UNRESTRICTED VERSION

Project Final Report and Retrospective of Work 2013-2021

Compressor Airfoil Protective Coating for Turbine Engine Fuel Efficiency

Demonstrated on the T56, AGT 1500, and T700 Engine Platforms

For the Environmental Security Technology Certification Program
Project Number WP-201009

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14. ABSTRACT
Several DoD weapon systems were experiencing an unacceptable level of erosion and corrosion from operating in austere environments such as Iraq, Afghanistan, and over oceans. Particularly hard hit were engine compressors and compressor blades. The Army, Navy, and Air Force identified the three engines that underwent demonstrations and field evaluations as part of the CTMA initiatives. The AGT1500, T56, and T700 are installed in different platforms (two air and one tactical ground vehicle), yet all were experiencing unacceptable degrees of corrosion and erosion. Findings from the demonstrations and evaluations with the MDS Coatings Technologies (MCT) will each be highlighted within this report. All three projects were in response to engine compressor and compressor blade degradation from operating in excessive amounts of sand, dust, salt, water, volcanic ash, and other natural elements. The compressor and compressor blade degradation increase engine maintenance, fuel consumption and compressor airfoil replacement, which ultimately increases total operational costs. The subsequent erosion and corrosion negatively affected the engine performance, life span, and reliability.

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Acronyms & Abbreviations

AMARC	Aerospace Maintenance and Regeneration Center
ANAD	Anniston Army Depot
CAPVD	Cathodic-Arc Physical Vapor Deposition
CCAD	Corpus Christi Army Depot
CDPS	Compressor Discharge Pressure
CFF	Corrected Fuel Flow
CIP	Component Improvement Program
CML	Chord Maintenance Limit
CSHP	Corrected Shaft Horsepower
CTMA	Commercial Technologies for Maintenance Activities
DoD	Department of Defense
ECP	Engineering Change Process
EFH	Engine-Flight-Hours
ESTCP	Environmental Security Technology Certification Program

ETOW	Engine Time-on-Wing
FRC	Fleet Readiness Center
FPR	Full Production Release
GES	General Electric Strothers
HP	High Pressure Compressor Section
IPPCET	Integrated Propulsion and Power Cost Estimation Tool
LE	Leading Edge
LP	Low Pressure Compressor Section
LPR	Limited Production Release
MCT	MDS Coating Technologies Corporation
MEFHBR	Man Engine Flight Hours Between Removals
METS	Mobile Engine Test Stands
MRP	Military Rated Power

NCMS	National Center for Manufacturing Science
NMWR	National Maintenance Work Requirement
OC-ALC	Oklahoma City Air Logistics Center
OIF	Operation Iraqi Freedom
OSD	Office of the Secretary of Defense
PS	Pressure Side
QEC	Quick Engine Change
SAFR	Storage, Analysis, Failure Evaluation and Reclamation
SASAI	Standard Aero San Antonio Incorporated
SA WPG	Standard Aero Winnipeg
SFC	Special Fuel Consumption
Shp	Shaft Horsepower
SIT	Sand Ingestion Test
SS	Suction Side
TE	Trailing Edge
TiN	Titanium Nitride

TSO	Time Since Overhaul

1.0 INTRODUCTION

1.1 Project Overview

Several DoD weapon systems were experiencing an unacceptable level of erosion and corrosion from operating in austere environments such as Iraq, Afghanistan, and over oceans. Particularly hard hit were engine compressors and compressor blades. The Army, Navy, and Air Force identified the three engines that underwent demonstrations and field evaluations as part of the CTMA initiatives. The AGT1500, T56, and T700 are installed in different platforms (two air and one tactical ground vehicle), yet all were experiencing unacceptable degrees of corrosion and erosion. Findings from the demonstrations and evaluations with the MDS Coatings Technologies (MCT) will each be highlighted within this report. All three projects were in response to engine compressor and compressor blade degradation from operating in excessive amounts of sand, dust, salt, water, volcanic ash, and other natural elements. The compressor and compressor blade degradation increase engine maintenance, fuel consumption and compressor airfoil replacement, which ultimately increases total operational costs. The subsequent erosion and corrosion negatively affected the engine performance, life span, and reliability.

All three projects were championed by the Office of the Deputy Assistant Secretary of Defense - Material Readiness and managed by the National Center for Manufacturing Sciences. MDS Coating's BlackGold® was the coating tested in these three demonstrations.

1.2 AGT1500 Demonstration and Evaluation Findings

The first of the three engines to be tested with the MDS Coating BlackGold® was the AGT1500. Results of this test helped inform the testing protocol for the other two tests.

1.3 Engine Test Summary

In our effort to determine the effects of compressor erosion and the benefits that a protective coating can offer, a sand ingestion test (SIT) was conducted at ANAD in Anniston, Alabama on two (2) AGT1500 engines between May and September 2012. One engine had a protective coating applied on most of the compressor airfoils by MCT while the compressor airfoils on the other engine were uncoated. A cross section of the AGT1500 engine revealing the compressor airfoils is shown in Figure 1).

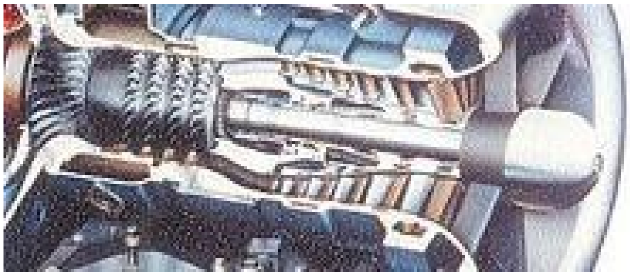


Figure 1: AGT1500 Compressor Cross-Section

The purpose of the test was to compare the erosion performance of compressor airfoils coated with MCT's BlackGold®erosion and corrosion resistant coating (henceforth referred to as BlackGold®) to uncoated airfoils. This report documents the condition of the uncoated and coated compressor airfoils during and after the SIT.

1.4 Coating Configuration

MDS's BlackGold® coating was evaluated in the tests. The coating is a multi-layer ceramic metallic matrix applied via a Cathodic Arc Physical Vapor Deposition Process (CAPVD). MDS's BlackGold® coating was evaluated in the tests. The coating is a multi-layer ceramic metallic matrix applied via a Cathodic Arc Physical Vapor Deposition Process (CAPVD).

2.0 TEST PROTOCOL-AGT1500

2.1 Executive Summary- AGT1500, T56 & T700

Gas turbine engine degradation due to operations in austere environments has adversely affected both commercial and military aviation operations. When gas turbine engine compressor airfoils degrade due to particulate (sand, dust, volcanic ash, salt, and water) ingestion, engine performance deteriorates resulting in higher fuel consumption, increased emissions of pollutants, reduced engine reliability, increased engine maintenance and higher operational costs.

Erosion and corrosion protective coatings, developed by MDS Coating, has provided significant operational benefits for commercial and military aircraft engines. MDS Coating's ER-7 coating began operations on the CH-53 (GE T64 engine) and the CH-46 (GE T58 engine) helicopters in 2004 and 2006 respectively. Uncoated T64 engines averaged 100-plus hours engine time-on-wing (ETOW) during Operation Iraqi Freedom (OIF). Numerous ER-7 coated T64 engines exceeded 1,000 hours in OIF operations with a high-time coated engine reaching 2,023 hours ETOW – an increase from three months to 40 months on- wing operations. Coated T58 engines powering CH-46 helicopters operating in OIF increased the ETOW from approximately 500 to 800 hours. Of even greater importance, ER-7 coated T58 engines eliminated a safety-of-flight issue by eliminating the liberation of uncoated T58 1st stage rotor blades due to the onset of leading edge (LE) curl erosion.

Between 2010 and 2015, the U.S. Army, Navy and Air Force, with funding support from the Environmental Security Technology Certification Program (ESTCP) and Navy and USAF Component Improvement Program (CIP), successfully completed test and evaluation (T&E) projects on the Rolls Royce T56 (C-130H aircraft), Honeywell AGT1500 (Abrams M1A1 tank), and GE T700 (MH-60 helicopter) engines.

A comparative engine sand ingestion test was completed by Standard Aero on an uncoated T56 engine and a T56 engine with MDS Coating's BlackGold® coating. The uncoated engine lost 16% power and the coated engine lost 5% □ a 3X factor improvement in performance retention. Additionally, the coated engine was consuming 1.5% less fuel at the end of the test than the uncoated engine.

The Army also conducted a comparative sand ingestion test on an uncoated and BlackGold® coated engine. The significant protection demonstrated by the BlackGold® coated compressor rotor blades led to the Army conducting a Field Service Evaluation on five (5) Abrams tanks with coated AGT1500 engines. Post-Field Service Evaluation inspections confirmed the coating's ability to protect the compressor airfoils and retain engine performance.

The initial T700 T&E efforts focused on demonstrating the BlackGold® coating's ability to protect against corrosion and mitigate the onset of Leading Edge (LE) curl erosion on 1st stage compressor airfoils. Severe erosion and corrosion component level tests were completed that exceeded industry standard tests and demonstrated the coating's ability to protect against both erosion and corrosion. LE erosion bench tests demonstrated the coating's ability to mitigate the severity of LE erosion, but the coating did not eliminate the onset of LE curl.

The National Center for Manufacturing Sciences' (NCMS) Commercial Technologies for Maintenance Activities (CTMA) Program leveraged government funding and significant cost share from industry partners to further test the BlackGold® coating for potential production applications on NAVAIR's GE T700 engine, the Army's Abrams M1A1 Tank Honeywell AGT1500 engine, and the USAF's Rolls Royce T56 engines.

These projects consisted of the following major tasks:

- Develop joint qualification requirements and engineering changes
- Complete engine sand ingestion test with coated and uncoated compressor airfoils
- Execute low- and high-cycle fatigue tests
- Conduct instrumented engine test for quantifying engine performance
- Certify BlackGold® coating and MEERER™ low surface finish post- coating process for Limited Production Release (LPR) on 20 compressor sets
- Perform a Business Case Analysis

Due to the proven test results and a positive Return-on-Investment (ROI) analysis, NAVAIR decided to skip Field Service Evaluation trials and expedite production implementation via an LPR on 20 coated compressor sets. In support of Limited Production Release (LPR), NAVAIR initiated an Engineering Change Proposal (ECP) and plans to issue a revised ECP to support Full Production Release (FPR) in FY22

2.2 Technology Transfer

From initial component level testing conducted in 2009, the program took 11 years to implement via LPR in 2020. The following recommendations are made in order to accelerate transition to operational aircraft so that the military services may realize operational and lifecycle cost benefits sooner:

1. Require that all evaluation and certification test requirements be identified and agreed upon upfront and jointly by the original equipment manufacturer and NAVAIR, Army and Air

Force project engineers. Establishing a comprehensive test program upfront versus doing tests sequentially as new test requirements are suggested could have accelerated the schedule towards production implementation by a few years.

