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Analysis Of Turboshaft Engine-Low Power Margin

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Abstract: ***A turboshaft engine is a variant of a jet engine that has been optimized to produce a shaft power to drive machinery instead of producing thrust. Turboshaft engines are most commonly used in applications that require a sustained high power output, high reliability, and small but powerful light weight engines, inclusive of helicopters, auxiliary power units, boats, ships, tanks, hovercraft, and stationary equipment. Mostly occurred problems in turboshaft engine is negative power margin, thermal margin, low power margin, torque pressure, Vibrations, Uncontrolled Acceleration, stall during acceleration, failure to accelerate properly etc. We are considering engine, that is single shaft turbine engine, with two stage axial compressor, one stage centrifugal compressor, reverse flow combustion chamber and one axial turbine with maximum output power of 805 KW. Lower power margin is the most commonly occurring problem in turbo shaft engine that is used in helicopters. It is caused due to heavy contaminations in air path which leads to fouling. This also results in reduced air flow of compressor which leads to lower power; along with other reasons for lower power is damage of hot core components like power turbine blades and impeller. Low power margin is defined as reduction of output shaft power below the minimum required power to lift the helicopter. The engine encounter with low power is confirmed by pilot by measuring the torque with corresponding altitude and ambient temperature. If the result is not matching with the requirements then engine is sent to test bed to find out the problem. The low power engine received from customer is confirmed by testing the engine in test bed, if power loss is within the acceptable limit then compressor wash is carried out through which 25% to 35% power is regained. After compressor wash if power is not regained then the engine is sent to Repair and Overhaul division and snag is rectified and sent back to test bed for final analysis. If engine is regains the power, then the engine will be dispatched. The engine performance is analyzed through graphs mainly Power vs rpm, during testing the parameters, power, mass flow rate, delta pressure, GG rpm, PT rpm, ambient temperature etc. are calibrated in test bed using FADEC system. In this paper we compare the power losses due to power turbine blade life cycle completion, impeller damage and chipping of blade found on fist axial compressor, rectification of snags, procedure followed to rectify the snags, final engine performance comparison and to confirm which snag because more power loss.***

I. INTRODUCTION

Turboshaft engines are the gas-turbine engines that convert the chemical energy in fuel and air into mechanical energy on a shaft. The turbo-shaft engines find application in various industries apart from aviation. The mechanical energy on the shaft can be used for various purposes, such as, helicopter rotors, electric generator and hydraulic pumps. The most commonly occurred snag in turboshaft engine is low power margin, vibration, negative power margin, thermal margin. Low power margin in turboshaft engine is defined as reduction in power due to aging of components, high TET, components damages.

Low power occurs in engine due to compressor fouling. Compressor fouling is defined as the deposition of dust particles oil, grease on compressor blades, and inlet guide vanes of size 2 to 10 μm deposition of dust particles on blades changes the shape of blade and obstruct the flow which will reduce the mass flow rate. The reduction in 0.1 mass flow rates will lead large amount of power loss. This problem is rectified by compressor washing, which is done by following specific procedure.

The damaged components might be replaced or snag is rectified if possible. If snag in PT blade life cycle completes then the blade will be replaced. The engine performance is tested in test bed by following certain procedure corresponding to snags and following parameters is calibrated like delta pressure, mass flow Rate, fuel pressure, fuel temperature, TGT, TET. The engine power is checked at different rpm may be one point or two points mentioned by OEM. If the power found satisfactory at that rpm then the engine performance is good.In addition to that the engine performance at different snags is analyzed and after rectification again their performance is analyzed.

NOMENCLATURE:

TET	Turbine Entry Temperature
XNHR1	Corrected Gas Generator Speed
PWSDR1	Corrected Output Shaft Power
W2P2	Corrected Compression Inlet Air Flow
T41R1	Corrected Gas Generator Inlet temperature
EGT	Exhaust Gas Temperature
ROH	Repair/Overhaul
GG RPM	Gas Generator Rpm
SHP	Shaft Horse Power
FOD	Foreign Object Damage
PT RPM	Power Turbine Rpm
OEM	Original Equipment Manufacturer.

LIERATURE REVIEW:

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High Jet pipe Temperature

High JPT is a phenomenon where the temperature of the exhaust gas goes above the specified limit as the result of rich air fuel ratio. Rich air fuel ratio may be caused mainly because of improper functioning of the burner and decrease in the dimension of the combustion chamber throat area. Due to these defects the exhaust gas temperature goes above the specified limit (647°C) causing damage to the blades of the turbine wheel.

The engine control system is designed so that the exhaust gas temperature will normally be maintained within a safe margin. However no system can be designed to compensate for operational malpractices. It is foolish to treat over temperature lightly. The fact that the turbine does not fly or the engine melt away is no reason to assume that the engine cannot be or has not been damaged. Several momentarily high over temperature may have as profound an effect on the engine as a single prolonged one of the lesser degree. Excessive internal temperature aggravates such condition as creep or deformation of sheet metal parts and
shortens the life of the engine in general. So it is an important aspect to study the cases for high

Jet Pipe Temperature and the rectification procedure involved in high JPT.

Causes for high JPT

The important causes for high JPT are improper functioning of burners and variation in combustion chamber throat area. Improper functioning of JPTL and fuel accessories may also account for high JPT.

Effects of high JPT

Due to high JPT the exhaust gas temperature goes beyond the limit which melts the blades of turbine and also it may damage the engine itself.

