 Ship Engine to NAVAIR for Demo Test

Upon completion of the ATP test, the engine was shipped to NAVAIR for installation in a government test cell where the Environmental Accelerated Simulated Mission Endurance Test (EASMET) will be executed.

4. Conclusions

The CTMA project to develop advanced coating technologies and processes to apply them on an advanced gas turbine engine was successfully completed. These coating technologies included ngTBC, TBC Shield, and TBC Slotting. Additional coating basecoats were also applied with the advanced coatings.

The advanced coatings and slotting technologies were applied to the high-pressure turbine hardware of a T408-GE-400 engine. In turn, the advanced coated hardware was assembled in the test engine in a rainbow configuration for side-by-side comparisons. An acceptance test was conducted of the test engine with advanced coated hardware and confirmed acceptable performance and good condition of the advanced coatings prior to the sand/dust/saltwater demo tests.

5. Project Benefits

5.1 Benefits for the General Public

The T408-GE-400 engine test vehicle provides a unique opportunity to utilize a specific military application to demonstrate advanced coating technologies that will provide increased durability, performance retention, and cost reduction across multiple commercial applications. Such benefits include:

- Improved aircraft availability for operation
- Reduction in aircraft maintenance costs for aviation components
- Improved durability and performance retention for operation in austere environments

The vehicle will be used to validate the industry partner's unique coating treatment approach. Many industrial efforts are focused on developing new coating compositions, rather than providing treatments that can be applied to the current coating composition. Some deployments have identified that the first generation of these technologies significantly decrease lifecycle costs of aircraft engines, but these have only begun to scratch the surface of the potential of this technology. This CTMA project provided an opportunity to demonstrate applicability for multiple generations of these treatments, increasing effectiveness and a broad range of objectives even beyond coating protection. For example, the same tooling has been used for both on-wing coating treatments as well as advanced inspections. These on-wing/ module/on-site technologies are so adaptive and flexible, that the concept can be used to overcome a wide range of obstacles and could be adapted to improve durability of other technologies such as power generators, vehicles, etc. Potential uses could include inspections, cleaning, repairs, lubrication, wear and corrosion protection. By demonstrating the benefit of the first generation of these coating treatments on this engine test, it validates a change in coating development strategy opening up a new technology space to meet a variety of needs including performance improvements, decreased lifecycle costs, improved safety and lower cost products.

The industry partner has been working to stand-up a new industry of on-site coating processing providing new jobs and opportunities for expert maintenance skill trades development. These areas include high-tech skill set development in the fields of robotics operations, and mechanical and materials expertise.

There is a large market for commercial engines in regions that provide harsh environmental conditions for aircraft engines. Academic institutions, government labs and the aircraft industry globally have been developing solutions to improve lifecycle costs when flying in these regions. By advancing these technologies within the U.S., the American industrial base is securing our nation's competitive advantage in this field of technology, leading to improved worker skills and contributing to the support of the economy.

5.2 Benefits for DOD

Aircraft engine sand/dust and salt-water ingestion causes increased maintenance and performance impacts across all of the DOD Services. By demonstrating this technology on a DOD asset, the advanced coating technologies will be more easily deployed on DOD aircraft across all the Services as these coatings are compatible with the current hardware materials and coatings across all aircraft engines. Inclusion of advanced coatings will reduce lifecycle costs and increase DOD aircraft operational flexibility, decrease engine downtime, and ultimately improve readiness. Additionally, the ability to mitigate dust buildup on nozzle and blade surfaces can protect engine performance and operability margins. As described prior, austere environments require additional hours of maintenance time for every hour of flight time, as compared to clean environments. The goal of advanced coatings is to decrease TBC coated hardware related maintenance in the sandy and corrosive saltwater environments to be near that of the clean environments. Sand/dust deposits on certain flow path hardware typically reduce turbine efficiency thereby reducing the performance and sometimes the operability of the engine. By reducing these dust thicknesses, through the use of advanced coating solutions, the performance of the engine is expected to be maintained for longer periods. This improved time-on-wing will reduce fuel costs and allowing the Services greater operational flexibility. The use of on-site treatments helps with the maintenance flexibility needed by the DOD; these treatments have the ability to be applied in remote locations to extend the serviceable life of the engines.

Current DOD engines experience performance loss and/or in-flight shutdowns due to turbine blade distress; advanced coatings will reduce dust deposit thicknesses and slow down turbine distress improving the robustness of the engines.

This effort will also provide the data needed for future programs for the DOD; many different coating strategies and technologies are included in this effort. By validating the most effective strategies, research can be guided to continue to develop improved capability coating systems. By demonstrating the on-site technologies, further collaboration on on-site technologies will follow potentially including advanced inspection, cleaning and repair technologies.