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A.G. VARELIS

TECHNOECONOMIC STUDY OF ENGINE DETERIORATION AND COMPRESSOR WASHING FOR MILITARY GAS TURBINE ENGINES

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Angelos G. Varelis

Technoeconomic Study of Engine Deterioration and Compressor Washing for Military Gas Turbine Engines

Supervisor: Prof. P. Pilidis

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ABSTRACT

Despite spending much of their operating life in clear air, aircraft gas turbine engines are naturally prone to deterioration as they are generally not fitted with air filters. Engines are particularly at risk during takeoff and landing, and whilst operating in areas of pollution, sand, dust storms, etc. The build-up of contaminants, especially on the compressor surfaces, leads to a dramatic reduction in compressor efficiency, which gives rise to a loss of available power, increased fuel consumption and increased exhaust gas temperature. These conditions can lead to flight delays, inspection failures, withdrawal from service, increased operating costs and safety compromises.With the growing interest in life cycle costs for gas turbine engines, both engine manufacturers and operators are investigating the tradeoffs between performance improvements and associated maintenance costs.

This report introduces the problem of output and efficiency degradation in two aero gas turbine engines (the T56–A–15 and the F110–GE–129) caused by various deterioration factors. Their causes are broadly discussed and the effects on powerplant performance are simulated and analyzed.

One of the key factors leading to performance losses during operation of these engines is compressor fouling. The fouling can come from a wide variety of sources; hydrocarbons from fuel and lubricating oils; volcanic ash; pollen; marine aerosols; dust; smoke; pollution, etc. The presence of these fouling sources acts as a bonding agent for the solid contaminants, 'gluing' them to the compressor surfaces. Thus, the aggravation in terms of power output, fuel consumption and additional time to carry out a typical mission will be assessed and an economic analysis will be attempted in order to quantify the effects of compressor fouling on the additional costs which arise, because of this specific deterioration.

The effect of compressor fouling can be maintained by frequent cleaning to improve efficiency, resulting, hence, in improved power output, fuel savings

and prolonged engine life. Compressor cleaning is thoroughly presented, and the implementation of on-wing off-line cleaning on the performance of the F110 engine was investigated from a technical and economical standpoint.

Finally, according to the results obtained, the optimal frequency of compressor washing for the F110 engine is estimated, in order to eliminate safety compromises, improve performance and reduce the engine’s life cycle cost.

AKNOWLEDGEMENTS

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I would also like to extend my sincere thanks to all the friends from Cranfield University and especially to Elias Tsoutsanis, who, despite his PhD studies, was always available for discussion and willing to support me in many aspects of my University life, including, of course, the broader understanding of anything related to the operation of a gas turbine engine.

Moreover, I would like to express my appreciation to the Hellenic Air Force for providing me with the opportunity to study in Cranfield University, in a Department that was and still remains of my greatest interest, and to my colleagues from the 111 Combat Wing Engine Maintenance Department for all the things we shared in our everyday work in the last 10 years. My passion for gas turbine engines comes from working with such capable, professional and enthusiastic people.

Finally, and most important, I would like to dedicate this work to my wife Anna and my sons Yioryo and Anastasio for their patience, unceasing support and sacrifices during my studies in Cranfield University.

"True wisdom comes to each of us
when we realize how little we understand
about life, ourselves, and the world around us."

Socrates

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NOTATION

Symbol	Meaning	Units
A	Aspect Ratio	-
A-K (s)	Start of Mission Profile Stage	-
A-K (f)	End of Mission Profile Stage	-
A_N	Exhaust Nozzle Area	m^2
A_{NGV}	Turbine Nozzle Guide Vane Area	m^2
C	Celsius	-
F	Fuel Flow	kg/sec
FW	Weight of Fuel Consumed	kg
g	Acceleration due to Gravity	m/sec^2
K	Kelvin	-
L	Lift	N
Mn	Mach number	-
P	Pressure	N/m^2
Q	Non-dimensional mass flow	-
S	Wing Area	m^2
T	Thrust	N
T/W	Thrust to Weight Ratio	-
T.S.	Throttle Setting	(%)
W	Weight	kg
t	Time	sec
t_{cumA}	Mission Completion Time “mission A”	sec

Symbol	**Meaning**	**Units**
t_{cumB}	Mission Completion Time "mission B"	sec
D_{climb}	Distance Covered Towards Target During Climb	km
D_{accel}	Distance Covered Towards Target During Accel	km
D_s	Drag at the Start of the Stage	N
D_f	Drag at the Finish of the Stage	N
D_{av}	Average Drag of the Stage	N
F_s	Fuel Flow at the Start of the Stage	kg/sec
F_f	Fuel Flow at the End of the Stage	kg/sec
F_{av}	Average Fuel Flow of the Stage	kg/sec
F_{eff}	Effective Fuel Flow of the Stage	kg/sec
FW_{TO}	Weight of Fuel Consumed during "Take-off"	kg
FW_{Climb}	Weight of Fuel Consumed during "Climb"	kg
FW_{Accel}	Weight of Fuel Consumed during "Acceleration"	kg
FW_{Cruise}	Weight of Fuel Consumed during "Cruise"	kg
$FW_{Air\text{-}combat}$	Weight of Fuel Consumed during "Air-Combat"	kg
$FW_{Re\text{-}Climb}$	Weight of Fuel Consumed during "Re-Climb"	kg
$FW_{Re\text{-}Accel}$	Weight of Fuel Consumed during "Re-accelerate"	kg
$FW_{Cruise\ Back}$	Weight of Fuel Consumed during "Cruise back"	kg
$FW_{Dec\text{-}desc\ to\ land}$	Weight of Fuel Consumed during "Decelerate-Descend to Land"	kg
FW_{Land}	Weight of Fuel Consumed during "Landing"	kg
$FW_{LowLevelPass}$	Weight of Fuel Consumed during "Low-Level-Pass"	kg
h_s	Altitude at Start of the Stage	m

Symbol	**Meaning**	**Units**
h_f	Altitude at the End of the Stage	m
L_s	Lift at the Start of the Stage	N
L_f	Lift at the End of the Stage	N
L_{av}	Average Lift of the Stage	N
$(MOE)_{OV}$	Overall Mission Operational Effectiveness	(%)
$(MOE_A)_{FW}$	Mission Operational Effectiveness for Mission A due to the Effect of Fuel Consumed	(%)
$(MOE_B)_{FW}$	Mission Operational Effectiveness for Mission A due to the Effect of Fuel Consumed	(%)
$(MOE_A)_{time}$	Mission Operational Effectiveness for Mission B due to the Effect of Total Mission Time	(%)
$(MOE_B)_{time}$	Mission Operational Effectiveness for Mission A due to the Effect of Total Mission Time	(%)
M_s	Mach Number at the Start of the Stage	-
M_f	Mach Number at the End of the Stage	-
SFC_{3000}	SFC at 3000 m Altitude	mg/N.sec
SFC_{8000}	SFC at 8000 m Altitude	mg/N.sec
SFC_{AV}	Average SFC for the Stage	mg/N.sec
T_t	Total Thrust Available	N
T_{ts}	Total Thrust at the Start of the Stage	N
T_{tf}	Total Thrust at the End of the Stage	N
T_{av}	Average Thrust for the Stage	N
T_{es}	Excess Thrust at the Start of the Stage	N
T_{ef}	Excess Thrust at the End of the Stage	N

Symbol	Meaning	Units
TFW_A	Weight of Total Fuel Consumed during Mission A	kg
TFW_B	Weight of Total Fuel Consumed during Mission B	kg
V_s	Velocity at the Start of the Stage	m/sec
V_f	Velocity at the End of the Stage	m/sec
V_{av}	Average Velocity for the Stage	m/sec
W_{gs}	Aircraft Gross Weight at the Start of the Stage	kg
W_{gf}	Aircraft Gross Weight at the End of the Stage	kg
α	Acceleration	m/sec^2
Γ_c	Compressor Flow Capacity	-
ΔFW_A	Percent Increase in Weight of Total Fuel Consumed during Mission A due to Engine Deterioration	(%)
ΔFW_B	Percent Increase in Weight of Total Fuel Consumed during Mission B due to Engine Deterioration	(%)
Δt_{cumA}	Increase in Mission Completion Time for Mission A due to Engine Deterioration	sec
Δt_{cumB}	Increase in Mission Completion Time for Mission B due to Engine Deterioration	sec
η_c	Compressor Isentropic Efficiency	-
η_{cc}	Combustion Efficiency	-
η_T	Turbine Isentropic Efficiency	-
μ	Rolling Resistance	-
€	Euro	-

ACRONYMS

BPR	By-Pass Ratio
CPR	Compressor Pressure Ratio
DOD	Domestic Object Damage
ESHP	Equivalent Shaft Horsepower
FPR	Fan Pressure Ratio
FOD	Foreign Object Damage
GE	General Electric
GPA	Gas Path Analysis
GTE	Gas Turbine Efficiency
HAF	Hellenic Air Force
HP	High Pressure
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ISA	International Standard Atmosphere
IGV	Inlet Guide Vanes
LCC	Life Cycle Cost
LCF	Low Cycle Fatigue
LP	Low Pressure
LPT	Low Pressure Turbine
LUI	Life Usage Index
MOE	Mission Operational Effectiveness
NGV	Nozzle Guide Vanes

OPR	Overall Pressure Ratio
PLA	Power Level Angle
P&W	Pratt and Whitney
RPM	Rounds Per Minute
RR	Rolls Royce
SFC	Specific Fuel Consumption
SL	Sea Level
SLS	Sea Level Static
TET	Turbine Entry Temperature
T.O.	Take–off

1. INTRODUCTION

1.1. Background

The gas turbine engine has been at the centre of advances in military air vehicle capability for over half a century. During that time, significant developments in engine and airframe technology have enabled a rapid evolution from the post Second World War, piston-engined, subsonic, propeller-driven fleet, to a myriad of air platforms encompassing sub–to–supersonic flight capability, firmly established around the gas turbine engine as the main powerplant. Thus, high performance aircraft, as used in modern aviation, especially for military purposes, have become complex in design and are required to operate under severe temperatures and stresses.

Sustained funding in gas turbine research and development by governments and industry has been the key enabler in improving engine specific power output and efficiency to meet the increasing demands of the new air platforms. However, although today many conflicts are under way all over the world, most of the Western countries have tried to reallocate budgets from Defence to social programs. This reduction in funds means that every company within the airspace industry must increase its competitiveness by moving towards enhancements of in-service products, resulting in greater reliability and availability, as well as improved performance and safety, despite the coincident increase in the cost and complexity of the gas turbine engine. Therefore, concurrently with the engine technology, many ongoing investigations are seeking in finding ways to decrease operating costs, either through reduced wear, decreased maintenance requirements, or increased component safe life limits. Regrettably, these improvements are very expensive in additional parts or part change-outs that may not be in the best interest of the individual users. Consequently, every user is responsible for pushing for developments in areas that he believes will provide the greatest return. A great deal of this push has been in the area of enhancing gas path analysis techniques, material improvements and engine life cycle costs through fuel consumption and component usage analysis.

Therefore, any extension of life expectations and/or reductions in fuel usage of an aircraft gas turbine engine directly lower the life cycle cost and depend upon the type of operation undertaken, the operating conditions experienced and the rate of in-service engine deterioration. According to Stevenson & Sararavanamuttoo (1995), each type of the latter has an adverse effect on the performance and reliable operational life of an aircraft and, therefore, contributes to an increased life cycle cost.

As a result of a comprehensive literature review, concerning engine performance degradation, as well as the author's personal experience of aero-engines in the Hellenic Air Force, it was realised that in-service deterioration of any mechanical device, such as an aircraft's engine is inevitable. Several cases have been reported at the past on engine loss of performance and flame-out on Boeing 747s at cruising altitude as a result of volcanic ash [Flight International, 1982]. The occurrence of severe fouling has been reported on a Fairchild A-10 aircraft, due to gun firing and continuous ingestion of gun exhaust into engine intakes [Scott, 1982], leading to engine stall and severe loss of performance.

From an economic point of view, a 1 percent increase in Specific Fuel Consumption (SFC) from a single-engined aircraft of 45 aircraft fleet could increase the expenditure due to additional fuel by a million dollars a year [Jay & Todd, 1978]. In a typical powerplant gas turbine, the increase in operating cost due to performance deterioration between major overhauls, which is approximately three years, is one and a half million dollars [Diakunchak, 1992]. In the case of cogeneration plants, the loss of revenue due to reduced output can also be severe. Consequently, from operational, economic and safety considerations, gas turbine performance deterioration has emerged as a very important topic of research and fault classification, quantification and identification are three essential steps in any turbine engine deterioration model development.

One of the key factors leading to performance losses during engine operation is compressor fouling. This is the adherence of particles and small droplets to the blading surface. Also, the flow capacity and thereby, the pressure ratio of the unit are reduced. This leads to an overall loss in power output and efficiency of a gas turbine. Fouling causes increased surface roughness of compressor blading, thereby reducing its efficiency. In extreme cases, fouling may also result in surge problems. Despite the use of advanced filtering methods and filter maintenance, the ingestion of substances that can cause fouling cannot be completely suppressed. The fouling rate depends largely on the site location, surrounding environment, the layout of the air intake system, atmospheric parameters, and engine maintenance. While the first four factors cannot be influenced during the operation, the engine maintenance is the critical one for preventing extra costs resulting from degraded engine performance.

1.2. Aim of the thesis

This study has been undertaken in order to determine the impact of component deterioration on the overall performance of two aero gas turbine engines (the Allison T56–A–15 and the General Electric F110–GE–129 engines) by utilizing Gas Path Analysis techniques and, also, investigate the effects of compressor fouling on the additional costs which arise because of this specific degradation. Finally, it will attempt to quantify the various cost savings resulting from the incorporation of compressor washing on the F110 engine.

It must be noted that engine health monitoring methods (and in particular Gas Path Analysis), along with on-line compressor washing of industrial gas turbine engines, have been widely studied and applied in a great variety of engines, including the T56–A–15 [English, 1995; Vorilas, 1998; Basendwah, 2004; Arebi, 2006; Benjalool, 2006]. However, improvements and modifications of the above methods and studies, still need to be made, so as to make them more practically applicable and, thus, increase the benefits that these methods can offer to the engine operator. These modifications and enhancements mainly result from the recommendations of previous studies, as well as from the intentions and background of the author.

1.3. Thesis Scope

Since both engines were designed more than thirty years ago, their philosophy, mainly in terms of maintenance, is quite different than the one that modern engines have. Moreover, it becomes more and more technically challenging to incorporate new maintenance techniques, so as to increase performance, life and reliability and, in the mean time, keep the overall operating costs low. A wide literature survey revealed that very limited similar studies have been reported in the open literature, thus indicating the need to study such an important aspect of military air operations. Therefore, this study was undertaken, so as to investigate the implementation of compressor washing on military gas turbine aero engines, a decision that would make the choice of keeping the T56 and the F110 in service a more economically and technically sound one.

1.4. Thesis Layout

As this thesis touches on a number of areas, it has been divided into chapters in such a manner as to afford maximum understanding. The intention being to provide the reader with some of the required background in engine deterioration and compressor washing, the theory and methods used in this study and the results. Thus, this dissertation includes the following chapters:

- **Chapter 1**: "Introduction". Background and reasons for undertaking this study, as well as its objectives.

- **Chapter 2**: "Literature review". Describes broadly the various types of engine deterioration, along with the different methods existing today generally for all types of compressor cleaning and especially for on-wing off-line engine cleaning.

- **Chapter 3**: “General engine description and modelling”. The important data (for the purposes of this study) of the two aero-engines is analyzed and the two engines are modelled using proprietary programs of the University (Turbomatch, PYTHIA).

- **Chapter 4**: “Analysis of engine’s deterioration”. The various types of engine’s deterioration for both the T56 and the F110 engines are analyzed, along with the effects they have on the corresponding engine’s behaviour.

- **Chapter 5**: “Operational effectiveness analysis”. A case study is investigated, in order to determine the effects of compressor fouling on the operational behaviour of the F110 engine.

- **Chapter 6**: “Technoeconomic study of compressor washing”. A preliminary assessment of the effects of compressor washing on fuel savings (economy of operation) and creep life is attempted, along with a rough estimation of the optimal compressor washing frequency for the F110 engine, in order to improve performance and reduce the life cycle cost of the engine.

- **Chapter 7**: “Conclusions and recommendations for future work”. The results obtained from the previous chapters are analyzed and reviewed, and recommendations for further possible analysis of this specific study are proposed.

2. LITERATURE REVIEW

2.1. Performance Degradation

In an ideal world, a gas turbine engine would operate with the same performance from the time it enters service until it is removed. However, this is not met in practice, as the engine, during its useful life, will inevitably encounter a wide variety of physical problems and its performance will eventually degrade. Additionally, if the engine is considered as a number of different modules, then the degradation in any one module will affect adversely the engine's overall performance. Therefore, when examining the effects of degradations it is important to understand the effects of individual modules degradations [Little, 1994].

The level of degradation experienced will vary from one engine type to another and even between engines of the same type [Little, 1994], [Naeem, 1999]. A literature review into the quantitative effects of engine degradation provided some insight into the effects of different deterioration factors [Grewal, 1988], [Sallee, 1980] and [Saravanamuttoo and Lakshminarasimha, 1985]. These papers were based on various engine types and provided different values for the levels of degradations anticipated; however, they did not provide good agreement on the relative magnitude of components degradations. Nevertheless, a general trend, which was anticipated, was that the levels of degradation were lowest for industrial engines and increased for aero-engines.

2.1.1. Degradation Rate

A gas turbine has a wide range of applications: aero, marine and industrial. In any of the above applications, prior to an engine entering service the manufacturer or the user will subject the engine to a break-in run and acceptance test in the test bed. This run allows the engine to slowly adjust to its particular configuration and clearances without damaging each individual component. However, once the engine enters service, it will be exposed to loads not previously subjected. These new loads will have a noted effect on component deterioration and engine performance. It should be noted that the rate of engine deterioration is not linear, as the deterioration curve is characterised by a steep initial slope that becomes flatter in the middle and will increase again as the hours of operation are accumulated.

2.1.2. Causes of degradation

According to Seddigh and Saravanamuttoo (1991), performance degradation is attributed to deterioration in the mechanical condition of the engine components, and can be assessed by examining the changes to the gas path of the engine.

The causes of the degradation are mainly caused by:

- Fouling
- Erosion
- Corrosion
- Thermal distortion
- Foreign Object Damage (FOD) or Domestic Object Damage (DOD)
- Rubbing wear
- Faults due to engine operating conditions and maintenance practices.

These physical faults cause changes in one or more of the independent parameters which describe individual gas path component performance. Independent parameters generally include:

- Compressor Flow Capacity (Γ_c),

- Compressor Isentropic Efficiency (η_c),
- Turbine Nozzle Guide Vane Area (A_{NGV}),
- Turbine Isentropic Efficiency (η_t),
- Combustion Efficiency (η_{cc}) and
- Exhaust Nozzle Area (A_N).

The set of independent parameters applicable to a particular engine is determined by the engine's configuration. However, these parameters, although fundamental in nature and leading directly to the detection of faults down to module level, are not readily or practically measurable. Changes in the independent parameters, which describe component performance, cause consequent changes in the dependent (measurable) engine performance parameters. This set of dependent parameters, which are applicable to each engine, also depend on its configuration and application, however, only a subset of these parameters is usually provided in the engine's standard instrumentation set. A typical set of dependent parameters includes:

- Spool Speeds
- Shaft Power
- Component Temperatures and Pressures and
- Fuel flow.

The following figure shows the effects of engine degradation on compressor characteristics:

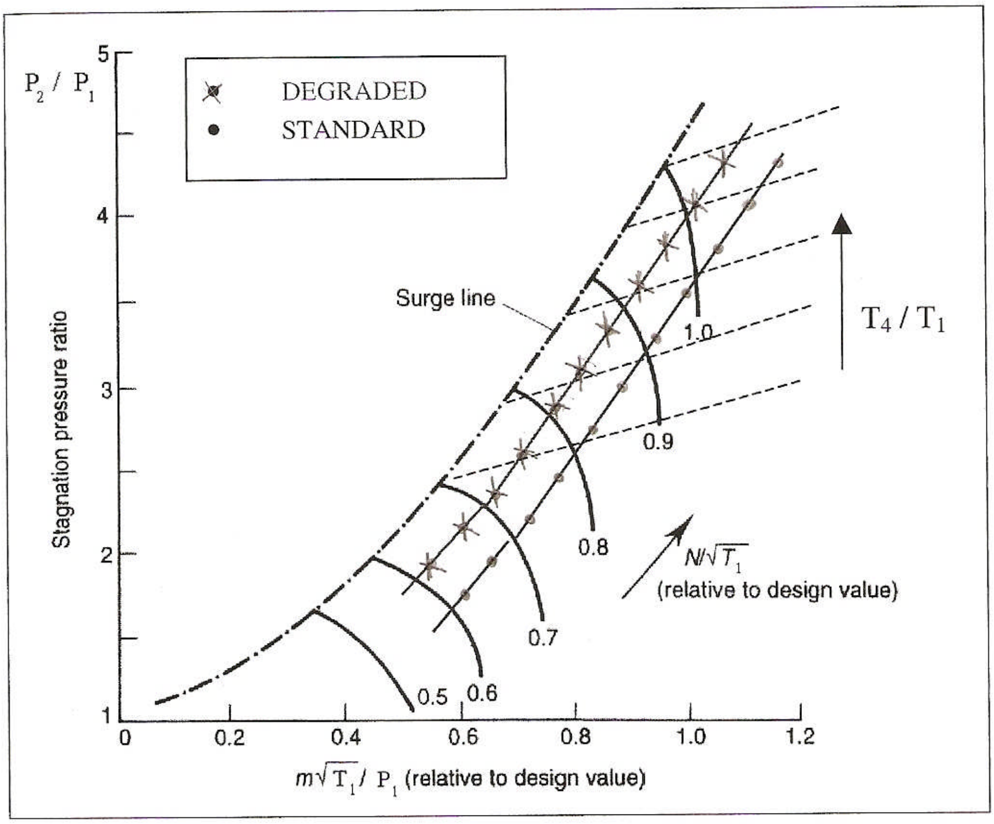

Figure 2.1.Compressor characteristics – Engine degradation [Paul, 2002]

In Figure 2.1 the (x) line indicates a degraded engine and the (•) line represents a normal engine. When degradation occurs, the engine's running line moves closer to the surge line. For the degraded engine to operate at the same non-dimensional speed as the normal engine, it must operate at a higher T4/T1. Conversely, if the two engines operate at the same Turbine Entry Temperature (TET), the degraded engine will be operating at a lower non-dimensional speed and pressure ratio and, hence, will be less efficient.

Finally, what needs to be defined is the relationship between physical faults and component faults. In much of the literature on Gas Path Analysis, the term 'fault' is used to define the change in one or more of the independent parameters, which describe the engine's performance. In other words, a fault is a change in compressor flow capacity or isentropic efficiency. These faults should not be confused with physical faults like fouling or erosion. Physical faults can be represented or simulated by component fault sets. These sets consist of changes in one ore more independent parameters. For example compressor fouling is represented by reductions in compressor flow capacity and compressor isentropic efficiency.

2.1.2.1. Fouling

Fouling can be defined as "the degradation of flow capacity and efficiency caused by adherence of particulate contaminants to the gas turbine engine aerofoil and annulus surfaces" [Diakunchak, 1992]. The fouling of the gas turbine compressors is usually caused by particles with a diameter of 5 microns or less, which can adhere to component surfaces and is recognised as the most common cause of engine performance degradation facing users today [Aker and Saravanamuttoo, 1989].

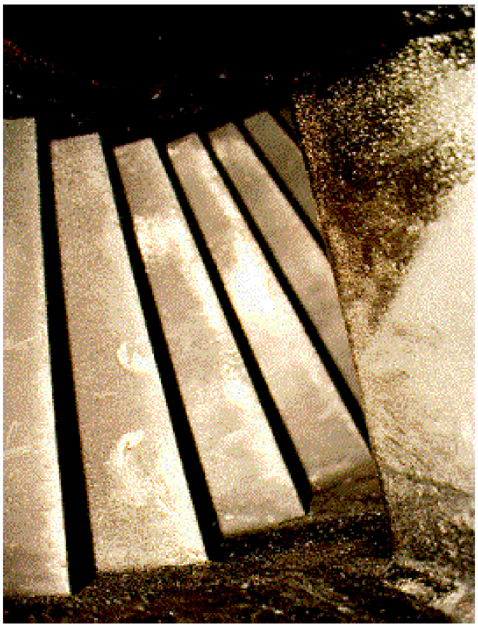

Figure 2.2.Fouling caused by severe carbonaceous oily type of deposits, because of oil leaks in the bearing system (Courtesy of Turbotect)

Although fouling can occur in both compressor and turbine components, compressor fouling is far more common and usually has a greater effect on engine performance. It has been found [Hoeft, 1993] that about 70-85% of all gas turbine engine performance loss accumulated during operation is attributable to compressor fouling.

The contamination of the air depends on the location and may consist of salt, pollen, insects or herbicides in coastal or rural regions, hydrocarbon aerosols or dust in industrial areas and volcanic ash, water droplets and air-borne salts for aero-engine applications. Moreover, as far as turbine components are concerned, fouling is usually caused by particulates like soot/carbon and other fuel burned contaminants, which are produced as a result of the combustion process. Fouling is much worse if the air mass flow contains oily or sticky substances which "glue" particulates to the component surfaces. These sticky substances may be present in the atmosphere or may occur as a result of oil leaks in the engine. In the back end of the compressor, where the temperatures are high enough, there is the additional problem of oil particles being "baked" on the gas path surfaces, producing thus a fairly thick coating [Diakunchak, 1992].

Although all compressors are susceptible to fouling, attempts made to determine the sensitivity of fouling of axial compressors ended up with controversial results. Lakshminarasimha and Saravanamuttoo (1986) stated that fouling is proportional to stage pressure ratio and claimed that fouling will be more severe for smaller engines due to the smaller flow passages. Moreover, Tarabrin et al (1998a) also stated that the susceptibility of fouling was found to be higher for smaller engines. However, according to Aker and Saravanamuttoo (1989), the tendency for fouling was found to be higher in an experiment for a larger engine size, which was attributed to a higher stage loading. Finally, Seddigh and Saravanamuttoo (1991) stated that the degree and the rate of fouling as well as the effect on engine performance varies according to several parameters, such as compressor design, compressor aerofoil loading, aerofoil incidences, aerofoil surface smoothness/coating, type and condition of airborne contaminants and climatic conditions. In the same way, turbine fouling will depend on the ability of the contaminants to reach the turbine and to adhere to the gas path surfaces, as well as on the type of fuel used.