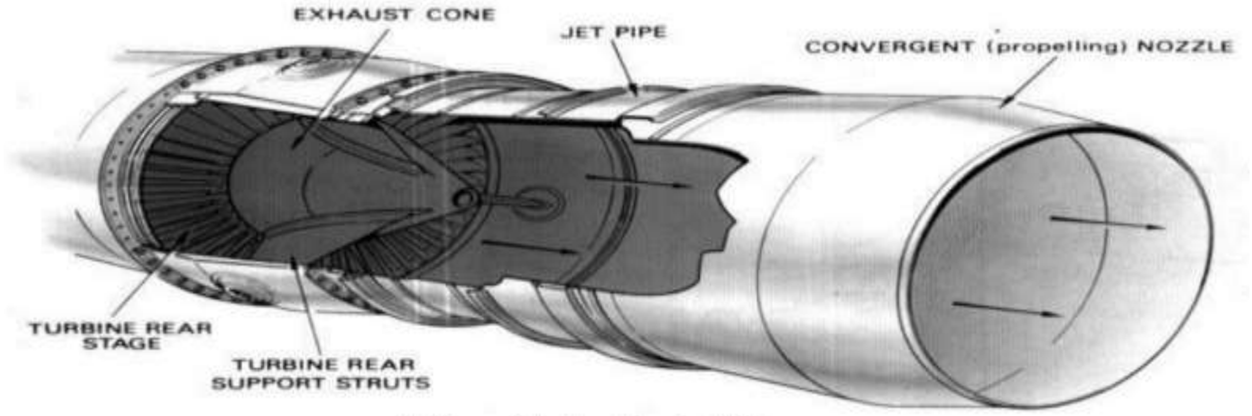

Fig-3.1 Jet Pipe

Jet pipe specification
Weight (including insulating bracket) - 68.6Kg. Length-92.865 inch.

Speed(rpm)	Thrust (lbs.)	JPT(K)	SFC(lb/lb/hrs)
9500	4200	900	1.106 max

High JPT is a phenomenon where exhaust gas temperature becomes more than the

specified limit. If JPT becomes more than the specified limit, there is a danger of turbine blade damage/failure. The High JPT is governed by fuel flow and air flow through the engine. High JPT can be attributed to malfunctioning of burners and throat area of combustion chamber.
Checks to be carried out at unit; Check JPTL, Check Thermocouple, Check Trimmer, Check fuel accessories. If all the above checks are satisfactory and high JPT still persists then following checks are to be carried out. Rig test burners and adjust burner flow to minimum side, check throat area of the flame tube and correct if required to check & ensure compressor efficiency during final acceptance testing.

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Gas turbines are sometimes operated in very hostile conditions due to service exigencies. These environments are characterized by degradation modes such as fouling, thermal barrier coating degradation and blockage of cooling holes which affect the creep life of engines. Therefore this paper presents a performance-based creep life estimation model capable of predicting the impact of different forms of degradation on the creep life of gas turbines. The model comprises performance, thermal, stress, and life estimation models. High pressure turbine blade was selected as the life limiting component of the gas turbine; therefore the integrated model was employed to investigate the effect of engine degradation on the creep life of a high pressure turbine blade of an aero derivative model gas turbine engine using a Creep Factor approach. The results shows that engine degradation affect the performance of gas turbine component which in turn affect their creep life.

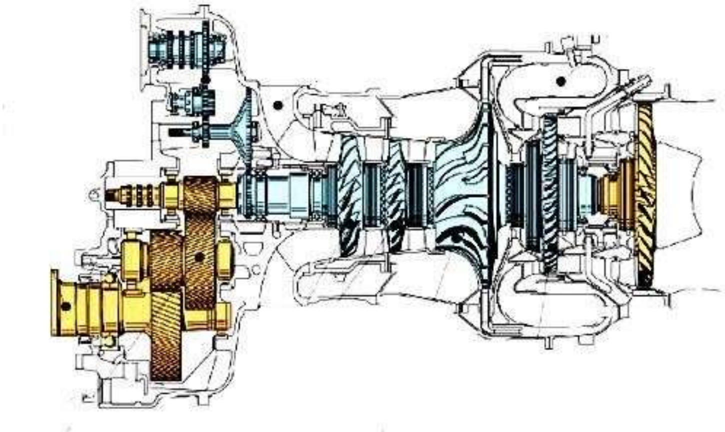
This paper presents a novel creep life analysis model which has been used to assess the impact of fouling, TBC degradation and plugging of film cooling holes on the creep life of HPT blades. The results show that compressor fouling, TBC degradation and plugging of cooling holes have significant detrimental effect on the creep life of the turbine blades. For instance, at FI of 1% and 3%, the HPT blade creep life reduced by 39% and 79% respectively from its reference creep life. Similarly, 25% loss of TBC thickness from its reference value reduced the overall cooling effectiveness by approximately 4% which subsequently reduced the Creep Factor from unity (1.0) to 0.482. This means 25% loss of TBC could halve the blade creep life.

Theory and analysis of power in turboshaft engine

1. Description of engine

TM 333 2B2 is a single shaft turbine engine with two stage axial compressor, one stage centrifugal compressor, reverse flow combustion chamber and one axial turbine.

