ABSTRACT
As a cost savings measure, aircraft engine users often have hot section components reconditioned and re-installed during engine rebuilds and overhauls. This paper discusses the United States Navy's test program to determine the risk/reward potential of refurbishing LM2500 high pressure turbine (HPT) blades. In a parallel effort, various marinized HPT blade coatings will be tested and their performance evaluated. General Electric's LM2500 gas turbine is the main propulsion engine aboard the US Navy's newest surface combatants (FFG 7, DD 963, CG 47, AOE 6 and DDG 51 class ships).

HISTORICAL BACKGROUND
General Electric's LM2500 gas turbine engine is used as the main propulsion engine aboard the newest United States Navy surface combatants, including the Arleigh Burke class destroyer (DDG 51) and the Ticonderoga class cruiser (CG 47). The LM2500 was first introduced in the 1970's aboard the DD 963 class destroyer and the FFG 7 class frigate. To date, over 400 engines have been placed in service, and have accumulated in excess of 5,000,000 hours of operation. During the early days of the gas turbine propulsion program, if the gas generator section was removed from service for any reason, the high pressure turbine (HPT) blades were replaced with new components. This policy was instituted because of the lack of experience regarding the gas turbine degradation rate in the marine environment and because the HPT blades were considered the life limiting component of the engine. As dictated by subsequent operational experience, technical documentation was adopted providing revised guidance to the overhaul depot for HPT blades replacement criteria; the updated policy was to replace HPT components which had accumulated 6,000 (later changed to 8,000) operating hours and was accomplished as engines rotated through the overhaul depot. As a result of this policy, the engine overhaul depot began to accumulate stage 1 and 2 HPT blades which had been removed during engine overhauls. It is difficult to characterize this stockpile of US Navy LM2500 HPT blades. Because engine rotor sets were not segregated, their relevant historical data was lost when the blades were stored. Because these blades came from several different ship classes, the lost information includes total operating hours/blade, power operating profile and type of inlet filtration system used for a given ship class. Although the detailed history of each blade is unknown, the following generalizations can be made. There are approximately 8,000 HPT blades in the stockpile. The blades have between 3,000 and 15,000 operating hours with an average of 10,000 hours. All the blades had a nominal 5 mil thick BC21 coating (CoCrAlY) applied via a physical vapor deposition (PVD) process. It is also important to note that
these blades, in direct contrast to industrial and aero applications, were exposed to many hours of continuous lower power operations. Due to the increasing operational age of the average LM2500 engine in the fleet, nearly all engines currently rotating through the repair depot exceed the Navy 8,000 hour limit, requiring HPT blade replacement. This has resulted in increased demand upon the supply system. The purchase of new blades is becoming cost prohibitive as well as untimely, since it requires long lead times. In an effort to reduce the cost of overhauling LM2500 engines at the depot, Naval Sea Systems Command (NAVSEA) tasked the Naval Surface Warfare Center (NSWC) to determine the feasibility of refurbishing "used" high pressure turbine blades as opposed to rebuilding overhauled LM2500 gas generator sections with new components. This task included

reviewing the general practice of repairing components in the industry and would eventually lead to a cost benefit and risk analysis of the proposed project.

AUSTRALIAN NAVY RAINBOW ROTOR

The Royal Australian Navy operates six frigates based on the Oliver Hazard Perry (FFG 7) class frigate design, which is propelled by two LM2500 gas turbine engines. The Australian Navy contracts Air New Zealand (ANZ) to complete LM2500 engine overhauls. Engine serial number GGA-226 was originally installed aboard HMAS CANBERRA (FFG 18, RAN 02) in the GTM 1B position. It was removed from service in 1990, after having accumulated approximately 14,202 hours, due to high vibration and general wear and tear. It was sent to ANZ for overhaul. While at the depot, the high pressure turbine was rebuilt using both new BC23 (CoCrAlHfP1) coated stage 1 and 2 blades as well as refurbished blades coated with platinum aluminide (PtAl) and BC 21. This non standard configuration rotor was then installed aboard HMAS DARWIN in the GTM 1B position as a test case by Australian Defence Industries (ADI) service engineers. The refurbished blades had been repaired by the Chroming Company (Gardena, CA). The majority of the originally provided blade pairs were deemed repairable and recoated with a nominal 2-3 mil thick platinum aluminide coating deposited with a pack cementation process. Part of the refurbishment process included returning the components to their original drawing dimensions. Some new BC 23 coated blades were installed as a baseline by which evaluations could be made.