The first stages of the compressor are typically the areas of worst fouling and due to their effect downstream the impact on power loss is high [Upton, 1974], [Mezheritsky and Sudarev, 1990]. Moreover, according to Tarabrin et al (1998b), the overall amount of depositions decreased rapidly from the Inlet Guide Vanes (IGV) to the fourth stage and for the stages downstream of stage seven the depositions were found insignificant.

Figure 2.3.Industrial gas turbine compressor fouling [Basheer, 2006]

The result of fouling is the built up of material on the surfaces of the internal gas path which changes the shape of the aerofoils, and, consequently, changes the incidence angle of the following aerofoils, increasing the surface roughness and decreasing the throat area of the compressor [Diakunchak, 1992]. According to Mezheritsky and Sudarev (1990), who performed experiments to separate the effects of roughness and total thickness of the deposition layer on compressor efficiency and pressure ratio, roughness is the major contributor to fouling.

Due to the change in the aerodynamics and the flow area reduction, the mass flow, the efficiency and the compressor pressure ratio will be reduced. A poor efficiency results in the compressor requiring more work, leaving less for driven equipment [Upton, 1974], and the lower pressure ratio limits the turbine work. Moreover, the higher surface roughness increases the thickness of the boundary layer, reducing the flow capacity of the engine. The decrease in mass flow will necessitate an increase in the rotational speed to maintain a required power level, while the decrease in isentropic efficiency will cause an increase in TET, thus reducing the engine life and increasing the engine operating costs. Another effect of fouling is to reduce the compressor surge margin. Previous studies on compressor deterioration also indicate that a reduction in flow capacity should be coupled with an equal reduction in compressor pressure ratio [Grewal, 1988].

Although it has been established that the reduction in flow capacity is more significant than the reduction in efficiency, there is no fixed relationship between the two parameters, since the relationship varies with the engine type and the operating environment. Some information available in the open literature indicates the fouling causing a 5% reduction in inlet flow will also reduce the compressor isentropic efficiency by 2.5% [Saravanamuttoo and Lakshminarasimha, 1985].

Similarly to compressor fouling, turbine fouling results in a reduction of the effective nozzle guide vane area (and thus the turbine flow capacity) as well as a reduction in the turbine isentropic efficiency. It has been established [Diakunchak, 1992] that the reduction in turbine isentropic efficiency is of the order of 1%, while the reduction of the turbine flow capacity is assumed to be of the order of 2%.

Figure 2.4.Gas turbine fouling [Basendwah, 2004]

For the purposes of this study the magnitude of reduction in isentropic efficiency and flow capacity for both the compressor and the turbine will be assumed as described above.

2.1.2.2. Erosion

Erosion is another major cause of engine performance deterioration. According to Diakunchak (1992) “erosion is the abrasive removal of material from the flow path components by hard particles suspended in the air or gas stream”. The particulates that are causing erosion are usually 20 μm or more in diameter and remove material from components by continuous pitting and cutting of the metal surfaces. They are hard particles such as dirt, dust, sand, ash, salt, carbon/soot (the carbon particles are produced as a result of inefficient combustion) and industrial pollutants. They may be either ingested along with the intake air or are the result of pieces of the engine itself breaking off and being carried downstream. Pieces of ice breaking off from the intake or pieces of carbon breaking off from the fuel nozzles can also cause erosion.

The amount of foreign particles ingested will be greatly influenced, especially for aero-engines, by the engine intake, as some aircrafts will be much more susceptible to ingesting particles than others. This is evident with aircrafts such as the Lockheed Martin F-16, where the intake acts as a large air scoop and is located below the belly of the aircraft, and for which FOD is a major problem. This is in contrast to some Russian fighter aircraft designs, such as the MIG-29, where every precaution has been taken to reduce the possibility of ingesting FOD. When the MIG-29 is on the ground, the main intakes are blocked off and flow is directed to the engines through doors located on top of the aircraft [Little, 1994].

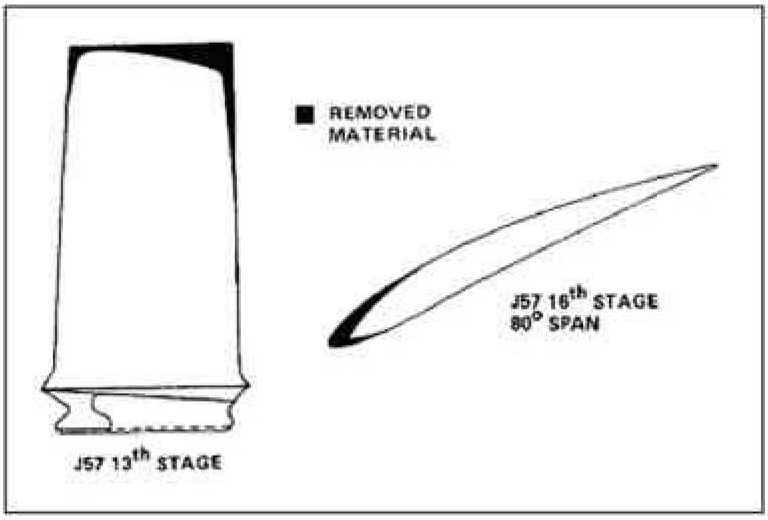

Figure 2.5.Compressor blade erosion [Grewal, 1988]

Unlike fouling, erosion usually causes permanent damage and a permanent loss of performance, which can only be restored through the repair or replacement of components. However, in some cases, two categories of performance degradation, caused by erosion, can be met: temporary and permanent. A temporary loss of performance occurs during the period of particle ingestion. This is often exhibited with aero-engines during formation flying, where the ingestion of hot exhaust gases has been known to result in engine stalling. The permanent loss of performance occurs due to blade erosion. The severity of erosion increases from the front to the rear stages of both the compressor and the turbine.

The erosion of engine components can result in changes in the airfoil profile, an increase in the blade surface roughness, changes in the inlet metal angle (and hence changes in the airfoil incidence), an increase in the airfoil throat opening and an increase in the blade tip and seal clearances. Changes in the airfoil profile include increased bluntness of the leading edge, thinning of the trailing edge, and reduction in leading edge radius, chord reduction, airfoil thinning and loss of camber. Although thinning of the airfoil trailing edge can result in performance improvements, however the structural integrity of the component is normally compromised. The eroded blades lose their ability to increase the total pressure of the stage efficiently. Pressure losses occur because of the increased tip clearances and profile losses resulting from changes in the boundary layer [English, 1995].

In both the compressor and the turbine, erosion causes a reduction in isentropic efficiency due to increased surface roughness, changes in the airfoil profile and increased tip clearances. Compressor erosion results in a reduction in compressor flow capacity, even though the inlet area has increased. Moreover, compressor erosion causes a drop in the engine pressure ratio, which lowers the mass flow rate for a constant non-dimensional speed. Similar to compressor fouling, the operating line of an eroded compressor is raised, thus reducing the surge margin [Escher, 1995]. On the other hand, turbine erosion causes an increase in nozzle guide vane area, which effectively results in an increase in the turbine flow capacity. However, for both compressor and turbine erosion, the effect on flow capacity is greater than the effect on isentropic efficiency. Sallee (1980) highlights that a ten percent increase in aerofoil surface roughness correlates to a one percent drop in fan efficiency, and Grewal (1988) identified that the overall effects of erosion can result in a loss of performance of the compressor or the turbine by as much as five percent.

For the purposes of this study, the magnitude of reduction in isentropic efficiency will be considered in the same way as with fouling (i.e. half the magnitude of reduction in flow capacity).

2.1.2.3. Corrosion

Corrosion can be defined as "the loss of material from gas path components caused by the chemical reaction between these components and contaminants that enter the gas turbine with the inlet air, fuel or injected water/steam" [Diakunchak, 1992]. There are two main types of corrosion:

Wet corrosion, that takes place on the compressor airfoils and is usually caused by salt, mineral acids and reactive gases, such as chlorine and sulphur oxides, in combination with water. One way to protect the compressor from corrosion attack and subsequent loss of performance is through coatings as well as keeping the blades as clean as possible.

High temperature corrosion (or sulphidation), which takes place at the hot end of the turbine, attacking turbine airfoils. This type of corrosion is caused by elements such as sodium, vanadium and lead, in metallic compound form.

Figure 2.6.Compressor blade corrosion [Grewal, 1988]

The effects of corrosion are, in many ways, similar to the effects of erosion. With corrosion a loss of blade material is detected, along with an increase of the blade roughness. This leads to reduction of the blade performance and thus reduction of the isentropic efficiency of the compressor or the turbine.

Mass flow, as with erosion, is reduced in the compressor, while in the turbine there is an increase in the turbine effective area and thus turbine flow capacity due to the pitting of material, thinning of metal sections and distortion due to the weakening of the material [Vorilas, 1998].

2.1.2.4. Thermal distortion

Thermal distortion is a fault that normally occurs at combustor exit/turbine entry where temperatures are highest. Distortion is caused due to cocking of fuel nozzles, changes of fuel spray angles, changes in compressor performance, as well as warping of the combustor liners, causing changes to the radial and circumferential temperature patterns at the combustor exit. The operation at sustained high temperatures can result in temporary or even permanent damage of the downstream components such as cracked, bowed, warped, burned turbine Nozzle Guide Vanes (NGV), NGV area changes, increased seal clearances and relative thermal growth between the static and rotating blades (which can cause rubbing or changes in clearances) [English, 1995].

According to Diakunchak (1992), what is worth mentioning is that, although a change in the combustor outlet temperature profile is normally caused by a fault in the combustor, combustor deterioration is not considered to directly affect engine performance. Combustor efficiency normally remains constant with time. Therefore, since combustor deterioration does not cause a change in the engine’s performance parameters, it cannot usually be detected using gas path performance analysis.

The effect of thermal distortion on engine performance is the reduction of the airfoil performance (caused by the damage of the turbine blades) and an increase in the secondary flow losses, causing, thus, a reduction of the turbine isentropic efficiency. The flow area will also be affected by the blade distortion but the most significant effect will be on the turbine isentropic efficiency [Macleod et al., 1992].

2.1.2.5. Foreign Object Damage and Domestic Object Damage

Foreign Object Damage is caused by the ingestion of relatively large objects (like hailstones, runway gravel, bolts or small birds), which, when ingested in the engine, cause damage to the gas path components. On the other hand, Domestic Object Damage is caused when pieces of the engine such as blade sections or large carbon particles from the fuel nozzles break off and hit gas path components like the combustor liners or the turbine blades downstream.

The damage from foreign objects varies from non-recoverable (with cleaning) deterioration of engine performance, to catastrophic failure, as in the case of blade off or large object ingestion in the engine.

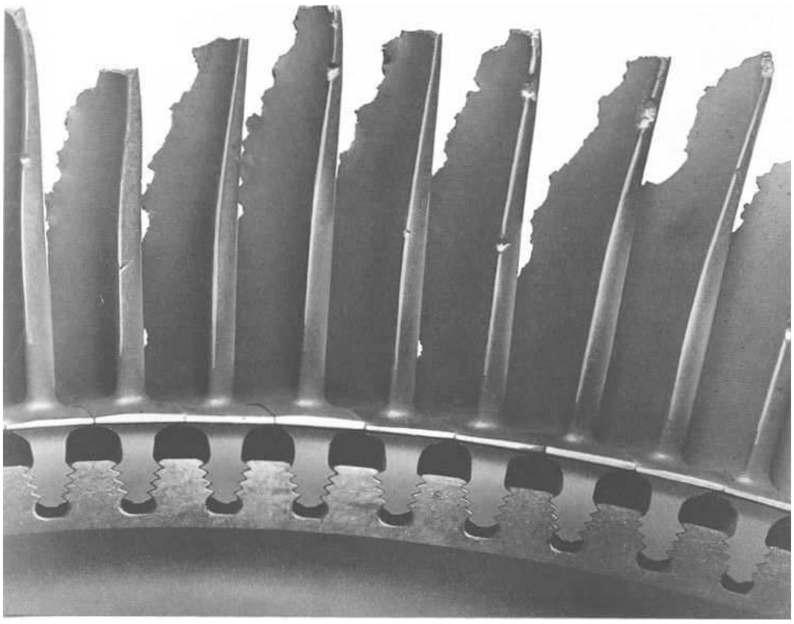

Figure 2.7.FOD of Industrial Gas Turbine Blades [Grewal, 1988]

The effect of both FOD and DOD on the engine performance parameters lies mostly on the components isentropic efficiency, as the impact of the object could cause increased roughness and distortion of the blades, affecting their performance. The change in flow capacity varies, depending on the type of FOD or DOD damage. Thus, for example in the case of lost blade, an increase in flow capacity will be experienced, while in the case of foreign objects blocking the gas path, the flow capacity will decrease.

2.1.2.6. Rubbing Wear

If the rotor becomes unbalanced or misaligned because of shaft bearing damage then excessive blade tip rubbing can occur. This is a typical service fault that can result in excessive blade tip and seal wear, which causes an increase in blade tip clearance. In aero engines blade tip rubbing can also occur as a result of distortion of the engine casing due to flight loads. The distortion of the casing alters the spacing between the casing and the rotating blades, causing blade tip wear and/or eccentricities in tip and seal clearances and increased air leakage. The most significant result of rubbing wear is the reduction of isentropic efficiency of the component affected [English, 1995].

2.1.2.7. Engine Operating Conditions and Maintenance Practices

Given that component interaction is one of the major causes of engine degradation, the operating cycle and maintenance techniques of the engine will have a significant effect of the type of deterioration experienced and the rate at which the deterioration occurs.

According to Diakunchak (1992), engine transient operation at start cycles, as well as rapid throttle movements and operation of the engine at maximum power for prolonged periods of time can have a big impact on the performance degradation of the engine, due to the severe temperature gradients encountered during those cycles. Since, at ignition, the combustor exit temperature gradients exceed for a short period (until the control system regulates the fuel and air flow) that experienced during normal operation, hot end components such as combustors and turbine blades are more prone to thermal distortion, oxidation and corrosion. In addition, for industrial gas turbines, operation at peak rating, along with frequent emergency trips from base load will also have a negative effect on engine performance.

Moreover, maintenance practices will also affect the engine performance and the rate of component deterioration. Quality standards can vary significantly between users, manufacturers and overhaul facilities. It has been identified that the differences in performance degradation due to variation in maintenance practices could be as great as 13% [Sallee, 1980]. The control system must be properly maintained to ensure correct fuel scheduling during starting and normal operation, in order to prevent excessive temperature gradients. Also, the fuel system must be maintained properly to prevent contaminants from getting into the engine. Similarly, poor maintenance of the combustor section can cause higher circumferential and radial temperature gradients, increasing thus the performance deterioration rate [Diakunchak, 1992].

In the above paragraphs an attempt has been made to describe the various most significant causes of engine performance degradation, along with their effects on engine performance itself. However, for the purposes of this study, only compressor and turbine fouling along with turbine erosion/corrosion (which produce quite similar results and will be treated as identical) will be simulated and their effects will be analytically examined.

2.2. Compressor Cleaning

The deterioration of a gas turbine compressor due to fouling is recognised as one of the most common symptoms of a gas turbine engine performance [Lakshminarasimha et al., 1994]. The principal and most obvious consequences of compressor fouling are reduced power output and increased heat rate. More insidious effects include an increase in the turbine entry temperature, at a given power setting, and a decrease in the compressor surge margin. However, because the principal effect of compressor fouling is a reduction in power output and an increase in heat rate, neither of which is usually measured, many engines operate for significant periods of time in a fouled and thus uneconomic condition [Aker and Saravanamuttoo, 1989]. Initially, this was not a significant problem, in that fuel was relatively inexpensive, and regular scheduled maintenance took care of the problem, before it reached the critical point. Presently, oil and gas are such that previously insignificant inefficiencies have been translated into considerable additional operating costs. To recover the performance loss and overcome this extra cost a combination of two methods can be employed. The first line of defence is the employment of a high quality air filtration system. However, as fouling will inevitably occur, compressors should also be cleaned to remove the deposited particles.

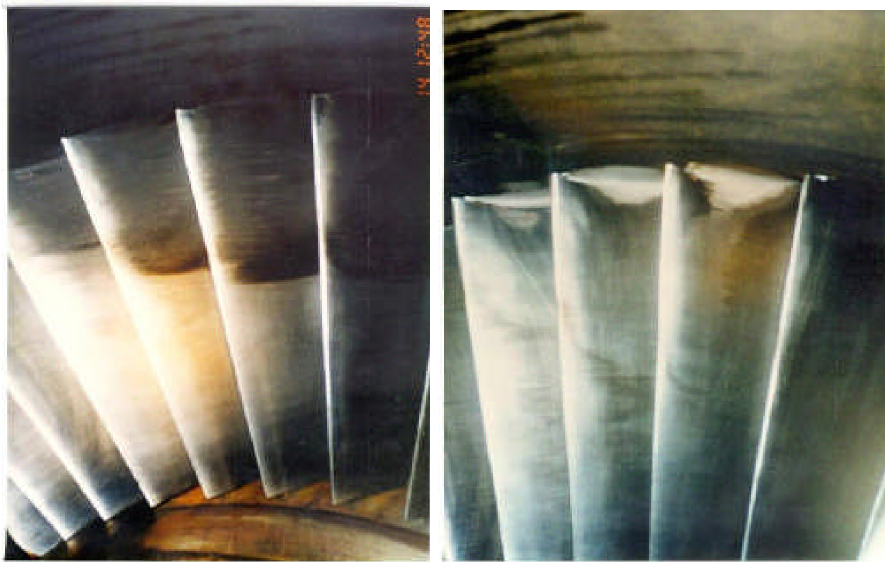

Figure 2.8.Compressor blades before and after cleaning [Courtesy of Turbotect]

The area of compressor cleaning is an area where strong and contradictory opinions exist as far as cleaning procedures, cleaning media and techniques are concerned. A useful set of papers relating to compressor cleaning have been provided by Stalder & Van Oosten (1994), Stalder (1998), Mund and Pilidis (2004 & 2006) and Meher-Homji and Bromley (2004). Cleaning effectiveness is usually site specific and, thus, approaches that may work for one site may not be appropriate for another. Therefore, operators must determine the best approach for their engines in terms of wash technique, the types of cleaners to use and the optimum cleaning frequency. This is a complex technical-economical decision which also depends on the service that the engines are in. Several different methods of compressor cleaning have been applied over the years. These can be classified in three major categories: manual cleaning, abrasive (so-called 'grit-blasting'), and wet cleaning (which is also divided into offline washing and on-line washing, with the latter being the most popular among the others).

Table 2.1.Advantages & disadvantages of compressor cleaning methods [42]

Method	Advantages	Disadvantages
Manual cleaning (brushes, washing agent)	• Very effective	• Engine shut down • Laborious
Grit blasting (Charcoal, rice nutshells, synthetic resin particles)	• simple and fast • no engine down-time • Effective in cold environments	• less effective at rear stages & for oily deposits • clogging of internal cooling passages • Increased surface roughness • Erosion • Damage of blade coating
Soak, crank, offline washing (demineralised water, washing agents)	• Very effective	• Engine shut down
Fired, online washing (demineralised water, washing agents)	• No interference with load profile • Extends intervals of crank washes	• Less effective • Cannot replace offline washing (complementary)

2.2.1. Manual cleaning

The most obvious method to wash a compressor is the manual procedure, where the engine has to be shut down, disassembled and cleaned manually using brushes and detergent. By using this method the power recovery that can be achieved is the best (Leusden et al, 2004), but it is laborious and requires a shut down and cleaning of the engine, thus it is not as useful for industrial gas turbines as for aero-engines.

2.2.2. Abrasive cleaning

The abrasive or grit-blasting methods were developed since the 1970s, in order to overcome the manual labour. Charcoal, rice, nutshells or synthetic resin particles were injected into the air-stream of the operating engine and the particle acceleration achieved (because of the engine’s high air speeds) removed the deposits quite satisfactory, without any downtime.

This method was widely used for aero engines [Brittain, 1983]. However, two major disadvantages existed: the removal of oily deposits was not satisfactory for the last stages of the last stages and, therefore, care had to be taken to remove this contamination [Kulle, 1974]. Moreover, the effect of the impact of large particles on the blades was considered harmful for the gas turbine, as far as erosion was concerned; especially for the state-of-the art engines, where protective blade coatings are applied, these can be removed and harm the engine downstream. As a result this method was more or less abandoned.

2.2.3. Wet cleaning

A milder but still effective [Boyce et al., 1985] method to wash off the deposits of a gas turbine is the wet cleaning, which has become the leading applied method, since it ensures operational safety, reliability and optimum efficiency. Two different wet cleaning techniques are generally applied, the offline (crank wash) and the online.

2.2.3.1. Offline washing

The basic objectives of offline washing are to clean a dirty compressor and to restore power and efficiency to virtually “new and clean” values [Meher-Homji and Bromley, 2004]. The offline compressor washing is probably the method by which the most effective power recovery can usually be achieved, when performed correctly, and provided the operating period between offline washing is not too long. Because of the required downtime in order to perform a crank wash, this is often performed concurrently with other maintenance work on the gas turbine. It is accomplished with the engine shut down and cooled, and the starter motor turning the engine in the order of 20% of the normal operational speed, resulting in a reduced airflow through the engine.

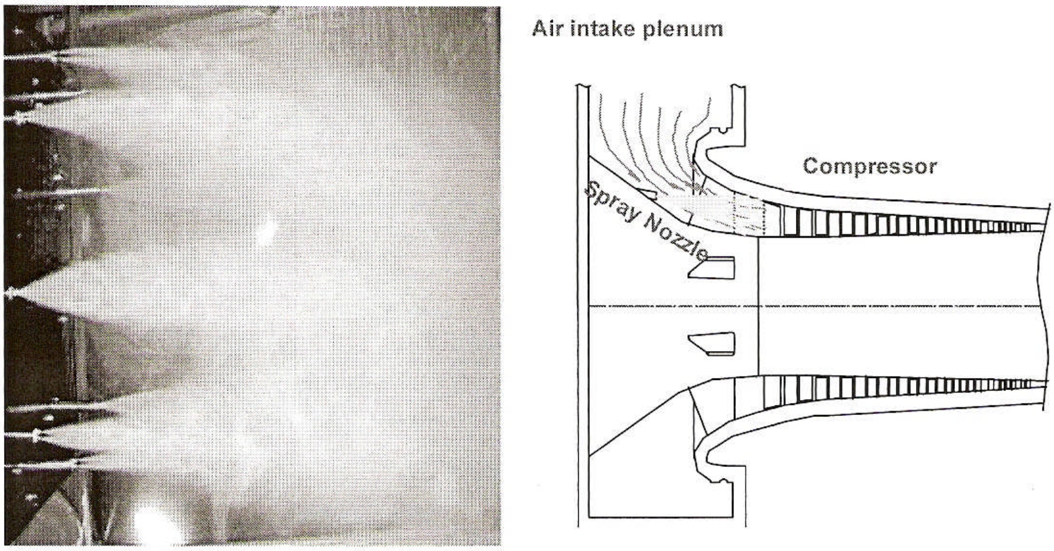

Figure 2.9.Cleaning fluid spraying through the air intake [Mund, 2006]

The downtime for a crank wash depends mainly on the size of the engine, since larger heavy-duty engines can take 8-10 hours to cool (in order to avoid thermal stresses of the components), whereas light aero or aero-derivative engines will cool in about 1.5 to 3 hours [Thames et al., 1989]. The crank wash is carried out in several steps, which involve the injection of a soap and water solution via nozzles or jet lances, a soaking period, to allow the soapy cleaning fluid to penetrate into the fouling deposits (thus dissolving salts and emulsifying oil and grease components), followed by several rinse cycles, in which the engine is accelerated and then allowed to stop. The amount of rinse water required and the number of rinse cycles varies from site to site, according to the gas turbine model and the amount of dirt removed during the offline wash. A useful method of determining the effectiveness of the offline washing (and therefore the need for additional wash or rinse cycles) is to collect samples of the effluent water from all available drain ports.

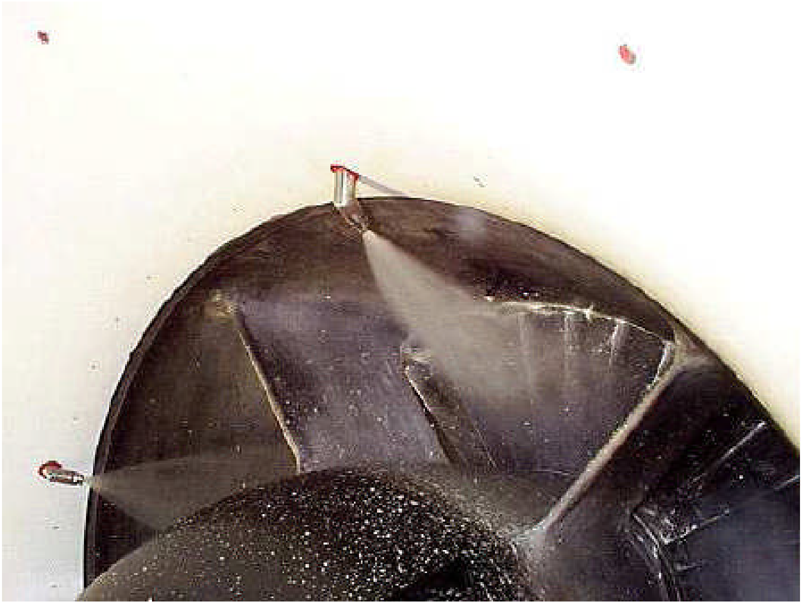

Figure 2.10.Offline cleaning process [Margolis, 1991]

Offline washing is currently the leading applied method for aero-engines [Testman, 1999], and its efficiency is very high. Moreover, the power recovery achieved is close to the level achieved during major engine overhauls. Offline washing systems should be designed to achieve the highest washing efficiency with the smallest injection mass flow, since a smaller offline injection mass flow will significantly reduce the required size, volume and cost of washing skids and the overall water and cleaner consumption. In addition, the quantity of the effluent water to be disposed of has to be minimised, since this is transported up to the exhaust during the wash procedure, and early concerns were raised that the liquid solvent could chemically attack various engine parts (from sealing and cooling systems and instrumentation air systems to exhaust nozzle subcomponents), causing chemical erosion [Langford, 1977].

Finally, (according to Meher-Homji and Bromley (2004)), offline washing should be conducted at variable speeds, in order to enable penetration of the wash and rinse fluid through the entire axial flow compressor. By doing this, the pattern of the centrifugal forces on the injected solution through the compressor will decrease and allow better wetting and distribution on the blade and vane surfaces of all stages. By contrast, offline washing at high and constant cranking speed will result in lower cleaning efficiency. Conductivity measurements and checks on the clarity/turbidity of the drain water will help assess cleaning efficiency.