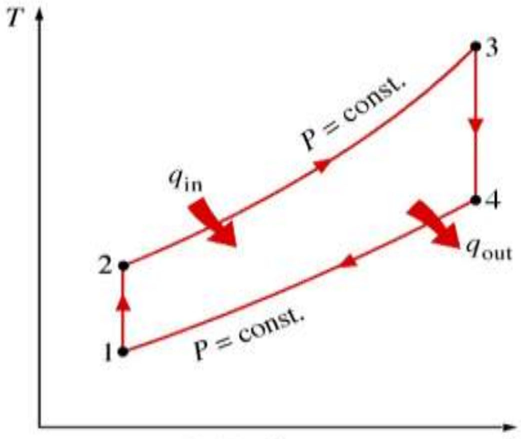
- ✓ Intake diameter :- 0.745 m
- ✓ Gas generator speed: 45000 rpm
- ✓ Power turbine : 37562 rpm
- ✓ Output shaft speed : 6000 rpm
- ✓ Power: 1105 SHP (805kw)
- ✓ SFC: 0.323 kg /kw-hr



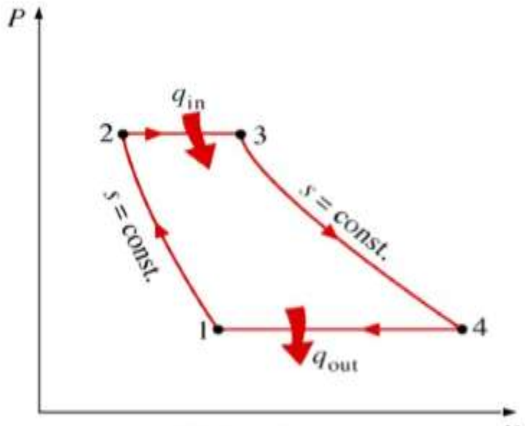
1.1 Brayton Cycle: Ideal Cycle for Gas-Turbine Engines

Gas turbines usually operate on an open cycle. Air at ambient conditions is drawn into the compressor, where its temperature and pressure are raised. The high pressure air proceeds into the combustion chamber, where the fuel is burned at constant pressure. The high- temperature gases then enter the turbine where they expand to atmospheric pressure while producing power output. Some of the output power is used to drive the compressor. The exhaust gases leaving the turbine are thrown out (not re-circulated), causing the cycle to be classified as an open cycle.

- Isentropic compression (in a compressor)
- Constant pressure heat addition
- Isentropic expansion (in a turbine)
- Constant pressure heat rejection



(a) *T-s* diagram



(b) *P*- υdiagram

II. LOW POWER MARGIN

It is defined as the reduction of output shaft power below the acceptance limits, which intern will affect the performance of engine and helicopter. It will occur due to damages of components and compressor fouling.

2.1 The main reasons causing low power margin

- ✓ Compressor fouling
- ✓ High TET
- ✓ Thermal margin
- ✓ Impeller damage
- ✓ Negative power margin
- ✓ Ageing of engine component

Low power and low compressor mass flow observed in the engine is due to compressor fouling with deposits. It could be from the environment and settled due to the air pressure of the compressor. If periodical cleaning is not carried out or even if carried out but not effective, the deposits will become harder which leads to scaling, which can be cleaned effectively by overhaul process.

2.2 Effect of compressor:

Heavy contaminations in air path leads to fouling resulting in reduced air flow of compressor which leads to lower power. Particles get deposited to the parts in the path of air and its reduced mass flow.

2.3 Following parts consist of air flow:

- IGV (Inlet Guide Vanes)
- Stage axial compressor
- I Stage NGV
- II Stage axial compressor
- II Stage NGV
- Impeller
- Compressor cover

III. COMPRESSOR FOULING

Fouling of compressor blades is an important mechanism leading to performance deterioration in gas turbines over time. Fouling is caused by the adherence of particles to air foils and annulus surfaces. Particles that cause fouling are typically smaller than 2 to 10µm (1MICRON=10^{-4}CM).Compressor fouling is due to the size, amount, and chemical nature of the aerosols in the inlet air flow, dust, insects, organic matter such as seeds from trees, oil from leaky compressor bearing seals, ingestion of the stack gas or plumes from nearby cooling towers.
Fouling often leads to changes in airfoil shape, surface roughness, or changes in airfoil inlet- angles. Compressor fouling reduces the compressor mass flow rate, pressure ratio and the cycle efficiency which subsequently leads to a reduction in power and increase heat rate. Fouling must be distinguished from erosion, the abrasive removal of material from the flow path by hard particles impinging on flow surfaces. These particles typically have to be larger than 10µm in diameter to cause erosion by impact. Erosion is probably more a problem for aero engine applications, because state-of- the-art filtration systems used for industrial applications will typically eliminate the bulk of the larger particles. Erosion can become a problem for engines using water droplets for inlet cooling or water washing.

Fig. Compressor blade fouling

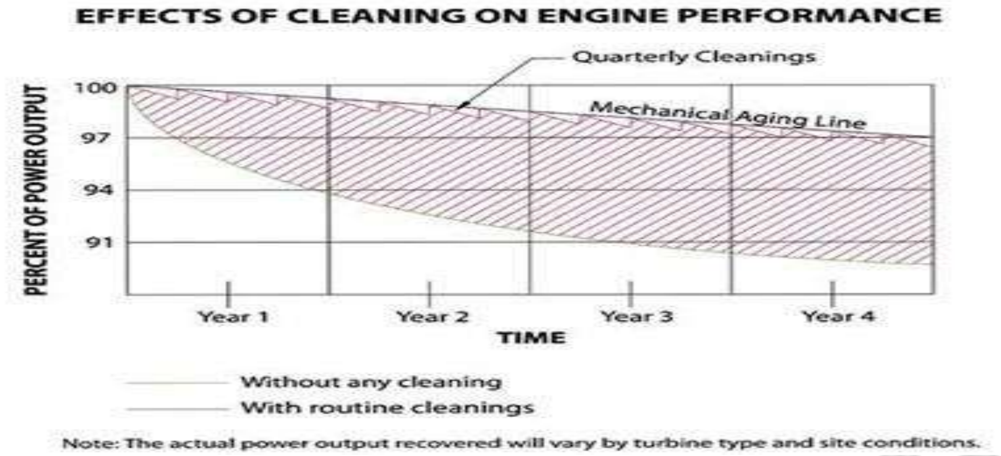
IV. COMPRESSOR WASH

4.1 Compressor washing:

Compressor washing is the single most cost-effective maintenance procedure for any jet engine. Jet engine performance is affected by both gas turbine thermal efficiency and the mechanical health of the components. Since the compressor typically consumes 60-70 percent of power generated, compressor health is critical to engine health management. Contamination in the compressor section leads to deteriorating thermal efficiency which causes reduced engine performance. Not only is performance affected, but damage to the compressor blades caused by contamination can lead to engine failure. Compressor washes can dramatically improve engine performance, increase engine life cycles and lower operating costs by:

- Lowering fuel consumption.
- Improving the compressor efficiency
- Reducing exhaust gas temperatures (EGT)
- Increasing hot section parts lives
- Reducing corrosion
- Extending time between overhauls (TBOs)

Most compressor wash chemicals are formulated to break down the organic bonds of the contaminants and dissolve the inorganic matter. This allows the contamination to be flushed out of the engine.


EFFECTS OF CLEANING ON ENGINE PERFORMANCE

Note: The actual power output recovered will vary by turbine type and site conditions.

Graph: Time Vs. Percent of power output

V. ENGINE TESTING:

Two types of engine testing are done usually they are, production engine testing and development/ prototype engine testing. Production engine testing involves only limited measurements and engine acceptance. Important parameters are RPM, Thrust, fuel flow, compressor delivery pressure, typical vibration, and engine exhaust Temperature. Development / prototype engine testing involves detailed instrumentation and data processing.About 800 parameters like pressures, temperature, vibration, strain signals, cooling flows, secondary flows etc. are measured. Engine testing is conducted in a test cell fully equipped to measure all desired parameters. New facilities have been built to simulate conditions encountered at high Mach numbers and high altitudes in the flight spectrum. Engine performance is generally defined in terms of thrust, fuel flow and air mass flow. Gas turbine engine performance is considerably influenced by changes in ambient pressure and temperature. Increase in inlet pressure is an advantage to the engine while increase in inlet temperature is dis advantage to the engine. In order to compare the performance of the engine on different dates and at different places it is necessary to correct the performance of a given engine to standard day condition known as international standard atmosphere sea level static conditions (ISA SLS).This correction is essential for comparing the performance of different engines.

In order to correct the engine performance to ISASLS condition there are two important correction factors known as pressure correction factor known as delta and temperature correction factor known as theta. Delta= ambient pressure (absolute) under engine test/ISA SLS reference pressure. Theta=ambient temperature in kelvin/ ISA SLS reference pressure namely
288 k. The test performance of the engine is corrected to ISA SLS conditions and the engine is accepted based on the corrected performance; this is carried out for all production engines. ISASLS correction has to be carried out for development engine also.

VI. Typical Test Cell:

A typical sea level engine test bed will be provided with cross sectional area to give air flow through the test bed of about 6m/sec and an inlet to give a smooth flow of air into the engine. The test bed will be provided with means of loading the hydraulic pumps and the electrical alternator. There will be a range of measuring equipments to cover about 1000 parameters of steady state, transient and dynamic information. All performance parameters are gathered electronically, complete with correction factors and calibrated curves applied prior to the calculation of engine performance and read out of corrected data at terminals in the engineering departments to enable decisions to be made while the test is in progress. Engine performance is generally defined in terms of engine air flow, fuel flow and thrust. Thrust is usually measured by mounting the engine in a frame work which itself is suspended from the fixed structure by means of flexure. This arrangement enables the engine in its framework to be made freely only in the axial direction. The amount of axial movement is restrained and the resulting form is normally measured by a strain gauge load cell. The air intake to the engine is generally through a bell –mouth or a venture designed as an air meter.

The bell-mouth/air meter has to be calibrated against another standard or by carefully traversing the throat with pitot probe and establishing the flow co-efficient which is defined as the ratio of the actual mass flow to the isentropic (ideal) mass flow. There are two types of fuel flow measurement, one known as turbine flow meter and the other is bulk meter. The flow meter has a miniature turbine suspended in a tube through which fuel flows. The other is referred to as a bulk meter having a positive displacement impeller. The impeller is rotated in proportion to the flow rate. For accurate fuel flow measurements turbine flow meters are employed.

VII. ANALYSIS OF ENGINE PERFORMANCE BY TESTING IN TEST BED

The DI engine is tested in test bed for performance analysis of engine and if power is low below the acceptance limit then the engine snag is rectified and required maintenance is performed and sends it back to test bed for final performance. The engine power is checked at two rpms to justify overall performance of engine as mentioned below.

XNHR1	PWSDR1(KW)	TET(K)
43640	>754	<1402
41986	>534	<1268

7.1 ENGINE No: X Power loss: 50kw

Reason: GG impeller life cycle completed /M01 calendar life.