The various process steps, such as applying abradable and sacrificial anti- corrosion coatings in the non-flow path area of the Blisk stages, required to deliver the final coated Blisk configuration highlights the need to implement lean-manufacturing steps in order to enhance supply chain efficiency and reduce the cost to supply the final coated Blisk stage configuration.

2. If other Services also have an operational requirement, set-up a true joint Service effort where the other Services are required, as a minimum, to produce an ROI analysis based on potentially implementing the technology onto their engine fleets in support of their operational requirements. Some level of funding support should also be required to truly have a joint Service program.

2.3 Benefits

DoD Benefits

Protective compressor airfoil coatings provide protection for military engines in both harsh military environments and less austere operational environments. Protecting the compressor against erosion and corrosion results in retaining engine performance for longer operational hours.The performance retention leads to:

- Increased ETOW
- Lower compressor/engine repair and overhauls
- Decreased field repairs
- Lower maintenance costs
- Reduced scrap rates and consumption of critical materials such as titanium
- Lower fuel consumption
- Lower lifecycle costs
- Increased aircraft readiness and availability

The coating was originally applied for the U.S. Marine Corps CH-53 and CH-46 helicopter engines. Since initial implementation in 2004, MDS Coating's erosion/corrosion resistant coating has been evaluated on numerous engine applications for both the U.S. Army and Air Force.

The coating has either completed or is completing airworthiness certification tests for the following platforms:

- Army's CH-47 Helicopter (Honeywell T55 engine)
- USMC's CH-53K Helicopter (GE T408 engine)
- Army's Light Utility Helicopter (SAFRAN Arriel engine)

- USMC & USAF MV/CV-22 TiltRotor (RR AE1107C engine)
- Army's Abrams Tank (Honeywell AGT1500engine)
- Air Force's C-130H (RR T56 engine)
- Air Force's KC-135 (F108 engine)
- Air Force's C-17 (F117 engine)
- Army's HH-60 (GE T901 engine)
- NAVAIR's MH-60 (GE T700 engine)

Public Good/Industry Benefits

- Additionally, the erosion/corrosion resistant coatings have transitioned to both commercial aviation and industrial gas turbine engines with some applications and benefits listed below:
    - Worldwide air carriers have been flying with MDS Coating's BlackGold® coating since 2012 and have realized fuel and parts savings benefits.
    - Delta Air Lines demonstrated fuel savings on a CFM56 coated engine Total projected average fuel savings per year over a typical engine tour of between 10 to 15 years will exceed 1%.
    - Reduced fuel consumption directly leads to reduced CO_2 and NO_x emissions.
    - Performance retention and spare parts savings in industrial gas turbine engines

2.4 Project Partners

- U.S. Army Aviation (Utilities Program Office)
- U.S. Navy – NAVAIR Patuxent River
- U.S. Marine Corps ALS
- U.S. Navy – Fleet Readiness Center (FRC) East
- U.S. Air Force – Oklahoma City Air Logistics Center (OC-ALC)
- U.S. Army – TARDEC
- U.S; Army – Anniston
- Office of the Secretary of Defense (OSD) Maintenance
- Department of Defense – ESTCP
- General Electric Aviation
- MDS Coating Technologies (MCT)
- Naval Air Systems Command (NAVAIR)
- Rolls-Royce (participating via Component Improvement Program (CIP)
- Standard Aero
- Honeywell (via PM Abrams)
- National Center for Manufacturing Sciences (NCMS)

3.0 TEST ARTICLES

3.1 Uncoated Compressor Configuration and Condition – AGT1500

The AGT1500 engine selected for the sand ingestion test in the uncoated engine compressor configuration was a low-time operational engine selected by ANAD. They concluded that the compressor, combustor, turbine, and recuperator of Engine LE82956 was in similar physical condition to typical low-time engines and would be representative. Airfoils were uniquely identified by ANAD before the SIT to maintain traceability after sand ingestion.

3.2 Coated Compressor Configuration and Condition

The AGT1500 engine selected for the sand ingestion test in the coated engine compressor configuration was a low-time operational engine selected by ANAD. ANAD concluded that the compressor, combustor, turbine, and recuperator of Engine ANAD 388 was in similar physical condition to typical low-time engines and would be representative. Airfoils were uniquely identified by ANAD before the SIT to maintain traceability after sand ingestion.

The coated compressor contained airfoils with the BlackGold® coating except for two (2) uncoated airfoils per stage as reference and four (4) parts per stage with an experimental coating. The BlackGold® coating outperformed the experimental coating on all stages and results for the experimental coating were not included in this report. The impeller was coated with BlackGold® coating.

It is important to note that the coated and uncoated baseline blades are the same due to the very thin coating that only adds thickness measured in microns.

3.3 Test Set-Up AGT1500

3.31 Sand Ingestion Test Set-up

Four (4) sand ingestion nozzles were oriented normal to the flow stream and positioned 90° apart. The sand ingestion setup is shown below in Figure 2.

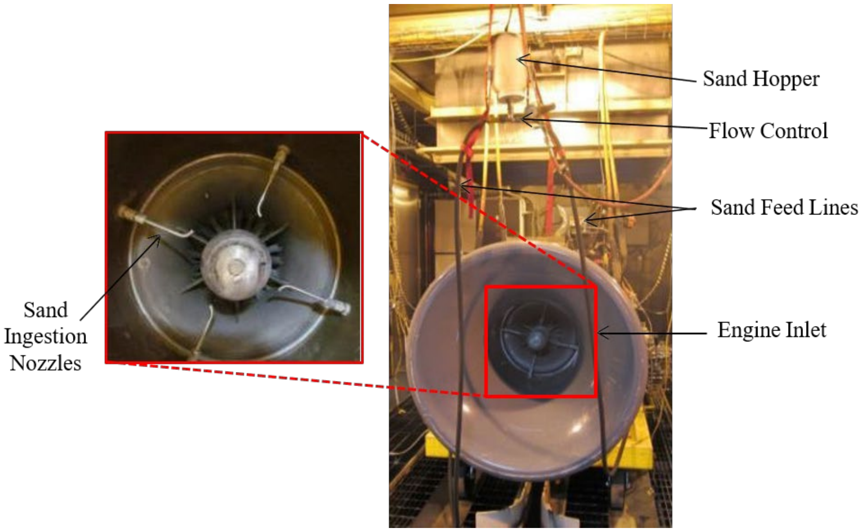


Figure 2: Sand Ingestion Setup

4.0 TEST PROCEDURES MEDIA SAND - AGT1500

4.1 Composition

Both engines ingested a media sand composition mixture.

4.2 Uncoated Engine Test Sequence

The test stopped after an interim period of media ingestion in order remove the engine from the test stand and split the compressor case to allow photographs and chord loss measurements on the LP and HP rotor blade stages.

The engine was re-installed in the test cell for further testing. The SIT continued until f severe erosion was observed on the uncoated 1st stage HP rotor blades via borescope inspections.

4.21 Coated Engine Test Sequence

The engine was run and stopped at an initial period. and the engine was removed from the test stand. The compressor case was split, and the LP and HP rotor blade stages were photographed. Based on the inspection of the compressor and turbine, ANAD made the decision to continue testing.

The test was stopped again at an interim period and the engine was removed from the test stand. The compressor case was split, and the LP and HP rotor blade stages were photographed.

The engine was re- installed in the test cell for further testing. The SIT continued until the same amount of sand was ingested by the coated engine as the uncoated engine.
The chord loss and surface finish on the LP and HP rotor blade stages was measured. Images of each stage were taken, as well as optical scans of the 1st, 3rd and 5th stage LP rotor blades and the 1st and 4th

stage HP rotor blades. Engine performance runs were calculated after each one-hour interval of ingesting sand.

5.0 COMPRESSOR AIRFOIL EROSION COMPARISON-AGT1500

5.1 Overview

The uncoated and coated compressor airfoils were measured for chord loss, mass loss, and surface roughness. The stator vanes were not coated for the sand ingestion test engine.

5.2 Chord Loss

5.21 Chord Loss-Compressor Airfoils

Chord loss erosion is a contributing factor to the removal of compressor airfoils during engine maintenance. The chord length measurement is used to quantify and compare the chord loss erosion between coated and uncoated airfoils.

Measurements were taken at the high erosion area per the National Maintenance Work Requirement (NMWR) document 9-2835-255-2 which was typically located near the tip with the LP rotors and at the center of the erosion scar for the HP rotors. Chord length was measured before the engine test and at the interim and final inspection points. The sample size of the compressor rotor blades measured is shown in Table 1, and all measured blades below were from the sand ingestion test.

Table 1: Chord Length Measurement Sample Size

Configuration	Sample Size per Stage
Uncoated	10
BlackGold®	14

5.3 Chord Loss-Impeller

The chord loss of the impeller was measured using a gage block to provide a reference plane and various sized pin gauges to determine the LE material loss. An average chord loss was calculated from ten (10) coated and ten (10) uncoated airfoils. A diagram of the measurement is shown in Figure 3.

Figure 3:Uncoated Impeller Chord Loss Measurement

The chord length of the rotor blades was measured using a digital caliper with 0.0005 inch resolution and 0.001 inch accuracy. The chord loss of the impeller was measured using pin gages.

The chord loss improvement factor (IF_{Closs}) of the coated parts compared to uncoated parts is defined in equation (1) below as the ratio of the quantity of sand ingested for the coated parts to drop below the Chord Maintenance Limit (C_{ML}) over the quantity of sand for the uncoated parts to drop below the C_{ML}.

$$\text{IFCloss} = media \text{ ingested of coated} < C_{ML} \;/\; media \text{ ingested of uncoated} < C_{ML} \qquad (1)$$

For the purpose of this calculation, it was assumed that chord loss is linear with respect to sand ingested. The impeller was measured directly for chord loss rather than chord length. The data is also displayed as a percent of the C_{ML}, where a value of 100% would indicate no chord loss and a value below 0% would indicate chord loss below the C_{ML}.

The chord length of the LP and HP rotor blades at the interim test point is expressed as a percent of the chord maintenance limit (C_{ML}). Values below zero represent airfoils that have exceeded C_{ML} and would be scrapped during engine induction at the maintenance facility. 1st stage LP rotor blades were not included in the calculations because both the uncoated and coated blades exhibited roughness along the LE which is not permitted per the NMWR. All coated stages protected against chord loss significantly better than all uncoated stages.

The application of the BlackGold® coating provided chord loss improvement for LP rotor blade stages 2-5 and for HP stages 1-4. The uncoated LP rotor stages 4&5 and HP rotor stages 2-4 exceeded C_{ML} and would have been scrapped at the interim inspection point; whereas, the BlackGold® coated blades did not exceed C_{ML} and could be re-inducted for a second tour at the interim inspection point.