Figure 2.11.Offline cleaning injection pipe [Margolis, 1991]

2.2.3.2. Online washing

Online washing (or fired washing) is very popular since it is currently the most advanced method to control fouling by avoiding the problem from developing. Online wet cleaning is performed fired, generally under full load with little or no reduction of the unit’s capacity and speed [Margolis, 1991]. The washing techniques and systems have nowadays evolved to a point where it can be done safely and effectively.

Being considered to be not as efficient as the crank wash, the optimal compressor cleaning can normally be achieved by adopting a combined program of regular and routine online washing with frequencies of daily to once per month and durations between five to thirty minutes, plus periodic offline washing during planned outages [Meher-Homji and Bromley, 2004]. An online washing program should always be started on a clean engine, after an overhaul or a crank wash. It is not recommended to perform online washing on a heavily fouled engine, because large quantities of dirt removed from the front stages would instantaneously pass through the compressor.

The primary objective of online washing is to extend the operating period between offline washes by minimizing the built-up of deposits in the compressor and thereby reducing the ongoing incremental power losses. Consequently, online and offline washing are complementary. Frequent online washing helps to decrease the fouling rate, but, over longer periods, a gradual performance loss will still occur (Figure 2.12).

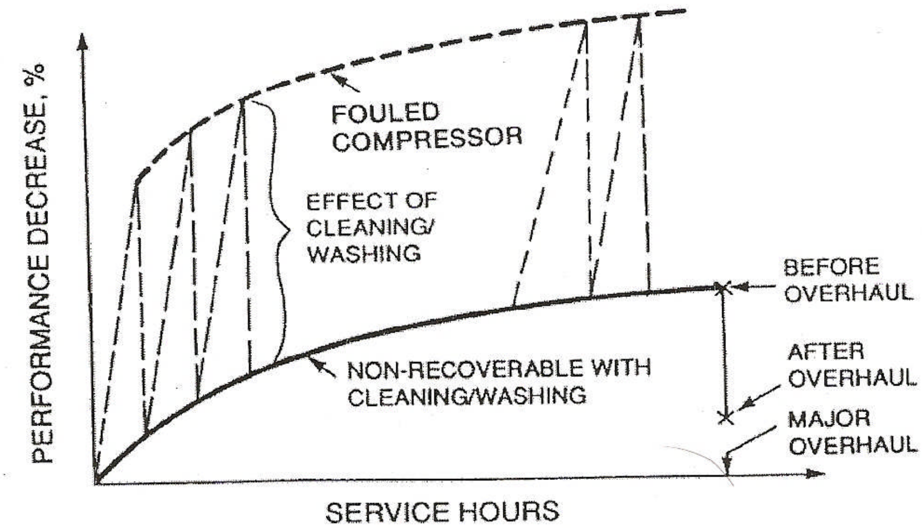

Figure 2.12.Typical deterioration behavior of a gas turbine [Li, 2005]

Since the principal cause of the reduced mass flow rate through the compressor is fouling, the restoration of both the design air mass flow and lost power is of paramount importance and, therefore, regular online cleaning will keep inlet guide vanes clean and free from deposit built-up. However, the droplets of the cleaning solution may only survive up to the sixth stage and most will have vaporized by then. Consequently, online cleaning has no effect on downstream stages. On the other hand, offline washing is more effective and must therefore be used to recover these losses [Margolis, 1991].

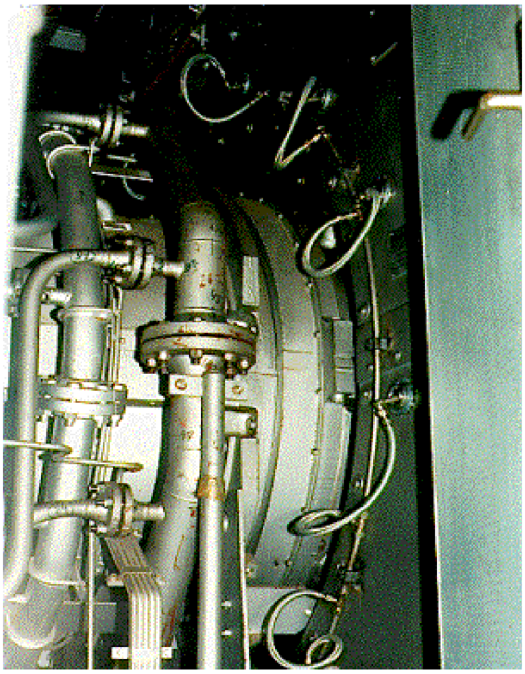

Figure 2.13.On-line compressor washing system constituted by injection nozzles and washing agent channel ring in a 39 MW gas turbine [Courtesy of Turbotect]

The washing device can either be provided by the original gas turbine manufacturer, or can be installed or replaced by a retrofit washing device from an external supplier. The design of such a device should be able to obtain the highest possible cleaning efficiency with the lowest injection mass flow rate, because a high injection mass flow rate will increase the blade loading and will create more stress on downstream blading. Moreover, high mass flow nozzles create larger sized droplets, which means that they are more influenced by gravity and tend to drop out of the airstream before reaching the compressor blade surface, increasing thus the risk of blade erosion. In addition, effective online cleaning requires that the IGV are thoroughly wetted with appropriately sized water droplets, which is obtained by a uniform and finely distributed atomized cleaning solution.

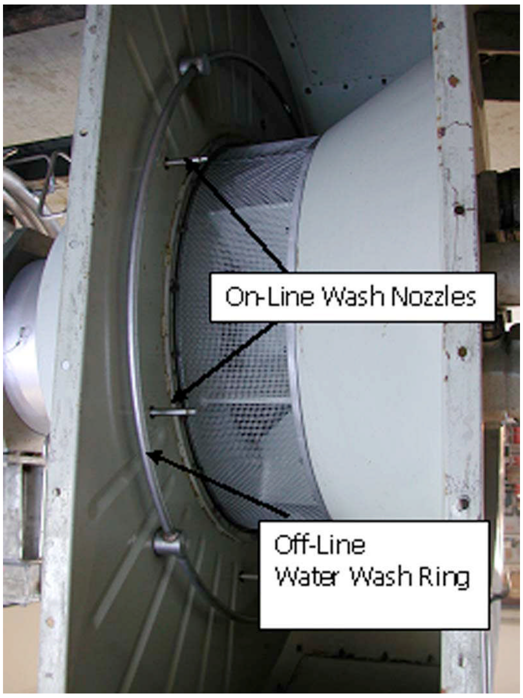

Figure 2.14.Inside view of air plenum showing the off-line water wash ring and the on-line water wash nozzles [Courtesy of Turbotect]

The nozzle of the online cleaning system is probably the most critical component and a proper design will assure the overall effectiveness of the cleaning process, since important issues such as nozzle location, injected mass flow, wash frequency and use of detergent can become immaterial if the installed nozzles do not perform. Although many different types and designs of online injection nozzles are used among the gas turbine users (as far as mass flow rate, operating pressure, spray pattern and droplet size range), there is a fairly common agreement within the industry that online droplet size should be within the range of 50 to 250 microns.

A useful review of gas turbine online wash systems along with a historical perspective of compressor online washing developments have been published by Mund and Pilidis (2004 & 2006). The different types of nozzles and online wash system designs used in the industry are surveyed and categorized according to operating pressure and mass flow rate.

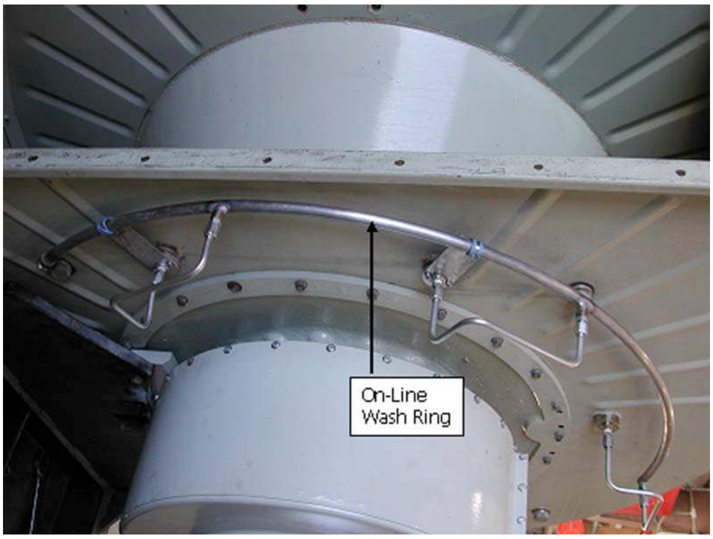

Figure 2.15.Gas turbine plenum showing the on-line water ring on the outside of the plenum [Courtesy of Turbotect]

The cleaning procedure involves the injection of a mixture of water and chemical detergent via atomizing spray nozzles positioned around the compressor air intake plenum. Depending on the nature of the fouling material, online washing may be performed with or without cleaning fluid. In most cases, however, the use of an approved cleaner (detergent) will improve the effectiveness of the washing operation. This is particularly true if the fouling material contains any quantity of oil or grease. Therefore, depending on the type of deposits (i.e. portion of water-insoluble compounds), detergent cleaners may be used for every online wash or for every second or third online wash, but not less frequently than once per week. Note that the longer detergent washing is not done, the greater the risk of downstream contamination due to large portions of insoluble compounds suddenly being removed when the next detergent wash is performed. Thus, frequent online washing using detergents is advisable to minimize the accumulation of insoluble materials. However, what is mandatory in online washing is the use of demineralised water, because, since the turbine is in operation, high temperature corrosion damage may occur if the sodium and other contaminated metals enter the combustion path.

The duration of each online wash can be varied according to the degree of fouling, engine size and/or plant experiences. Typical online cleaning cycles are in the order of 10 to 20 minutes and a flushing or rinsing cycle (using only demineralised water) of about the same duration should be applied after each cleaning cycle with detergent. This type of regular online wash regime will extend the operating period between outages required for offline cleaning, which is particularly important for base load plants [Leusden et al., 2004, Meher-Homji and Bromley, 2004, Boyce and Gonzalez, 2007].

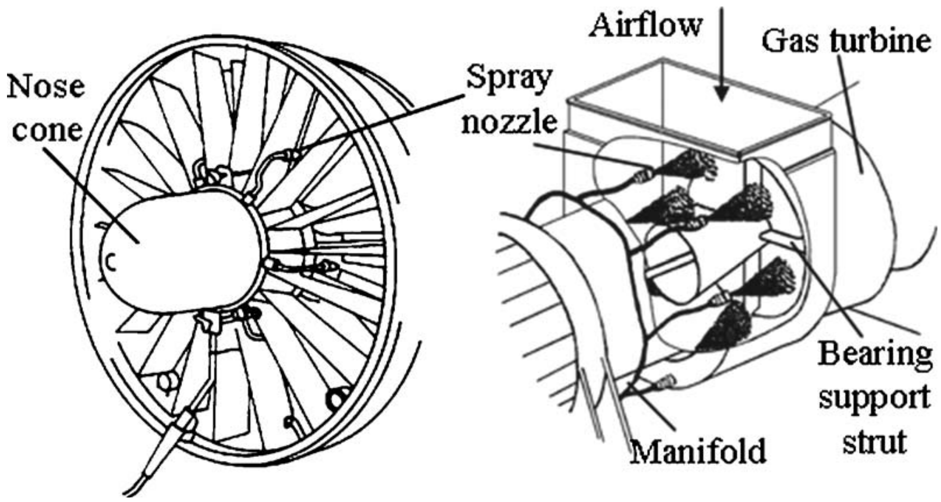

Figure 2.16.Washing device for aero-engines and adaptation for a stationary application [Asplund, 1996 & 1997]

A comprehensive review of compressor washing techniques, that summarizes online and offline cleaning benefits and penalties from extensive field data can be found in Stalder (2001). Also considerations towards many different aspects of compressor washing can be found to a greater extend in the open literature.

2.3. On-wing Cleaning of Aero Engines

Although on-line washing is extensively used in power generation and oil & gas applications, it is easily understood that such a technique cannot find place when considering an aero-engine installed on an aircraft. The most obvious method, which is manual cleaning, can only be performed when the engine is removed from the aircraft for any kind of repair or for major overhaul and is time consuming. Therefore, a number of aircraft engine on-wing washing patents and techniques have developed over the years, so as to reduce or eliminate the aforementioned negative effects of fouling, without sacrificing too much time to perform them.

U.S. Patent No. 5868860 to Asplund (1996) discloses the use of manifold for washing of aero engines. It is implemented by spraying small quantities of finely-divided liquid (in quantities corresponding to 0.5-60 l/min and at an overpressure of 50-80 bars and velocity of 100-126 m/sec) onto and through the engine, so that the liquid particles (120-250 μm in diameter) will follow the same routes as those earlier taken by the air-borne contaminants through the compressor [3]. Therefore, the high liquid velocity, together with rotation of the engine shaft, will enhance the cleaning efficacy.

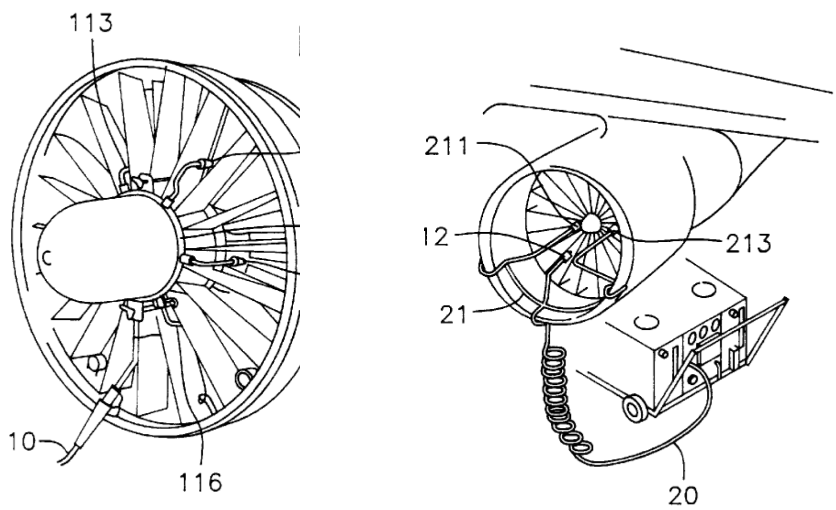

Figure 2.17.U.S.Patent No.5868860 for on-wing washing of aero-engines modified for engines with or without inlet guide vanes [Asplund, 1996]

According to the patent owner, the liquid recommended, which best satisfies the environmental requirements, is a specific liquid retailed under the trade name R-MC (a surfactant that eats into and removes surface dirt).

U.S. Patent No. 6394108 to Butler (2002), called “Inside-Out Gas Turbine Cleaning Method”, discloses a thin flexible hose, which one end is inserted from the compressor inlet towards the compressor outlet, in between the compressor blades. The hose is slowly retracted out of the compressor, while liquid is being pumped into the hose and sprayed through a nozzle, which is located at the inserted end of the hose [11]. However, the washing efficacy of this method is limited by the compressor rotor not being able to rotate during washing.

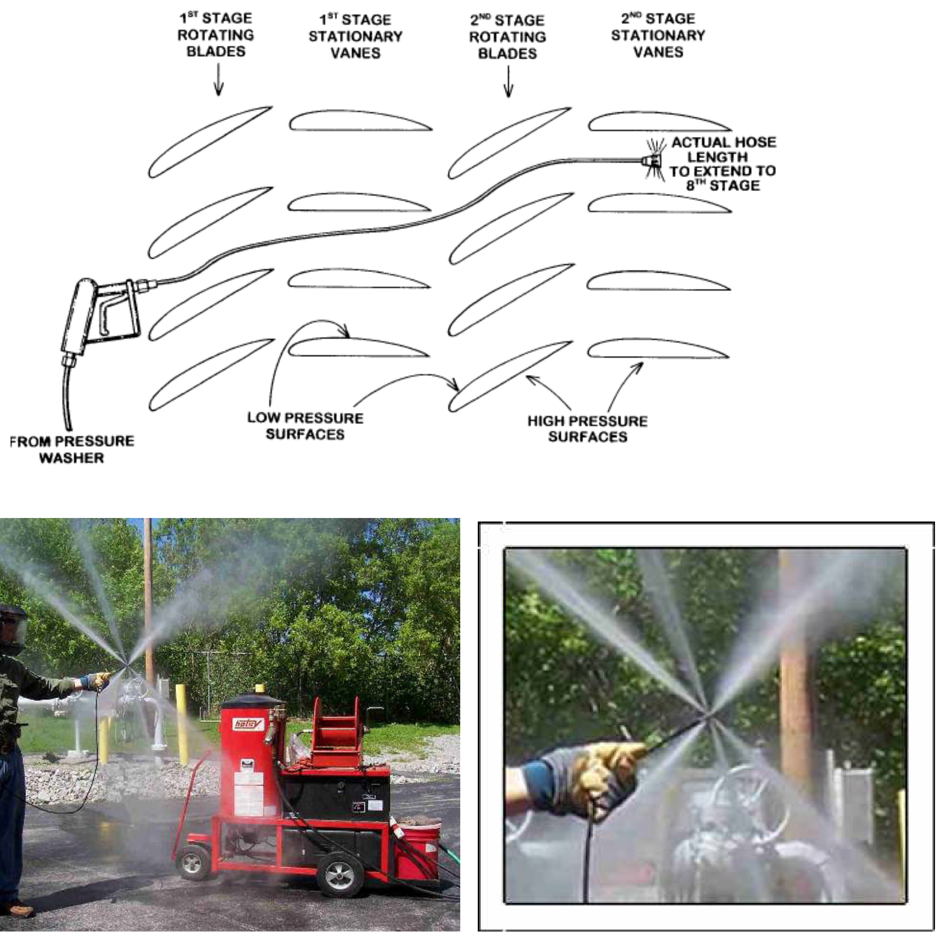

Figure 2.18.U.S. Patent No.6394108 demonstrating the philosophy of the “Inside-Out Gas Turbine Cleaning Method” [Butler, 2002]

WO/2005/120953 to Hjerpe (2005), from Gas Turbine Efficiency AB, is another on-wing aviation wash system. It includes a universal manifold, automated positioning (with or without contact to the engine inlet) and 100% capture of effluent and treatment, allowing closed loop washing at the gate. Hjerpe claims that using this particular system, major airlines can achieve fuel savings of up to 1%, turbine wash times of as low as 30 minutes per engine and carbon dioxide reductions of 3.1 kg for every 1 kg of fuel saved [20].

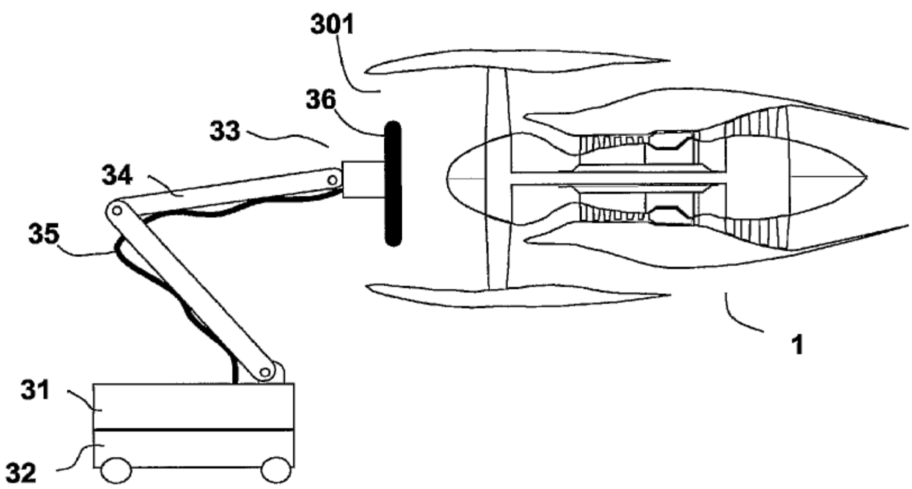

Figure 2.19.WO/2005/120953 washing system for aero engines, demonstrating the no-contact spray head wash unit [Hjerpe, 2005]

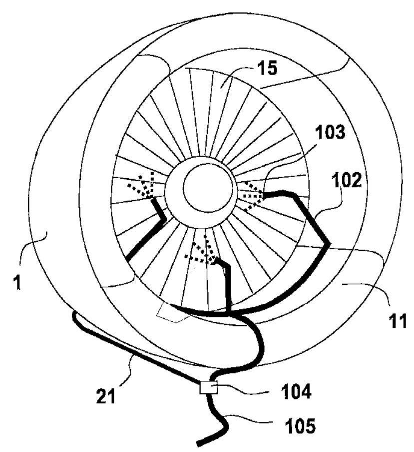

Figure 2.20.WO/2005/120953 washing system demonstrating a manifold installed in a turbofan engine with nozzles for injecting the wash fluid into the engine inlet [Hjerpe, 2005]

Another washing system is the WO/2006/107476 to Rice and Tierney from United Technologies Corporation (2006), called “Mobile On-Wing Engine Washing and Water Reclamation System”. This system features a cart which is pulled up to the parked airplane containing everything needed to wash the engines. The cart includes a storage container for effluent, as well, so the whole process is a "closed loop", where water is injected into the engine and recovered at the exhaust end. Key to the application is an array of injectors that is fitted to the engine inlet. Featuring four nozzles, the injector array is sized for the particular engine being washed -- with a smaller radius used for, say, business jets, and a larger one used for engines powering wide body aircraft. The array consists of three nozzles arranged to spray into the centre of the engine, thereby reaching the core, and a fourth nozzle to cover the outer diameter, thereby covering the fan [54].

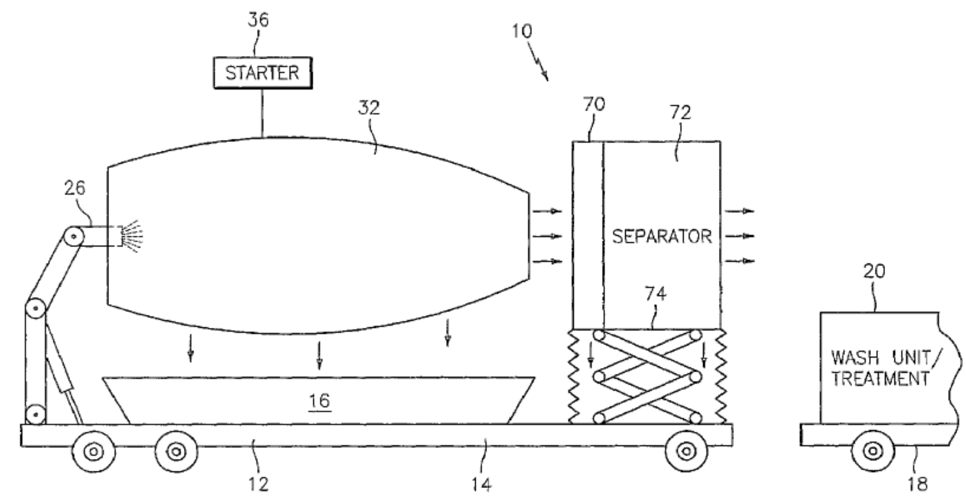

Figure 2.21.WO/2006/107476 washing system for aero engines, illustrating an embodiment of a mobile on-wing engine washing and water reclamation system [54]

The system uses atomized water in a fine mist. As a result, there are no toxic chemicals, hazardous wastes or detergents involved. There is another benefit of using a spray of atomized water: there are no adverse chemical reactions to gas path coatings and sealants in the engine. This is an especially important consideration for hot section components that may have expensive thermal barrier and corrosion resistant coatings.

The engine is rotated, using the electric starter motor, to about 20% of its idle speed, and the mist is sprayed into the inlet. According to the inventors, the mist penetrates deeper into the engine core, saturating and cleaning all surfaces. Conventional washing methods, the company asserts, are not as effective because the denser washing mixture is partially centrifuged out into the bypass fan duct and therefore does not reach into critical gas-path components [54]. The effluent is collected during the wash process and the water is purified for re-use.

In 2004 P&W started utilizing GTE’s cleaning systems in commercial aviation hubs based in United States, Europe and Asia for the deployment of an on-wing engine wash service called EcoPower®. The engine wash process is not limited to Pratt & Whitney engines; it can be applied to all turbine engines, and a selection of injector arrays has been designed to fit just about any engine size. According to P&W, the new EcoPower® system can wash engines in as little as one quarter the time (roughly 60-90 minutes), and the water used is between 16-42 gallons (60-160 litres), depending on the size of the engine [51]. With multiple-engine cleaning capability, a commercial twinjet can be cleaned in approximately two hours at the end of the flight day. The service is typically offered overnight, while the aircraft is parked at the gate.

Figure 2.22.P&W’s EcoPower® compressor washing system [51]

P&W Global Service Partners launched the EcoPower® service business in late 2004, and to date it has completed more than 2,500 washes for about 50 customers in 10 countries. Currently, EcoPower® wash improves engine performance and extends time on wing for operators of P&W, GE, International Aero Engines, CFM International and RR engines. EcoPower® wash is claimed to reduce fuel burn by as much as 1 percent and increase exhaust gas temperature margin by as much as 15 degrees C. Therefore, (according to P&W) a fleet of 30 767 Boeing can save up to 2.8 million lbs of fuel a year, saving thus around 1.5 million annually in fuel costs [51]. The EcoPower® engine wash service is presently offered at seven locations around the globe: New York (JFK), Dallas (DFW), Los Angeles (LAX), Victorville, California (VCV), Singapore (SIN), Seoul, South Korea (ICN), Amsterdam, The Netherlands (AMS).

Finally, Lufthansa Technik (a maintenance, repair and overhaul company) has also developed a new method for washing engines called "Cyclean™ Engine Wash" [35]. It features a mobile machine which can be used without either the thrust reverser or the engine cowlings having to be opened. A headpiece with two nozzles tailored to each engine type can be attached directly to the fan spinner via a rapid action hose coupling. This allows the heated water to be sprayed directly into the core engine through the fan while the engine is rotated by the starter (dry cranking). Thanks to the revolving injection nozzles, the entire core engine is optimally washed and, moreover, special fan nozzles ensure that the water is finely nebulized at a pressure of up to 100 bars.

Figure 2.23.Cyclean™ Engine Wash System developed by Lufthansa Technik [35]

According to Lufthansa, the implementation of this new technique results in the enhancement of the engine efficiency so that costs are cut, while the environment benefits from lower CO_2 emissions [35]. Cyclean™ is available for every engine type and is offered by the company's Airline Support Teams worldwide. The new engine washes are not just available at Lufthansa Technik stations, but can also be performed directly in the field.

2.3.1. Risks and Benefits of On-wing Off-line cleaning

On-wing off-line cleaning techniques produces multiple benefits for both the aero-engine itself and for the environment as well. However, in the same time, some risks are also associated with its use.