7.1.1 Engine performance in terms of power:

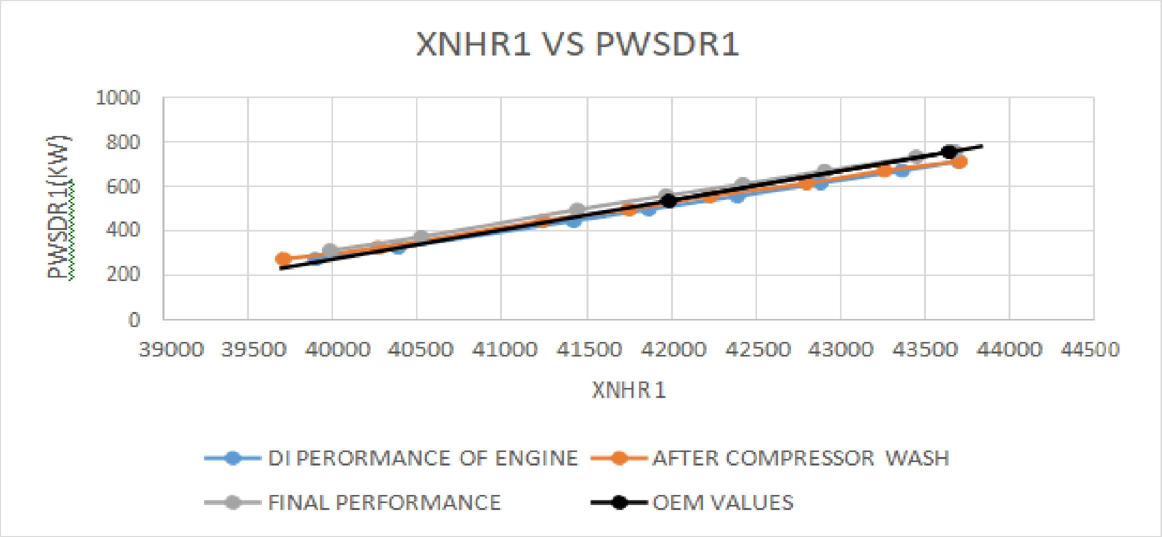
PWSDRI	CCT	XNHR1

DI ENGINE PERFORMANCE	AFTER COMPRESSOR WASH PERFORMANCE	FINAL PERFORMANCE		
704.444	**717.543**	**754.27**	>754	43640
507.881	**521.415**	**558.005**	> 534	41986

After compressor washing 13 kW improved in power is noticed and for further power improvement engine is stripped.

Confirmation Test: Low power by 37kw

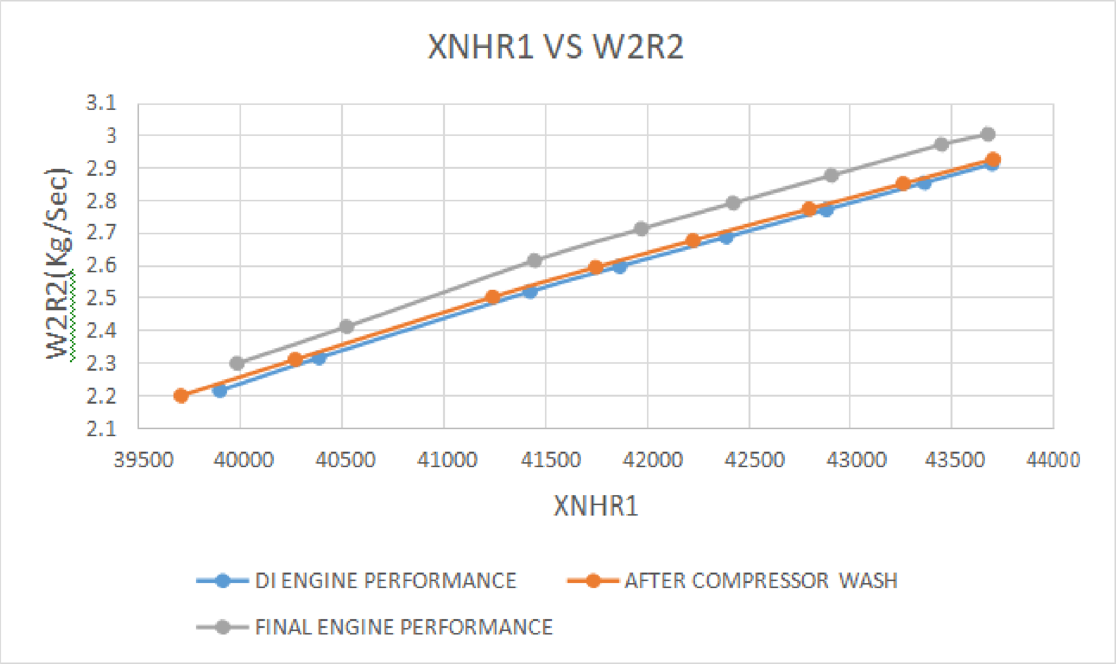
1. Bulk strip the engine (separate M01 & M02)
2. M01 open into two halves & restore the calendar life
3. Unit –strip M02 (less IGV ASSLY, 1_{st} stage axial wheel with GG shaft ,45 tooth gear, PT shaft ASSLY)
4. C/O cleaning & NDT as per process schedule
5. C/O health inspection as per O/H manual
6. C/O unit build M02 & final build
7. Prepare the engine for test



Graph 1 Comparison of overall performance of the engine by power

7.1.2 Engine performance in terms of mass flow rate:

W2R2 @ 42000 tr/m			CCT
DI ENGINE PERFORMANCE	AFTER COMPRESSOR WASH PERFORMANCE	FINAL PERFORMANCE	
2.623	**2.64**	**2.718**	2.65 <>2.82



Graph 2 Comparison of overall performance of engine by mass flow rate

Hence, by disassembly, performing NDT check along with cleaning of parts and assembly of parts it is concluded that engine has recovered 50 KW power in final performance as shown in above graphs.