Figure 4: Coated Impeller near interim inspection point

The coated impeller demonstrated improvement over the uncoated part. The coated impeller (Figure 5) shows very little damage compared to the uncoated part after similar erosion at the interim inspection point). The application of the BlackGold® coating provided enough protection that it is projected that a coated impeller will operate for at least one additional tour versus an uncoated impeller.

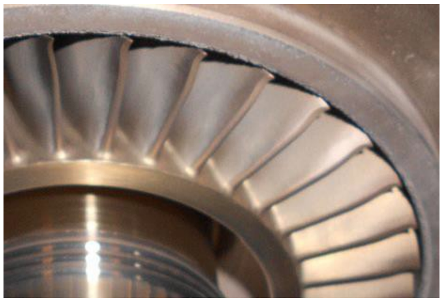


Figure 5: Coated impeller with very little damage

5.4 Mass Loss

The mass loss measurement displays an overall amount of material loss across the entire airfoil. The mass loss measurement is used to compare material loss due to erosion between coated and uncoated parts.

The coated parts were weighed after application of the coating. As each part was uniquely identified, the same coated and uncoated parts were weighed before and after the test. The sample size of the compressor rotor blades measured is shown in Table 2.

Table 1: Mass Measurement Sample Size

Configuration	Sample Size per Stage
Uncoated	10
BlackGold®	14

The mass of the airfoils was measured using a digital scale with 0.0001 gram precision.

The mass loss improvement factor (IF_{Mloss}) of the coated parts compared to the uncoated parts is defined in equation (3) below as the ratio of mass loss of the uncoated rotor blades over the coated.

$$IF_{Mloss} = \frac{M_{uncoated}}{M_{coated}}$$

The difference between the mass of the LP and HP rotor blades at the start and end of the is presented below in Figure 6.

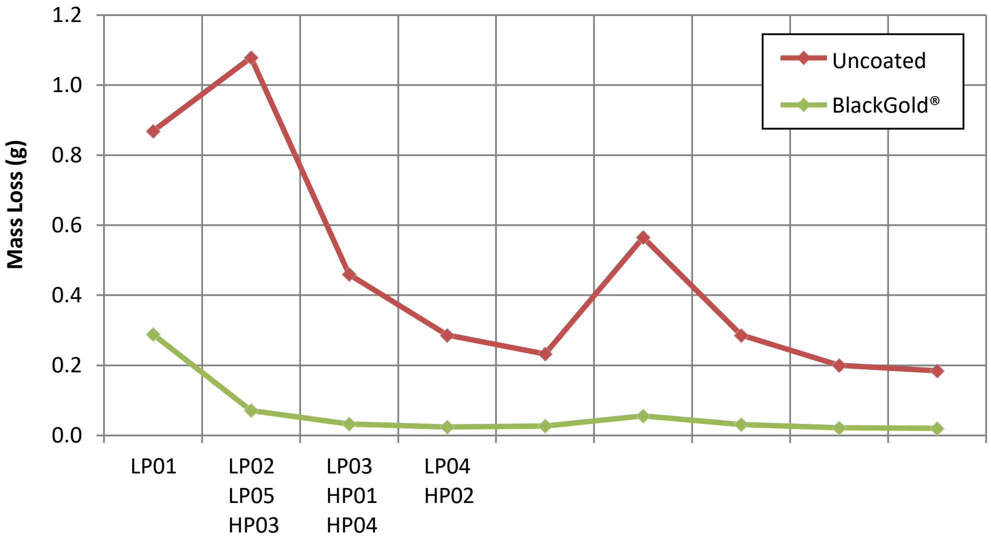


Figure 6: Average Mass Loss/RED Represents Uncoated while GREEN represents Coated

The BlackGold® coating significantly reduced the mass loss of the rotor blades, averaging a 14X improvement factor across all stages.

5.5 Surface Roughness

The degradation of surface finish can lead to lower engine performance. The surface roughness measurement is used to determine the degradation of the surface due to erosion for the purpose of comparing roughness between coated and uncoated airfoils. Surface roughness measurements were taken in the high erosion area, near the tip of the airfoil (70-100% span) and near the leading edge on the pressure side. The exception was the LP rotor stage 1 where three (3) measurements were completed at 25, 50 & 75% span locations and averaged. Measurements were taken before and after the sand ingestion test. The sample size of the compressor rotor blades measured is shown in Table 3.

Table 2: Surface Roughness Measurement Sample Size

Configuration	**Sample Size per Stage**
Uncoated	2
BlackGold®	14

A thin (<0.0005 in.) layer of an anti-reflective coating was added to the coated parts to assist with the optical scanning and was removed before the SIT. Coated parts were scanned after the BlackGold® coating was applied and the ACCU3D optical scanner was used. Sample size of parts measured is shown in Table 4. This table simply states the number of blades scanned, on what stages, and what coated or uncoated configuration.

Table 3: Optical Scanning Sample Size Per Stage

Stage	**Uncoated**	**BlackGold®**
Low Pressure Rotor 1	2	3
Low Pressure Rotor 3	2	3
Low Pressure Rotor 5	2	3
High Pressure Rotor 1	2	3
High Pressure Rotor 4	2	3

Optical scans were obtained using an optical scanner with an accuracy of 12.7 µm at 2σ.

Scanned data is presented as a comparison between an uncoated and coated part. The full image of both parts highlights the difference in material loss between the uncoated (in blue) and coated (in semi- transparent light blue) rotor blades.

Models created by optical scanning have some uncertainty at areas of high curvature due to the reflectance of light during acquisition and point detection errors during the generation of 3D points.

Scanned data is presented as a comparison between an uncoated and coated part. The full image of both parts highlights the difference in material loss between the uncoated (in blue) and coated (in semi- transparent light blue) rotor blades.

Models created by optical scanning have some uncertainty at areas of high curvature due to the reflectance of light during acquisition and point detection errors during the generation of 3D points. With respect to airfoils, leading and trailing edges can demonstrate some radius loss as shown in Figure 7. For the purpose of comparing erosion zones, this uncertainty is accounted for during alignment and does not impact the analysis.

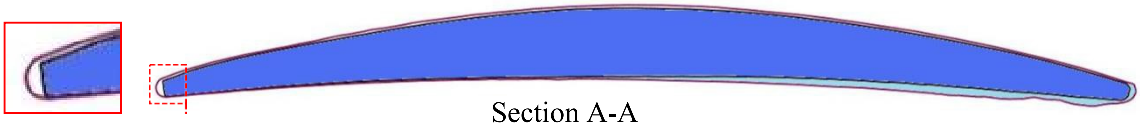
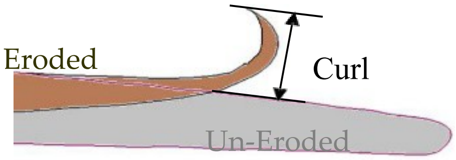


Figure 7: Optical Scanning Uncertainty at a Training Edge

Optical Scan comparisons were completed between uncoated and BlackGold® coated rotor blades in the high erosion regions for all LP and HP rotor blade stages.

5.5 Leading Edge Curl

Figure 8: Leading Edge Curl Measurement



Leading edge curl measurements were performed on the 1st stage LP rotor blade. This was accomplished by aligning the scanned model taken of a blade after the SIT with the same blade modeled before the SIT. The distance between the SS of the un-eroded blade to the top of the raised material on the eroded blade is the Curl Distance, shown in Figure 8. A measurement of this distance is taken at the five (5) locations along the span of the airfoil with the highest curl, determined visually.

The coated part showed a 1.3X improvement in leading edge curl distance over the uncoated airfoil.

6.0. TEST PROTOCOL - T56

6.1 Test Protocol - T56

6.11 Test Articles

6.12 Uncoated Compressor Configuration and Condition – T56

The T56-A-7 engine selected for the sand ingestion test in the uncoated compressor configuration was pulled from the Aerospace Maintenance and Regeneration Center (AMARC) facility. Engine# AD00103943 had 50.6 hours' time-since-overhaul (TSO) on both the compressor and turbine. SASAI inspected the engine and the compressor rotor blades and vanes. The uncoated engine and compressor rotor blades and vanes were assessed to be in very good condition and approved by

Air Force and NAVAIR to be the test article for the uncoated engine test. Four new existing titanium nitride (TiN) coated 1st and 2nd stage rotor blades were installed in the uncoated compressor engine configuration. In this case, the coated reference blades did not use the BlackGold®. These TiN coated blades were for comparison purposes only and installed by another vendor other than MDS.

6.13 Coated Compressor Configuration and Condition – T56

The T56-A-7 engine that was selected for the sand ingestion in the coated compressor configuration was removed off-wing from an Arkansas National Guard C-130H aircraft. Engine # AD00104758 had 1,045.9 hours TSO on both the compressor and turbine sections. SASAI inspected the engine and MCT measured and documented the condition of the compressor rotor blades and vanes. The engine was assessed to be in very good condition and approved by Air Force and NAVAIR to be the test article for the coated engine test.

The first and second stage rotor blades had the existing TiN based erosion resistant coating configuration. The first and second stage rotor blades were replaced with new blades coated with MCT's BlackGold® erosion/corrosion resistant coating. The (Figure 9) bar graph summarizes the chord loss for the 3rd through 14th stage compressor rotor blades as measured at the blade tip. On average, the 3rd through 14th stage rotor blades lost 0.8% chord. Note that the 6th stage rotor blade is located at a bleed port which could be contributing to double the chord loss above the average for the 3rd through 14th stage.

MCT cleaned the 3rd through 14th stage rotor blades and applied its BlackGold® coating on these rotor blades in the “as-is” condition. The 1st through 13th stage vane sectors were also cleaned and coated with the BlackGold® coating in the “as-is” condition. The 14th stage full-ring sector was not coated and was tested in the uncoated, bare material configuration. Two BlackGold® coating configurations were supplied for the coating configuration:

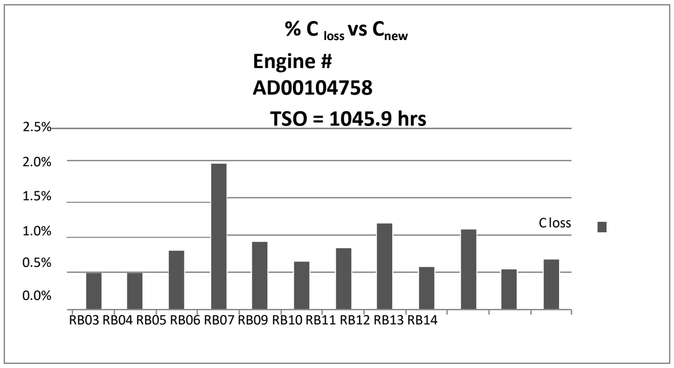


Figure 9: Initial Chord Loss of Compressor Rotor Blades Used for Coated Engine Configuration

Both coating configurations were applied via the same Cathodic-Arc Physical Vapor Deposition (CAPVD) process resulting in the same coating morphology between the two coating configurations. The process was tailored to provide different LE erosion protection based on the operational environment within an engine stage. The final compressor airfoil configuration for the coated compressor is listed below in Table 5.