The most obvious benefit is the saving in fuel consumption. All companies related to compressor washing methods acknowledge that the implementation of any method, irrespective of the provider, will lead to better fuel savings and thus contribute positively to the company's economics. In addition, the engine's performance and efficiency are improved and, in the same time, the decrease in the exhaust gas temperature (because of the cleaning) can be as much as 15 degrees Celsius. Therefore, the time on-wing of any aircraft is considerably extended and possible flight delays, inspection failures, increased operating costs and safety compromises are minimized. What should also be mentioned is that there is a significant benefit to the environment as well, since by performing on-wing off-line cleaning, the carbon dioxide emissions to the environment are substantially reduced.

On the other hand, if during cleaning the cleaning efficacy is not satisfactory, contaminants can be detached from the gas path and they can provoke adverse chemical reactions to the gas path coatings and sealants. In addition, the cleaning process should optimally be a closed loop method, since, if the effluent and treatment are not 100% captured, there is a significant environmental hazard from toxic chemicals, hazardous wastes and detergents.

2.4. Performance simulation software

Several publications describe engine-performance deterioration and engine diagnostics using gas-path analysis techniques. One of the most powerful programs is the one called ‘PYTHIA” which is developed at Cranfield University. PYTHIA is an advanced gas turbine performance modelling and diagnostic software developed by Escher (1995). PYTHIA provides graphical user interface and uses the core of Turbomatch (another general gas turbine performance modelling program that has also been developed at Cranfield University) to perform engine performance simulation. The diagnostic system of PYTHIA, based on the linear GPA, non-linear GPA, and genetic algorithm techniques, is an integrated system of a variety of functions which include [Li and Singh, 2005]:

- Gas turbine design-point performance adaptation.

- Gas turbine performance calculation.

- Gas-path fault diagnostic using linear GPA, non-linear GPA and generic algorithm.

- Generation of engine fault patterns for the purpose of diagnosis, including the simulation of engine measurement for clean and degraded engine conditions, selection of instrumentation set, real engine test data acquisition and noise reduction, data pre-processing to correct the engine test data to engine diagnostic conditions.

- Sensor fault diagnostic using GPA.

For a clearer and complete discussion of the advantages and disadvantages of GPA and its various analysis modes and mechanisms mentioned above, the reader may wish to examine other work [Escher, 1995; Dabrowski, 1999; Kleinakis, 1999]. However, what needs to be mentioned here are the number of assumptions on which GPA techniques rely. Those directly applicable to the study of both T56–A–15 and F110–GE–129 engines are as follows:

- The gas path flow is assumed to be one-dimensional, in that temperatures and pressures are the same at every point in any plane normal to the gas flow.

- The gas flow conditions are considered to be steady-state such that equilibrium thermodynamic analysis can be performed throughout the engine. The analysis requires accurate measurement of the gas state conditions.

- The gas flow is considered adiabatic; cooling losses are ignored.

- Performance measurements are assumed to be free of sensor noise; noise has the ability to hide engine faults and introduce error into the analysis. Sensor problems and the influence of noise have already been investigated by a number of previous authors.

As far as Turbomatch is concerned, it is a simulation program developed by the School of Engineering at Cranfield University and is based on FORTRAN. It aims to facilitate design-point and off-design performance calculations for gas turbine engines (both aero and industrial). This scheme uses “codewords” in order to simulate the action of the different components of the engine, with the aid of various pre-programmed routines known as “bricks”, resulting finally in output of engine thrust, fuel consumption, SFC, etc, together (optionally) with details of individual component performance and of the gas properties at various stations within the engine.

3. GENERAL ENGINE DESCRIPTION & MODELING

3.1. The T56–A–15 engine

The Rolls-Royce–Allison T56–A–15 is a single spool turboprop engine that powers the C130H military cargo transport aircraft, driving a Hamilton Sundstrand propeller. The engine consists of an axial flow turbine power section and a reduction gear assembly which are joined together by a torquemeter assembly. The reduction gear assembly drives a single propeller shaft. A cutaway and the external view of the T56–A–15 engine are illustrated in Figure 3.1. The engine weights approximately 840 kg and is rated at 4910 Equivalent Shaft Horsepower (ESHP) with standard day conditions, 13,820 RPM and a TET of 1077^{o}C. It develops about 2.6 horsepower per pound of weight at maximum power.

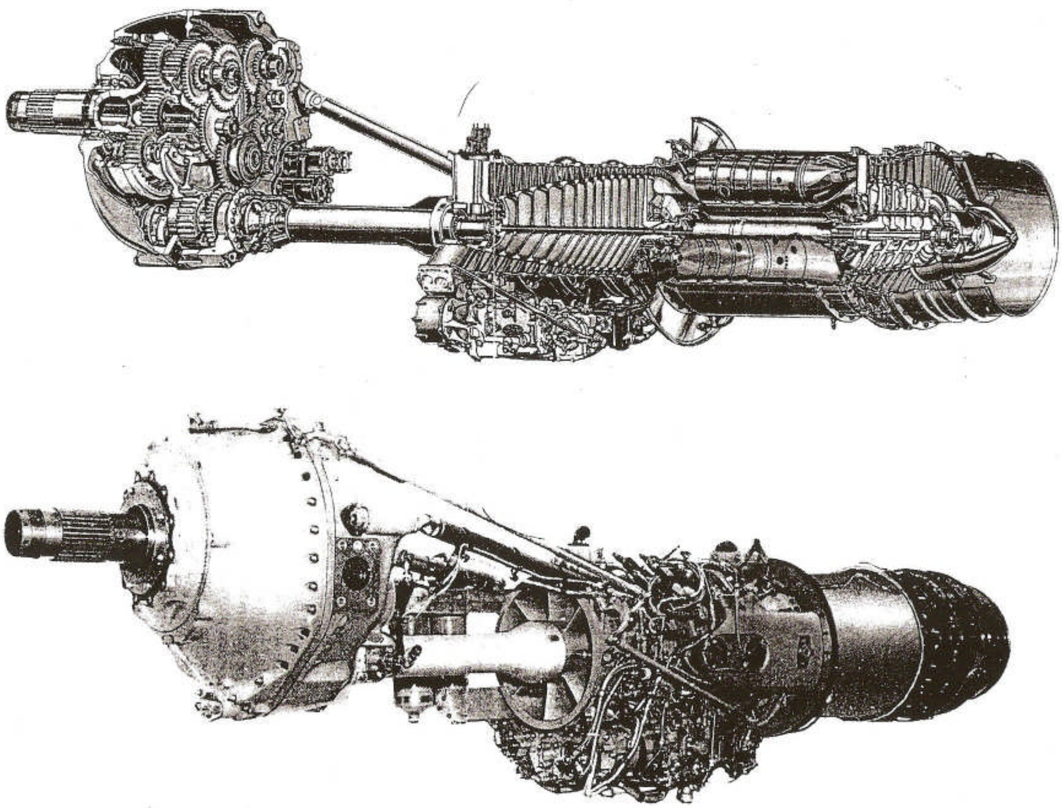

Figure 3.1.Cutaway and external view of the T56–A–15 engine [Jane's, 2007]

A characteristic of this constant speed turboprop is that changes in power are not related to engine speed; power is related to Turbine Entry Temperature. During flight the propeller maintains a constant engine speed. This speed is known as the 100% rated speed of the engine (Flight Range Mode); and is the design speed at which most power and overall efficiency can be obtained. Since RPM remains constant, power changes can be affected by simply changing the fuel flow. For example, an increase in fuel flow causes an increase in energy available in the turbine. The turbine absorbs more energy and transmits it to the propeller in the form of torque. The propeller then, in order to absorb the increased torque, increases propeller blade angle, thus maintaining constant engine RPM.

The T56–A–15 engine has a 14-stage axial flow compressor. This compressor supplies air for combustion, internal engine cooling and operation of the engine pneumatic systems. The pressure ratio of the compressor is 9.5:1. There is also provisional for stall prevention by the use of bleed valves installed on the 5th and the 10th stages of the compressor. The bleed valves are open during acceleration and until the engine reaches 94% (13,000 RPM), allowing a great deal of the compressor discharge air to escape before reaching the combustion area. This reduces the compressor loading of the compressor and the turbine is able to accelerate the engine rapidly (since its load is far below the maximum).

The T56–A–15 combustion section consists of 6 annular perforated combustion liners with dual orifice fuel atomizers, mounted around the inner combustion casing with one-piece outer casing. The ignition is achieved with two igniter plugs installed in diametrically opposite combustors. Crossover tubes ensure that the flames are spread to the other combustion liners.

The T56–A–15 turbine is a 4-stage turbine assembly. The tips of the blades of the first three stages of the turbine are shrouded to increase turbine efficiency. The 1st stage turbine rotor blades are hollow for cooling purposes. Cooling air, passing along the outer part of the combustion liners, is also directed to the first stage nozzle guide vanes and the turbine discs of the first three stages.

Finally, the exhaust nozzle of the T56–A–15 engine is a convergent one and of fixed area. There is a small amount of thrust produced by the nozzle. However, 75 to 80% of the power is used to drive the propeller.

The modeling of the T56–A–15 engine was conducted using the PYTHIA software. The “bricks” used and an illustration of the engine station numbering are shown in Figure 3.2. Since clean engine performance data is readily available by the engine manufacturer [16] for various power settings, the engine clean and deteriorated performance was simulated for four power settings: 90% Normal (1230K), Normal (1283K), Military (1322K) and Take-off (1350K).

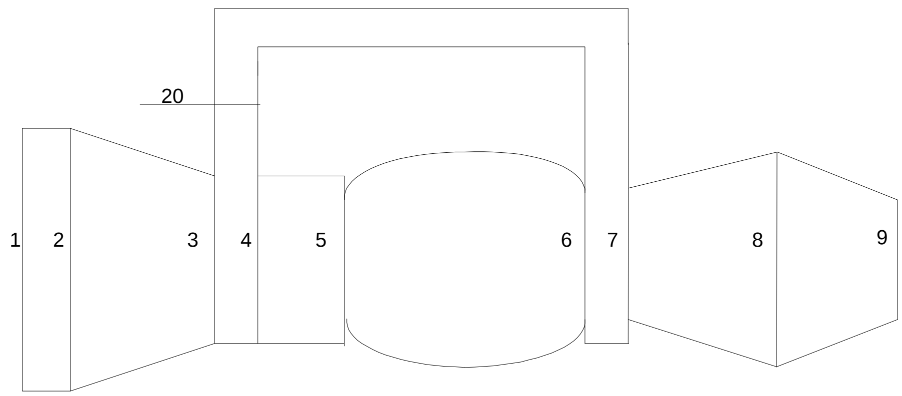

Figure 3.2.PYTHIA model of the T56–A–15 engine

The Turbomatch sub-model produced by PYTHIA, in accordance to the user’s inputs, can be found in Appendix A.

3.2. The F110–GE–129 engine

The F110–GE–129 is the successor to the F110–GE–100 engine, as far as design, materials, operating temperatures and thrust levels are concerned. It is a commercially successful fighter engine, which was manufactured by General Electric. It was developed in the mid-80s, first flew in August 1988 and entered operational service in January 1992. Since then, it powers a considerable percentage of currently flying F-16 aircrafts.

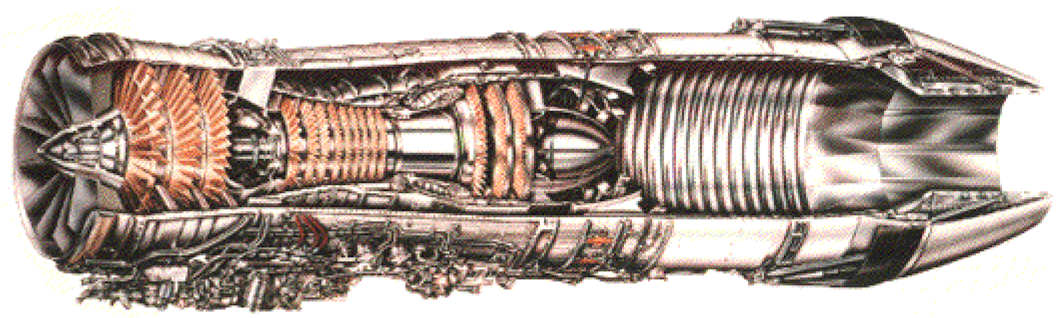

Figure 3.3.Cutaway view of the F110–GE–129 engine [Jane's, 2007]

The type of the engine is a two-shaft, axial flow, mixing type, low bypass ratio turbofan with afterburner. The fan has inlet guide vanes with variable trailing edge flaps. There are three fan stages with solid titanium blades. Both the inlet and the fan guide vanes are individually replaceable. The By-Pass Ratio (BPR) is 0.76, the Fan Pressure Ratio (FPR) is 3.3 and the airflow is between 118–122 kg/sec. The HP compressor has nine stages on one piece inertia-welded rotor. The inlet guide vanes and the first three stators are variable and the pressure ratio is 9.1. The HP turbine is a single stage one with hollow blades and vanes, both impingement and film-cooled and the turbine entry temperature is 1735K. The LP turbine has two stages, is tip shrouded but uncooled. The afterburner is a mixed flow type, with convoluted flow mixer. Flows mix in plane of flameholder, and 90% of the core flow is completely burned before fuelling of any bypass air is initiated. The afterburner temperature, when the reheat is lit, is 2100K. The exhaust nozzle is a variable area type, made up of convergent and divergent flaps and seals and outer flaps. Finally, the engine performance is summarized in the table below.

Table 3.1 Performance ratings of the F110–GE–129 engine (SLS, ISA) [23]

Maximum "dry" thrust	77.97 kN
Maximum thrust with A/B	141,07 kN
SFC without A/B	18.4 mg/N sec
SFC with A/B	55.09 mg/N sec

Similarly to the T56–A–15 engine, a model of the F110 engine was built using PYTHIA, in order to study its off-design performance in various power settings (1600K, 1660K, 1700K and 1735K). An illustration of the engine station numbering with the "bricks" used is shown in figure 3.4 below. Moreover, the Turbomatch sub-model produced by PYTHIA for the F110–GE–129 engine, in accordance to the user's inputs, can be found in Appendix B.

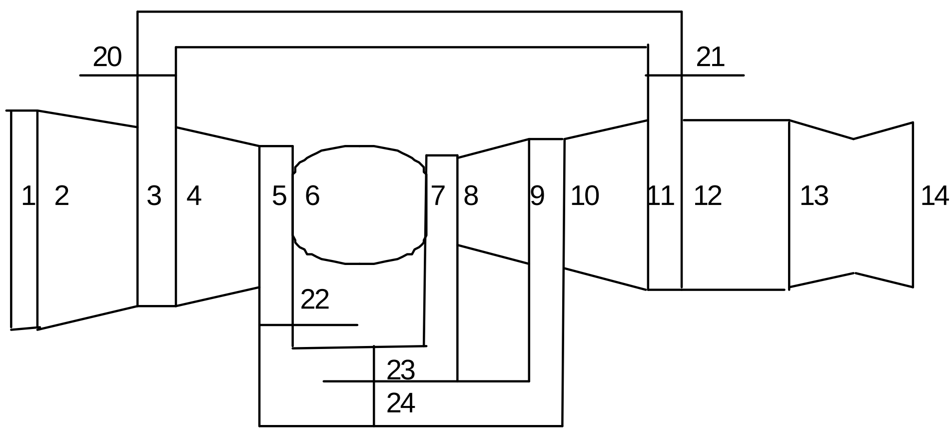

Figure 3.4.PYTHIA model of the F110–GE–129 engine

4. ANALYSIS OF ENGINE'S DETERIORATION

A common practice in the past to generate a deteriorated engine performance was to implant mechanically damaged components in otherwise good engines. Having obtained the baseline signature of the engine, the damaged parts were inserted (either one by one or in combination) and the engine was retested to gather the deteriorated data. The baseline and the deteriorated data would then form the basis of the engine performance analysis. However, apart from the fact that this process was extremely expensive, the data gathered were not reliable enough for subsequent fault diagnostics, since the damaged components, that were used to simulate the deterioration, would almost definitely cause more damage to the engine than in actual circumstances.

Nowadays, computer simulations developed by both the engine manufacturers and by individuals (companies, Universities) who may be interested in the various aspects of power generation, can provide the user with accurate baseline and deteriorated data, without compromising flight safety or incurring fuel and maintenance costs required by expensive operational testing. These models permit the implementation of a great variety of faults to be analyzed, thus helping to a systematic investigation of the engine's deterioration and engine's health prediction.

4.1. Simulation of the engine's deterioration

As shown in chapter 2, most physical faults cause changes in one or more of the engine's independent performance parameters (efficiencies, flow capacities). These changes in independent parameters cause subsequent changes in the engine's dependent parameters (temperatures, pressures, fuel flows and power output). Therefore, the deterioration of component is simulated by modifying one or more of the engine independent parameters, which define the component characteristics. Deteriorated performance is then determined by re-matching the engine components with the adjusted characteristics, since overall performance is governed by the performance of the individual components.

In this report deteriorated performance has been simulated by changing characteristics at the component level. However, performance models have also been developed, which simulate performance degradation at the sub-component level (e.g. at particular compressor stages) [Lakshminarasimha & Saravanamuttoo, 1986; Aker & Saravanamuttoo, 1989; Tabakoff et al, 1990, Mathioudakis & Stamatis, 1994, Dimitriadis, 2006]. This method is called the stage stacking technique, and has been used to model compressor fouling and erosion. This technique can also be used to model turbine performance.

4.2. Simulated faults representation

The choice of the faults that are implanted during a deterioration simulation is usually influenced by the environment in which the engine under study operates. Thus, given that both the engines studied in this thesis (T56–A–15 & F110-GE-129) are aero engines that may operate from unprepared airfields in dusty environment and fly at relatively low altitudes, physical faults such as fouling and erosion were given high priority.

Fouling: Both compressor and turbine fouling are represented by a reduction of the flow capacity at the inlet of the component, plus a simultaneous reduction of the isentropic efficiency of the component. Therefore, a blockage in the inlet area of the component due to fouling is assumed, along with a decrease in the component isentropic efficiency, due to surface roughness.

Erosion: As far as compressor is concerned, erosion is represented by a reduction of both inlet flow capacity and isentropic efficiency. Turbine erosion is, however, represented by an increase of the flow capacity, along with a reduction of the turbine isentropic efficiency.

For both the above two phenomena, the change in the flow capacity will be represented by changing the non-dimensional mass flow Q of the component maps ($W\sqrt{Ti}/AP = constant$).

Table 4.1.Representation of component degradation

Fault	Represented by	Range
Compressor fouling	Drop in Γ	0.0-(-5.0%)
	Drop in η_c	0.0-(-2.5%)
Compressor erosion	Drop in Γ	0.0-(-5.0%)
	Drop in η_c	0.0-(-2.5%)
Compressor corrosion	Drop in Γ	0.0-(-5.0%)
	Drop in η_c	0.0-(-2.5%)
Turbine fouling	Drop in Γ	0.0-(-5.0%)
	Drop in η_T	0.0-(-2.5%)
Turbine erosion	Rise in Γ	0.0-(+5.0%)
	Drop in η_T	0.0-(-2.5%)
Turbine corrosion	Rise in Γ	0.0-(+5.0%)
	Drop in η_T	0.0-(-2.5%)

The physical faults that were finally chosen along with the independent parameters used to simulate them are shown in Table 4.1. In order to describe the degree of deterioration modeled, a deterioration percentage was introduced. This deterioration percentage indicates the independent parameter ratio for every fault implanted and is combining the adverse effect upon the engine's performance of variation in (i) flow capacity and (ii) the efficiency of any gas-path component. For the purpose of this investigation it is presumed that a 1% variation in flow capacity will be accompanied by a 0.5% variation in isentropic efficiency. Linear relationships are assumed: 2% deterioration represents the combined effect of 2% and 1% change in non-dimensional mass flow and isentropic efficiency respectively.

Although there is a vast amount of published literature on gas turbine performance deterioration, the applied degradation magnitude to each component, when simulating gas turbines performance deterioration, is either arbitrarily selected or based on any available published experimental results. Therefore, in the present thesis, the values mentioned by Diakunchak (1992) and Escher (1995) were taken as guidelines, from which the implanted faults were estimated. Table 4.2 shows the summary of how component isentropic efficiency changes vary with degradation. These values were applied in all calculations to the appropriate components.

Table 4.2.Component isentropic efficiency variation with degradation

Physical Fault	**Non-dimensional Mass Flow Change (A)**	**Isentropic Efficiency Change (B)**	**Ratio A:B**
Compressor fouling	Γ_C ↓	η_C ↓	~1:0.5
Compressor erosion	Γ_C ↓	η_C ↓	~1:0.5
Compressor corrosion	Γ_C ↓	η_C ↓	~1:0.5
Turbine fouling	Γ_T ↓	η_T ↓	~1:0.5
Turbine erosion	Γ_T ↑	η_T ↓	~1:0.5
Turbine corrosion	Γ_T ↑	η_T ↓	~1:0.5

As it is seen from the above table, compressor fouling, compressor erosion and compressor corrosion are simulated using exactly the same percentage of deterioration. Consequently, the effects of compressor erosion and compressor corrosion are expected to be the same as compressor fouling and therefore, only compressor fouling will be studied here. In the same way, turbine erosion and turbine corrosion are represented using exactly the same amount of deterioration and thus, only turbine fouling and turbine erosion will be studied.

Changes in engine performance and engine component characteristics can be described by 'Parameter Deltas'. A parameter delta indicates the change between deteriorated and undeteriorated (or baseline) performance. In this report the following definition for parameter delta has been used:

$$Parameter\_Delta = \frac{Deteriorated\_Value - Baseline\_Value}{Baseline\_Value} x100\%$$

This conversion has been used so that an increase in a parameter delta represents an increase in the parameter value when compared to its baseline or undeteriorated value.

When the engine performance deterioration reaches 5-6% (compared with the "healthy" condition) maintenance action will normally take place or the engine will be removed from service. Therefore, the maximum deterioration percentage was chosen to be 6%, so that the user will obtain a clear view of the rate of deterioration and the relationship (linear or non-linear) between the independent and dependent parameters.

Finally, what should be noted again is that the simulated deteriorated performance results have not been validated, because the published data available for comparison is and will remain very limited, since it is proprietary data. For this reason, and also because the component fault sets have been arbitrarily selected and defined, the accuracy of these physical fault models is somehow questionable.

4.3. The T56–A–15 engine

4.3.1. Compressor fouling

Figures 4.1 to 4.4 illustrate the effects of compressor fouling on the measured parameter deltas. As seen in Figure 4.1 there is a significant reduction in compressor pressure ratio, due to the effects of engine re-matching with the reduced compressor mass flow. The turbine inlet NGV's are chocked, hence the compressor delivery pressure falls in order to satisfy the non-dimensional mass flow requirement of the turbine. A reduction in fuel flow also occurs primarily as a result of the drop in compressor flow capacity, as less air needs to be heated in the combustor. Another significant result of compressor fouling is the large drop in shaft power output (Figure 4.3). Apart from the power drop, the increase in heat rate is also another indication that is expected with the onset of compressor fouling. This is shown in the results as an increase in Exhaust Gas Temperature (EGT) (Figure 4.2).