In August 1992, US Navy representatives conducted a video borescope inspection of engine GGA-226 aboard HMAS DARWIN. At the time of the inspection, the engine had accumulated 2,536 hours since overhaul. The purpose of the inspection was to compare and contrast the condition of the new
various blade coatings to extend the projected blade lifecycle. The LM2500 Component Improvement Program (CIP) was to test the ambition testing program. Originally, supporting history for BC longterm performance was unknown, the Navy embarked on an stage 1 and 2 blades coated with BC 21 (CoCrAl). Because its original LM2500 engines delivered to the U.S. Navy had HPT type II (approx. 1350 degrees F) hot corrosion degradation, the Navy decided to re-evaluate platinum aluminide as an HPT blade coating. Aside from performance, platinum aluminide coating corrosion is evident in the thumbprint A and B areas (See Figure 1) as well as along the leading edge and tip cap. In some extreme cases, the tip cap area (extending 0.03" from the tip) has eroded away. A summary of some of the early US Navy HPT blade experience was given by Grossklau, 1986. More recent experience has confirmed the general trends reported. Although engineers still consider the HPT blades to be the life limiting component of the engine, to date that life cannot be quantified. At present the U.S. Navy has ten engines exceeding 20,000 hours of operation. Each of these engines has some coating remaining of the airfoil surfaces of the HPT blades.

Beginning in the 1970's and continuing into the mid-1980's, the US Navy evaluated several marinated blade coatings installed in an LM2500 rotor aboard the merchant ship GTS Admiral William S. Callaghan. At the time, the Callaghan was contracted to the Military Sealift Command (MSC) for intense cargo transit between Eayonne, New Jersey and Bremerhaven, Germany. Engine serial number GGA-806 accumulated extensive engine operation at this time. A metallurgical evaluation of blades after 1,077 hours of service has been reported by Grossklau et al, 1986. Six blades coatings were tested in the 10th build of that rotor (GGA-806/10) and their performance evaluated via borescope inspection after 3,613 hours. Three of the coatings (Plasma Sprayed BC 22 [CoCrAlHf], BC 23 and BC 23 + Cr) were in good condition with minimum wear. The remaining three coatings (BC 21, TBC [BC 21 + Zirconia] and NAVSEA Hi Cr) showed significant coating erosion and isolated base metal penetration. It is important however to note that this engine, installed aboard a merchant ship, was exposed to radically different intake ducting and power profiles as compared to U.S. Navy ships. This test platform was found to exhibit an advanced corrosion rate in relation to engines in Navy service.

The Navy conducts borescope inspections throughout the fleet of statistically selected engines in an effort to characterize the condition of engines across ship class, power profiles, deployment locales and engine configuration. In support of this program, hundreds of borescope inspections have been conducted throughout the fleet. Based on this experience, several broad conclusions can be made regarding the condition of the hot section of LM2500 engines as they accumulate operating time. The combustor section is problem free with little or no degradation after 15,000 hours of operation. In the history of the LM2500 program, less than 10 engines have been removed and replaced due to burning within the combustor exceeding service limits. Regarding the condition of the HPT stage 2 blades, coating and metal corrosion is not a major problem. Because the combustion gases are relatively cool by the time they reach the stage 2 blades, BC 21 has proven effective in providing high temperature protection and extending component life. Typically, it is the stage 1 blades and nozzles (vanes) that exhibit the majority of the corrosion. After 7,500 hours, the initial signs of coating corrosion become present in the thumbprint "A" area and along the leading edge of the stage 1 blades. At 15,000 hours, more widespread coating corrosion is evident in the thumbprint "A" and "B" areas (See Figure 1) as well as along the leading edge and tip cap. In some extreme cases, the tip cap area (extending 0.03" from the tip) has eroded away. A summary of some of the early US Navy HPT blade experience was given by Grossklau, 1986. More recent experience has confirmed the general trends reported. Although engineers still consider the HPT blades to be the life limiting component of the engine, to date that life cannot be quantified. At present the U.S. Navy has ten engines exceeding 20,000 hours of operation. Each of these engines has some coating remaining of the airfoil surfaces of the HPT blades.