6.14 Reference Turbine – T56

The test approach consisted of removing the turbine from each of the sand ingestion test engines and replacing it with a low-time reference turbine. The objective was to isolate the contribution of an eroded compressor on engine performance by removing the turbine that had been exposed to sand ingestion in both the uncoated and coated test engines. The reference turbine was installed post-sand ingestion test and used in the performance tests conducted at SA WPG.

Engine # AD00104855 was removed from AMARC storage and was inspected by SASAI. The engine had 240.9 hours and experienced foreign object damage on the compressor airfoils. The turbine was in very good condition and approved by the Air Force and NAVAIR to serve as the reference turbine and replace the "sand" turbine, in both the uncoated and coated engines, that had been exposed to the sand media during the sand ingestion test.

Table 4: Coated Engine Test Configuration

RB = Rotor Blade; FV = Fixed Vane

Stage	Uncoated Blades	BlackGold configuration1	BlackGold configuration 2
RB01	4	29	4
RB02	4	42	4
RB03	4	63	-
RB04	4	69	-
RB05	4	78	-
RB06	4	74	4
RB07	4	78	-
RB08	4	78	-
RB09	4	74	4
RB10	4	78	-
RB11	4	78	-
RB12	4	78	-
RB13	4	78	-
RB14	4	74	4
FV01 –FV13	-	-	2 half sectors
FV14	Complete ring	-	-

The test engines were summarized as follows:

- Engine # AD00103943 or uncoated engine”: uncoated compressor with 50.6 hours TSO.
- Engine # AD00104758 or coated engine: coated compressor with 1045.9 hours TSO.
- Engine # AD00104855: reference turbine with 240.9 hours TSO.

6.15 Test Facilities and Set-Up – T56

SA WPG’s indoor engine test facility is shown in (Figure 10.) This facility was used to establish the baseline and post-sand ingestion test performance for both the uncoated and coated engines. The performance was measured with the reference turbine installed in both the baseline and post-sand ingestion test configurations. The indoor test cell allowed for greater instrumentation of the compressor and turbine that was not possible with the outdoor test facility. For example, this facility allowed for measuring compressor discharge, turbine inlet and exhaust gas temperatures; calculation of air flow; and calculation of engine correction factors such as corrected pressure ratio and speeds.

6.16 Sand Ingestion Test Facility – T56

The sand ingestion test was conducted at SASAI’s outdoor METS located in San Antonio, TX (Figure 11) displays the test set-up consisting of the sand hopper and the sand nozzle configuration and orientation at the inlet.

5.1.7 Test Procedures – T56

The (Figure 12) schematic depicts the engine test sequence at both SA WPG and SASAI. Performance tests were conducted at SA WPG with the uncoated and coated engines in the reference turbine configuration and the sand ingestion tests were conducted at SASAI at the intervals depicted.

Figure 10: Engine Test Facility at SA WPG

Figure 11: Engine Sand Ingestion Set-Up METS at SASAI

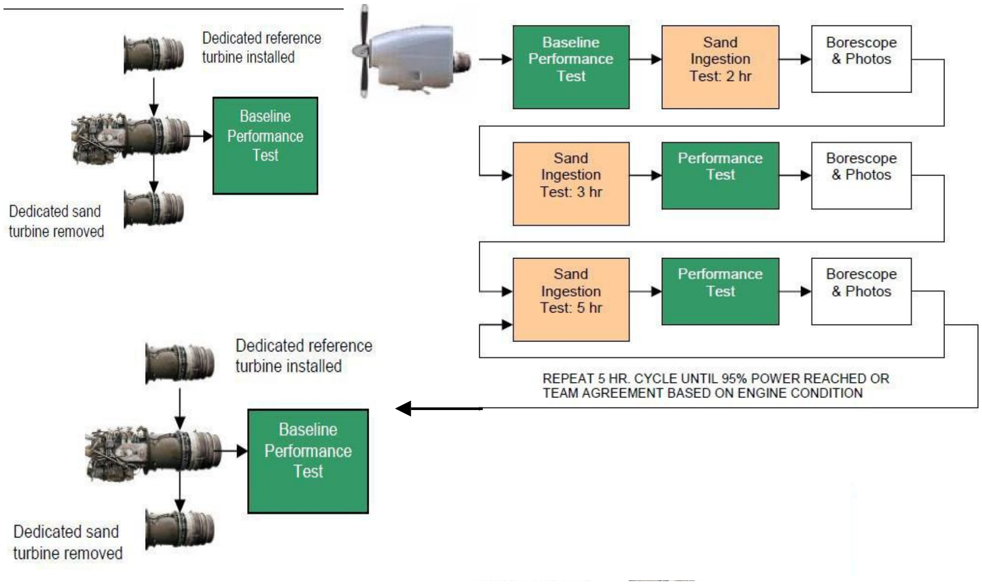


Figure 12: Engine Test Sequence

6.17 Baseline Performance Test

Both the uncoated and coated engines were first tested at SA WPG's test facility. The power was calculated at a military power condition and corrected to standard day conditions. The uncoated engine's baseline performance was rated at 104% shaft horsepower (shp). The coated engine's baseline performance was rated at 102.5% shp – an indicator of the difference of approximately 1,000 hours TSO between the uncoated (TSO = 50.6 hrs) and coated (TSO = 1,045.9 hrs). Both engines were then shipped to SASAI for sand ingestion testing on the outdoor METS.

6.18 Sand Ingestion Test

Both the uncoated and coated engines were tested on SASAI's outdoor METS in a Quick Engine Change (QEC) configuration Figure 17. The uncoated engine commenced testing on 4 April 2011 and ended on 5 May 2011. The coated engine commenced testing on 12 July 2011 and ended on 30 September 2011. (Figure 13) shows the power settings and intervals conducted during each one hour of ingesting sand and the nine-point performance check on the METS. All performance was corrected for standard day, sea level operating conditions.

The coated engine duplicated the average ingestion rate as the uncoated engine.

On the METS, performance runs were conducted on the uncoated and coated engines after the 2nd and 5th hour of ingesting sand. Thereafter, performance runs on the METS were conducted on the uncoated and coated engines after every 5th hour of ingesting sand.

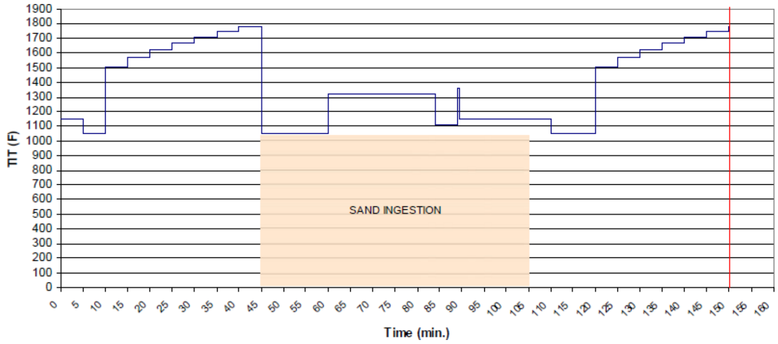


Figure 13: Nine-Point Performance Check & Sand Ingestion Power Settings

At the end of the sand ingestion test, the uncoated engine measured approximately 80% shp on the METS at military rated power (MRP). The coated engine measured approximately 92% shp on the METS at MRP after also ingesting 135 lbs. of the sand mixture.

6.19 Performance Tests with Reference Turbine

At the conclusion of the sand ingestion test, both the uncoated and coated engines were shipped to SA WPG's test facility for performance testing. In order to further isolate the effects of an eroded compressor on engine performance, the turbine sections in both the uncoated and coated engines were removed and replaced with the "reference" turbine from Engine # AD00104855.

7.0. COMPRESSOR AIRFOIL EROSION COMPARISON – T56

7.1 Blade Condition During Engine Tests

Uncoated Versus Coated Blades

At different intervals throughout the engine sand ingestion test, borescope photos were taken via access from the 5th and 10th stage compressor bleed ports. The uncoated 5th stage blade exhibited significant thinning while the coated blade retained thickness.

The difference in thickness between the uncoated and coated 10th stage rotor blades is, again, clear. The uncoated 10th stage blade exhibited significant thinning while the coated blade retained airfoil thickness.

Blade Condition Post Test

Both the uncoated and coated engines were inducted into SASAI's maintenance facility and the compressors removed. The case was removed, and the vane sectors disassembled. The rotor blades were measured on the rotor and the rotor blades and vanes were photographed.

8.0 Chord Loss Comparison

Chord measurements were taken of the compressor rotor blades on both the uncoated and coated engines at SASAI on 17 November 2011. The measurements were conducted using a Mitutoyo digital caliper with 0.0005 inch resolution and 0.001 inch accuracy. Measurements were taken at the blade tip approximately 0.025 inches from the tip. The uncoated reference blades were measured on each stage of the coated engine.

Table 5: Chord Measurements: Conducted on Uncoated and Coated Engine

	Uncoated Engine		**Coated Engine**		
Stage	**Uncoated Blades**	**Current TiN**	**BlackGold® Configuration 1**	**BlackGold® Configuration 2**	**Uncoated Reference**
RB01	4	4	4	-	2
RB02	4	3	4	3	1
RB03	4	-	4	-	1
RB04	4	-	4	-	1
RB05	4	-	4	-	1
RB06	4	-	4	3	1
RB07	4	-	4	-	1
RB08	4	-	4	-	1
RB09	4	-	4	3	1
RB10	4	-	4	-	1
RB11	4	-	4	-	1
RB12	4	-	4	-	2
RB13	4	-	4	-	1

RB14	4	-	4	1	1

The Configuration 1 coated blades provided greater chord retention than the uncoated rotor blades. The 6th and 9th stage BlackGold® coated blades in Configuration 2 did not exhibit chord loss at the end of the sand ingestion test.

8.1 Finish Comparison

Surface finish measurements on the coated blades and the uncoated reference blades in the coated engine configuration were conducted by MCT at SASAI on 28 February 2012 using a Hommelwerke T500 Profilometer with the following settings:

Traverse Length: Cut-Off Length: 0.20 in.
0.01 in.

