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10 YEARS LATER; A TECHNICAL AND FINANCIAL REVIEW OF THE UNITED STATES NAVY'S HIGH PRESSURE TURBINE BLADE REFURBISHMENT PROGRAM

Robert Neff
NAVSEA Philadelphia Code 934, US Navy, USA
robert.neff@navy.mil

Matthew Driscoll
NAVSEA Philadelphia Code 934, US Navy, USA
matthew.driscoll@navy.mil

ABSTRACT

In 1999, the United States Navy implemented an LM2500 High Pressure Turbine Blade Refurbishment Program. Traditionally, the US Navy had replaced high pressure turbine components each time an engine was removed from a ship during its depot overhaul visit. Following successful testing of several Rainbow rotors built up with refurbished LM2500 blades, as well as experience gained by the Royal Australian Navy, refurbishment of stage 1 and 2 high pressure turbine blades was adopted vice the replace with new part strategy previously utilized. This paper takes a fresh look at the blade refurbishment effort from two perspectives, first, an updated technical assessment is made of Rainbow rotor components as well as parts which were implemented as part of the refurbishment program to evaluate their current (2009) condition and define service life expectations. Secondly, a financial assessment is made of the program itself, defining the cost avoidance of refurbishing customer owned blades versus the cost to procure new components. The financial analysis will also include commentary on risk mitigation based upon the hundreds of thousands of operating hours on these components have acquired while deployed at sea.

INTRODUCTION

In the early 1990s, the United States Navy began investigating the feasibility of refurbishing the LM2500 high pressure turbine (HPT) blades for its LM2500 gas turbine engines. The US Navy has a fleet of 400 LM2500 engines used for propulsion aboard its surface combatant ships. The Navy learned that aero and industrial turbine users had been refurbishing numerous turbine components in an effort to reduced engine overhaul costs. From 1975 to 1999, the Navy had replaced HPT components with new production hardware during the overhaul and repair of most of its gas generators. There were some exceptions when low time engines were returned to the depot for oil leaks or vibration related problems, however, the vast majority of engines replaced HPT blades and vanes as standard practice. Fortunately for the Navy, some individuals had the foresight to accumulate and store these hot section components which

were removed from the engines, based primarily on their known value. This enabled the US Navy to build a vast store of thousands of high pressure turbine stage 1 and 2 blade sets.

In 1994, engineers at the Naval Surface Warfare Center began investigating the potential of repairing and refurbishing these hot section components for re-use in overhauled Navy LM2500 gas generators. Discussions with the engine OEM raised a number of possible concerns with this program, including the potential negative impact of wholesale blade failures in the fleet. From the OEM perspective, these blades did not lend themselves to a refurbishment process due to the significantly different "overlay" coating (vice aero derivative diffusion coatings) which was used in the marine environment for Type I and II hot corrosion protection. The overlay coating used on the Navy blades, known as BC 21 and BC 22, were essentially CoCrAl (Cobalt, Chromium, Aluminum) based coatings. Significant detail of the coating composition and application process are defined in ASME GT-2002-30263; Driscoll, McFetridge, Arseneau.

Despite the warnings from the engine OEM, the Navy continued to research blade refurbishment because of the potential cost savings associated with this program. The Navy learned of a Rainbow rotor test being conducted by the Australian Navy with one of its LM2500 engines which included refurbished blades. A field assessment of those parts, performed jointly by the Royal Australian and US Navies, performed by borescope inspection, indicated that after thousands of hours of accumulated engine operations, the refurbished blades were virtually indistinguishable for other control, new production blades in the same rotor with identical runtime. This finding spurred additional interest which led the Navy to establish its own Rainbow rotor testing. It should be noted that at this point, in 1997, the Navy had not performed any Rainbow rotor testing for nearly 20 years on LM2500 engines. The lack of ongoing blade coating tests was related to the fact that the Navy was satisfied with both the life and performance of the BC 21 production coating. The Navy was realizing more than 20,000 hours of service with its hot section components on most gas generators. A program was

developed to assess various high pressure turbine blade coatings along with refurbished parts and used production components as control pieces for several Rainbow rotors which were constructed by the Navy.