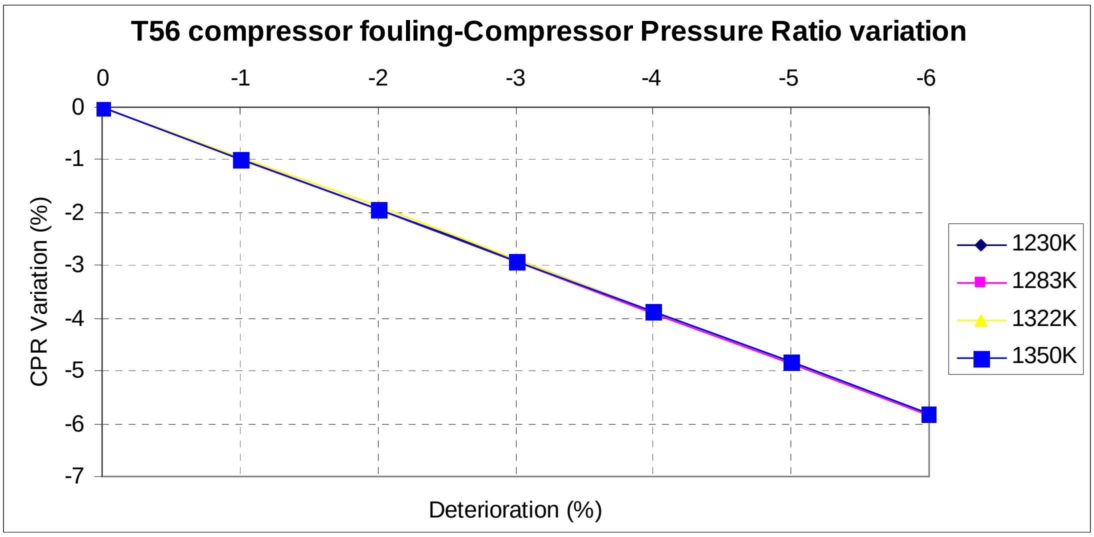

Figure 4.1.CPR variation for T56 compressor fouling

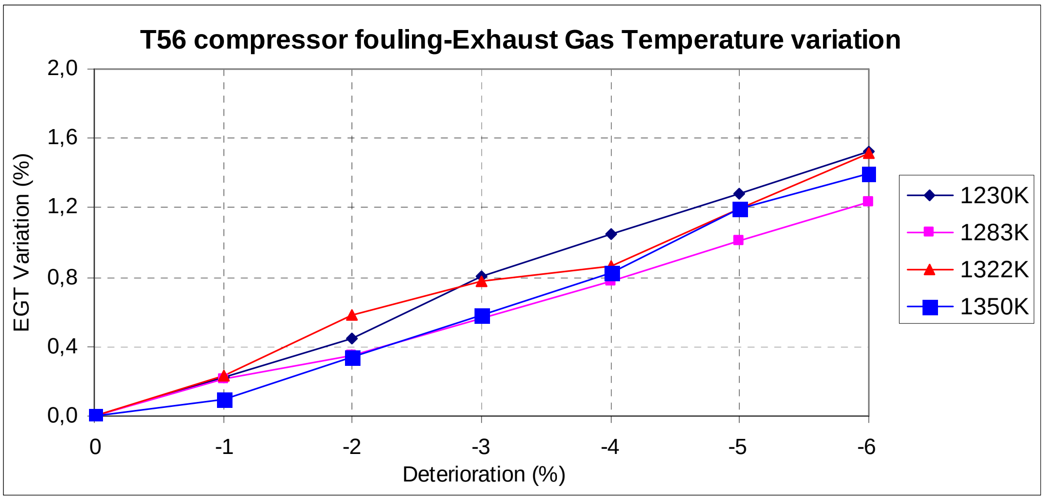

Figure 4.2.EGT variation for T56 compressor fouling

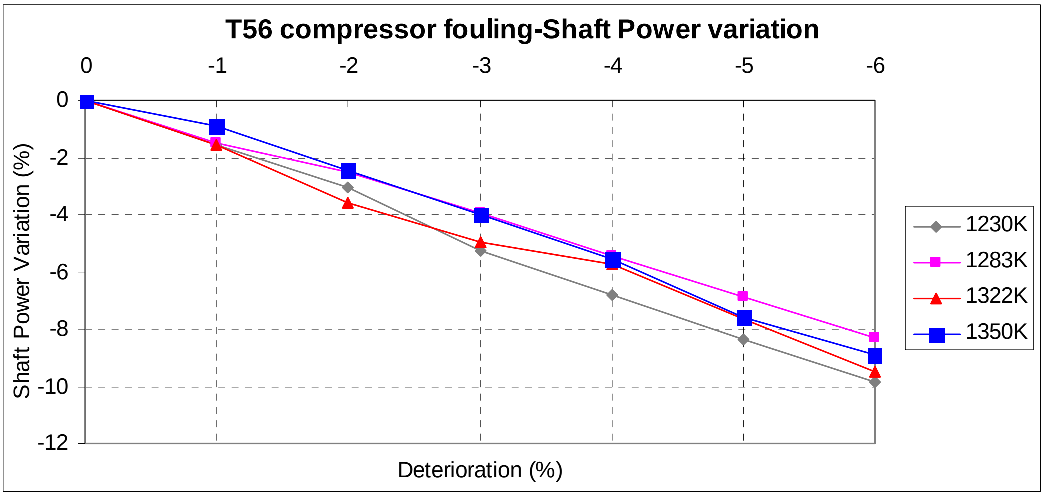

Figure 4.3.Shaft Power variation for T56 compressor fouling

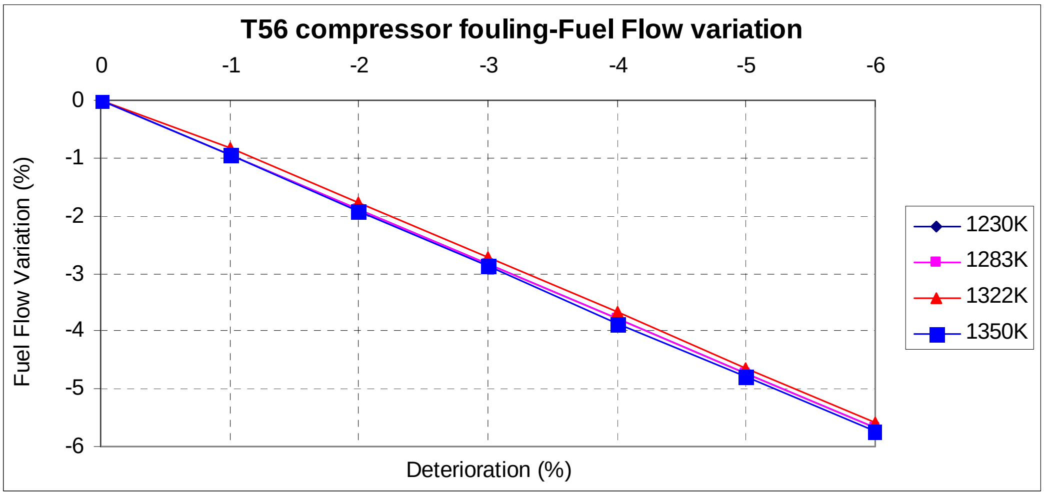

Figure 4.4.Fuel Flow variation for T56 compressor fouling

4.3.2. Turbine fouling

Figures 4.5 to 4.8 illustrate the effects of turbine fouling on the T56–A–15 measured performance parameters. The reduction in turbine effective area/non-dimensional mass flow is responsible for causing the compressor pressure ratio to increase. This is due to the engine re-matching to account for the reduction in turbine effective area. As the effective area is reduced the turbine non-dimensional flow is reduced to keep the turbine inlet mass flow parameter Q constant ($W\sqrt{Ti}/AP = const$).

The drop in isentropic efficiency causes the more significant contribution to the drop in shaft power output, which is also reduced because of the increase of EGT and thus a decrease in the turbine work.

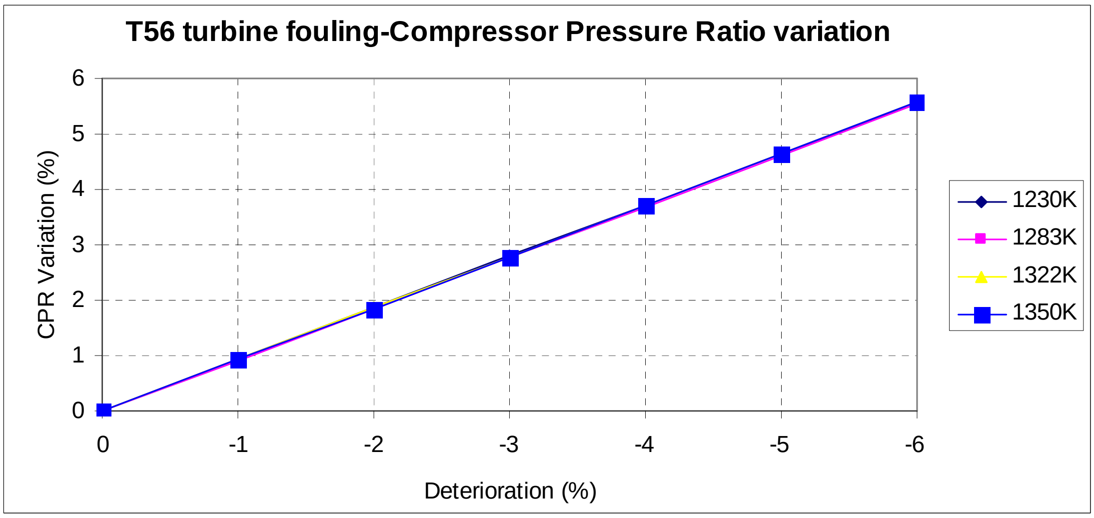

Figure 4.5.CPR variation for T56 turbine fouling

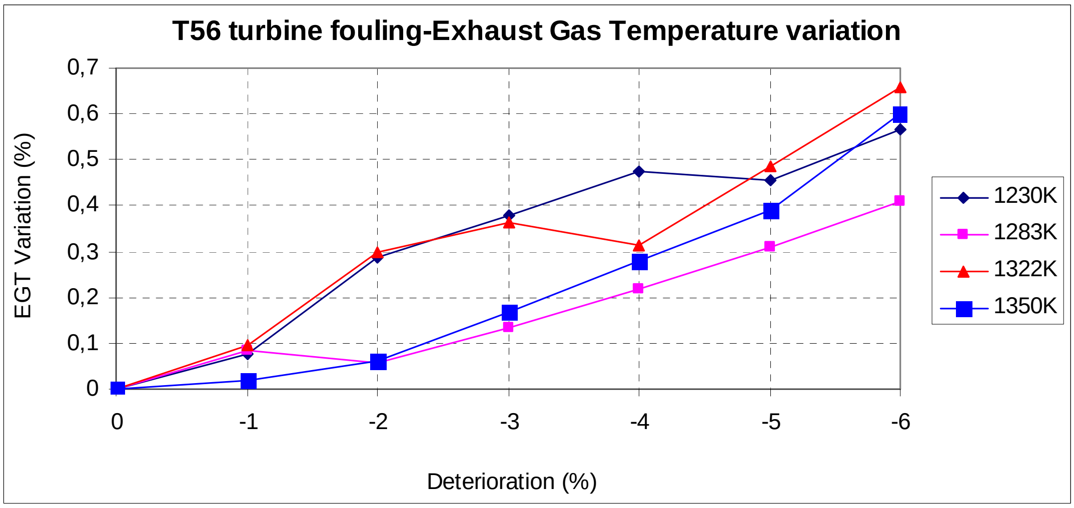

Figure 4.6.EGT variation for T56 turbine fouling

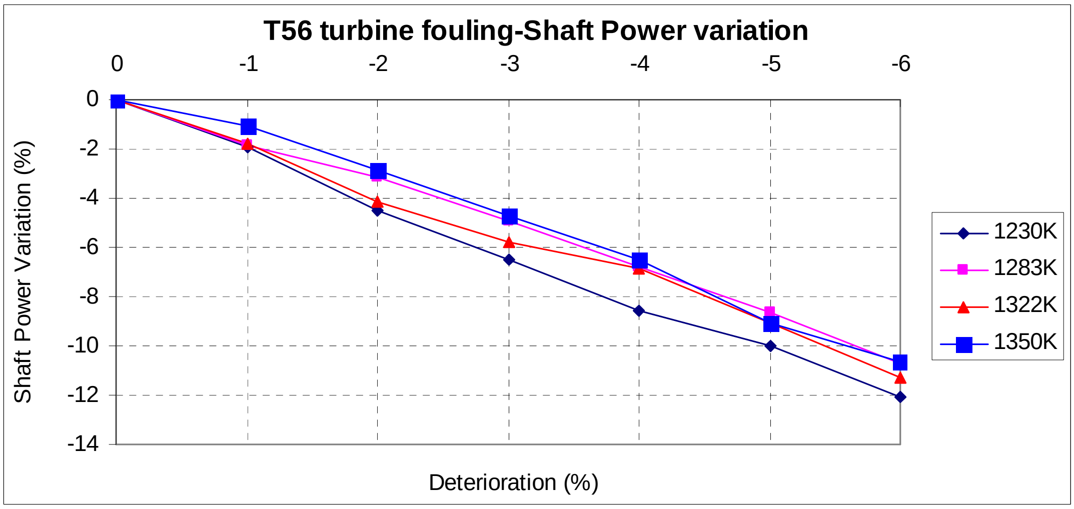

Figure 4.7.Shaft Power variation for T56 turbine fouling

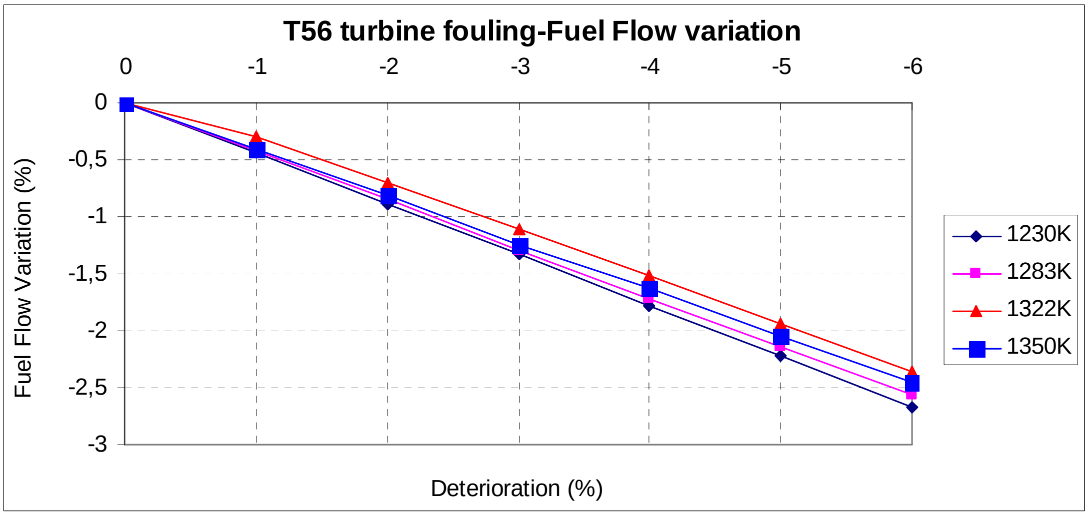

Figure 4.8.Fuel Flow variation for T56 turbine fouling

4.3.3. Turbine erosion

The graphs in Figures 4.9 to 4.12 show the effects of turbine erosion on the T56 dependent parameter deltas. The increase in turbine effective area causes a reduction in compressor pressure ratio. The increase in fuel flow occurs as a result of the increase in turbine effective area. The isentropic efficiency has a negligible effect on fuel flow. The decrease in shaft power (which is the result of the reduction in isentropic efficiency) is not so significant, because even if the turbine work is reduced as the EGT increases, the compressor work demand from the turbine has decreased.

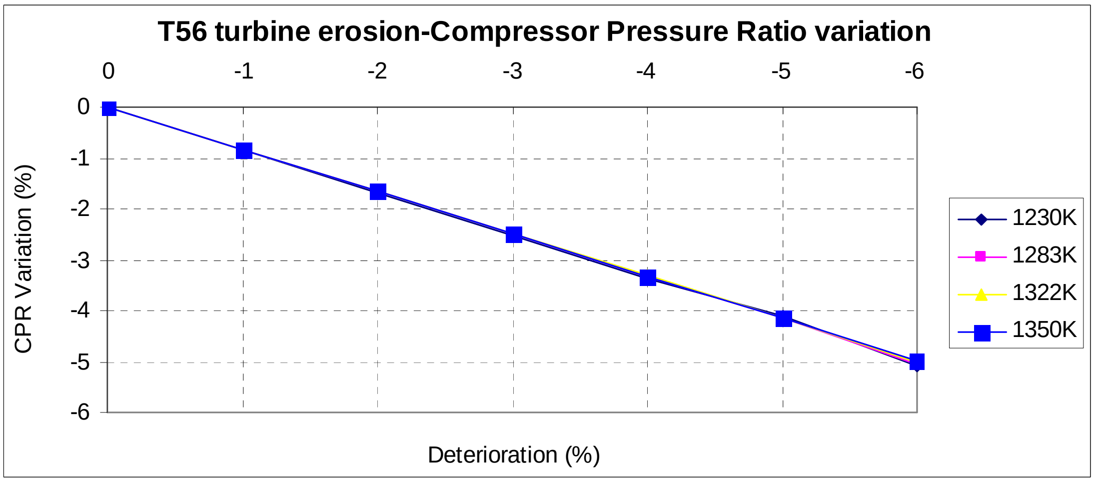

Figure 4.9.CPR variation for T56 turbine erosion

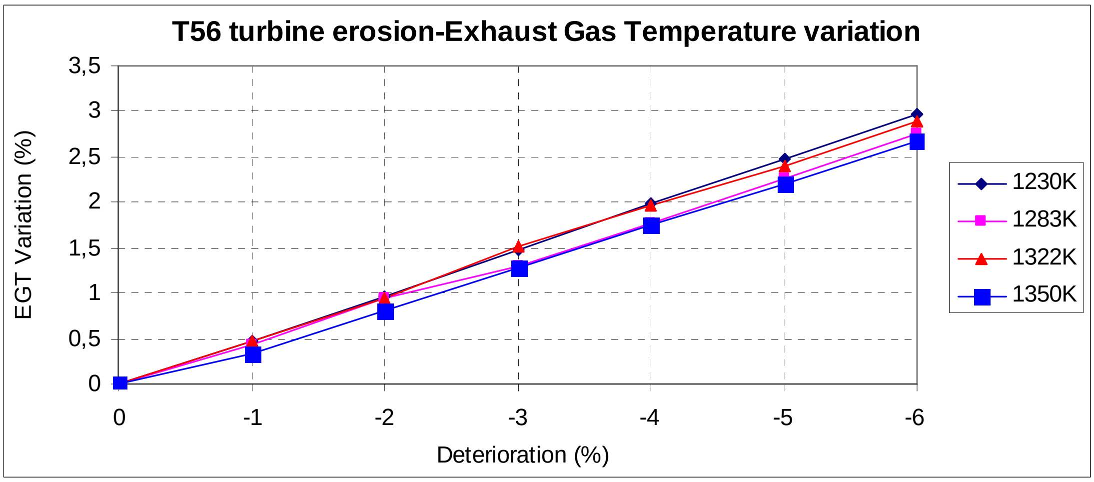

Figure 4.10.EGT variation for T56 turbine erosion

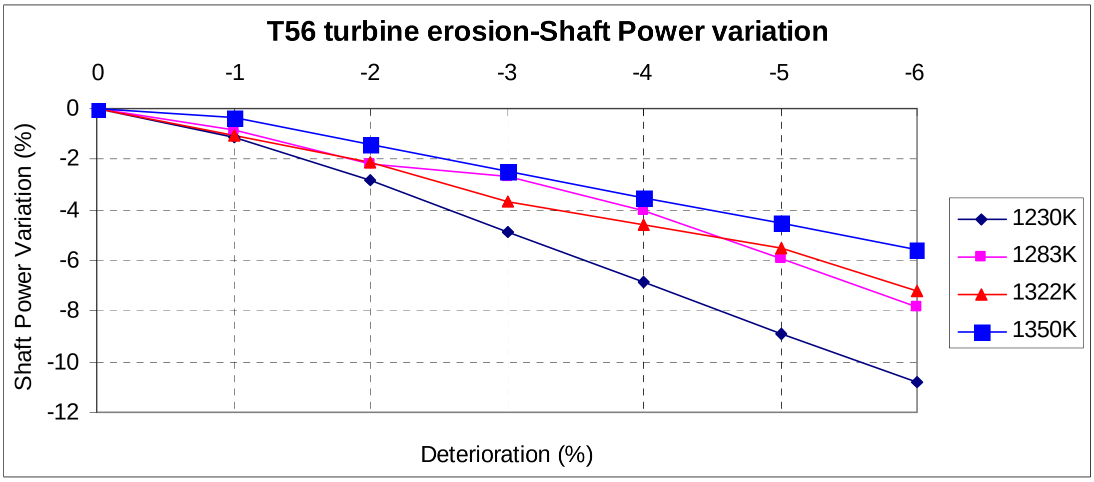

Figure 4.11.Shaft Power variation for T56 erosion

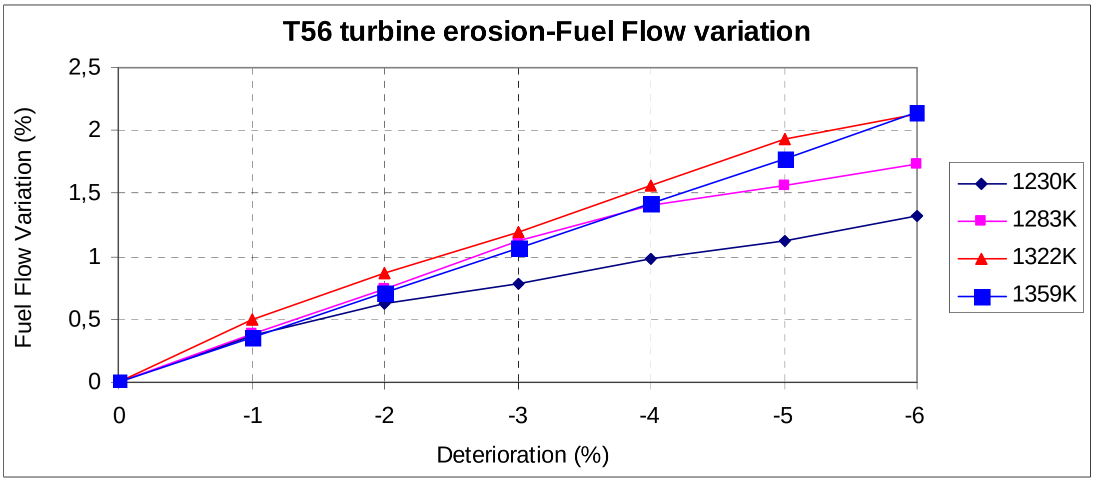

Figure 4.12.Fuel Flow variation for T56 erosion

4.4. The F110–GE–129 engine

4.4.1. Compressor fouling

The effect of compressor fouling on the F110–GE–129 engine was studied for two different situations: (i) if only the Low Pressure Compressor (the Fan) is fouled and the High Pressure Compressor (the Core) experiences an insignificant amount of fouling and (ii) if both the Low Pressure Compressor and the High Pressure Compressor are fouled with the same amount of deterioration.

Pressure Ratio: As seen from Figures 4.13 and 4.14, there is a reduction in pressure ratio due to the effects of engine re-matching with the reduced compressor mass flow. The turbine inlet NGV's are chocked, hence the compressor delivery pressure falls in order to satisfy the non-dimensional mass flow requirement of the turbine. What needs to be emphasized here is that if only the LPC is fouled there is a moderate reduction in pressure ratio. However, the reduction becomes significant (more than double) if both the LPC and the HPC are fouled. This can be easily explained if the reduction in mass flow is considered (Figures 4.15 and 4.16), since the LPC deterioration causes a 3-4% reduction only, whereas the simultaneous LPC and HPC deterioration causes an average 13% reduction in mass flow.

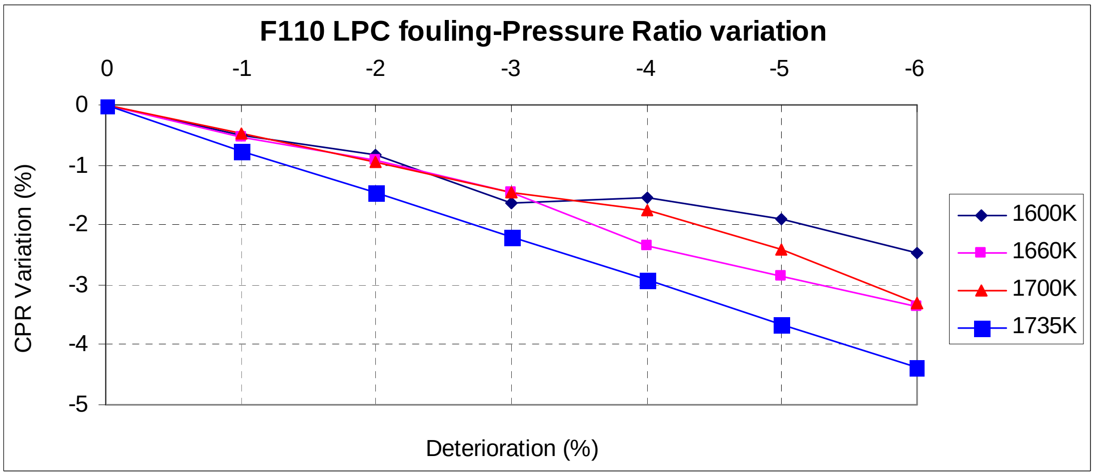

Figure 4.13.Pressure Ratio variation for F110 LPC fouling

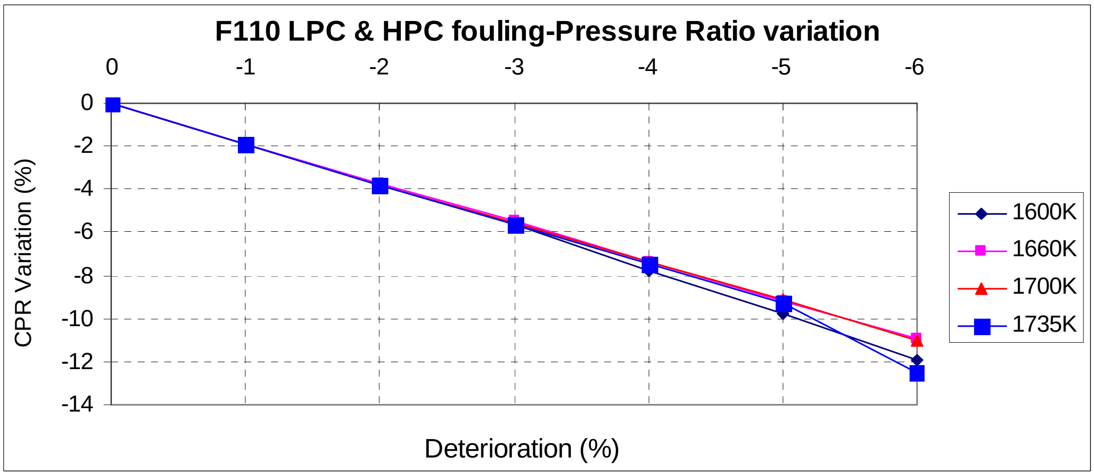

Figure 4.14.Pressure Ratio variation for F110 LPC & HPC fouling

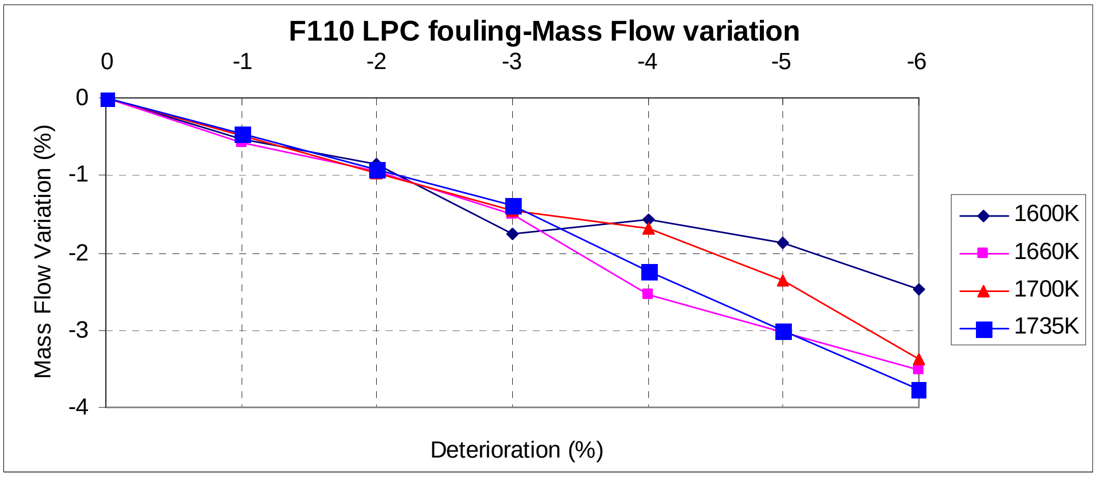

Figure 4.15.Mass Flow variation for F110 LPC fouling

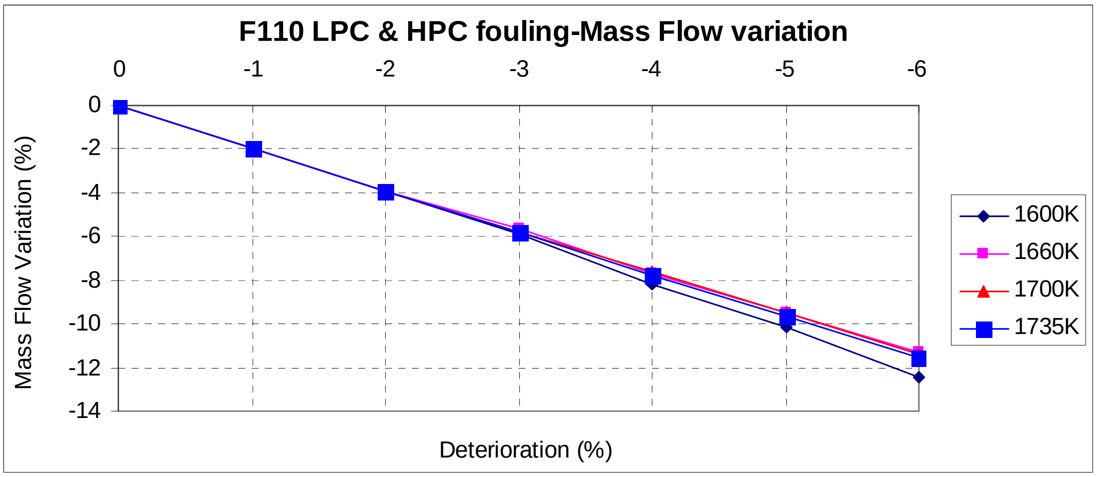

Figure 4.16.Mass flow variation for F110 LPC & HPC fouling

Net Thrust: Another significant result of the F110 compressor fouling is the drop in the two prime engine performance parameters, namely the Net Thrust and the Specific Thrust. If only the LPC is fouled, a linear drop in Net Thrust is observed (Figure 4.17), which is proportional to the amount of deterioration experienced. However, if both the LPC and the HPC are fouled, then the drop in engine performance is significant, since Net Thrust decreases with a steep angle (Figure 4.18).