Measurements were completed near the tip of the airfoil (70-100% span) and at mid chord on the pressure-side (PS). The tip region of all stages was determined to be an area of high erosion from the analysis of parts received from the field.

The BlackGold® coating was applied on the uncoated 3rd through 14th stage compressor blades from Engine # AD0010475 in the “as-is” condition. The 3rd through 14th stage rotor blades were cleaned, but no surface treatment was performed on the blades either pre- or post- coating. The coating was applied on new 1st and 2nd stage rotor blades.

The average post-test surface roughness on the pressure-side for the uncoated 1st through 14th stage rotor blades was 42.9 µ-inches. In comparison, the average surface roughness on the pressure-side for the coated 1st through 14th stage rotor blades was significantly lower.

The average post-test surface roughness on the pressure-side for the uncoated 1st through 14th stage rotor blades was 18.4 µ-inches. In comparison, the average surface roughness on the pressure-side for the coated 1st through 14th stage rotor blades was lower.

8.2 Visual Comparison – Rotor Blades – T56

Photographs were taken of all the uncoated and coated rotor blade and vane stages and optical scans were conducted on uncoated and coated rotor blades for a select number of stages.
Optical scan comparisons have also been summarized in this report.

Photographs were taken on 17 November 2012.

A summary for the 1st, 2nd, 6th, 9th, and 14th stage rotor blades that compares uncoated to BlackGold® coated rotor blades follows:

1st Stage Rotor Blades

The typical gold- colored TiN coating was completely removed along the pressure-side of the 1st stage rotor blade.

The chord loss of the uncoated, TiN coated and BlackGold® coated blades was comparable to previous tests.

2nd Stage Rotor Blades

The typical gold- colored TiN coating was completely removed along the pressure-side of the 2nd stage rotor blade.

In the 2nd stage, the difference between the BlackGold® coating's two configurations was noticed.

6th Stage Rotor Blades

The 6th stage compressor rotor blades with the BlackGold® coating in both the coating configurations was compared to an uncoated reference blade in the coated engine from the pressure-side view. The uncoated blade exhibited significant thinning and LE and TE cropping as shown in (Figure 15). Both coating chord protection and retained overall blade and TE thickness as compared to the uncoated reference blade.

The Configuration 2 coated blade retained chord length, blade thickness and surface finish at the end of the sand ingestion test.

(Figure 14) below shows the uncoated blade exhibiting thinning, chord loss erosion and TE cropping.

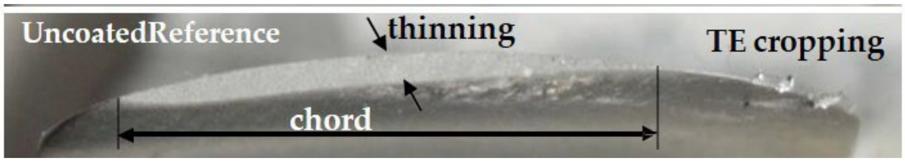


Figure 14: 2nd Stage Uncoated Rotor Blades : Top View

Figure 15: 6th Stage Uncoated Rotor Blades: Pressure-Side and LE Views

9th Stage Rotor Blades

The 9th stage rotor blades with the BlackGold® coating in both coating configurations. Coating configuration 1 exhibited some LE chord loss, but retained overall blade and TE thickness as compared to the uncoated reference blade which exhibited significant thinning and LE and TE cropping. The 9th stage compressor rotor blade with coating Configuration 2 retained chord length, blade thickness and surface finish at the end of the sand ingestion test..

14th Stage Rotor Blades

The 14th stage rotor blades with the BlackGold® coating in both coating configurations was compared to an uncoated reference blade in the coated engine. The coated blades provided greater erosion protection than the uncoated blades for both chord and thickness.

8.3 Visual Comparison – Various Vane Sectors – T56

MCT applied its BlackGold® coating on the 1st through 13th fixed vane stages. The 14th stage full-ring vane sector was not coated for this engine test. A summary of the photographs for the 1st, 6th and 13th stage vane sectors that compares uncoated to the BlackGold® coated vane sectors follows.

1st Stage Vane Sectors

The coated vane sector exhibited less erosion than the uncoated vane sector and provided significant erosion protection along the TE. The uncoated vane sector exhibited TE erosion along the entire span.

6th Stage Vane Sectors

The coated vane sector provided significant erosion protection along both the LE and TE near the outer band as compared to the uncoated vane sectors.

13th Stage Vane Sectors

The uncoated vane sector exhibited significant erosion along the LE and TE near the outer band, whereas, the coated vane sector provided erosion protection along the entire vane airfoil.

Optical Scan Comparison – Rotor Blades – T56

Optical scanning provided greater fidelity and accuracy in comparing blade thickness as well as better characterization of the erosion mechanism.

MCT created 3D models of uncoated and coated rotor blades using data from SA WPG's ATOS SO4M optical scan system. Scans were conducted on the following 6th stage rotor blades from the coated Engine # AD00104758:

- Uncoated
- BlackGold® coating in Configuration 1
- BlackGold® coating in Configuration 2

Scanned data is presented as a comparison between an uncoated and coated part. The full image of both parts (uncoated in blue and coated in semi-transparent light blue) shows the general difference in chord of the two parts.

In both coating configurations, the thickness and chord loss protection provided by the BlackGold® coated blades is clear with coating configuration 2 providing excellent LE protection.

Both coating configurations maintained greater chord length than the uncoated vane airfoils by providing both LE and TE erosion protection.

SA WPG also conducted optical scans on new rotor blades and five rotor blades per stage from the uncoated and coated engines. The optical scan results for the uncoated and BlackGold® coated rotor blades for all 14 stages were completed.

9.0. CORROSION TEST RESULTS – T56

Based on results from competitive evaluations conducted by various engine manufacturers, the CTMA program awarded MCT a contract in 2009 to conduct further erosion and corrosion tests on its BlackGold® erosion/corrosion resistant coating on various compressor airfoil material types.

The coating was applied blades over four separate coating runs to demonstrate repeatability of the process.

The corrosion test results clearly demonstrate the BlackGold® coating's ability to significantly delay and minimize the effects of corrosion on 17-4 PH stainless steel compressor rotor blades.

A cyclical erosion and corrosion resistance test were conducted in order to determine if exposure to a corrosive environment would adversely affect the coating's erosion resistant properties and, conversely, if exposure to an erosive environment would adversely affect the coating's erosion resistant property.

The erosion tests were conducted per ASTM G83 standards and the corrosion tests followed the ASTM B117 Standards.

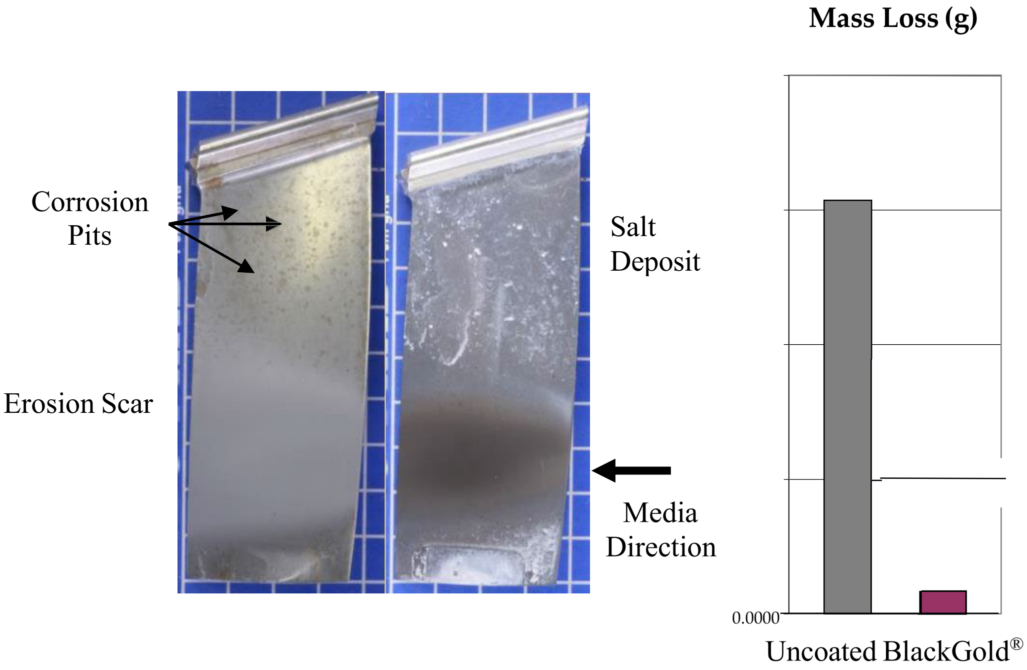


Figure 16: Erosion/Corrosion Cyclic Test Uncoated vs. Coated 17-4 PH Material Compressor Rotor Blade

10.0. FREQUENCY AND FATIGUE TEST RESULTS-T56

NAVAIR provided Component Improvement Program (CIP) funding to Rolls-Royce to complete frequency and fatigue tests on uncoated and BlackGold® coated T56 Series III 2nd stage compressor vanes and 6th stage rotor blades. Both the uncoated and coated blades and vanes tested were from the same manufacturing lot in order to isolate any frequency shifts or fatigue debits resulting from MCT's coating process.

10.1 Frequency Tests

6th State Rotor Blades

Frequency screening tests were conducted at different modes on uncoated and BlackGold® coated 6th stage rotor blades: The frequency changes did not create any new resonances within the engine's operating range and remained within the historical scatter and frequency range of the blades.

2nd Stage Vanes

Frequency screening tests were conducted at three different modes on uncoated and BlackGold® coated 2nd stage vanes.: The application of the remained within the historical scatter and frequency range of the vanes.

10.2 Fatigue Tests

6th Stage Rotor Blades

Rolls-Royce conducted standard step, high- cycle fatigue tests on 15 uncoated and 15 BlackGold® coated 6th stage rotor blades in the 1st bending mode. The coated rotor blades remained well within the historical mean-strength range and scatter.

2nd Stage Vanes

Rolls-Royce conducted standard step, high- cycle fatigue tests on uncoated and BlackGold® coated 2nd stage vanes in the 1st bending mode. remained within the mean-strength range and scatter.

11.0 TEST RESULTS-T56

Table 7 summarizes the performance of the uncoated and coated engines with the reference turbine installed at SA WPG.

11.1 Power Retention Comparison

The starting value of 104% shp (see Figure 17) for the uncoated and 102.5% shp for the coated engine most probably reflects the approximately 1,000 greater hours in TSO for the coated versus the uncoated engine. With the reference turbine installed, the uncoated compressor contributed to an approximate 16% loss in shp while the coated compressor contributed to an approximate 5% loss in shp – or approximately 3x greater power retention than the uncoated engine. At the 95% shp engine off-wing condition, the coated engine had 5% greater shp than the uncoated engine.