Because of the excellent performance of the refurbished blades, the US Navy decided to re-evaluate platinum aluminide as an HPT blade coating. Aside from performance, platinum aluminide provided a potential cost savings to the Navy based on its relative expense compared to the BC 21/23 coatings. Also, General Electric had decided that platinum aluminide was to become the standard production HPT coating for industrial LM2500 engines, forcing a split in their production line which could raise new engine costs. In the interest of commonality, platinum aluminide merited additional evaluation. The initial refurbishment program began to evolve into a dual test, evaluation of both blade repairability and the performance of new coating materials.

MARINIZED COATING EXPERIENCE

In response to the threat of type I (approx. 1600 degrees F) and type II (approx. 1350 degrees F) hot corrosion degradation, the original LM2500 engines delivered to the U.S. Navy had HPT stage 1 and 2 blades coated with BC 21 (CoCrAl). Because its longterm performance was unknown, the Navy embarked on an ambitious testing program. Originally, supporting history for BC 21 had been established using burner rig tests. The early focus of the LM2500 Component Improvement Program (CIP) was to test various blade coatings to extend to projected blade lifecycle. Starting in the late-1980's and early-1990's, General Electric developed several states of the art blade coatings for use in the marine environment (Type 1 and 2 corrosion) and with the
potential to increase engine efficiency by increasing gaspath temperatures without affecting hot section component lifecycles. As a testbed, GE installed a single shank HPT rainbow rotor of prototype blade coatings at an industrial power generation facility (Sithe Energies) in San Diego, CA. This engine (SN 481-584), which operated at near steady state condition, ran at or near full power (27,000 HP) with dual fuel capability (Natural Gas, JP 4). In order to keep the US Navy apprised of the latest coating developments, GE invited Navy representatives to conduct periodic internal inspections at the Sithe facility on two occasions. As reported in Navy borescope reports, a rotor map was developed and several coatings evaluated at 4,000 and 10,500 hours of operation respectively. Variations of seven different coatings were evaluated during the inspection. Three of the coatings (BC 52, PBC 22 and Platinum Aluminide) were in good condition with minimal wear. The four remaining coatings (BC 22, TBC, BAJ-BC22 and aluminide) showed significant signs of coating erosion and base metal penetration.

**DEVELOPMENT OF RAINBOW ROTOR TEST**

In light of the Royal Australian Navy success with refurbished platinum aluminide coated HPT blades, NSWC proposed that two US Navy Rainbow rotors be constructed using refurbished LM2500 HPT blades. After receiving approval, NSWC approached the Naval Aviation Depot (NADEP) at Cherry Point, North Carolina for the purpose of repairing the assets. Although Cherry Point's analysis of sample blades proved encouraging, they reported that they were in the process of gearing up for airfoil repairs but would not be up and on-line for several years. In order to proceed with a U.S. Navy test, NSWC advertised its intention via solicitation to contract the repair and recoating of 250 "used" HPT blades for a future engine test. Although some twenty companies responded to the initial inquiry, only two companies (General Electric and Chroming Co.) responded with quotations. On a competitive basis, a contract was awarded to General Electric to repair the blades to specifications defined by the TF39 and CF 6 (aero engine equivalents) shop manuals. The contract did not reference an LM2500 repair manual because marine HPT blades had not previously been refurbished and serviceable criteria did not exist. Based on several informal evaluations by interested industry personnel, it was estimated that between 10 and 30 percent of the stockpiled blades would exceed the referenced service limits and could not be repaired.