In 1997, a contract was awarded to refurbish and recoat 100 LM2500 HPT blades (paired blade configured). The low bidder on the contract was the engine OEM. Despite their stated concerns with refurbishing marine high pressure turbine blades, two complete rotor sets of repaired blades were repaired under this contract. The parts were repaired and provided to the Navy in support of the program protocol. In addition to these parts, other blades were refurbished by several other companies who volunteered to provide them at no cost to the Navy in order to validate their technical capabilities along with establishing a side by side competitive environment for coating performance assessment. In the end, refurbished blades from three separate companies were provided to the Navy for testing. In addition, numerous blade coatings and varying coating thickness were provided to support Rainbow rotor buildup.

This paper provides an updated assessment of ongoing Rainbow rotor testing; some of the elements include ones from the initial testing. In 1999, based upon early visual and metallurgical analysis of sample components, the United States Navy made a calculated decision to begin refurbishing its high pressure turbine blades and vanes. The decision was based upon an number of considerations including potential cost savings, mitigated risk, longterm availability of production paired blade configured parts and depot downtime associated with material shortages. A Navy contracting solution was developed to support Direct Vendor Delivery (DVD). This contract, focused in support of the Navy's overhaul depot, required the vendor to pick up high pressure turbine components which had been removed from Navy gas generators during the overhaul process, manage those components through their refurbishment process and return those same parts to the depot with a defined schedule in order to support engine repairs and depot turn around times. Although this DVD process came with initial growing pains, the vendor and the Navy's overhaul depot eventually mastered the cycle which permitted a 25% reduction in depot turn around times from those prior to the contract award. This DVD process remains in effect at the Navy's depot today. The Navy's contracting partner, Chromalloy Corp, has also reduced its internal refurbishment cycle in support of the Navy's needs. Follow-on contracts have steadily reduced the turn around time for the component repairs.

PREVIOUS EXPERIENCE:

Since the beginning of the program, there has been an array of data points available to compare coating performance. In total, there have been 7 rainbow rotors built up and tested in service. All with the intent of finding the optimum balance of performance, cost, and longevity.

One of the most difficult aspects of this program is idealizing a coating and revolving contract that best fits the US Navy's varying operating profile. Unlike a steady state generator, the main engine on a US Navy ship operates through a variety of

profiles with very minimal time at a constant temperature. This means that the coating utilized must be able to best withstand Type I and Type II corrosion as well as continual cycling.

The coatings that have been analyzed over the years include various application processes, vendors and general coatings. These include:

- Platinum Aluminide with a Thermal Barrier Coating
- Platinum Aluminide
- BC-21 / BC-22 / BC-23
- BC-52
- Sermaloy-J
- PBC23+Chrome
- P&W High Chrome
- BC-21 with a Thermal Barrier Coating

Currently the evaluation is still ongoing but the data thus far has provided the Navy to move forward with the program of blade refurbishment to reduce total overhaul cost.

The original four Rainbow Rotors were rightfully placed on various platforms in order to produce results that were most applicable to true maritized US Navy applications. These platforms included a Ready Reserve Merchant ship, a high-power steady state power generation plant, and two lower power Frigate-type platforms.

The coatings applied were continually compared to the OEM baseline in order to evaluate the validity of the refurbishment programs. Through continual metallurgical analysis and borescope evaluations the program was driven towards the field investigation of several coatings which include:

- GE PBC-22 (Production Standard)
- GE BAJ BC-22
- Refurbished PtAl
- PtAl with a Thermal Barrier Coating
- Sermaloy J (Similar to coatings used on Rolls Royce Engines)

The detail of the make-up and application of each coating is further documented in GT-2004-53461, Neff, et al. While evaluating coating performance, operational factors must be considered in order to understand why the life expectancy is not always consistent. These factors include fuel quality, operational power profiles, the design and maintenance of demisters, water wash frequency and water quality.

The final two Rainbow Rotors that were built up were installed on CG-52 and FFG-46. These low/medium power applications have accumulated over 34,000 combined hours of operation. All of the other rotors have been removed from service or are no longer accumulating operating hours. An assessment of each of these applications was completed.

The rotor on CG-52 had accumulated 7,192 hours when it was removed from service for a non-related failure. At that time the decision was made to evaluate and rate the blades, then reinstall those that did not have base metal attack into an overhauled engine to further evaluated coating performance. The performance of the coatings from this rotor was the focus

reference 1. This 'hybrid' rainbow rotor has accumulated 5,200 additional hours since it was reinstalled onto CG-56.