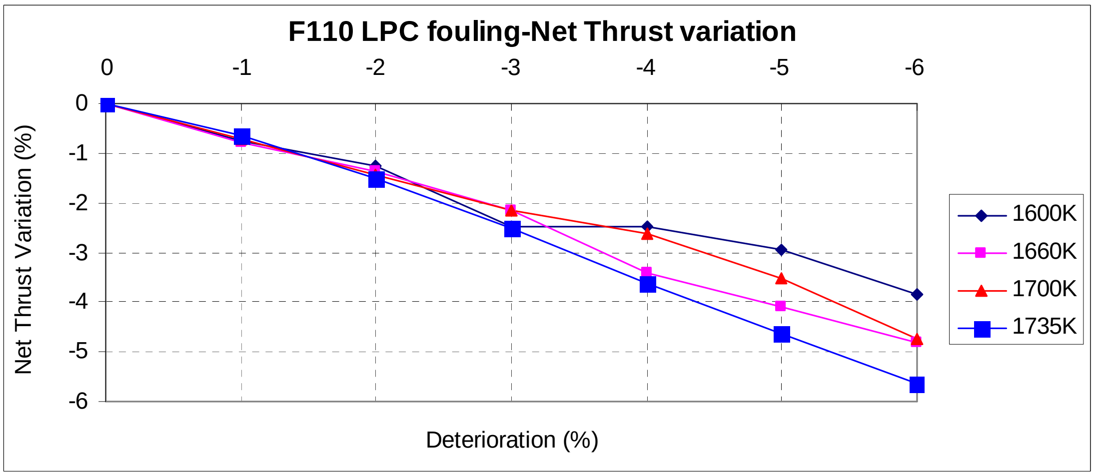

Figure 4.17.Net Thrust variation for F110 LPC fouling

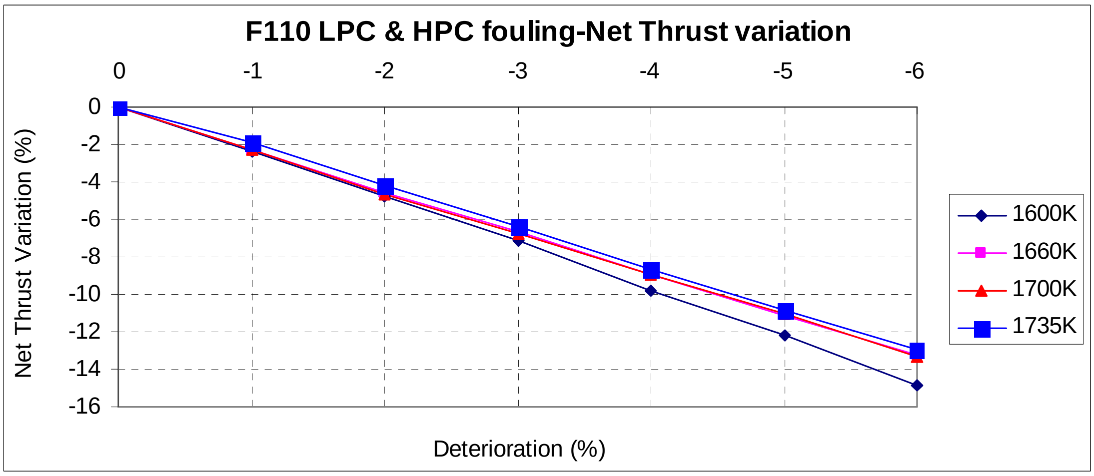

Figure 4.18.Net Thrust variation for F110 LPC & HPC fouling

Specific Thrust: As far as Specific Thrust is concerned, in the case of the LPC fouling, the reduction of mass flow rate is almost equal with the reduction in the Net Thrust available (Figure 4.19) and, thus, the effect on Specific Thrust is minimal (1.5% for 6% fouling). Similarly, if both compressors are equally fouled, although the reduction in mass flow is significant, it is balanced by an analogous reduction in Net Thrust and therefore a moderate (2%) variation is observed (Figure 4.20). However, what needs to be noticed here is that as TET increases, the reduction in Specific Thrust decreases, since in higher TETs the engine is more efficient.

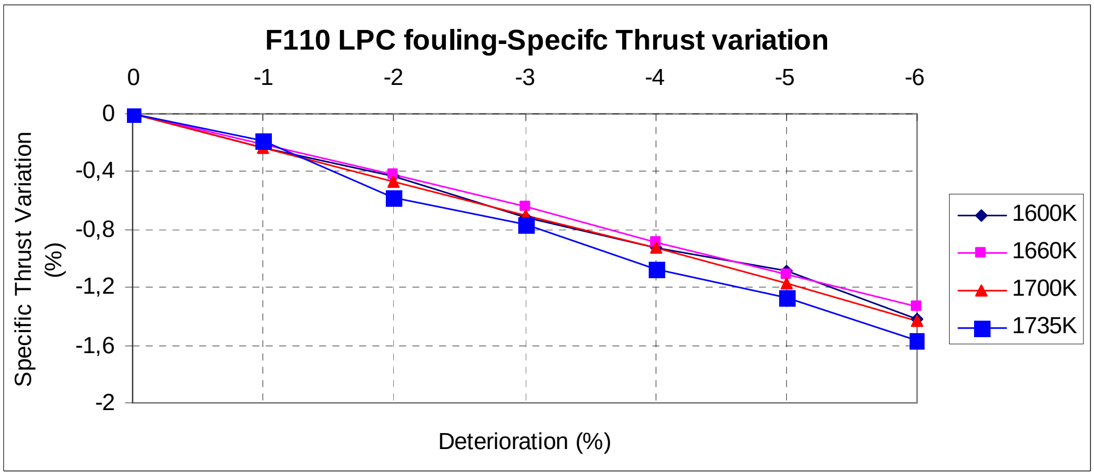

Figure 4.19.Specific Thrust variation for F110 LPC fouling

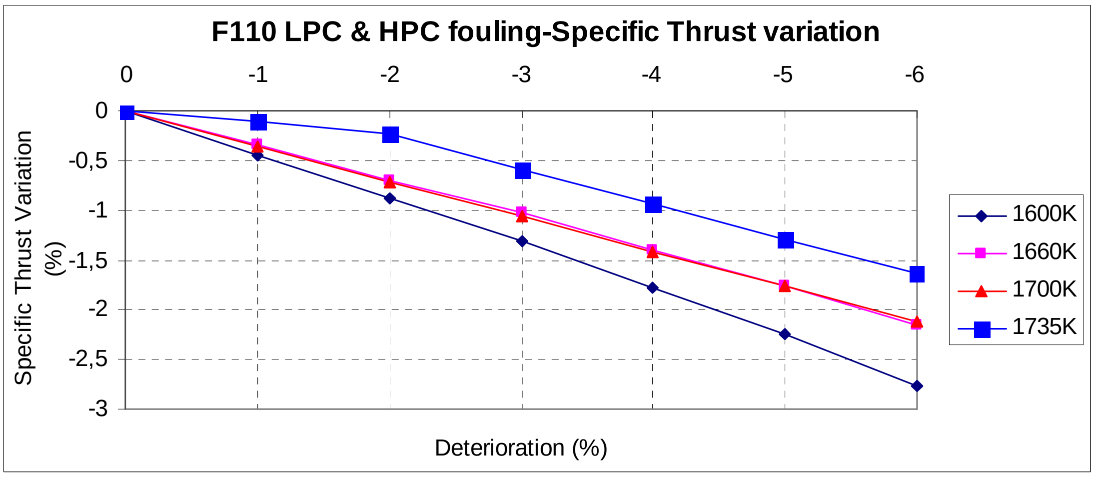

Figure 4.20.Specific Thrust variation for F110 LPC & HPC fouling

Fuel Flow: A reduction in fuel flow occurs (as it is expected) as a result of the drop in compressor flow capacity, as less air needs to be heated in the combustor. The reduction in fuel flow is again proportional to the reduction in mass flow, since, if only the LPC is fouled the reduction is moderate (3-4%) for the maximum deterioration (Figure 4.21), whereas, if both (the LP and the HP) compressors are equally fouled by a 6% deterioration, there is a 10% reduction in the fuel needed (Figure 4.22).

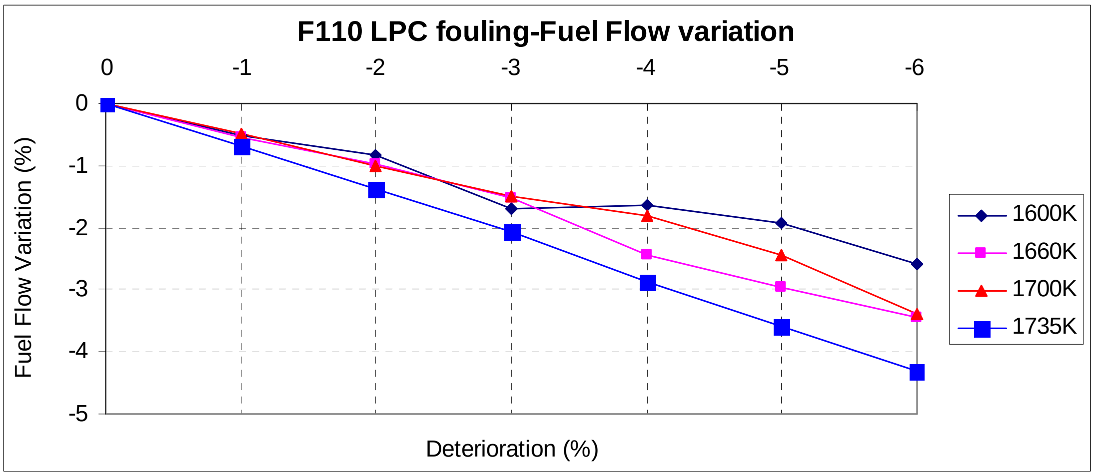

Figure 4.21.Fuel Flow variation for F110 LPC fouling

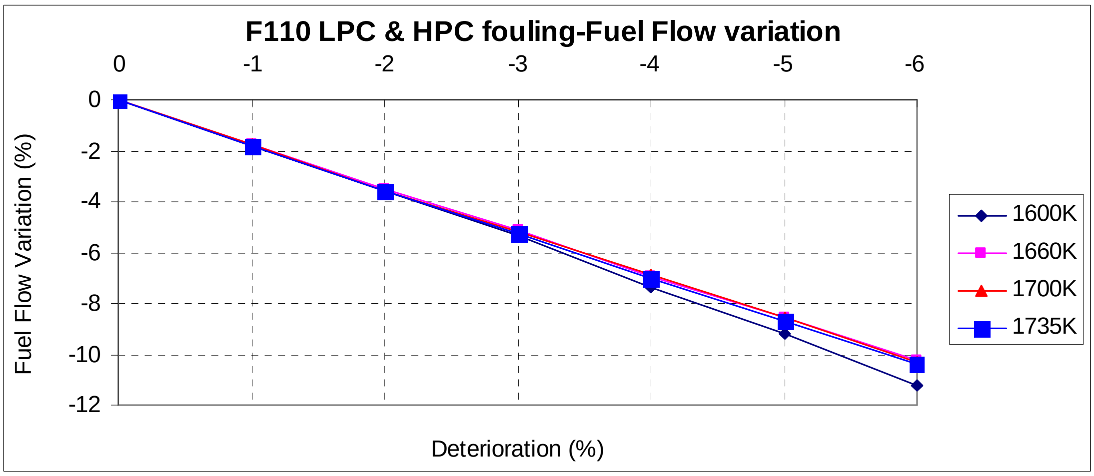

Figure 4.22.Fuel Flow variation for F110 LPC & HPC fouling

Specific Fuel Consumption: The effects of compressor fouling are not so severe to the SFC of the F110 engine. Since the overall pressure ratio is decreased the SFC is expected to increase. Also, although the fuel needed is decreased, the SFC is increased, since the reduction in Net Thrust predominates over the reduction in the fuel flow rate.

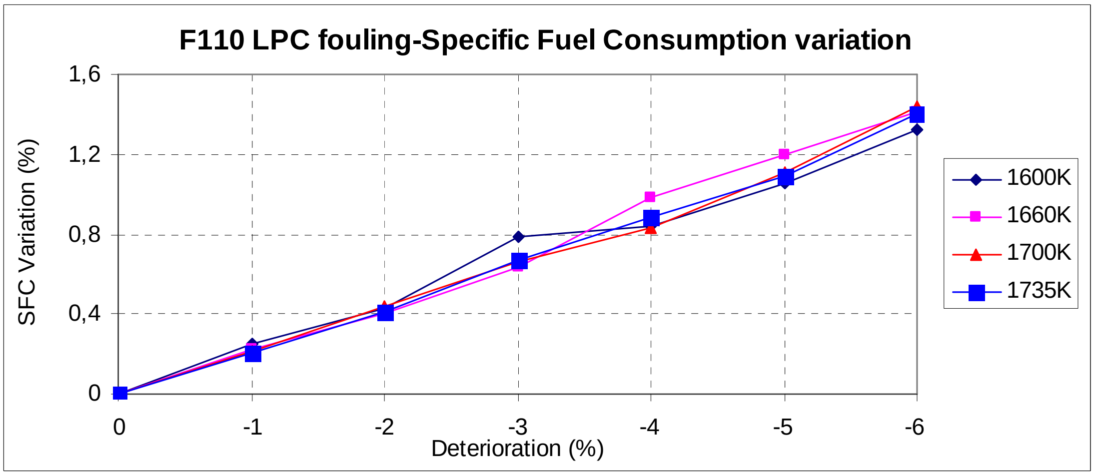

Figure 4.23.SFC variation for F110 LPC fouling

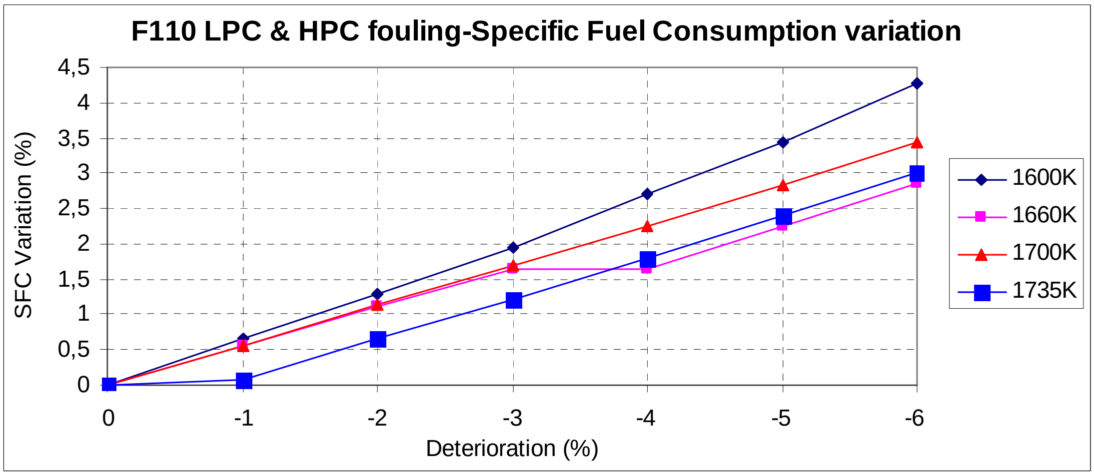

Figure 4.24.SFC variation for F110 LPC & HPC fouling

4.4.2. Turbine fouling

The effects of High Pressure and Low Pressure Turbine (HPT and LPT respectively) fouling on the F110 measured performance parameters are shown in Figures 4.25 to 4.30 below. As can be noticed from the plots, although the decrease in the Overall Pressure Ratio is quite similar as it was for compressor fouling the drop in mass flow rate is much bigger. Moreover, the decrease of Specific Thrust is becoming noticeable only if the deterioration percentage is more than 5%, since the deterioration percentages of Net Thrust and mass flow (although high enough) are quite similar. Finally, the increase of Specific Fuel Consumption is more for this case than it was for compressor fouling, because the deterioration of Net Thrust is more rapid than the deterioration of fuel flow.

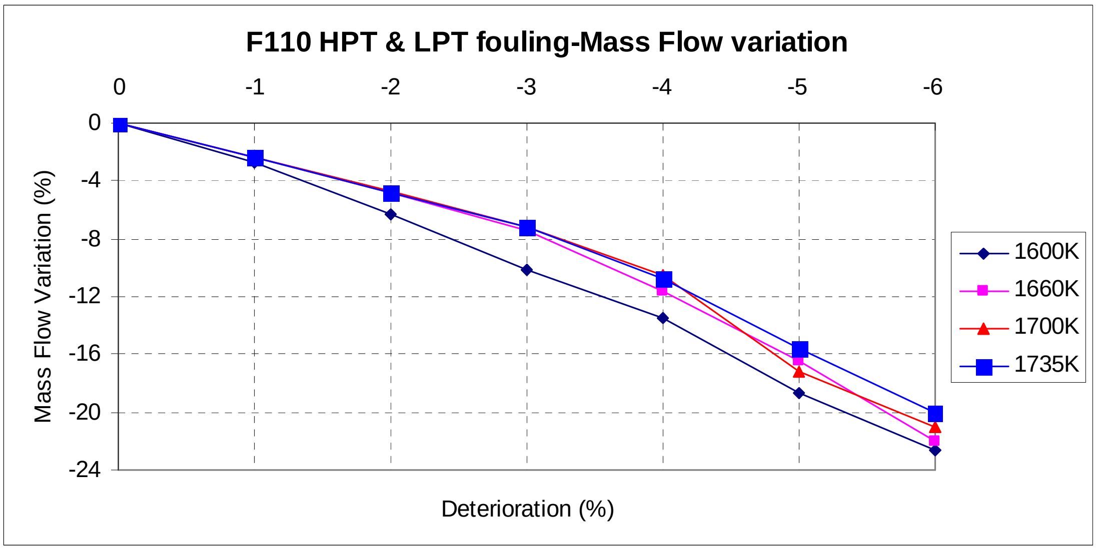

Figure 4.25.Mass Flow variation for F110 HPT & LPT fouling

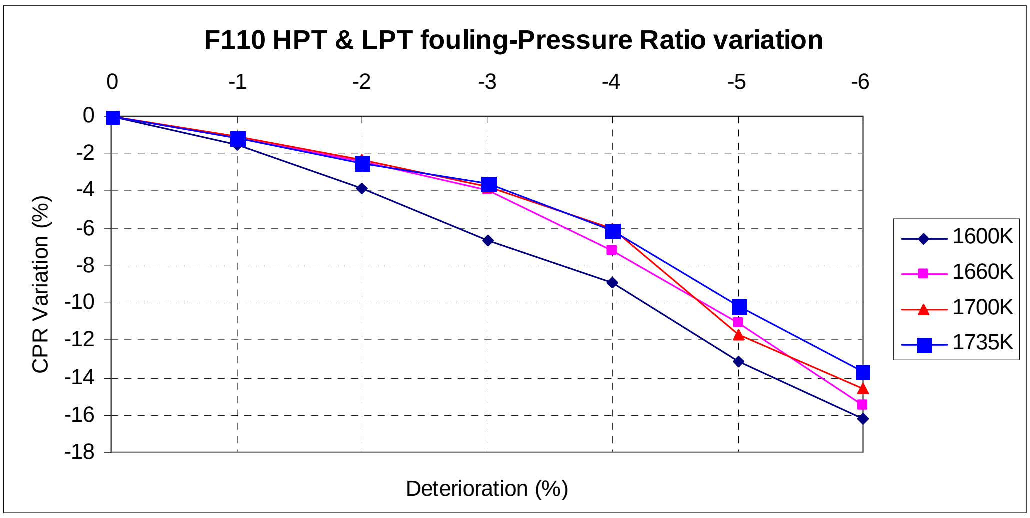

Figure 4.26.Pressure Ratio variation for F110 HPT & LPT fouling

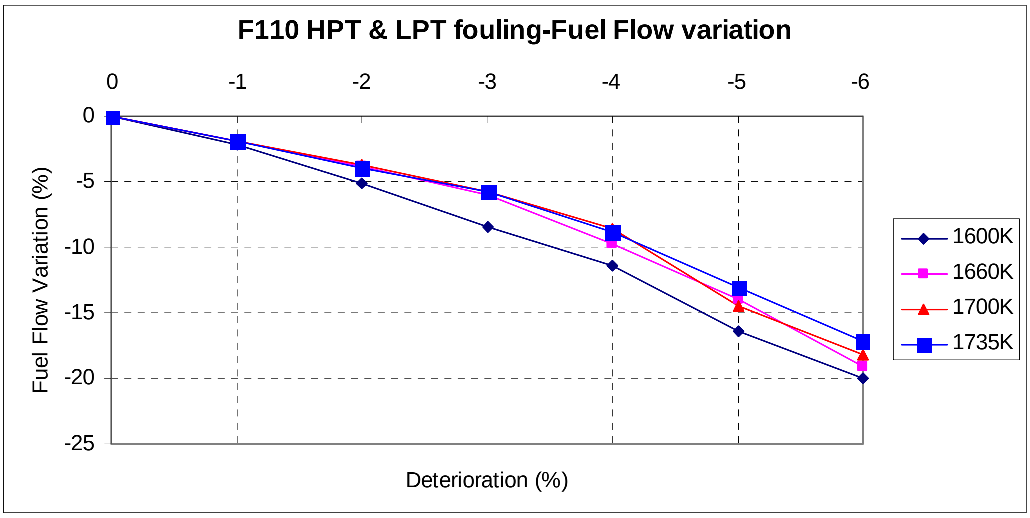

Figure 4.27.Fuel Flow variation for F110 HPT & LPT fouling

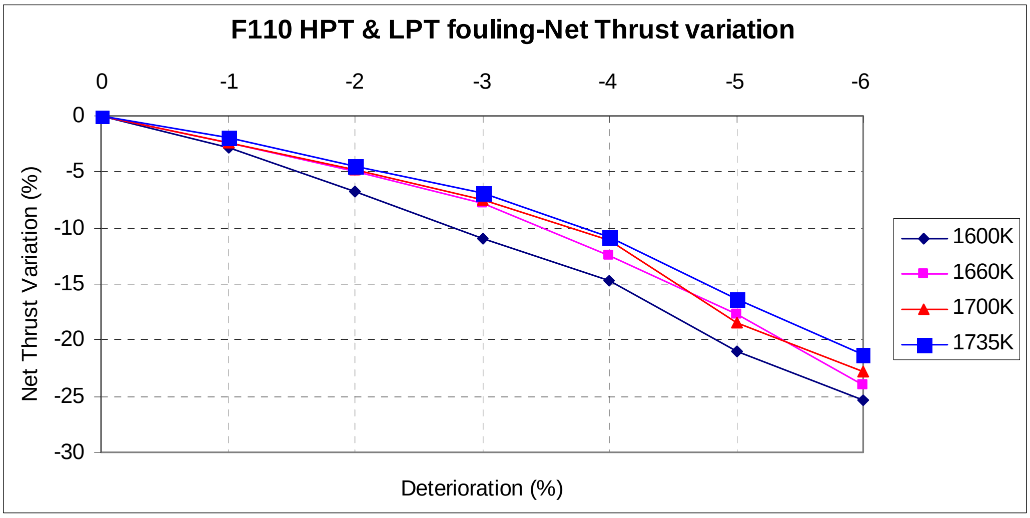

Figure 4.28.Net Thrust variation for F110 HPT & LPT fouling

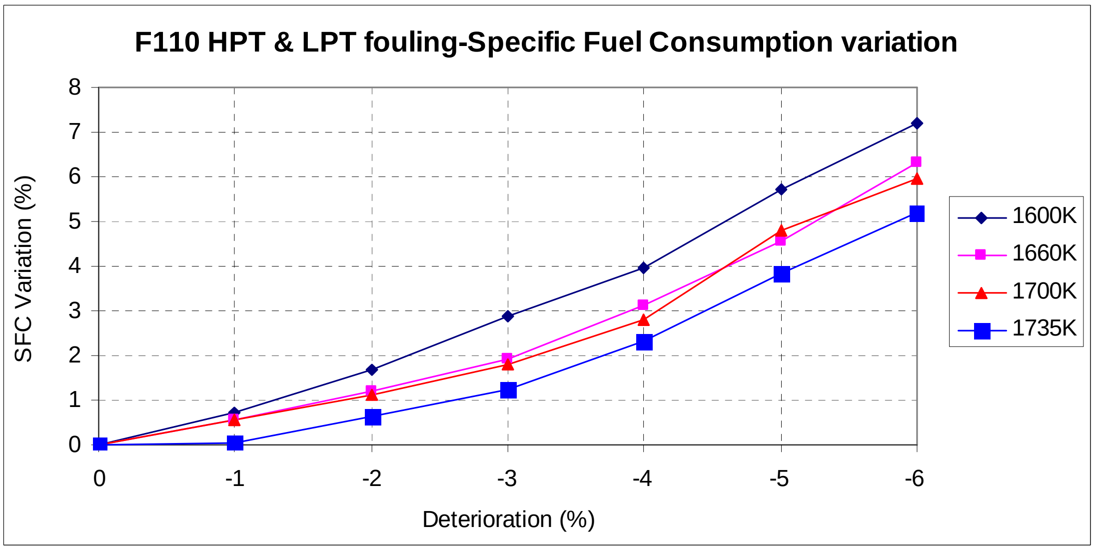

Figure 4.29.SFC variation for F110 HPT & LPT fouling

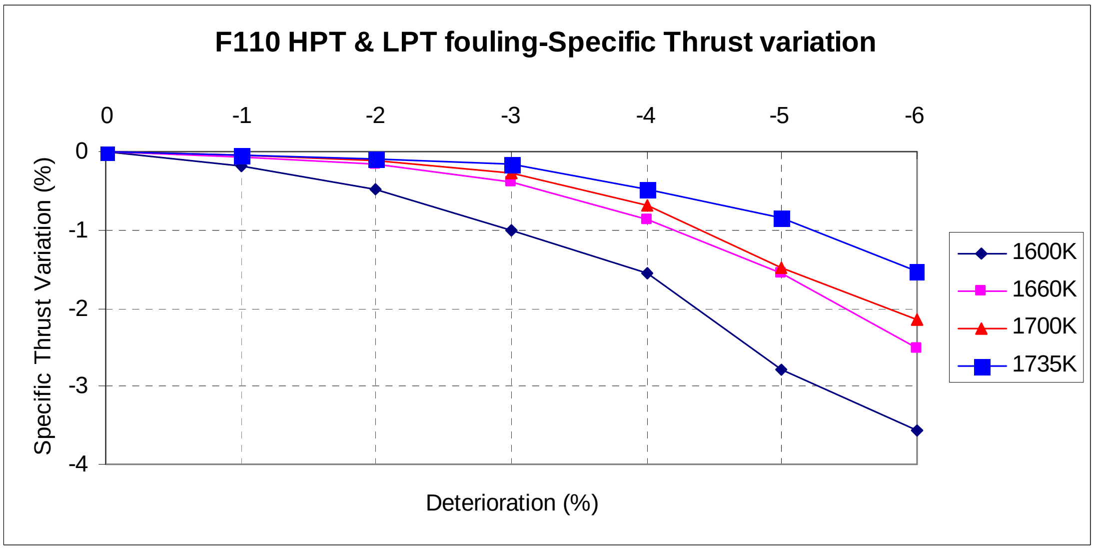

Figure 4.30.Specific Thrust variation for F110 HPT & LPT fouling

4.4.3. Turbine erosion

The last case simulated is the erosion of both the High and the Low Pressure Turbine of the F110 engine. The effects of turbine erosion to the F110 dependent parameter deltas are shown in the following graphs.