The following is a brief description of the repair process implemented upon the BC 22 and platinum aluminide coated blades. First the used HPT blade pair is soaked in an acidic bath to eliminate any remaining airfoil coating. The contractor reported that during this process, many of the blade pairs automatically split into their two halves. If they had not, the next step in the procedure was to mechanically separate the blade pairs into halves. In some cases, side plates had been brazed to the sides of the shank (dovetail) for support. If these side plates were in place, they were removed and discarded. Following the pair separation, the blades go through an intensive inspection process to determine their serviceability. If within repairable limits, the blades are returned to original length dimensions by welding material to the tip cap area. Although HS 188 weld material is used on the tips of new marine LM2500 blades, Inconel 625 has been approved for aircraft engines and was used in refurbishing these blades. An extra set of cooling air holes are drilled through the concave surface of the airfoil into the internal serpentine passages to provide additional film cooling. A nominal cut is taken along the trailing edge of the blade to ensure that the trailing edge cooling air holes are clear and unclogged. The blade halves are then coated (often by a subcontractor). Following the coating process, the pairs are placed into a fixture and brazed back together. Following the repair and recoat, the blades are subjected to airflow and airflow tests to ensure the internal passages are unrestricted. Airflow requirements are less than those defined for new engines. Metallurgical analysis is also conducted on a sample of a repair batch to ensure coating integrity and braze reaction. Radiographic, magnetic particle and fluorescent penetrant inspections were also conducted.

As applies to the GE contract, US Navy blade fallout was much greater than initially anticipated. Nearly 50 percent of the blades provided to the contractor for refurbishment were rejected as beyond repair limits. A superficial look at these rejected parts following coating removal indicates that many blades were rejected for surface cracks along the leading edge of the blade on the platform. Some metallurgy was conducted of these parts, the results indicating that these "surface cracks" are nominally 1 to 2 mils in depth and do not pose significant threat of blade failure. Because of the somewhat more limited risk associated with a Navy engine failure at sea, it could prove cost effective in the
future to evaluate rejected blades on a case by case basis and institute more liberal inspection criteria to lessen the magnitude of blade fallout.

After the contract was awarded on a competitive basis, General Electric personnel proposed that a small sample of the refurbished blades be recoated with their most technologically advanced coatings. GE proposed that a thermal barrier coating (TBC) and BC 22 applied by an alternate process be included in the testing. The Navy was not enthusiastic about the inclusion of TBC in the Rainbow rotor. Prior experience with TBC, in both the Callaghan engine (GGA-806/10) and the Sikhote Energies engine (481-584), had the coating spalled from the leading edge and concave surface of the airfoil exposing base metal. In each case, other coatings on the same rotor were performing appreciably better under the same conditions. General Electric countered that the coating had undergone additional modifications and should adhere better to the base metal. GE now uses platinum aluminate as a bond coat for the thermal barrier coating rather than the MCAlY overlays. GE also proposed that a newly developed process for applying BC 22 coating at room temperature. Composite plated CoCrAlHf coatings were deposited on stage 1 and 2 blades by BAJ Limited. CrAlHf particles are entrapped in a cobalt plating matrix and heat treated to obtain an equivalent PBC 22 composition by diffusion. The contract was modified to include these alternate coatings. These advance coatings, and other coatings were discussed by Nagaraj et al, 1995.

Although they were not awarded the Navy contract, Chromizing volunteered to provide 24 sample refurbished blades for testing. These blades were chosen from the stockpile, repaired in accordance with the contract specification and recoated with platinum aluminate. Chromizing proactively sought to be included in the testing to compare their blades versus the General Electric platinum aluminate. One interesting aspect of Chromizing's inclusion was that 25 blades were chosen at random from the Navy stockpile and provided for repair. Only one blade was deemed beyond acceptable limits. This is in drastic contrast to the fallout rate associated with GE.

Because a parallel Navy program employed silicon aluminate HPT blade coatings, NSWC established contact with Sermatech Int. regarding the Sermalloy J coating. This aluminum silicide coating (Sermalloy J), applied via a slurry alumination process, had mainly been used to touch up parts coated by other processes, Sermatech also voluntarily repaired and recoated a small number (18) of blades for inclusion in the rotor test. NSWC conducted extensive metallurgical examinations of both Chromizing's platinum aluminate and Sermatech's Sermalloy J repaired blades, and decided to include these components in the Rainbow rotor for testing. In addition as part of a Navy development program, both coatings are undergoing burner rig testing for type I and II corrosion. Those results are not yet available.