7.2 ENGINE No: Y

Power loss: 16kw

Reason: Chipping found on one of the blade of 1st axial compressor

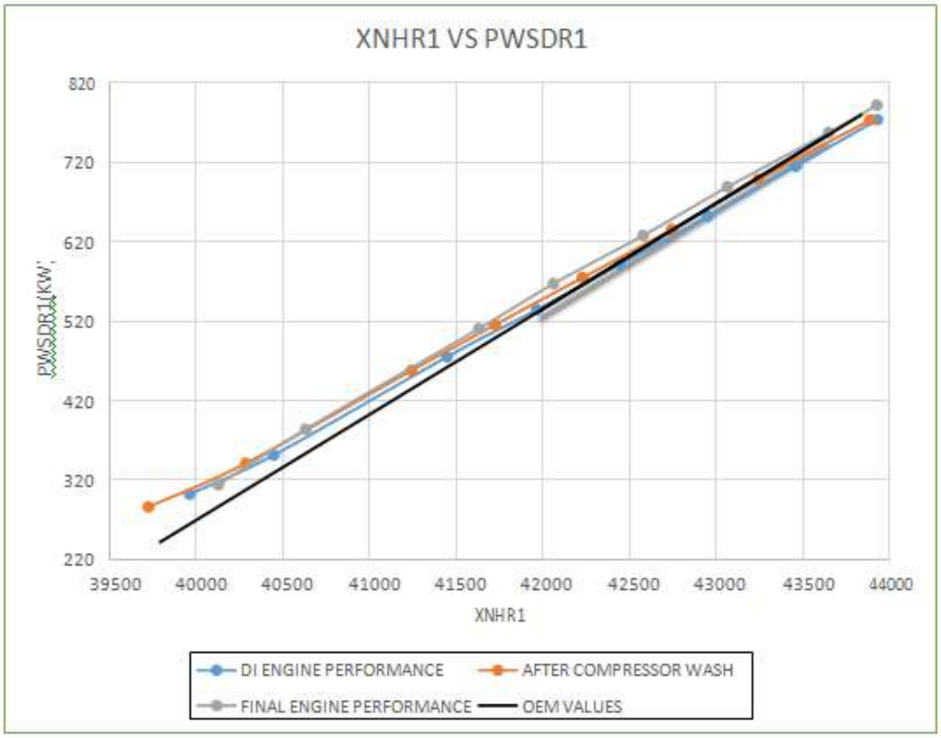
7.2.1 Engine performance by power:

PWSDRI			CCT	XNHR1
DI ENGINE PERFORMANCE	AFTER COMPRESSOR WASH PERFORMANCE	FINAL PERFORMANCE		
737.856	**744.987**	**757.553**	>754	43640
537.023	**545.759**	**556.493**	> 534	41986

After the compressor wash 7 kw of power has been improved

CONFIRMATION TEST REPORT:

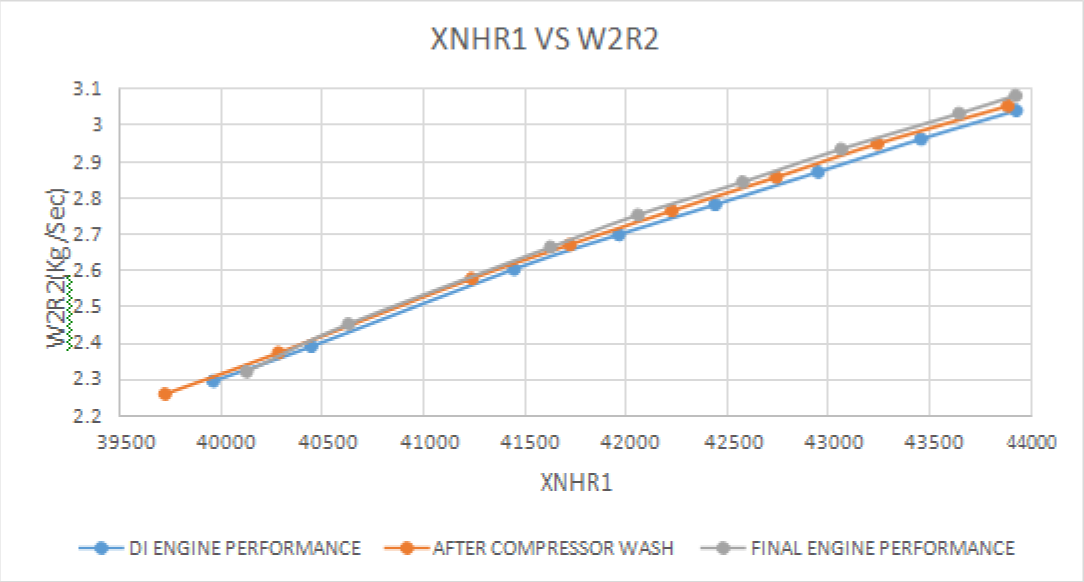
1. Bulk strip the engine (SEPARATE M01 & M02)
2. M01 N/D & unit strip m02 (less igv assembly, 1st stage axial with GG shaft)
3. C/O cleaning & NDT as per process schedule
4. C/O health inspection as per O/H manual
5. Remove & replace 1st stage axial compressor blades by cat A
6. C/O unit build M02 & final build
7. Prepare the engine for test.



Graph 3 Comparison of overall performance of the engine by power

7.2.2 Engine performance by mass flow rate:

W2R2 @ 42000 tr/m			CCT
DI ENGINE PERFORMANCE	AFTER COMPRESSOR WASH PERFORMANCE	FINAL PERFORMANCE	
2.704	**2.723**	**2.723**	**2.65 <>2.82**



Graph 4 Comparison of overall performance of engine by mass flow rate

Hence, by disassembly, assembly of parts and also performing NDT check along with cleaning of parts it is concluded that engine has recovered 16 KW power in final performance which is represented in graph shown above. It also illustrates the effect of compressor fouling leads to reduced compressor mass flow and compressor efficiency recovered after cleaning and reassembly of parts.

7.3 ENGINE No: Z

POWER LOSS: 46kw

REASON: PT blades life cycles completed/oil cooler drain found bend /midlife check/injector main fold found with burning mark.