To date, the rotor on FFG-46 is still in operation. Those blades were recently inspected in 2009 with positive results.

A statistical life span was determined earlier on the US Navy refurbishment program for several of the coatings being evaluated. A summary of some of these life expectancies are listed in the table below. PtAl was expected to last between 9,000 to 15,000 hours (Driscoll, 2002). This was mainly determined from the results of the rotors on the HMS DARWIN and the ongoing inspections of the rotors still in the fleet. The analysis of the blades removed from CG-52 was consistent with the projected results of the original rotors. While the BC overlay coatings used on both new and refurbished blades showed slightly less substrate attack than the PtAl, the results were not drastic enough to drive the program away from the potential use of PtAl coatings. Currently the US Navy utilizes a Chromalloy PtAl coating as the standard for refurbished blades.

Coating	Expected Average Coating (HRS)	Expected Coating Life Standard Deviation (HRS)	3 Sigma Range 99% of Data (HRS)	
PtAl	12,000	1,000	9,000	15,000
BC-23	13,000	1,000	10,000	16,000

Table 1: Coating Life Expectancy used for Analysis (Driscoll, 2002)

Note: BC 23 is meant to represent the standard production coating at the time for comparison

The blades analyzed from the CG-52 rotor showed a nearly equivalent performance between the various BC coatings that were installed on the HMS DARWIN. The exception to this being the composite plated BAJ BC-22, which performed the best with regards to base metal attack. For that reason and for the sake of this analysis, it is assumed that the BC-22 coatings would fall within the projected life span previously determined for BC-23, with the possibility that the BAJ BC-22 would have a slightly higher average life span.

The Sermaloy-J coating being evaluated performed equivalent to the BAJ BC-22, showing no signs of base metal attack. Salt deposits caused the TBC blades to spall at the 80% span and attacked the underlying platinum aluminide bond coat.

ONGOING RAINBOW ROTOR

A borescope inspection was performed after approximately 4,900 hours TSR on the 'hybrid' rotor installed on CG-56 that was made up of new blades and reinstalled blades from the CG-52 rotor. The reinstalled blades had accumulated a total of 12,200 hours at the time of the inspection.

The stage-1 blades were all reported to be within satisfactory limits and with minimal signs of coating degradation in the thumbprint area of the blade. Figure 1 shows a typical stage-1 blade. It should be noted that since only those blades that had no signs of base metal attack were reinstalled, 57% of the stage-1 blades in this rotor are new blades.



Figure 1: Typical Stage-1 blade after 5,000 (new)/12,200 (refurbished) hours of operation

Although the stage-2 blades in this rotor began to show some signs of coating loss on the leading edge, there was no apparent sign of blade wall or base metal attack. Figure 2 is a typical stage-2 blade from this rotor.

Based upon prior experience, all conditions noted from the borescope inspection are satisfactory and indicate an "as to be expected" condition for a rotor with this many hours of operation. Only 12% of the stage-2 blades were new and were replaced only to provide a sample for metallurgical analysis.



Figure 2: Typical Stage-2 blade after 5,000 (new)/12,200 (refurbished) hours of operation

The 12,200 hours accumulated by many of the hot section parts seems to strongly support the Navy's original projections regarding refurbished (DVD) component life, particularly based upon the fact that these parts seem to have remaining life.

The latest rotor to be inspected was that on FFG-46, an Oliver Hazard Perry Class Frigate. This is a 20,500 hp application with the most severe inlet design, with respect to salt/water ingestion, in the US Navy fleet that utilizes the GE LM2500 GT.

This rotor has accumulated 21,650 hours since it was installed on the Frigate platform. Through the borescope inspection, the performance of the blade coating was consistent with that of the previous inspection 5 years prior

Even with over 8,800 hours since the previous inspection, there was very little significant difference in the performance of the coatings. The first and second stage HPT blades were in generally good condition, especially considering the total number of hours accumulated.

The most attack noted during the initial inspection appeared to be evident on the GEAE overhauled blades with the Howmet PtAl. A sample photograph is shown in figure 3.