ROTOR CONSTRUCTION

The US Navy Rainbow Rotor construction was completed in November 1995. The rotor buildup was accomplished at the Navy's LM2500 overhaul facility NADEP North Island (San Diego, CA). One of the concerns during the rotor buildup centered on the problem of balancing the HPT rotor. Because of the varying composition and thicknesses of the blade coatings, differences as great as 57 grams were found in total weight of stage 1 high pressure turbine blades. Because of the disparity in weight uniformity, the rotors could not be constructed exactly as planned. The initial plan was to have an equivalent number of each blade coating type included for testing. This plan needed to be altered to accomplish rotor balance. The final construction of the Rainbow rotor does include a representative sampling of all blade coating types.

PROPOSED TEST PLATFORM

One of the crucial aspects of this program is to ensure that the completed Rainbow rotor be deployed in such a way as to provide quick, relevant information regarding its performance. The Navy technical community agreed that a proposed test platform for this rotor should meet as many of the following (worst case scenario) criteria as possible:

1. Accumulate Operating Hours Quickly
2. Harsh Environmental Exposure
   a. Airborne Particulate Matter, Salt Ingestion (Japan ?)
   b. Sand Ingestion (West Coast Ship Deployed to Persian Gulf)
3. Routinely Operate At High Power Point
4. Deployment on Navy's Least Effective Inlet Filtration System

Based on the stated profile, the intended disposition for the Rainbow rotor will be aboard an FFG 7 class frigate, homeported in Yokosuka, Japan. This test bed will offer a good test for the various blade coatings.

TEST OBJECTIVES

The goals of the proposed Rainbow rotor testing are two-fold. Primarily, the test will help produce a cost benefit analysis for repairing/refurbishing LM2500 HPT blades. This analysis will define the risk/reward potential of this program. The cost to refurbish the subject blades was approximately one quarter the price of a new paired blade. This repair cost may be decreased further if a larger number of assets are repaired under competitive contract. Based solely on these numbers, if the refurbished blades could obtain between 7,500 - 10,000 hours service life, the cost savings would justify HPT blade repair. However, an element in the analysis which will be difficult to quantify pertains to the number of blades which may fail from high cycle fatigue, blade creep limitations and the collateral damage caused by such failures. A secondary objective of the program is to evaluate various coatings. BC 21 has afforded excellent protection on US Navy engines with over 20,000 hours service in some cases. The BC family of CoCrAl coatings are expensive from a material composition and coating process perspective. The aluminozied coatings are less costly. The coating test will evaluate coating performance as well as consider the respective costs associated with each. It may be determined that an inexpensive coating
which holds up well is more cost effective than a coating which exhibits slightly better performance but at substantially greater cost.

**ROTOR EVALUATION**

One of the key facets of the Rainbow rotor program is the methodology for evaluating and analyzing the rotor blades once placed in service. Currently, the Navy plans to conduct periodic video borescope inspections of the deployed rotor at approximately six month intervals. These visual inspections are effective at evaluating the performance of the different blade coatings as they accumulate run time. Because the typical Navy engine accumulates 800 hours per year, high time data takes years to acquire. If the program for refurbishing blades is deemed cost effective and the risks are shown to be minimal, it has been proposed that the prototype rotor be evaluated after a relatively short period of time based on confidence factors.

Based on the experience gained aboard the Australian frigate, which at this writing has accumulated 6,186 hours, NSWC has proposed that the US Navy refurbished high pressure turbine blades be analyzed after 18 months. The projected operating time on the blades can be estimated to 1200 - 1500 hours. At this point sample refurbished blades would be removed from the rotor and a complete structural analysis be conducted of the airfoil, internal cooling passages and the dovetail braze joint. Evaluation of these components would enable the Navy to make an engineering assessment and evaluation of the refurbishment process.

As applies to the Rainbow coating aspect of the testing, borescope inspections have proven to be an effective inspection method for appraising the coating condition. The initial test plan will be to remove a sample of each coating type after 3,000 hours and conduct metallurgical analysis. Since the Navy hopes to have the refurbishment issue resolved at that point, it is possible that small scale contracts for one or two complete rotor blade sets will be awarded for differing coating types to continue the coating evaluation aspect.

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