Turbine erosion causes a decrease in the mass flow rate and a decrease in the overall pressure ratio. As seen from Figure 4.31 below a 1% deterioration will cause a 2% decrease in the engine's pressure ratio. Moreover, the fuel flow will also decrease because of the decrease in mass flow, but since the fuel flow reduction will be slower than the Net Thrust drop, the Specific Fuel Consumption will increase by around 4-6% for the various TETs, if the maximum deterioration (6%) is experienced. Finally, a minor decrease in Specific Thrust is experienced because mass flow and Net Thrust follow a quite similar degree of reduction for the TETs studied.

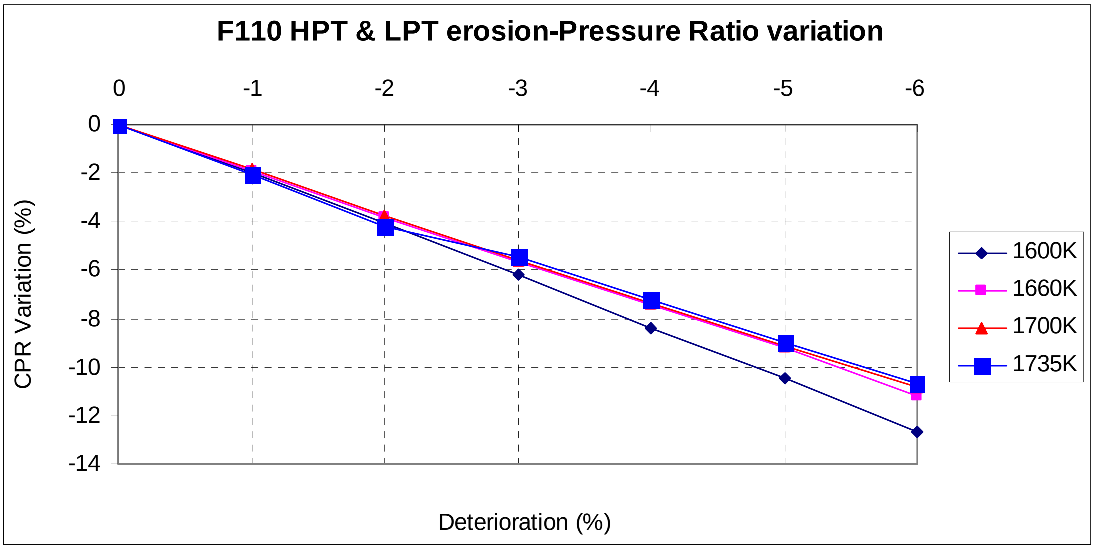

Figure 4.31.Pressure Ratio variation for F110 HPT & LPT erosion

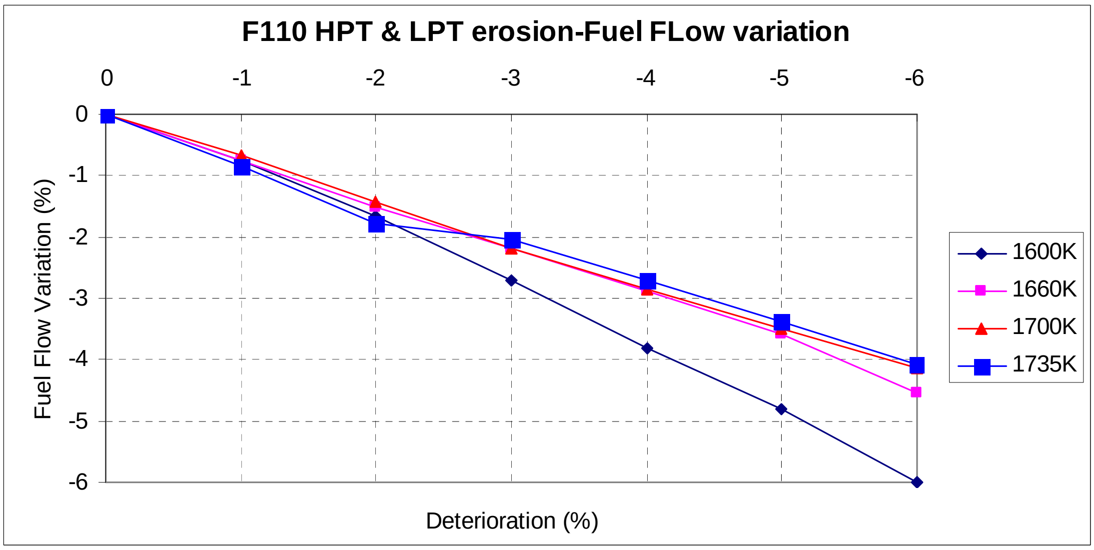

Figure 4.32.Fuel Flow variation for F110 HPT & LPT erosion

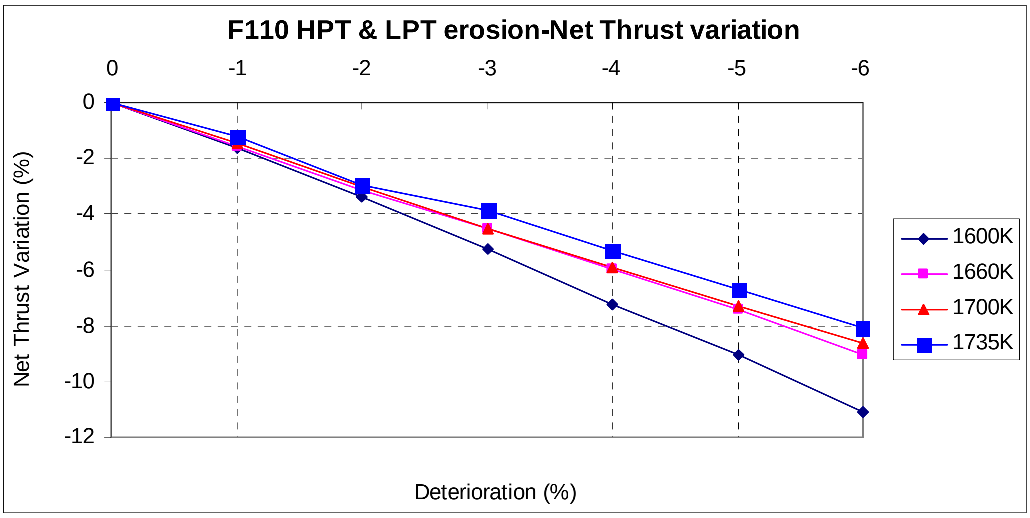

Figure 4.33.Net Thrust variation for F110 HPT & LPT erosion

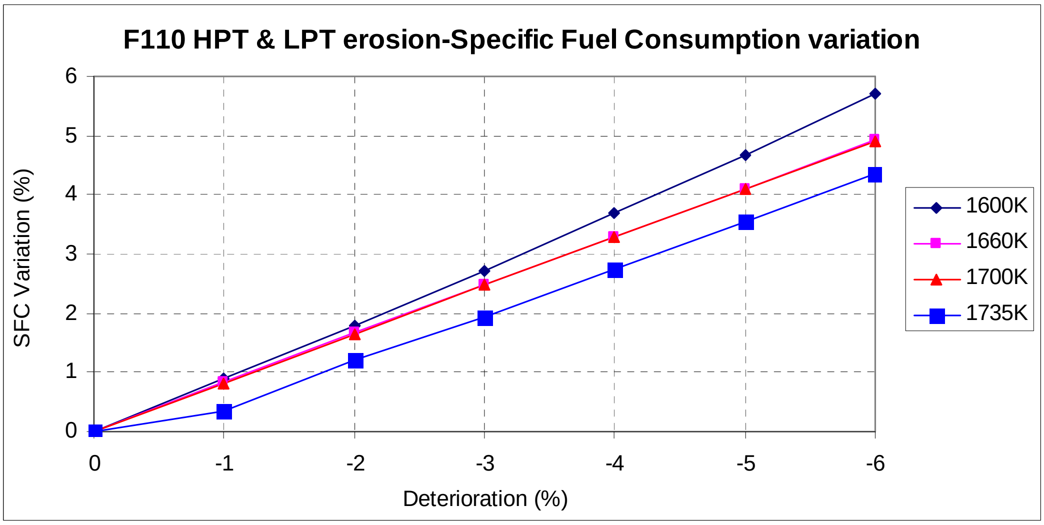

Figure 4.34.SFC variation for F110 HPT & LPT erosion

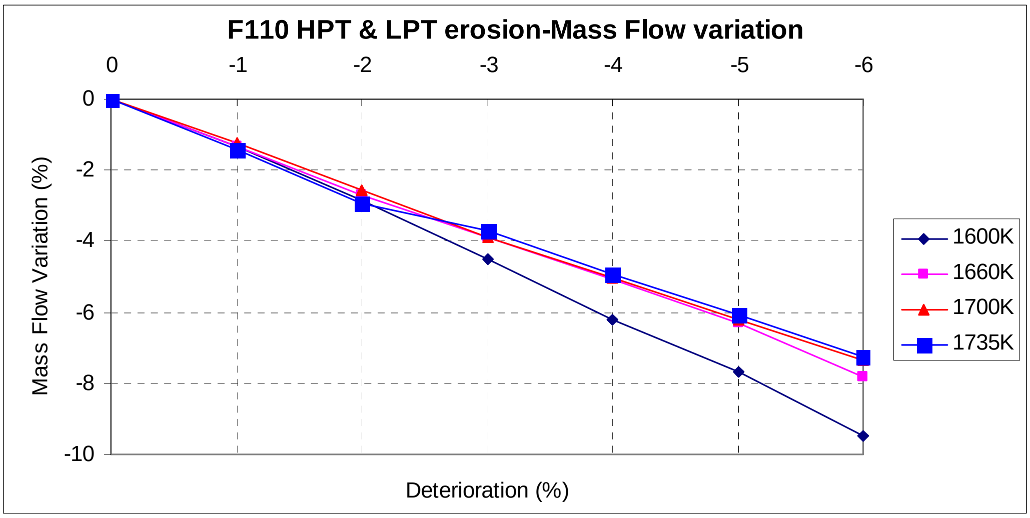

Figure 4.35.Mass Flow variation for F110 HPT & LPT erosion

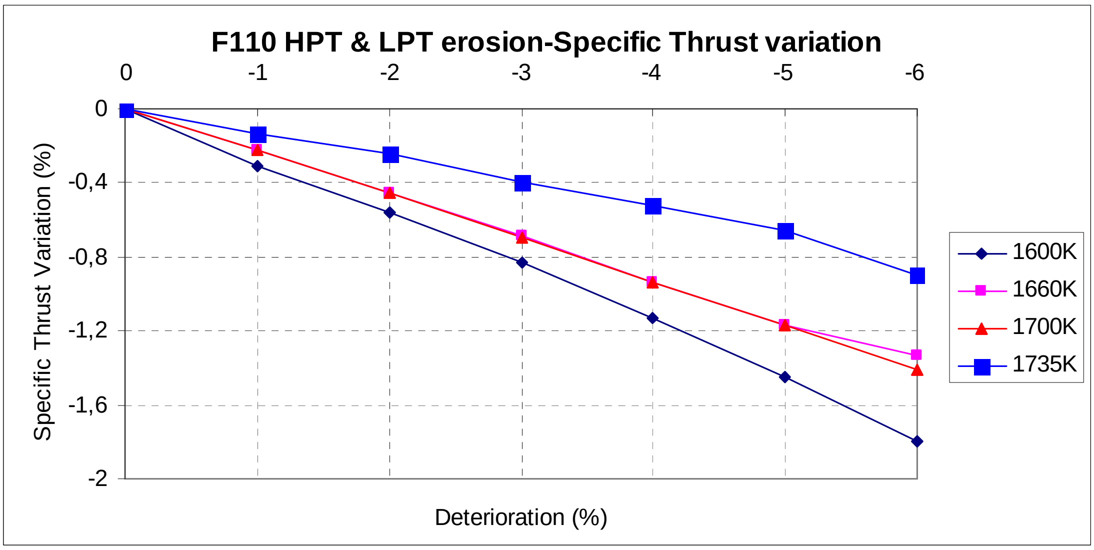

Figure 4.36.Specific Thrust variation for F110 HPT & LPT erosion

5. OPERATIONAL EFFECTIVENESS ANALYSIS

In order to represent the effect of engine deterioration (compressor fouling) upon the operational effectiveness of an aircraft, focusing especially in extra fuel consumed and extra time needed to complete a mission, a case study will be carried out: the F-16's F110 engine compressor fouling will be studied more thoroughly, and the results will be analyzed from an operational point of view.

5.1. Mission Profiles

The F-16 is used by the various air forces all over the world for a wide variety of mission types, such as air intercept, air combat, air-to-ground, cross-country and low-level navigation. Some missions will be more severe in terms of life and fuel usage, due to the reason that different missions are flown at different altitude, Mach number and power setting. More importantly, the range of ambient ground temperatures for the above mission types is very important. In places with high average ambient temperatures such as Greece, the US, Australia or the Middle East, one can expect to endure more severe life usage indices accumulation rates but better (lower) SFC for the same mission profile. On the other hand, in colder climates lower life usage accumulation rates will be met along, however, with higher SFC. Temperature effects will not be taken into account in this study. Obviously, some account of seasonal or even daily variations in temperatures would also need to be considered by any agency investigating the effect of fuel usage on the availability of their particular application [43].

5.2. Mission Analysis

For the purpose of analysis in this study, after a brief survey with Hellenic Air Force pilots, the following two missions (representing typical roles of the F-16 aircraft) have been assumed, as being the most popular ones:

- Mission A (Air–to–Air role)
- Mission B (Air–to–Ground role)

For the purpose of fuel and mission analysis the values of thrust, fuel flow and specific fuel consumption have been used, as determined in chapter 4. The data related to the aircraft that is required is as follows.

Table 5.1.F-16 aircraft data [Jane's, 2007]

Wings, Gross	27.88 m^2
Wing span	9.45 m^2
Take-off Weight	12000 kg (Mission A)
	15000 kg (Mission B)

5.3. Mission A

This mission is based on the assumption that the aircraft is in readiness condition, 400 km away from the air target, and that the National Centre of Air Defence orders a quick take-off (a “scramble”) of all the available aircrafts, when enemy aerial offensive action begins. The mission can be broken down into the following stages:

A.	Short Take-Off:	At Mach 0.3 (Reheat ON)
B.	Climb & Acceleration:	Sea Level to 8000 m from Mach 0.3 to 0.8
C.	Acceleration:	From Mach 0.8 to Mach 1.5 at 8000 m
D.	Cruise to Target (400km from home base):	At 8000 m and Mach 1.5
E.	Air Combat:	At an average Thrust-to-Weight ratio of 0.75 descending from 8000 m to 3000 m in 3 minutes (Reheat ON)
F.	Re-Climb:	3000 m to 8000 m at Mach 0.8
G.	Re-Acceleration:	From Mach 0.8 to Mach 1.5 at 8000 m
H.	Cruise-Back to Descend Point (45 km away from home base)	At 8000 m and Mach 1.5
J.	Decelerate & Descend to Land	
K.	Land	

The detailed analysis for this mission is carried out in Appendix C. For simplicity, a decision has been taken not to present the intermediate states of deterioration (1-5%), and only the worst case scenario is of major interest in this report. Table 5.2 and 5.3 illustrate a summary of the performance characteristics of mission A, for a clean engine and for a 6% deteriorated engine.

Table 5.2.Performance data (mission A) of a clean engine

	MACH NO.	ALTITUDE	NET THRUST	FUEL FLOW	SFC	SPECIFIC THRUST
		(m)	(N)	(kg/sec)	(mg/N sec)	(N/kg/sec)
A(s)	0,000	0,0	141070	7,77	55,09	1143
A(f)	0,300	0,0	133270	7,92	59,44	1057
B(s)	0,300	0,0	67610	1,39	20,63	536
B(f)	0,800	8000,0	34856	0,84	23,97	470
C(s)	0,800	8000,0	34856	0,84	23,97	470
C(f)	1,500	8000,0	36878	1,07	29,12	376
D(0)	1,500	8000,0	36878	1,07	29,12	376
D(1)	1,500	8000,0	36878	1,07	29,12	376
E(s)	1,200	8000,0	97928	5,75	58,71	1065
E(f)	1,200	3000,0	121970	7,78	63,75	960
F(s)	0,800	3000,0	51105	1,27	24,88	443
F(f)	0,800	8000,0	34854	0,84	23,97	470
G(s)	0,800	8000,0	34856	0,84	23,97	470
G(f)	1,500	8000,0	36878	1,07	29,12	376
H(s)	1,500	8000,0	36881	1,07	29,12	376
H(f)	1,500	8000,0	36881	1,07	29,12	376
J(s)	1,500	8000,0	36881	1,07	29,12	376
J(f)	0,300	0,0	67610	1,39	20,63	536
K(s)	0,300	0,0	67610	1,39	20,63	536
K(f)	0,000	0,0	77559	1,37	17,63	629

Table 5.3.Performance data (mission A) of a 6% deteriorated engine

	MACH NO.	ALTITUDE	NET THRUST	FUEL FLOW	SFC	SPECIFIC THRUST
		(m)	(N)	(kg/sec)	(mg/N sec)	(N/kg/sec)
A(s)	0,000	0,0	131195	7,21	55,81	1120
A(f)	0,300	0,0	123941	7,35	60,34	1035
B(s)	0,300	0,0	62877	1,29	20,90	525
B(f)	0,800	8000,0	32416	0,78	24,12	460
C(s)	0,800	8000,0	32416	0,78	24,12	460
C(f)	1,500	8000,0	34297	1,00	29,56	368
D(0)	1,500	8000,0	34297	1,00	29,56	368
D(1)	1,500	8000,0	34297	1,00	29,56	368
E(s)	1,200	8000,0	91073	5,34	59,60	1043
E(f)	1,200	3000,0	113432	7,22	64,71	941
F(s)	0,800	3000,0	47528	1,18	25,14	434
F(f)	0,800	8000,0	32414	0,78	24,12	460
G(s)	0,800	8000,0	32416	0,78	24,12	460
G(f)	1,500	8000,0	34297	1,00	29,56	368
H(s)	1,500	8000,0	34299	1,00	29,56	368
H(f)	1,500	8000,0	34299	1,00	29,56	368
J(s)	1,500	8000,0	34299	1,00	29,56	368
J(f)	0,300	0,0	62877	1,29	20,90	525
K(s)	0,300	0,0	62877	1,29	20,90	525
K(f)	0,000	0,0	72130	1,27	17,83	616

5.4. Mission B

This mission is based on the assumption that, in case of a ground attack, the aircraft requires to operate at low level, and that the extra equipment required to be carried is hung, in addition to air defence weapons carried externally on the aircraft. It is also assumed that the target is at about 800 km from home base. Experience with the current generation of fighters clearly indicates that any air superiority fighter design, where performance optimization is made at medium level for the air-to-air role, will have a natural capability to operate at medium to low level in the offensive support role [43]. This mission can be broken down into the following stages:

A.	**Short Take-Off:**	**At Mach 0.3 (REHEAT ON)**
B.	Climb & Acceleration:	Sea Level to 200 m from Mach 0.3 to 0.8
C.	High speed/low level to target (800km from home base):	At 200 m and Mach 0.8
D.	Air Combat:	At an average Thrust-to-Weight ratio of 0.70 for 3 minutes (REHEAT ON)
E.	Low level pass over target:	At Mach 0.95 and 200 m for 20 sec
F.	Cruise-Back to Descend Point (3 km away from home base)	At 200 m and Mach 0.85
G.	Decelerate & Descend to Land	
H.	Land	

Stage wise, the detailed analysis for mission B is given in Appendix C. Also, similarly to mission A, Table 5.4 and 5.5 illustrate the performance characteristics of mission B for a clean engine and for a 6% deteriorated engine.

Table 5.4.Performance data (mission B) of a clean engine

	MACH NO.	ALTITUDE	NET THRUST	FUEL FLOW	SFC	SPECIFIC THRUST
		(m)	(N)	(kg/sec)	(mg/N sec)	(N/kg/sec)
A(s)	0,00	0,0	141070	7,77	55,09	1143
A(f)	0,30	0,0	133270	7,92	59,44	1057
B(s)	0,30	0,0	67610	1,39	20,63	536
B(f)	0,80	200,0	50551	1,40	27,70	470
C(s)	0,80	200,0	50551	1,40	27,70	470
C(f)	0,80	200,0	50551	1,40	27,70	376
D(s)	0,80	200,0	117760	7,88	66,92	376
D(f)	0,80	200,0	117760	7,88	66,92	376
E(s)	0,95	200,0	46615	1,40	29,95	1065
E(f)	0,95	200,0	46615	1,40	29,95	960
F(s)	0,85	200,0	49318	1,40	28,42	443
F(f)	0,85	200,0	49318	1,40	28,42	470
G(s)	0,85	200,0	49318	1,40	28,42	470
G(f)	0,30	0,0	67610	1,39	20,63	376
H(s)	0,30	0,0	67610	1,39	20,63	376
H(f)	0,00	0,0	77559	1,37	17,63	376

Table 5.5.Performance data (mission B) of a clean engine

	MACH NO.	ALTITUDE	NET THRUST	FUEL FLOW	SFC	SPECIFIC THRUST
		(m)	(N)	(kg/sec)	(mg/N sec)	(N/kg/sec)
A(s)	0,00	0,0	131195	7,21	55,81	1120
A(f)	0,30	0,0	123941	7,35	60,34	1035
B(s)	0,30	0,0	62877	1,29	20,90	525
B(f)	0,80	200,0	47012	1,31	28,06	460
C(s)	0,80	200,0	47012	1,31	28,06	460
C(f)	0,80	200,0	47012	1,31	28,06	368
D(s)	0,80	200,0	109516	7,31	67,58	368
D(f)	0,80	200,0	109516	7,31	67,58	368
E(s)	0,95	200,0	43351	1,32	30,15	1043
E(f)	0,95	200,0	43351	1,32	30,15	941
F(s)	0,85	200,0	45866	1,31	28,63	434
F(f)	0,85	200,0	45866	1,31	28,63	460
G(s)	0,85	200,0	45866	1,31	28,63	460
G(f)	0,30	0,0	62877	1,29	20,90	368
H(s)	0,30	0,0	62877	1,29	20,90	368
H(f)	0,00	0,0	72130	1,27	17,83	368

5.5. Operational Effectiveness Evaluation

Mission Operational Effectiveness (MOE) varies from user to user. For this particular study it is defined as the capability to complete a mission under specific circumstances. Following, arbitrary limitations and assessment criteria have been assumed for the purpose of definition of the overall effectiveness evaluation [Naeem, 1996]:

i. Limitations

- Overall 70% missions A and 30% missions B are to be flown.
- Each aircraft is to fly equal number of missions A and B.
- Mission is to be aborted in the following cases:
    - The aircraft is unable to climb to a specified altitude
    - The aircraft is unable to achieve a specified Mach number
    - The aircraft is unable to achieve a specified T/W ratio.

ii. Assessment criteria

a. Operational effectiveness reduces at a rate of 20% per 1% increase in fuel consumption.

b. Operational effectiveness reduces at a rate of 0.5% per 1 second increase in required mission time.

c. In case of mission abort operational effectiveness reduces to 0%, irrespective of fuel consumption and mission required time.

d. For the purpose of overall mission effectiveness evaluation, the following expressions are used:

$$(MOE)_{OV.} = [0.7*(MOE_A)_{FW} *(MOE_A)_{time}] + [0.3*(MOE_B)_{FW} *(MOE_B)_{time}]$$

Where $(MOE_A)_{FW} = 1 - [0.2*(\%\Delta FW_A)]$ and
$(MOE_B)_{FW} = 1 - [0.2*(\%\Delta FW_B)]$ and also,
$(MOE_A)_{TIME} = 1 - [0.005*(\Delta t_A)]$ and
$(MOE_B)_{TIME} = 1 - [0.005*(\Delta t_B)]$

$$(MOE_A)_{FW} = 1 - [0.2*(\%\Delta FW_A)] = 1 - (0.2*1.047) = 0.7906$$

$$(MOE_B)_{FW} = 1 - [0.2*(\%\Delta FW_B)] = 1 - (0.2*0.794) = 0.8412$$

$$(MOE_A)_{TIME} = 1 - [0.005*(\Delta t_A)] = 1 - (0.005*83.84) = 0.5808$$

$(MOE_B)_{TIME} = 1 - [0.005*(\Delta t_B)] = 1 - (0.005*1.78) = 0.9911$. Therefore,

$$(MOE)_{OV.} = [0.7*(MOE_A)_{FW} *(MOE_A)_{time}] + [0.3*(MOE_B)_{FW} *(MOE_B)_{time}]$$
$$= (0.7*0.7906*0.5808) + (0.3*0.8412*0.9911) = 0.3214 + 0.25 = 0.5715$$

Overall Mission Operational Effectiveness vs. Compressor Deterioration is shown in figure 5.1.