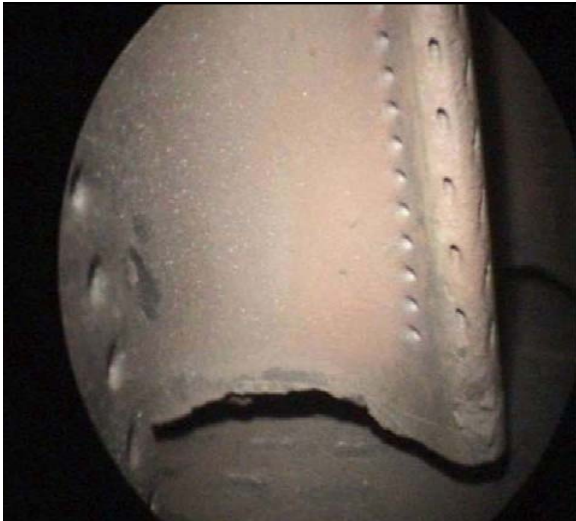


Figure 3: Typical Stage-2 GE Refurbished Platinum Aluminide after 11,657 hours of operation

One exception to what was found during the borescope inspection performed in 2004 was the TBC coated blades which have several areas of coating degradation on the leading edge of the airfoil as well as the thumbprint region.



Figure 4: Typical Stage-1 Thermal Barrier Coating (TBC) blade after 21,650 hours of operation

Currently both of the engines on Navy ships with the rainbow rotors are cleared for unrestricted operation. When the decision is made to remove the engines due to failure or for

metallurgical analysis, additional data will be available to clarify the projected life span of blades with each coating. This information will be weighed against the refurbishment cost for each coating and drive the US Navy towards additional savings.

FINANCIAL EVALUATION OF PROGRAM

The United States Navy uses a number of different criteria to measure and evaluate the cost effectiveness of both ongoing and proposed programs. For the blade refurbishment effort, several different criteria needed to be met in order to justify the cost investment required to begin such a program and then additional criteria used to evaluate its ongoing cost effectiveness to both the Navy and ultimately the nation's taxpayers. Three different criteria were used to initiate and continue to the LM2500 blade repair efforts, those criteria are:

- Return on Investment
- Pay Back Period
- Repair vs. New Part Cost

Table 2 defines the Navy's standardized calculations for evaluating both return on investment and period of payback for engineering programs. The return on investment (ROI) value generally must provide positive net valuation over the life cycle of the program in order to initiate financial approval. As defined in the accompanying Table, the return on investment formula is: $ROI = MCE/IMP\$$, whereby MCE represents maintenance cost effectiveness and IMP\$ represents implementation costs of a particular program. In order to gain approval for this effort, a financial evaluation team representing various Navy commands is briefed by a lead engineer on the relative merits of a particular program. The stakeholders within a program must sign an endorsement letter indicating they have been briefed on the program and agree in principle to its implementation, in the case of the LM2500 high pressure turbine blades, four different commands from operational, program management and material support arms of the Navy signed aboard to promote this effort. The financial evaluation team is provided a summary briefing and afforded an opportunity to question both data and merits of this program. In the case of the HPT blades, a gross return on investment on 208% was achievable over a 22 year program life which corresponded to the Mean Time Between Removal (MTBR) for the LM2500 engines in the fleet at the time of the proposal. Since that time, MTBR for the engine has increased to enable a 24 year program cycle, further enhancing the ROI benefits. It is hypothesized that with continued engineering developments addressing reliability concerns will enable additional program lifespan increases which support the original approval of the program by the financial team.

LM2500 High Pressure Turbine Blade Refurbishment		Pay Back Assessment
Life Cycle Management Costs (Present)		
Cost of component ownership year1	\$604K/engine	\$7,257,600
Cost Impact of Refurbishment	Parts/Year	\$1,452,400
Cost Impact of Engineering Effort		\$372,000
Increased Overhaul Costs (Projected)	Adj/Inflation	\$1,250,000
Total (Present Day Cost/Ship Class/Year)	PS/SC/Yr	\$4,163,200
Years Remaining in Service Life	Yrs to EOL	22
Life Cycle Maintenance Costs (Present)	LCMCp	\$92,030,420
Life Cycle Management Cost, Future		
Cost Savings Multiplier	20%	
Cost of Components Ownership/Year		\$234,191
Cost Impact of Repaired Blades/Year		\$105,563
Cost Impact of Engineering Support/Contracts/Year		\$25,000
Increased Overhaul Costs due to adverse effects/Yr		\$112,500
TOTAL (Future Cost/Ship Class?Year)	FS/SC/YR	\$477,254
Years Remaining in Service Life	Yrs to EOL	22
Life Cycle Maintenance Costs (Future)	LCMcf	\$10,499,588
Maintenance Cost Effectiveness		
(MCE = LCMCp - LCMCf)	\$	\$81,530,832
Development Testing, One Time Costs		\$172,000
Installation Hardware		\$220,000
Implementation Cost	IMPS	\$392,000
Pay Back Period (PBP = PS/SC/YR - FS/SC/YR)	PBP	0.11
Return On Investment (ROI = MCE/IMPS)	% ROI	208%