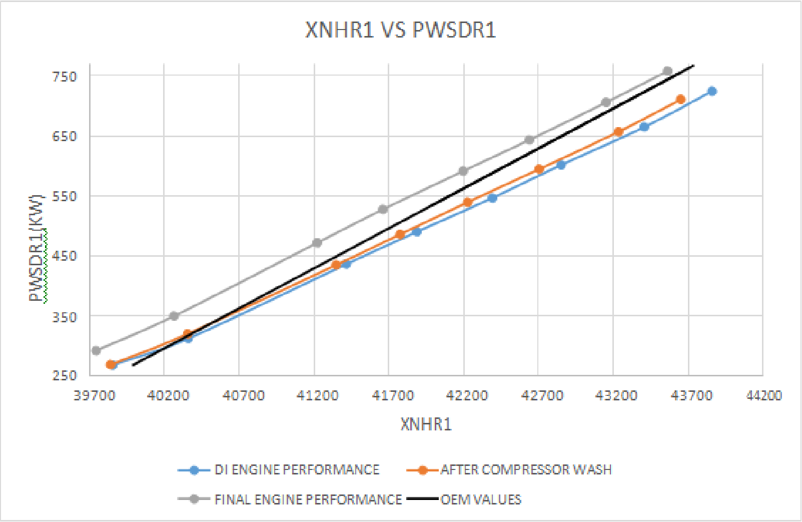
7.3.1 Engine performance interms of power:

PWSDRI			**CCT**	**XNHR1**
DI ENGINE PERFORMANCE	AFTER COMPRESSOR WASH PERFORMANCE	FINAL PERFORMANCE		
695.834	**708.224**	**765.047**	>745	43640
499.632	**509.451**	**566.44**	> 534	41986

After compressor wash no improvement in power is noticed.

CONFIRMATION TEST:

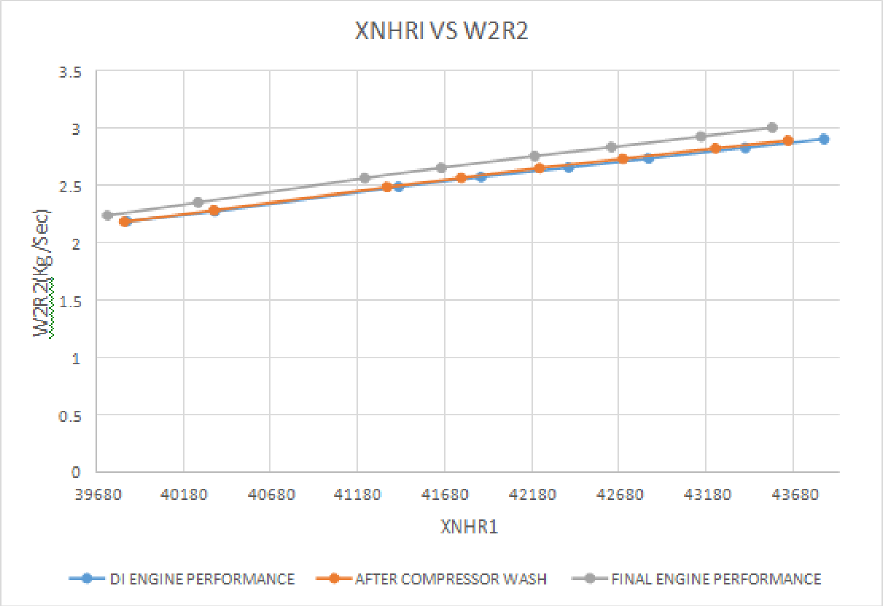
1. Bulk strip the engine (M01,& M02 separated)
2. M01 no damage –pack &preserve
3. Unit strip m02 (less IGV assembly,1st stage axial with gg shaft)
4. Carry out cleaning, NDT& health inspection as per overhaul manual.
5. Remove and replace PT blades by „Cat-A‟.
6. C/O unit build Mo2 by final build.
7. Prepare the engine for test.



Graph 5 Comparison of overall performance of the engine by power

7.3.2 Engine performance interms of mass flow rate:

W2R2 @ 42000 tr/m			**CCT**
DI ENGINE PERFORMANCE	AFTER COMPRESSOR WASH PERFORMANCE	FINAL PERFORMANCE	
2.591	**2.591**	**2.719**	2.65 < >2.82

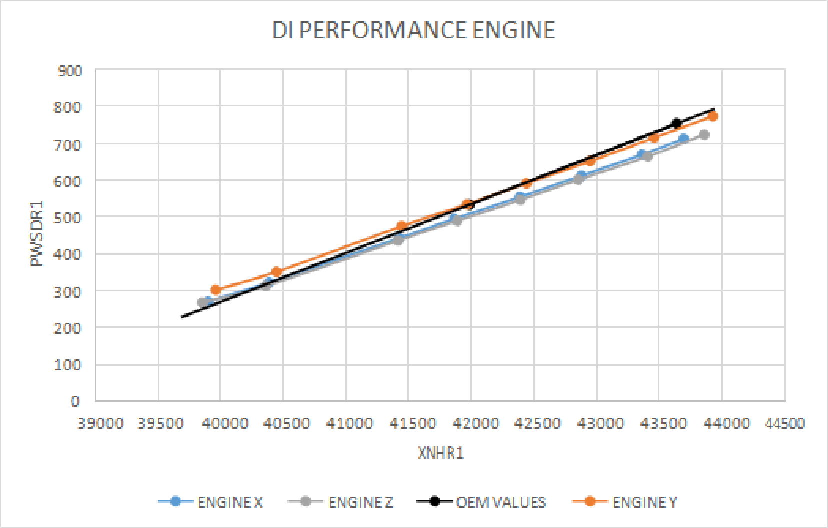


Graph 6 Comparison of overall performance of engine by mass flow rate

Hence, by disassembly, assembly of parts and also performing NDT check along with cleaning of parts it is concluded that engine has recovered 16 KW power in final performance which is represented in graph shown above. It also illustrates the effect of compressor fouling leads to reduced compressor mass flow and compressor efficiency recovered after cleaning and reassembly of parts.