11.2 Fuel Consumption Comparison

Figure 18 graphs Specific Fuel Consumption (SFC) for both the uncoated and coated engines with the reference turbine at the baseline and post-sand ingestion points as measured at SA WPG's test facility. The rate of increased SFC is approximately two times (2x) greater for the uncoated engine (0.035) versus the coated engine (0.017). For all engine performance parameters, the rate of deterioration was greater for the uncoated versus the coated engine. SASAI's report estimated between 1.0 to 2.0% SFC improvements with a coated engine at the engine off-wing power condition of 95%.

Table 6: Power & Fuel Uncoated vs. Coated Engine, SA WPG Test Data

	Uncoated Baseline	Uncoated Post-Sand	% Delta	Coated Baseline	Coated Post-Sand	% Delta
	3949.6 (104.0% shp)	3338.7 (88.5% shp)	15.5%	3894.2 (102.5%)	3706.2 (97.7%)	4.8%
Fuel Flow @ MilPower (lbs./hr.)	2201.7	1977.2	10.2%	2130.0	2090.2	1.9%
Fuel Flow @ Cruise(lbs./hr.)	1672.2	1524.0	8.8%	1625.8	1533.6	5.7%

Table 8 summarizes the performance deterioration of the uncoated engine as compared to the coated engine as measured at SA WPG with the reference turbine post-sand ingestion test. The uncoated engine tested with the reference turbine lost greater than 10% corrected shp (CSHP) and greater than 6% compressor discharge pressure (CDP) than the coated engine with the reference turbine. The uncoated engine consumed greater than 4% corrected fuelflow (CFF) and greater than 3% specific fuel consumption than the coated engine.

Table 7: Performance Summary Comparison Uncoated vs. Coated Engine Post-Sand Ingestion with Reference Turbine at SA WPG

Engine Test Parameter	**Uncoated vs. Coated**
CSHP Corrected Shaft Horsepower	10.6% < Coated
CDP Compressor Discharge Pressure	6.6% < Coated
CFF Correct Fuel Flow	4.5% > Coated
SFC Special Fuel Consumption	3.1% > Coated

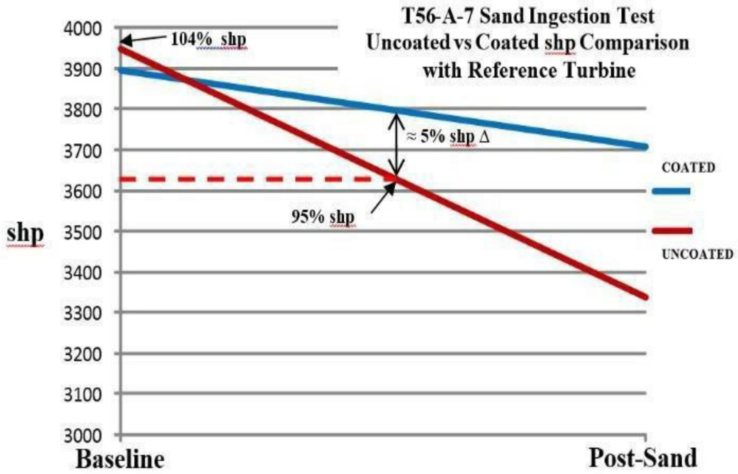
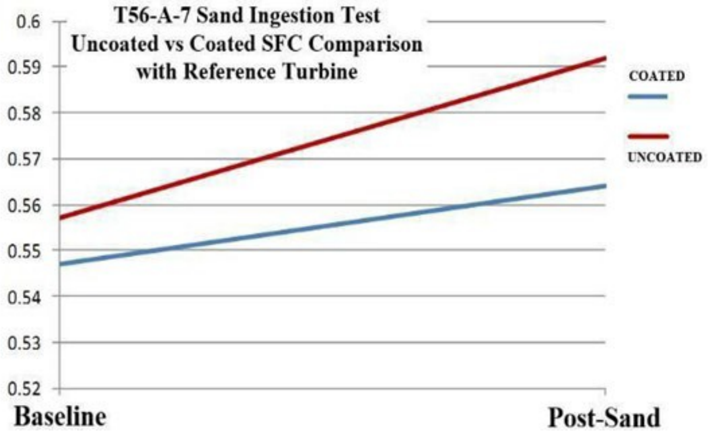


Figure 17: SFC Comparison, SA WPG Test Data Uncoated vs. Coated Engine with Reference Turbine

Figure 18: Shaft Horsepower Comparison, SA WPG Test Data



Engine Time-on-Wing (ETOW) Analysis

SASAI conducted an ETOW analysis based on the performance comparison between the uncoated and coated engines and from a previous SASAI T56 fleet fly-forward simulation. SASAI's fly-forward simulation model predicted T56 engine and module removals over a 14-year period between 2011 and 2025 that was previously conducted for the Air Force with the current engine compressor configuration. The results from the coated engine sand ingestion test were then incorporated into the simulation model in order to predict and compare T56 failure behavior. The failure model was previously developed by SASAI for Rolls-Royce in 2009.

The model used a Weibull distribution to model the relevant failure mode for compressor blade and vane erosion. The Weibull analysis assumed a constant beta (β) value due to no failure data available for analysis of a coated compressor, but adjusted the characteristic life eta (η) value to reflect increased life associated with a coated compressor. An η life factor of 2.7 was used in the model that was based on a linear depreciation model that compared the performance degradation of the uncoated and coated engines. In addition, the characteristic life factor accounted only for the effects of coated compressor rotor blades.

The Weibull analysis with a 2.7 η life factor estimated a 4.3% increase in ETOW for a zero- time engine. It is important to note that the inputs were based solely on the linear engine deterioration between the uncoated and coated engines. It did not account for the coated engine having approximately 1,000 hours TSO than the uncoated engine; that the coated compressor blades had, on average, 0.8% less chord than the uncoated engine to commence testing.

The ETOW sensitivity analysis section accounts for these undocumented benefits by assessing potential return-on-investment (ROI) at projected ETOW increases between 4-8%.

12.0 EMISSIONS IMPACT-T56

The engine sand ingestion test demonstrated that a BlackGold® coated T56 compressor will better retain engine performance throughout operations and, hence, consume less fuel. Each kilogram of fuel not consumed reduces CO2 emissions by 3.15 kg. The potential CO2 emissions reduction for both the Air Force and NAVAIR T56 engine fleet operating with a coated compressor is estimated at an annual average of 21,000 metric tonnes.

Air Force CO2 Reductions

The Air Force C-130H T56 Series III engine fleet (2,056 engines) averages 400 engine-flight-hours (EFH) per year. The average fuel consumption rate per flight hour is 245 gallons/ flight hour. Equation (1) calculates the total fuel consumed annually by the Air Force T56 Series III engine.

Taking the mid-point 1.5% SFC savings between the estimated 1- 2% fuel savings with the coated engine, results in potential annual savings of approximately 3.02M gallons or 9.218 M kg (20.28M lb.) of fuel per Equation (2).

Applying the 3.15 kg reduction in CO_2 per every kg of fuel not burned, results in approximately 25.94M kg/year or 25,940 metric tonnes reduction of CO_2 emissions for the Air Force T56 Series III engines operating with a coated compressor per Equation (3).

NAVAIR CO2 Reductions

Table 9 summarizes NAVAIR's projected average fuel consumption for their T56 Series III and Series IV engines powering the following aircraft between 2014 and 2024.

Aircraft	**Average fuel consumption/yr. 2014- 2024 (M gallons)**
C-130	23.7
P-3	22.8
C-2	5.2
E-2	10.4
Total	**62.1**

Table 8: Average Fuel Consumption for T56 Powered NAVAIR Aircraft

Since NAVAIR's T56 engine fleet operates primarily in maritime versus erosive environments, the fuel consumption reduction due to operations with a coated compressor is estimated at a lower value of 0.75% decrease or 466k gallons/year less fuel consumed as calculated in Equation (4).

The corresponding decrease in CO_2 emissions would be 4.4M kg/year or 4,400 metric tonnes of CO_2 per Equation (5).

Total potential CO_2 emissions reduction for both the Air Force and NAVAIR T56 engine fleet could exceed 33,000 metric tonnes per year.

Fleet Fuel Consumption/year = (# fleet engines) * (EFH) * (Fuel Consumption/EFH) (1)
= (2,056 engines) * (400 EFH/year) * (245 gallons/EFH) = 201,488,000 gallons/year

(2)

Fuel Savings/year (kg) = (gals of fuel saved) * (3.05 kg/gal of fuel)
= (3.02M gal fuel/year) * (3.05 kg/gal) = 9.218M kg fuel/year (3)

CO_2 reduction (metric tonnes) = (kg fuel/yr.) * (3.15 kg/kg fuel) * (0.001 metrictonnes/kg)
= (9.218M kg fuel/yr.) * (3.15 kg/kg fuel) * (0.001 metric tonnes/kg) = (4)
29,037 metric tonnes

(5)

Fuel Savings/year (kg) = (gals of fuel saved) * (3.05 kg/gal of fuel)
= (466,000 gal/year) * (3.05 kg/gal) = 1,421,300 kg fuel/year
CO_2 reduction (metric tonnes) = (kg fuel/yr.) * (3.15 kg/kg fuel) * (0.001 metrictonnes/kg)
= (1,421,300 kg fuel/yr.) * (3.15 kg/kg fuel) * (0.001 metric tonnes/kg)

13.0 RETURN ON INVESTMENT (ROI) ANALYSIS-T56

The results from the comparative sand ingestion tests demonstrated numerous performance benefits that can translate into the operational environment of the T56 engine powering the C-130. It can also be argued that similar benefits could be realized for the AE2100 engine powering the C-130J aircraft and for the T56 Series 3.5 engine upgrade. Though the E-2, C-2 and P-3 aircraft operate primarily in maritime environments, operational benefits could also be realized with the BlackGold® erosion/corrosion resistant coating on its T56 series engines. Corrosion test results conducted on T56 compressor airfoils coated with the BlackGold® erosion/corrosion resistant coating is discussed in an earlier section. Note: Specific or actual coating costs are considered proprietary to MDS Coatings.

The T56 comparative sand ingestion test demonstrated the following three benefits with the BlackGold coating:

- Performance retention resulting in increased ETOW.
- Reduced fuel consumption.
- Reduced erosion of compressor airfoils resulting in spare parts savings.

Since it is difficult to state that a coated engine will increase ETOW by an exact percentage or that fuel consumption will decrease by a certain percentage due to the different operational environments of the aircraft, a sensitivity analysis was conducted based on these three benefits. A starting point was established for ETOW increase, fuel consumption decreases, and potential partssavings based on the engine test results and post-test analysis.