Table 2, US Navy HPT Return on Investment

In addition to ROI, another criteria used to evaluate the potential effectiveness of proposed program is pay back period (PBP). Pay back period essentially represents the period of time required to recoup its implementation costs. For the US Navy, a standard requirement is that for programs requiring more than \$100,000 investment, a pay back period of 3-5 years is considered a maximum timeframe. With respect to the HPT blade refurbishment, a pay back period of slightly more than one month was achievable. It should be noted here that significant work was conducted by both industry and the Royal Australian Navy in order to minimize the US Navy's implementation costs. Existing Rainbow rotor testing by the Australian Navy, along with in place refurbishment infrastructure by OEM and the commercial sector enabled the Navy to costs which might otherwise have been requirements in order to proceed with this program.

A third evaluation criteria, existent within the Navy guidelines was a general policy that in order for repair/refurbishment of existing hardware to be contracted by the Navy, the cost to repair must not exceed 75% of the new part/component cost in order to justify the effort. With respect to this criterion, at the time of the implementation on this program, the cost for a new production OEM LM2500 high pressure turbine blade was \$5,400, as listed in the OEM's part catalog (1998). Because the Navy had a negotiated discount structure contracted with the engine manufacturer, the Navy was afforded a 54% discount off the advertised pricing for these blades, provided the Navy placed orders on long leadtime, 52 weeks in advance. In effect, because of this discount rate, a blade price of \$2916 was available to the Navy at the time of the program initiation. Based upon the not to exceed 75% repair contract hurdle, a maximum cost for HPT blade repair was \$2187/blade. In the 1998/1999 several blade refurbishment contracts were let, to both OEM and industry, in each case, the blade repair cost per unit was \$738-\$1032/blade. It must be noted that several contracts called for various blade coatings (these are described in referenced papers) which impacted the total cost of refurbishment for the blades and the Navy is unable to extract the cost to refurbish only versus the total cost to refurbish and recoat components. It is believed, based upon contracting analysis, that overlay coatings are perhaps 3X

more costly than diffusion coatings for the LM2500 blades. In addition, the cost to coat the blades, regardless of coating type and application method represents less than 25% of the blade repair/refurbishment cost. Based upon these costs, the 75% maximum contracting threshold was easily met when the Navy refurbishment program was begun.

The original Navy contract for high pressure turbine blades included a number of other components also required in the overhaul process for the LM2500 depot repairs. This paper focuses only on the HPT components which comprised the most costly and critical elements of the contract. Since the implementation of the high pressure turbine blade repair contract in 1999, a total of 82 engine sets of paired blade configured HPT blades have been refurbished for the Navy and installed in engines at the Navy's LM2500 overhaul facility in San Diego, California. A rotor set of paired blade components is comprised of 54 stage 1 HPT blades (108 airfoils) and 58 stage 2 HPT blades (116 airfoils). Single shank blades and vanes were also contracted for repair. The figured below depicts the paired blade and single shank configurations of LM2500 HPT blades. The Navy owns hundreds of each configuration of LM2500 engine type. For the single shank configuration, a total of 38 engine sets of blades have been repaired through the refurbishment contract. Table 3 below projects an estimated cost avoidance for the Navy since having implemented the blade refurbishment contract, it should be emphasized that since other components are included in the cost structure of the Navy's contract, that these costs are estimated and not exact due to the nature of the contract structure.