7.4 Comparison of power loss due to different snags:

DI ENGINE PERFORMANCE BY POWER				
ENGINE:1	ENGINE:2	ENGINE:3	CCT	XNHR1
704.444	**737.856**	**695.834**	>754	43640
507.881	**537.023**	**499.632**	> 534	41986

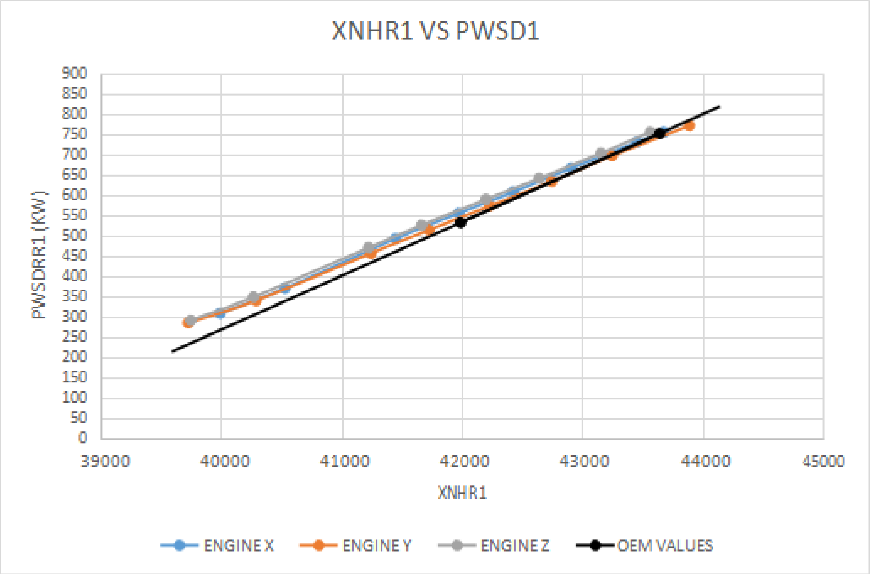


Graph7 Comparison of repaired X, Y and Z engine performance by power.

From the graph it is noticed that the engine Y with snag chipping in one of the 1st stage axial compressor the power loss is 16kw which lower than the other two engines. The engine Z and engine X with defect of PT blade life cycle completed and GG impeller damage respectively leads to power loss of 46kw and 50 kW. The three snags related to component damage in the hot core of engine which can be rectified by component replacement.

7.5 Comparison of final performance of engine:

Final engine performance				
ENGINE:1	ENGINE:2	ENGINE:3	CCT	XNHR1
754.27	**757.553**	**765.047**	>754	43640
558.005	**556.493**	**566.44**	> 534	41986



Graph 8 Comparison of final performance of X,Y and Z engines by power.

From the graph it is noticed that all three engines have regained minimum requirement which is replicated in graph by crossing the limit line. Some of the power is regained by undergoing compressor washing and other power by rectification of snag. All the engines recovered total loss of power, because it is component related snag and whole component has been replaced. The engine with PT blade and GG impeller damage leads to high power loss because they related to hot side of the engine. Since it is related to turbine side it doesn"t extract the total energy from hot gas and left the energy waste. The blade damage is due to high temperatures which will also increase creep of blade. Since this engine used in fighter helicopter due to heavy manoeuvre the fatigue cycles also increases, which cause fast blade life completion. Blade damage causes larger impact on engine performance since large amount of power get lost. Blade life can be increased by using cooling techniques and also by thermal barrier coating which will reduce the blade temperature to an acceptable limit.

ACKOWLEDGEMENT:

We acknowledge the valuable contribution of those people who helped us in our project work at HAL Engine Division at various stages of this project and also Hindustan Institute of Technology and Science for their valuable contribution in completion of this project.

RESULT:

The performance of the engine is tested in test bed and if power loss is within the margin then the compressor wash is carried out, through which 25% to 35% of power is regained in the engines. The overall power lose is regained through complete rectification of snag either by part replacement or repair of the component. The power of engines at different stages of testing of

different engines is shown in below table.

ENGINE No.	PERFORMANCE OF THE ENGINE BY POWER		
	BEFORE COMPRESSOR WASH	AFTER COMPRESSOR WASH	FINAL PERFORMANCE
X	50KW	13KW	50KW
Y	16KW	7KW	16KW
Z	46KW	NO POWER REGAINED	46KW

CONCLUSION:

Low Power snag in engines is confirmed in test bed due to inefficiency of compressor and turbine. As analysis of DI Engine Performance, After Compressor Wash and Final Engine Performance reveals the compressor mass flow and pressure ratio increase comparatively after repair which is illustrated in graphs. The power increases due to mainly cleaning of air flow path of components (Compressor, Inlet Guide Vanes, etc.…) and in some cases replacement of Power Turbine blades due to excessive rubbing and reassessment of washer to maintain changes on compressor and turbine on minimum value of limit as per Overhaul Manual to improve Engine Performance. The engine testing in test-bed is done by using procedure given by OEM for particular snag. By following the procedures mentioned in this paper the engine has been recovered. It is understood that the engine with damaged hot section parts has heavy power loss compared to other damages.

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