The sensitivity analysis was also based on the following C-130 operational data:

- Total Inventory: 2,056
- Average Engine Mean-Time-Between- Repair: 1,600 hours
- Average Engine Flight Hours/Year: 400 hours

ROI Sensitivity – ETOW Increase

Previous discussions show the engine performance retention of the uncoated and coated engine. Summarizing, the uncoated engine lost 16% shp from a starting point of 104% shp and an end point of 88% shp after ingesting 135 lbs. of sand. In contrast, the coated engine lost approximately 5% shp from a starting point of 102.5% to an end point of 97.67% after ingesting 135 lbs. of sand. These performance points further isolated the effects of an eroded compressor on power loss by replacing the turbine that was exposed during the sand ingestion test with a reference turbine that had no sand exposure. SASAI conducted an ETOW Weibell analysis that reviewed T56 engine induction data into their maintenance facility from 2011 to 2025 and accounted for the sand ingestion testing performance data for the uncoated and coated engines. SASAI's analysis concluded that a 4.3% increase in ETOW is possible in operating the C-130s with BlackGold coated T56 engines.

The 4.3% ETOW potential increase is used as a reference point for the ROI sensitivity analysis. However, the ETOW analysis did not account for the fact that the coated test engine had approximately 1,000 greater operational hours than the uncoated engine (1,045.9 hours versus 50 hours TSO). .

Table 10 on the next page summarizes potential ROIs at the different projected part savings increases. In each of the three sensitivities, the following parameters held constant:

- FC at 1.0%
- Fuel price at $4.00 per gallon
- Rotor Blade parts savings at 50%.

ROI Sensitivity – Fuel Savings

SASAI's performance analysis at the engine off- wing condition of 95% power determined SFC improvements of 0.9% at cruise conditions. SFC improvements were not calculated at maximum take-off power or low and high-speed ground idle. Other factors could also contribute to SFC improvements such as:

- Application of the coating configuration 2 on 3rd and 10th stage rotor blades.
- Lower surface finish retention for the optimized application of the coating on new rotor blades with average roughness (Ra) values less than 10 μ-inches versus the coated, used rotor blades with aver- age Ra values greater than 20 μ-inches.

Table 11 on the next page summarizes potential ROIs at the different projected SFC increases. In each of the three sensitivities, the following parameters held constant:

- ETOW at 4.0%
- Fuel price at $4.00 per gallon
- Rotor Blade parts savings at 50%.

11.1 ROI Sensitivity – Parts Savings

Based on the condition of the BlackGold® coated rotor blades in shown earlier in this report, it is reasonable to project that coated rotor blades will not be scrapped at the current 100% rate when inducted into the depot. Instead, the coated rotor blades would be re-inducted for at least one more operational tour.

Table 10 on the next page summarizes potential ROIs at the different projected ETOW increases. In each of the three sensitivities, the following parameters held constant:

- ETOW at 4.0%
- SFC at 1.0%
- Fuel price at $4.00 per gallon

11.2 ROI Sensitivity – Summary

Table 12 considers potential parts savings over a 5, 10, and 15-year periods.

Table 13 and Figure 19 show the potential ROI over a 15-year period for a middle-case scenario with the following parameters held constant:

- ETOW at 6.0%
- SFC at 1.25%
- Fuel price at $4.00 per gallon
- Parts savings at 50%.

In this scenario, the cumulative investment is returned by the fourth year as noted by the positive "net cumulative cost avoidance" curve at the fourth year. An almost 20% ROI (1.18 factor, $5.38M return) would be realized by the fifth year. The ROI would increase appreciably after five years as the erosion/corrosion resistant compressor coating becomes fully implemented in the C-130 fleet and the coated engines, on average, keep operating beyond the current ETOW.

Table 9: ROI ETOW Sensitivity

ETOW Increase	ROI 5 year	et Cum Cost Avoidance	ROI 10 Year	Cum Cost Avoid	ROI 15 year	NET Cum Cost Avoidance
4%	0.98	($0.599M)	2.2	$73.76M	2.9	$169.45M
6%	1.1	$3.34M	2.5	$87.38	3.2	$192.8M
8%	1.25	$7.27M	2.7	$100.49M	3.5	$214.57M

Table 10: ROI Specific Fuel Consumption Sensitivity

SFC Decrease	ROI 5 year	NET Cum Cost Avoidance	ROI 10 Year	NET Cum Cost Avoidance	ROI 15 year	NET Cum Cost Avoidance

1.00%	0.98	($0.599M)	2.2	$73.76M	2.9	$169.45M
1.25%	1.05	$1.45M	2.4	$82.65M	3.1	$189.28M
1.50%	1.12	$3.49M	2.5	$91.54M	3.3	$209.12M

Table 11: ROI Part Savings Sensitivity

Parts Savings	**ROI 5 year**	**NET Cum Cost Avoidance**	**ROI 10 Year**	**NET Cum Cost Avoidance**	**ROI 15 year**	**NET Cumulative Cost Avoidance**
25%	0.85	($4.320M)	2.0	$56.55M	2.5	$137.91M
50%	0.98	($0.599M)	2.2	$73.76M	2.9	$169.45M
75%	1.11	$3.12M	2.5	$90.96M	3.2	$200.98M

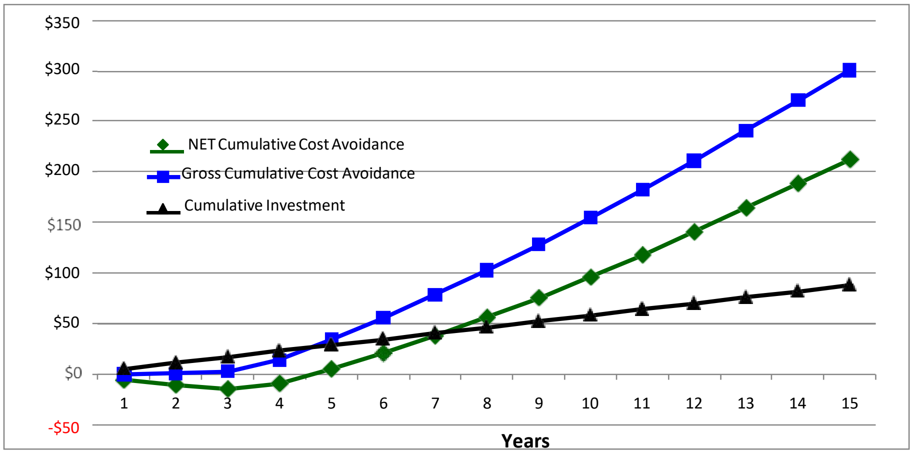


Figure 19: ROI Sensitivity for Middle Case Analysis Over 15 Years

Table 12: ROI Sensitivity for Middle Case Analysis After 5,10, and 15 Years

ROI 5 year	**NET Cum Cost Avoid**	**ROI 10 Year**	**NET Cum Cost Avoid**	**ROI 15 year**	**NET Cum Cost Avoid**
1.18	$5.38M	2.6	$96.24M	3.4	$212.51M
ETOW = 6% SFC = 1.25% Fuel Cost = $4.00/ gal Parts Savings = 50%					

14.0 INTRODUCTION - T700

The final engine tested as part of the Environmental Security Technology Certification Program initiative was the T700 for the rotary blade engine. That engine is used in at least two workhorse DoD helicopters that are critical in operations in Iraq and Afghanistan. The T700 was tested beginning in July 2012 at NAVAIR's Propulsion System Engine Facility (PSEF). During this timeframe, there was only one SIT test. Environment engine testing is planned, but has been delayed due to COVID-19 travel restrictions.

14.1 Background

Since 2003, NAVAIR's Propulsion Division has been at the forefront of supporting and implementing erosion protective coatings for the CH- 53E (2003) and CH-46 (2005) helicopters. At that time, both air vehicles benefitted greatly from the installation of the MDS Coating ER-7 erosion protection coating in support of U.S. Military operations in Afghanistan and Iraq. The ER-7 coating significantly increased the average ETOW for the CH-53's T64 engine in desert operations from than 100-plus hours for uncoated engines to 1,000-plus hours for coated engines. The average time-on-wing for the CH- 46's T58 engine increased from approximately 500 to 800 hours in desert operations and, most importantly, the ER-7 coating eliminated a safety-of-flight issue by eliminating the occurrence of uncoated first stage blade failures.

Based on these demonstrated benefits of operating with coated compressors in erosive environments, NAVAIR sought other potential engine candidates that could benefit from erosion/corrosion resistant compressor coatings. MDS Coating developed the BlackGold® coating to protect against both erosion and corrosion. NAVAIR identified the T700 engine and its operations in both arid and maritime environments as a logical candidate for testing and evaluating the BlackGold® coating. Funding support was provided via NAVAIR's CIP and DoD's ESTCP programs.

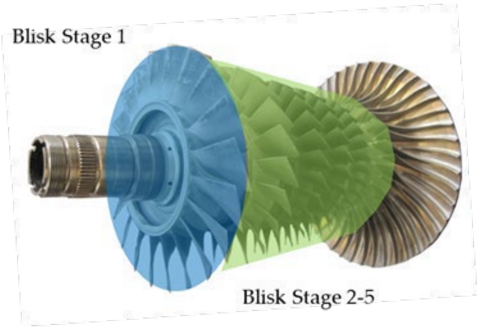
Additionally, the project leveraged previous initiatives (such as the Army's evaluation on Honeywell's T55 and AGT1500 engines with similar substrate material as the T700 engine) that successfully evaluated the BlackGold® coating's erosion and corrosion resistance capability. This effort also complemented NAVAIR's activity as a joint-service lead to explore the benefits of erosion/corrosion resistant coating on the H-60 helicopter and qualify this coating on T700 engines operated by the U.S. Army and U.S. Air Force.

14.2 Purpose

The purpose of this collaborative initiative was to: 1) test and evaluation erosion/corrosion protective coating for the T700 compressor; 2) conduct a Business Case Analysis (BCA) to implement the coating; and, 3) certify and potentially transition the coating onto the following joint-Service helicopter candidates: NAVAIR's MH-60, AH-1Z and UH-1Ys; the U.S. Army's H-60 and AH-64s; and the U.S. Air Force's H-60s.

Figure 20 depicts GE's T700-401C engine compressor with the Blisk stages identified where MDS Coating would apply the BlackGold® erosion/corrosion resistant coating. The blades were coated and uncoated (via hard masks) in ¼ segments in each stage.