	# of Engine Kits Completed	Cost/Blade (New)	Cost/Blade (Repaired)	Project Cost Savings
Stage 1 PBT (54/Engine)	130	\$5,400	\$1,050	\$30,537,000
Stage 2 PBT (58/Engine)	130	\$5,200	\$1,000	\$31,668,000
Stage 1 SST (88/Engine)	23	\$5,700	\$1,150	\$9,209,200
Stage 2 SST (90/Engine)	28	\$5,500	\$1,000	\$11,340,000

Table 3, US Navy HPT Blade Cost Comparison

The Table shows a significant cost savings realized over a 10 year period by having implemented the blade repair contract. Utilizing the Navy's previous ability to procure discounted production parts, the projected cost saving in the table may have been reduced to \$45M by successfully contracting required parts with a long lead contract. The investments costs to fund HPT blade repairs over the past 10 years are less than \$18,000,000. To further support the effectiveness of the program, it should be noted that production of paired blade configured HPT blades has ceased, therefore the entire overhaul program for the Navy's older configuration of LM2500 engines may have been impacted by not having transitioned into this repair contract structure. In further analyzing the Navy repair contract, the vendor has recorded both blades successfully repaired and those which fell out during the refurbishment effort as unrepairable. Although it's difficult to characterize all the reasons for the blades to fall out during the repair cycle, the most common reasons for rejection are gross physical damage caused by engine stall, airfoil

failure, insufficient internal airflow and inadequate water flow indicating internal cooling passages blockage. Table 4 shows the actual components fallout rate under the Navy's contract. Over a 10 year period, approximately 19% of the HPT stage 1 and 2 blades have proven to be unrepairable. The Stage 1 blades, which are more exposed to higher engine firing temperature, were 5 times more likely to scrap out during the repair process than the Stage 2 blades, which operate in a relatively cooler environment and have no leading edge cooling holes which can be blocked over time by gas path Constituents.

Table 4 clearly shows less single shank parts have been repaired under the Navy contract. For clarity, although the Navy's single shank population is three times its paired blade number, the single shank engines in general have not accumulated as much operating time and have not been removed from ships for repair at an equivalent rate compared to the older paired blade engines. Its assumed this disparity will be overcome in the proceeding years.

LM2500 HPT Blade Refurbishment Contract	Satisfactorily Repaired	Components Scrapped In Repair	Fallout Rate
HPT Stage 1 Blades (SST Configuration)	2031	850	29.50%
HPT Stage 1 Blades (PBT Configuration)	7046	3537	33.40%
HPT Stage 2 Blades (SST Configuration)	2564	136	5.00%
HPT Stage 2 Blades (PBT Configuration)	8752	650	6.90%
TOTAL	20393	5037	19.00%

Table 4, US Navy HPT Blade Scrap Rates

REFURBISHMENT BUSINESS CASE ASSESSMENT

To be fair, a financial evaluation of the HPT blade refurbishment program would not be complete without a detailed assessment of the program risks. As noted previously, the engine OEM recommended the Navy not consider refurbishment for marine LM2500 blades, due to their atypical operating profile and the unknown impact of Type I and II corrosion effects on blade composition and cooling passages. Since its implementation in 1999, the US Navy has overhauled 128 engines using refurbished HPT components. At the time of this writing (Fall 2009), the Navy engines have accumulated in excess of 437,000 hours of operation. To put this experience in context, the Navy has accumulated over 12,000,000 hours of operation on its fleet of 400 LM2500 engines since the 1970s, so while the experience to date with refurbished parts is not insignificant, it also continues to require monitoring. Navy data shows that production LM2500 engines routinely accumulate > 25,000 hours of service life before they are removed from the ship for overhaul. When engines are repaired at the depot, they are not "zero timed" but rather repaired to a standardized workscope based upon Navy experience. While discounted several lowtime extremes, overhauled LM2500s statistically accumulate between 10,000 & 15,000 hours of operation

before they are removed from service as non repairable aboard ship. This data includes the entire LM2500 population, not simply the engine with refurbished components. As such, a realistic goal for the refurbished blades is a life cycle of 15,000 hours (read: significantly less than new production blades). To date, the hightime refurbished blades in the Navy's Rainbow rotor have accumulated in excess of 21,650 hours (USS RENTZ).

RISK

The LM2500 OEM recommended the Navy not consider HPT blade refurbishment due to the inherent risk associated with using repaired versus new production parts during the overhaul cycle. One measure of risk of refurbished parts would relate to any performance impact or degradation associated with repaired components. The Navy has not been to account for any performance tradeoff using refurbished parts on LM2500 engines. The Navy rates its LM2500 engines at significantly lower power levels than some industrial engine users in order to realize long service life with the engines. This has been demonstrated over a 35 year period. In both the test cell environment and once installed aboard ship, the Navy cannot distinguish between production and overhauled LM2500 engines installed side by side in the same engine room aboard ship. The overhauled engines met the Navy performance requirements (FFG Class-20,500HP, CG Class-21,500HP, DDG Class-26,250HP), so in terms of actual performance, the risk associated with repaired hot section components seems limited or not measurable in the Navy application. With respect to reliability, from 1975 to 1999, using only production HPT blades on both new and overhauled engines, the Navy experienced 0.38 engine failures/year caused by or linked to HPT blade failures in service. Metallurgical evaluations of some of those events linked the blade failures to improper/insufficient blade wall thickness associated with improperly drill internal cooling passages on HPT Stage 1 blades. Since 1999, 2 LM2500 gas generator HPT blades failures have occurred on engines with refurbished blades. So far, no engineering evaluations have been completed on those components, which may offer some data for risk consideration. These analyses will be completed and presented along with this paper at the 2010 Turbo Expo. From a purely statistical standpoint, this data correlates roughly with the Navy's general experience with in place blade failures, however, it must be conceded that in each of the two incidences, the total accumulated operating time on those hot section components was significantly lower than the projected life cycle for the refurbished parts. At the 10 year point, the Navy can point to no data which supports an increase in HPT blade failures on refurbished parts; it also cannot claim that sufficient hightime operations have been acquired on enough Navy engines to confidently eliminate the concerns of refurbished blade life assurance. Industrial users of LM2500s related that they do not distinguish a reduction in lifecycle on repaired hot section components; this question remains open for additional data and interpretation by the Navy.

CONSIDERATIONS/ROAD AHEAD

- With a refurbishment program such as the one utilized by the US Navy, there must be continued analysis of coating performance even after the establishment or selection of vendors and coatings. Technology for coating application and make up continues to improve and additional at sea testing is necessary to determine possible viability for optimal changes and recognized savings.
- Before coating changes are made, it is pertinent that a thorough 'at condition' assessment is made to warrant driving a program change. For example, the performance of a Sermaloy J coating may warrant the build up of a full set of a Silicone modified Aluminide for at sea testing. However without proper evaluation, it could be years before a mistake is realized.
- Operating profiles, new acquisition programs, and hardware changes all need to be taken into consideration with their potential effects. More time at various plant configurations or with something such as a hybrid electric drive could shift engines to run more frequently at more or less corrosive firing temperatures.
- Currently there is less data on Single Shank blades utilizing refurbished PtAl coated blades. This is mainly due to the number of operating hours on SST platforms following an overhaul period. The Navy will continue to monitor single shank data and performance for comparison to the existing data including the possible necessity to further evaluate additional blade coatings.
- The repair and refurbishment of LM2500 high pressure turbine blades has resulted in overwhelming cost savings/avoidance when compared to its previous practice of installing new production blades during engine shop visits and overhauls. Actual cost savings of more than \$500,000 are being realized by repairing these components.
- After 10 years of utilizing refurbished HPT blades, the Navy believes the risks associated with this practice are largely minimized. These blades provide virtually indistinguishable performance with no downside to date.
- Although the refurbished parts have performed well over 10 years, the Navy believes continued monitoring of these parts is required due to relatively low number of hightime hours accumulated to date. Borescope inspections, metallurgical evaluations and engine failure assessments are required to continue to scrutinize the longterm viability of these parts. Additional hightime (greater than 15,000 hours) operating experience is needed to further address risk concerns.
- LM2500 users should make efforts to retain all hot section components for possible refurbishment any time they are removed from service as the cost savings are substantial. In addition, even after blades are characterized as "scrap" or unrepairable, it is advised that these parts be retained as new repair schemes are being developed which may make today's scrap, tomorrows repair assets.
- Users should expect that some fallout will be realized while parts are inducted for repairs. Fallout is related to a number of factors including operating profile, fuel cleanliness, intake efficiency and maintenance practices.

Users would be advised to retain blades as sets when possible to mitigate fallout rates.

- Establishing a good working relationship with your repair vendor is critical to program success. Vendors need to be advised of turn around time requirements, overhaul philosophy and logistics to ensure parts are available when required to facilitate engine repairs. Customers are advised to visit and even audit vendors to maximize confidence in contractual obligations.

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