Figure 20:General Electric Aviation T700 Engine with Stages Identified for Application of MDS Coating's BlackGold Coating



14.3 Project Tasks

The project consisted of the following tasks:

1. Component level erosion and corrosion tests on coated and uncoated T700 compressor Blisk stages and test specimens.
2. Engine sand ingestion in a rainbow configuration with uncoated and coated compressor Blisk and Vane stages
3. Tear-down inspection.
4. Business Case Analysis to determine feasibility of implementing coating onto NAVAIR's AH-1Z, MH-60 and UH-1Y helicopters.
5. Conduct low and high cycle fatigue tests for airworthiness.
6. Coat initial set of T700-401C compressors for LPR.

Figures 21 and Figure 22 show the rainbow coating configuration for a Blisk rotating state and Vane segments respectively.

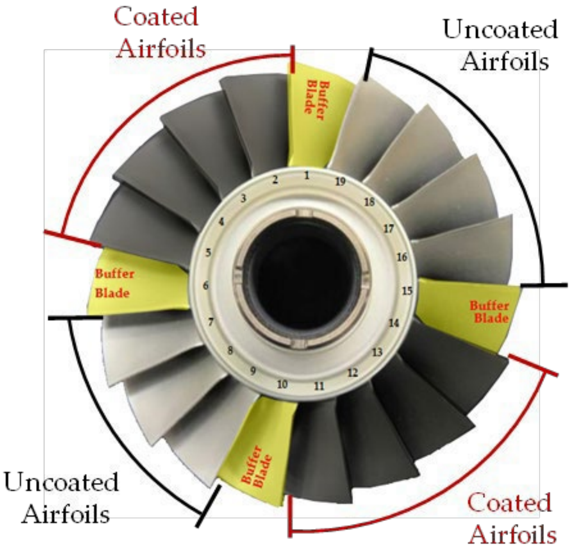


Figure 21: T700 Blisk Stage with Coated and Uncoated Airfoils

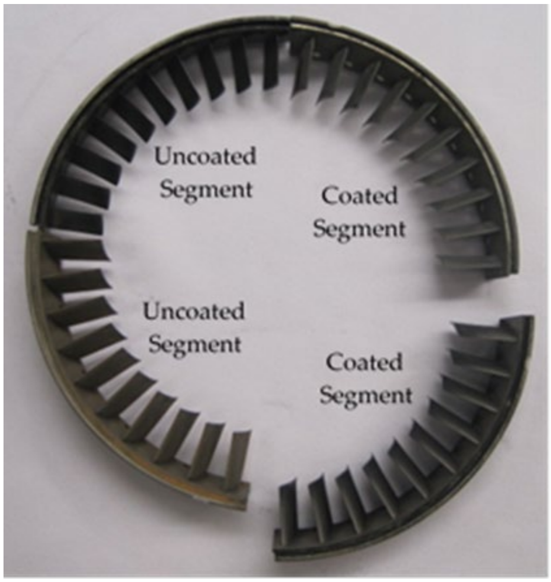


Figure 22: T700 Stator Vane Stage with Coated and Uncoated Segments

15.0 PROJECT NARRATIVE – T700

Initial Component Level Testing

The erosion testing consisted of evaluating the coating's ability to mitigate leading curl of the 1st stage compressor airfoils.

Third-party testing from the Penn State University's Applied Research Lab confirmed the BlackGold® coating's ability to protect against both engine erosion and corrosion.

Figure 23 shows the typical LE curl exhibited on uncoated 1st stage, T700 blisks.

Figure 23: T700 with Sharp LE 1st Stage Blisk Airfoils Establishing LE Curl

Engine Sand Ingestion

In 2011, NAVAIR conducted a comparative T700 sand ingestion test on both an uncoated and a BlackGold® coated compressor in order to determine the extent the coating would reduce scrapping expensive compressor Blisk stages.

The sand ingestion test confirmed that the BlackGold® coating would provide significant protection for the 2nd through 5th stage Blisks. NAVAIR and GE subsequently focused on completing airworthiness tests such as low- and high-cycle fatigue.

Return on Investment Analysis

NAVAIR conducted a ROI analysis using its' Integrated Propulsion and Power Cost Estimation Tool (IPPCET).

Based on the engine performance benefits demonstrated in the engine sand ingestion test with coated and uncoated airfoils, NAVAIR estimated an increase in mean engine flight hours between removals (MEFHBR) for BlackGold® coated T700-GE-401C engines. The increased MEFBHR reduces annual engine removals and decreases T700 engine maintenance costs for the NAVAIR fleet. Including the non-recurring engineering investment to certify the BlackGold®

erosion/corrosion resistant coating of $3.3M, the IPPCET model estimates a projected ROI factor of 11.3.

It is important to note that the IPPCET ROI analysis did not include potential spare parts savings associated with keeping the coated Blisk stages on engine for another tour and with reducing the number of Intermediate Level (I-Level) engine inspections that are sent to the depot for repair due to issues with the current anti-corrosion coating that will be replaced with the BlackGold® erosion/corrosion resistant coating. This maintenance cost driver will be closely monitored by NAVAIR after the BlackGold® coating is introduced into fleet operations. If the maintenance driver of sending I-Level inspected engines to the depot is reduced, the IPPCET ROI model will be updated accordingly.

Low Surface Finish Requirement

Additionally, field results on the Rolls Royce AE1107C engine powering the V-22 tilt rotor demonstrated that the BlackGold® coating in combination with a post-coating MEERER™ process, reduced compressor airfoil surface finish, retained the surface finish even after operations in harsh sand environments. The V-22 field results corroborated component level testing and led NAVAIR to include the MEERER™ process with the T700 BlackGold® coating.

GE then completed certification efforts to confirm that the MEERER™ process would not compromise the BlackGold® coating and that the retention of the low surface finish provides compressor efficiency benefits.

Limited Production Release

NAVAIR plans on installing BlackGold® coated compressor sets on T700-GE-401C as part of an initial LPR. The compressor sets had accrued very low operational hours (typically less than 50 hours) and were pulled from the Corpus Christi Army Depot's (CCAD) Storage, Analysis, Failure Evaluation and Reclamation (SAFR) facility. The compressor sets were inspected by NAVAIR and GE Strothers (GES) and processed by GES for the application of MDS Coating's BlackGold® coating.

Full Production Release

The limited ECP will be amended to support FPR in 2Q, FY22.

Army T700 Engines

The U.S. Army's fleet of HH-60 Utility and AH-64 Attack helicopters currently operate with the T700-GE-701D engines. Both the NAVAIR and Army T700 engines have common compressor sections. The opportunity exists for the Army's T700 fleet to also benefit from increased maintenance intervals and decreased maintenance costs associated with operating with the BlackGold® erosion/corrosion resistant coating.

ROI improvements could be greater than NAVAIR's projected 11.3 ROI factor based on the Army operating more frequently in harsher, arid environments. Even with the more powerful GE T901 replacing the Army's T700 engine fleet, it is projected that a great number of the over 5,000 T700 engines currently installed on HH-60 and AH-64 helicopters will continue powering those helicopters until at least 2030.

16.0 CONCLUSION-AGT1500, T56, & T700

The BlackGold® coating demonstrated protection against both erosion and corrosion and maintained low surface finish for the AGT1500, T56, and T700 engines.

In all three engines, the coating provided significant protection against chord and thickness loss - translating into increased parts savings and engine performance retention on all three (3) engine candidates.. Retaining engine performance results in decreased maintenance costs, fuel savings, increases mission readiness and completing missions.

- Program effectively leveraged funding resources from the DoD ESTCP and NAVAIR CIP to fund the non-recurring evaluation and certification tests.

This information, as disclosed to DOD in the RESTRICTED report, shall be protected as the proprietary and confidential information of NCMS and its members named herein in accordance with this agreement and applicable laws and regulations.

17.0 RECOMMENDATIONS

From initial component level testing conducted in 2009, the program took 11 years to implement via LPR in 2020. The following recommendations are offered to accelerate transition to operational aircraft so that the military services may realize operational and lifecycle cost benefits sooner:

- Have the original equipment manufacturer and U.S. military project engineers identify and agree on all evaluation and certification test requirements early in the process.

- Establish a comprehensive test program upfront versus doing tests sequentially.

- Implement lean-manufacturing steps in order to enhance supply chain efficiency and reduce the cost to supply the final coated Blisk stage configuration.

- Produce an ROI analysis based on potentially implementing the technology onto their engine fleets in support of their operational requirements.

Appendix Sand Ingestion Rates

Coated Engine - ANAD 388					
Test	Total Time (min)	Sand Ingested (lbm)	Total Sand Ingested (lbm)	Ingestion Rate (lbm/hr)	Inspection
#1	30	0.75	0.75	1.50	borescope
#2	60	0.75	1.50	1.50	
#3	90	0.75	2.25	1.50	borescope
#4	120	0.75	3.00	1.50	
#5	150	0.75	3.75	1.50	borescope
#6	180	0.75	4.50	1.50	
#7	210	0.75	5.25	1.50	borescope
#8	240	0.75	6.00	1.50	
#9	270	0.75	6.75	1.50	borescope
#10	300	0.75	7.50	1.50	
#11	330	0.75	8.25	1.50	
#12	360	0.75	9.00	1.50	
#13	390	0.50	9.50	1.00	half-case
#14	420	0.75	10.25	1.50	
#15	450	0.75	11.00	1.50	
#16	480	0.75	11.75	1.50	
#17	520	0.75	12.50	1.13	
#18	550	0.75	13.25	1.50	
#19	580	0.75	14.00	1.50	
#20	610	0.75	14.75	1.50	
#21	640	0.75	15.50	1.50	
#22	670	0.25	15.75	0.50	borescope
				Average Ingestion Rate:	1.41

Uncoated Engine - LE82956					
Test	Total Time (min)	Sand Ingested (lbm)	Total Sand Ingested (lbm)	Ingestion Rate (lbm/hr)	Inspection
#1	15	0.50	0.50	2.00	
#2	30	0.50	1.00	2.00	
#3	45	0.50	1.50	2.00	
#4	60	0.50	2.00	2.00	
#5	120	0.50	2.50	0.50	
#6	180	0.50	3.00	0.50	
#7	240	0.50	3.50	0.50	
#8	300	0.50	4.00	0.50	perf.test
#9	360	0.50	4.50	0.50	
#10	420	0.75	5.25	0.75	
#11	480	0.75	6.00	0.75	
#12	540	0.75	6.75	0.75	perf.test
#13	600	0.75	7.50	0.75	
#14	660	0.75	8.25	0.75	perf.test
#15	720	0.75	9.00	0.75	
#16	780	0.75	9.75	0.75	perf.test
#17	840	0.75	10.50	0.75	
#18	900	0.75	11.25	0.75	perf.test
#19	960	0.75	12.00	0.75	
#20	1020	0.75	12.75	0.75	perf.test
#21	1080	0.75	13.50	0.75	
#22	1160	0.75	14.25	0.56	
#23	1220	0.75	15.00	0.75	
#24	1250	0.75	15.75	1.51	perf.test