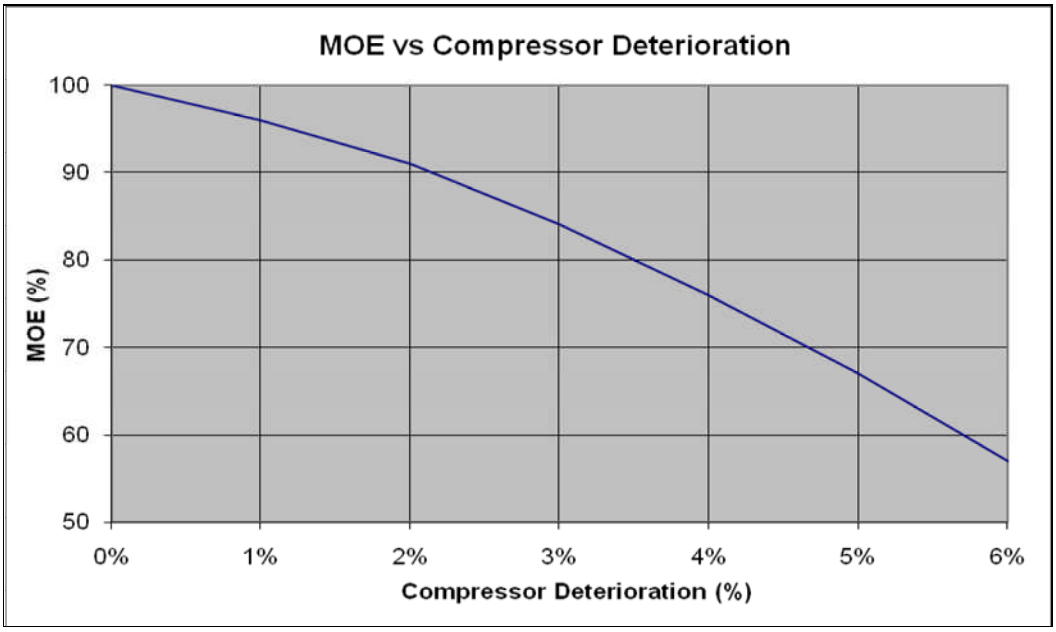

Figure 5.1.Mission Operational Effectiveness (%) vs. Compressor Deterioration (%)

5.6. Discussion of the Results

In the operation of an aircraft, the engines have the greatest influence on safety, economy of operation and performance than any other equipment, with the exception of the airframe. The influence of 'performance' is of major concern to the military aircraft whereas economy of operation is a priority in civil aviation, with safety in top spot of both users. Consequently, to maintain an acceptable level of safety, performance and economy in operating an aircraft, requires a great deal of attention to the integrity and performance levels of the engine fitted [45].

There are many criteria which contribute towards overall operational effectiveness of an aircraft. Among these, the fuel usage is the most important as the fuel consumed has a direct effect on the weapon carrying capability, range and the time to reach a target. The importance of these three factors for any military aircraft is well established.

Flight speed has a significant effect on the engine net thrust. Engine net thrust decreases with increasing flight speed at lower Mach Numbers, because momentum drug predominates whereas it increases with flight speed at higher Mach numbers, because as Mach number increases the ram compression starts to have more influence, increasing mass flow and nozzle pressure ratio and becomes the dominant effect. At a fixed TET condition the fuel flow also increases along with mass flow with increasing Mach No. Also, at constant Mach No, the net thrust, specific fuel consumption and fuel flow all decrease with increasing altitude, which is correct for a jet engine [43]. These facts are illustrated in Tables 5.2 and 5.4. Engine deterioration significantly affects the engine characteristics. Engine net thrust and fuel flow decrease, whereas specific fuel consumption increases continuously with increasing engine deterioration. Tables 5.3 and 5.5 illustrate this fact.

Time to take-off, time to climb to a specified altitude and time to accelerate to a specified flight speed all increase with the increase in engine deterioration for both missions A and B. This is due to less thrust available for deteriorated engine as compared with clean engine, which results in low acceleration during take-off roll and thus more time to attain take-off Mach number of 0.3. Also, the result of less available thrust for the deteriorated engine leads to lower best angle of climb and vertical speed of the aircraft and thereby more time to climb to a specified altitude. Finally, with reduced thrust available for a deteriorated engine, it becomes difficult for the aircraft to overcome the opposing drag. This reduces the acceleration, thus the aircraft is taking more time to attain a given flight speed. The result of all the above is the increase in the weight of fuel consumed in order to accomplish the above flight phases.

As far as actual fuel flow is concerned it is seen that it increases with increase in engine deterioration during cruise at specified flight speed. Therefore, more fuel is consumed for a deteriorated engine as compared with a clean engine for a fixed cruise distance. However, in this study the cruise distance is not fixed, rather the distance of target from home base is fixed. As the aircraft has already covered horizontal distance towards target during climb and acceleration stages, which varies with engine deterioration, as mentioned above, thus the remaining distance to be covered during cruise also varies (decreases) with engine deterioration. This results in reduction if fuel consumed and time for cruise to target with increasing engine deterioration in case of mission A. However, in case of mission B, fuel consumed increases with increasing engine deterioration, as the horizontal distance covered towards target during climb (S.L. to 200 m only) is less and has negligible effect on the remaining distance to be covered during cruise [44].

Especially in mission B the specific fuel consumption and the fuel flow (and thus the fuel consumed) continuously increases with increase in engine deterioration. What should be mentioned here is that, although in this study the air combat over battle zone stage is assumed to be at constant average thrust to weight ratio, however, aircraft with clean engine has an available thrust to weight ratio higher than that of aircraft with a deteriorated engine, and thus can enter into the ‘air combat’ phase at higher thrust to weight ratio if required [Naeem, 1996]. Moreover, the increase in fuel consumed for deteriorated engine is approximately 30% higher in case of mission B as compared with mission A. This is because of reducing specific fuel consumption with increasing altitude. As mission B is conducted at lower altitude and mission A at higher altitude, therefore fuel consumption is affected more in case of mission B than in mission A.

The increase in mission time with increasing engine deterioration is very large in case of mission A as compared to mission B. This is because of climb to a much higher altitude and acceleration to a supersonic Mach number in case of mission A. As lower climb and acceleration rates for aircraft with deteriorated engine are the two major causes of increase in mission time, therefore, mission time for mission A is affected most and the effect on mission time for mission B is negligible, as there is no acceleration to supersonic Mach number and climb is negligible (from S.L. to 200 m only) as compared with mission A [Naeem, 1996].

Another important point is that, if an aircraft with a clean engine is using the same fuel (same take-off and fuel weight) as an aircraft with a 6% deteriorated engine, it can carry an extra 30 kg (around 1% more) more of ammunition in both missions. The importance of this advantage for an aircraft with a clean engine is well established and cannot be ignored from operational effectiveness point of view.

Compressor fouling therefore reduces the mission operational effectiveness, which in turn can lead to many problems/complications that contribute towards operational inefficiency [45]. Some of them are listed below:

- In case of mass air raid at a target, normally the aircraft are required to take-off from different locations and meet at a specified TOT (Time on Target). The aircraft with the deteriorated engine will lag behind, because of low acceleration and more time required reaching at target and therefore negating the very spirit of mass raid at a target.

- In case of formation flying, the aircraft with deteriorated engine will not be able to accelerate to a specified flight speed, if this specified speed is very close to maximum achievable flight speed. This will result in mission abort and therefore will greatly reduce the mission operational effectiveness.

- In case of formation flying, when the specified flight speed is reasonably lower than the maximum achievable flight speed, although the aircraft with the deteriorated engine will not lag behind and will keep on flying with the rest of the formation, it will be, however at the cost of running the engine hotter (higher power setting), as compared with the clean engine and, therefore, higher effective fuel flow and life usage. This will result in even higher fuel consumption than determined during the analysis, because the aircraft with the deteriorated engine has flown with the aircraft with the clean engine and thus recovered the deficiency on account of mission time. This situation could ultimately lead to “aircraft with deteriorated engine asking for a priority landing on the reason of low fuel on its way back to home base”. This could also lead to a serious accident, in case the home-base runway is closed or damaged and the aircraft has to divert to another airfield for landing.

6. TECHNOECONOMIC STUDY OF COMPRESSOR WASHING

In this chapter a basic technoeconomic assessment of compressor washing for military engines will be carried out. The results obtained from chapter 5, as far as fuel consumed, for the two missions analyzed, are going to be used. In addition, a rough estimation of the cost for a compressor washing cycle will be presented and, finally, a preliminary assessment of the TET rise during a typical mission will be attempted, so as to highlight the effect of compressor fouling on the HPT blades available creep life.

6.1. Effects of Compressor Washing on Fuel Savings

As mentioned before, aircraft engines ingest foreign particles in form of aerosols, which enter the engine with the air stream. Although the majority of these foreign particles will follow the gas path through the engine and exit with the exhaust gases, there are particles with properties of sticking on to components in the engine's gas path, especially in the compressor section of the engine, causing what is known as fouling. In order to eliminate the negative effects of fouling, a number of engine washing techniques has developed over the years. However, every individual user should consider the best available method for compressor washing by taking into account the various parameters, which influence the everyday operation of his engines.

Following the survey carried out among the Hellenic Air Force F-16 pilots, a hypothetical, worst–case scenario was decided, in order to quantify the effects of engine deterioration on the additional costs which arise, because of this specific deterioration. What should be mentioned here is that this scenario is generalizing and is not taking into account the effects of other kinds of deterioration, which are also usually present in an aircraft engine, while in operation.

According to this scenario, every F-16 aircraft flies 2 sorties per day. This is "translated" in 3 hours per day per aircraft and, since every aircraft is usually operational 20 days per month, every engine operates 60 hours per month. Every F-16 is grounded in average one month per year, in order to perform time inspections and major overhauls and, therefore, it is operational for the remaining 11 months, flying in total 660 hours per year average. Finally, if we assume that every aircraft flies the 70% of its available time carrying out mission A and the rest 30% mission B, then 462 hours per year are consumed for mission A and 198 hours per year are consumed for mission B.

According to the mission analysis, carried out in chapter 5, every mission A takes 2231 sec to complete, so, in the available 462 hours, the aircraft will fly about 745 missions. Similarly, every mission B takes 5901 sec to complete, so the aircraft will carry out about 120 missions in 198 hours. As mentioned in chapter 5, if the engine is 6% deteriorated it will consume 30.23 kg more fuel per mission than a clean engine, if mission A is carried out, and 31.66 kg more fuel per mission than a clean engine, if mission B is chosen. So, in total:

(745.49 missions x 30.23 kg/mission)+(120.79 missions x 31.66 kg/mission) = 22536.3 + 3824.3 = 26360.6 kg / aircraft / year

Although the fuel price in case of an Air Force is directly agreed between the agencies of the various Directorates involved (and most of the times is not publicly announced), for the purpose of this study, it is assumed that the cost is 0.54€ per litre. Therefore, the total additional fuel cost that the Air Force will have to pay is 14,235€ per aircraft per year. Since HAF possesses currently a fleet of around 130 F-16s the total cost due to compressor fouling, as far as fuel is concerned, would be up to 1,850,550€ per year.

6.2. Effects of Compressor Deterioration on Creep Life

Creep is the progressive deformation that occurs under mechanical load and a constant temperature: it becomes a major concern when operating temperatures (in degrees Celsius) exceed 50% of the material's melting point (in degrees Celsius). [Cookson & Haslam, 2006]. This deformation is the result of slip occurring in the crystal structure, together with flow of the grain boundary layer. The consequence of this is a change in the dimensions of the hot-section components, to the point where the load-bearing area of the component can no longer withstand the peak operating stresses. If allowed to continue, this will eventually cause failure either through rupture or dimensional change [Little, 1994].

In practice, the rate of creep is a function of the stress, the temperature and the duration spent at each combination spent thereof. The resistance of a material to creep reduces as the temperature increases. In other words, for a given loading, a material will have a higher creep rate at a higher temperature: the damage caused by creep, like thermal fatigue, becomes exponentially more severe as the temperature is increased [Wu, 1994]. Therefore, creep presents the largest potential problem in applications involving high temperature and high stress. These are the conditions to which turbine blades and discs, and nozzle guide vanes are subjected. For an aero gas-turbine component, its temperature is the most influential variable in the creep process followed by the duration at that temperature. With the increase of the combustor-exit's temperatures in advanced engines, although less time is spent at high temperatures, the higher temperatures encountered can significantly reduce the creep life of each component [Naeem, 1998].

The determination of the life usage of the any engine, at each operating point, is a complicated process and requires the development of correlations between the measurable parameters, such as temperature, rotational speed, and stress.

In order to determine the TET rise, when the engine is 6% deteriorated, a preliminary assessment of the TET variation during mission A was performed. For the purposes of this study, the F110 Turbomatch file, created in chapter 3, was used and, since TET was set as handle, when the engine is running suffering no deterioration (clean), TET remains constant (1735 K). When, on the other hand, the engine is fouled, TET is increased accordingly, in order to achieve the same net thrust as with the clean engine. What should be mentioned here is that it is unknown whether the actual engine responds in a similar manner, and would require substantial engine data to verify this hypothesis. The result of the TET difference, for the above two situations (clean engine–deteriorated engine), is seen in figure 6.1.

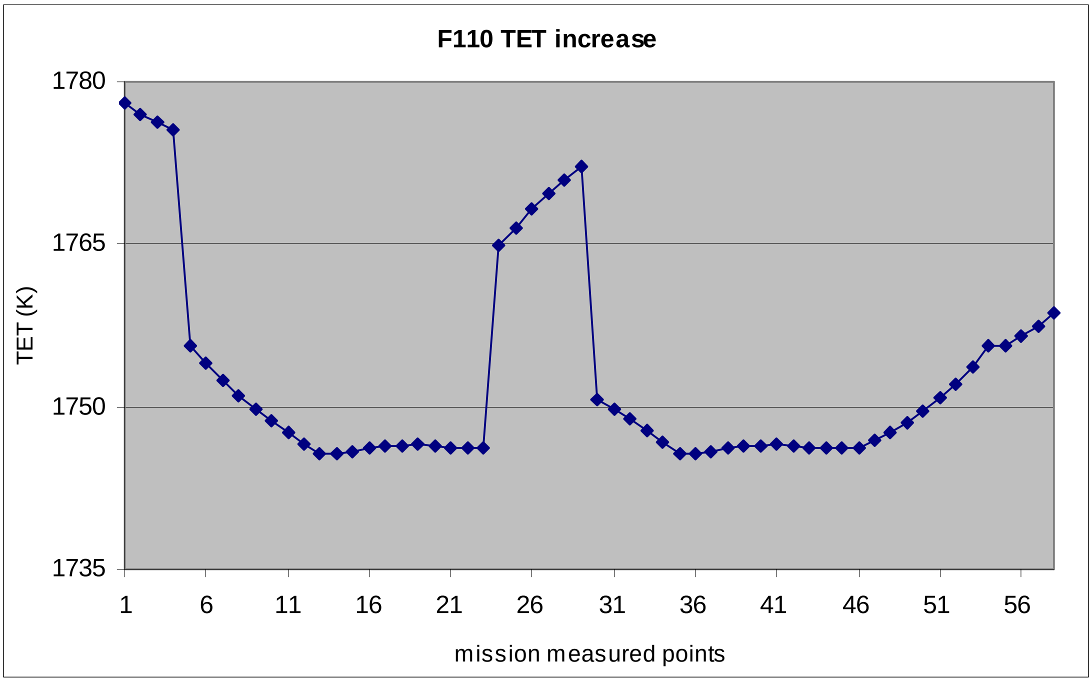

Figure 6.1.F110 TET increase due to engine deterioration

The above graph shows that for this specific mission TET increases 14 times from 15 K to 30 K (0.6% to 1.4% increase, compared to the design value i.e. 1735 K) and 10 times from 30^{o}C to 45^{o}C (1.7% to 2.5% increase, compared to the same value) during the whole mission. In order to quantify the above results it should be mentioned that, according to Singh (2006), a 15-20 K increase in blade metal temperature would typically reduce creep life by 50%. The two phases which contribute to the highest TET increase are the take-off phase and the reheat-on phase, which are the two most demanding phases of the whole mission.

A common method to represent how parameters such as temperature, stress and rotational speed affect the engine's creep life is the Larson–Miller parameter, which is useful in understanding and quantifying the time versus temperature trade-off for various materials. Its use results in a very effective method for rationalizing the time-temperature (and even rate-temperature) effects observed in stress–rupture and creep testing.

However, since many technical details of the F110 hot section blades, necessary to carry-out a thorough creep analysis using the Larson–Miller parameter, are not publicly revealed, a study of this kind is not feasible. Therefore, only the effect of the TET rise is represented here and the LMP study remains to be completed when and if the HPT blade's characteristics are acquainted by any reliable source.

6.3. Compressor Washing Frequency Optimization

After a thorough search in the open literature, no reference was detected, stating any kind of compressor washing plan, currently in use by any aircraft operator (civil or military), in order to reduce the adverse effects of compressor fouling. Therefore, with the aid of R-MC executives [30], it was estimated that every cleaning cycle would consume for this particular engine approximately 77 lit of cleaning fluid. Consequently, (since the cost of cleaning fluid is approximately 2 €/lit) the cost of a cleaning cycle would be around 154€ per engine.

Moreover, since this particular engine is used in a military aircraft and not in civil aviation, nor for power generation or oil & gas applications, a frequency optimization is not a straightforward procedure, since no revenue or profit loss can be estimated. Therefore, according to people involved with compressor cleaning [30], a frequent wash would be beneficial for any aircraft engine, since the deposits will not have time to accumulate and degrade significantly the engine's performance.

Table 6.1.Compressor washing cost (€) for different washing intervals

TOTAL FLYING HOURS	**ADDITIONAL FUEL COST DUE TO DETERIORATION**	**TIME INTERVALS**				
		10H	**20H**	**30H**	**40H**	**50H**
	(€)	**ANNUAL COMPRESSOR WASHING COST (€)**				
0	0	0				
10	216	154				
20	431	308	154			
30	647	462		154		
40	863	616	308		154	
50	1,078	770				154
60	1,294	924	462	308		
70	1,510	1,078				
80	1,725	1,232	616		308	
90	1,941	1,386		462		
100	2,157	1,540	770			308
200	4,314	3,080	1,540		770	616
300	6,470	4,620	2,310	1,540	1,155	924
400	8,627	6,160	3,080		1,540	1,232
500	10,784	7,700	3,850		1,925	1,540
600	12,941	9,240	4,620	3,080	2,310	1,848
660	14,235	10,164	5,082	3,388	2,541	2,033

Consequently, as seen from Table 6.1, a 30–hour interval would be chosen for this particular application, because it is a time interval in which the cost of washing is not high compared to the corresponding gain.

7. CONCLUSIONS & RECOMMENDATIONS FOR FUTURE WORK

7.1. Conclusions

Gas turbine aero-engines operate over a wide range of temperatures, speeds, power and environments. Therefore, in-service performance deterioration, resulting from the degradation of its components, is inevitable. The causes of this deterioration are diverse and depend upon each engine's usage and operation.

One of the key factors leading to performance losses during operation of these engines is compressor fouling. When flying at high altitudes the engine ingests the clean air prevailing at these altitudes. However, at the aerodromes, the air contains foreign particles in form of aerosols which enters the engine with the air stream. Typical particles found in the aerodrome air are pollen, insects, hydrocarbons coming from industrial activities and salt coming from nearby sea. Also, while the aircraft is grounded at the airport, there are additional particles to consider such as combustion residues in engine exhaust from taxing aircraft, chemicals coming from aircraft de-icing and ground material such as dust. The majority of the foreign particles will follow the gas path through the engine and exit with the exhaust gases. However, there are particles with properties of sticking on to components in the engine's gas path, especially in the compressor section of the engine. This is known as fouling [20].

Compressor fouling results in a change in the properties of the boundary layer air stream of the compressor components. The presence of foreign particles results in an increase of the component surface roughness. As air flows over the surface, the increase of surface roughness results in a thickening of the boundary layer air stream. The thickening of the boundary layer air stream has negative effects on the compressor aerodynamics in form of a reduced mass flow. At the blade trailing edge the air stream forms a wake. The wake forms a vortex type of turbulence, with a negative impact on the air flow. The thicker the boundary layer, the stronger the turbulence in the wake and the more it reduces the mass flow. Further, a thick boundary layer and stronger trailing edge turbulence result in a reduced compressor gain, which in turn results in the fouled compressor compressing air at a reduced pressure ratio. Anyone skilled in the art of gas turbine engine working cycles understands that a reduced pressure ratio results in a lower thermal efficiency of the engine [Hjerpe, 2005].

The compressor fouling not only reduces the mass flow and pressure gain but also reduces the compressor isentropic efficiency. Reduced compressor efficiency means that the compressor requires more power for compressing the same amount of air. The power for driving the compressor is taken from the turbine via the shaft. With the turbine requiring more power to drive the compressor there will be less power to create thrust for propulsion. For the aircraft pilot this means he must throttle for more fuel as to compensate for the reduced thrust. Throttling for more fuel means the consumption of fuel increases and thereby increasing the operating costs.

The performance loss caused by compressor fouling also reduces the durability of the engine. As more fuel has to be fired for reaching a required thrust level, follows an increase in the engine firing temperature. When the pilot in the runway throttles for take-off, the engine’s hot section components are under critical high temperature load. Controlling the combustion gas temperature is a key issue in engine performance monitoring. At a certain point it will be required that the engine is taken out of service for an overhaul, where hot section components are inspected and replaced if required.

Compressor fouling also has a negative effect on the environment. The difference in fuel consumption of a brand new engine, delivered from the factory, and an engine with a fouled compressor may typically be 1%. With the increase of fuel consumption follows an increase of emissions of green house gas, such as carbon dioxide. Typically, combustion of 1 kg of aviation fuel results ion formation of 3.1 kg carbon dioxide [20]. Further, high combustion temperature has a negative effect to the environment. With the increase of firing temperature, follows an increase in NOx formation.

Consequently, compressor fouling has negative effects to aero engine performance, such as increasing fuel consumption, reducing engine life and increasing emissions. The fouling rate depends largely on the site location, surrounding environment, the layout of the air intake system, atmospheric parameters, and engine maintenance. While the first four factors cannot be influenced during the operation, the engine maintenance is the critical one for preventing extra costs resulting from degraded engine performance. With the growing interest in life cycle costs for gas turbine engines, both engine manufacturers and operators are investigating the tradeoffs between performance improvements and associated maintenance costs.

This study has been undertaken to determine the impact of the compressor and turbine component degradation on the overall performance of two aero gas turbine engines (the T56-A-15 and the F110-GE-129 engines) by utilizing Gas Path Analysis techniques. Consequently, a wider knowledge on the deteriorated behaviour of the engine at different power settings has been gained, along with the information on the effects that various types of gas path faults can have on performance and the remaining useful life of the engines.

The engine computer simulation is proven to be an invaluable tool, as it can save the operator a lot of money. With the computer models the operator can choose the level of accuracy he can afford. From the data obtained by the simulations, he can then conduct a great variety of performance investigations getting thus a good insight view of the engine behaviour, saving, at the same time, a great deal of his resources, as expensive actual engine testing is not necessary. Although the assumptions (bleed flows, mechanical losses) that were made, when developing the two modelled engines, have the potential to limit the accuracy of the performance simulation model, a comparison of simulated and published data shows that the model agrees very closely with the undeteriorated performance specifications for the engines.

Both T56–A–15 and F110–GE–129 are relatively old engines, which are, however, used in substantial numbers by a large number of commercial and military operators around the world, its principal applications being the Lockheed Martin C–130H and F–16 respectively. Since both engines were designed more than thirty years ago, their philosophy, mainly in terms of maintenance, is quite different than the one that modern engines have. However, despite their age, they are likely to remain in service for many years to come. Maintenance costs tend to increase as an engine approaches retirement, so potential savings could be realized from the development and application of expert programs, which will reduce both operating and life cycle costs. This will happen through reduced wear, decreased maintenance requirements and increased component safe life limits. Therefore, it becomes more and more technically challenging to incorporate new maintenance techniques, so as to increase performance, life and reliability and, in the mean time, keep the overall operating costs low.

As far as the engine deteriorated performance simulation is concerned, the implantation of several physical faults in a controlled manner allowed the creation of a fault library for different power settings, so as to provide the user with more information when conducting fault diagnostics. This fault library will be particularly useful to the operator, since it allows him to gain an understanding of the effects of engine deterioration on the measured parameter changes of the engines. It will also be a powerful tool for the fault isolation process, at which he can compare the engine fault signature with the fault library, in order to arrive to the most probable fault.

Another advantage of the fault library is that it allows the engine user to obtain an understanding of operational problems such as fouling and erosion. However, it must be noted that the representation of physical faults, by the modification of engine independent parameters, has not been fully validated, due to the limited data available in the public domain. From the deteriorated data obtained, the user will certainly note that there is a linear relationship between the dependent and independent parameters. This can be explained due to the linearity of the aero-thermodynamic relations.

What needs to be highlighted, concerning the performance of the deteriorated engines, is that the major effect of compressor fouling is, for the T56–A–15 engine, the large drop in shaft power, and, for the F110 engine, the decrease in Net Thrust and the increase in Specific Fuel Consumption. The above effects can be diminished in a great extend through compressor washing (off–line for this type of engines), without, thus, the need to disassemble the engine. However, as far as turbine fouling, erosion and corrosion are concerned, it is a fact that the performance restoration will only occur through the engine disassembly and the replacement of the failed components.

In the operation of an aircraft the engine has a major influence on its safety, economy of operation and performance. The latter is of major importance for military aircraft, whereas economy of operation is a priority in civil aviation, with safety being regarded as of even greater importance in both sectors. Until a few years ago, the operators of military aircraft did not consider the inefficient operation of an engine as a serious economic problem, mainly due to the availability of cheap fuels. However, the subsequent rising in unit-fuel costs has caused the more efficient operation of gas turbines (in terms of fuel consumption) to become a matter of prime concern. The weight of the fuel carried has a direct effect on the cargo payload and/or number of passages that can be conveyed, in the case of civil aviation, and on the weapon carrying capability, range and the time to reach the target for military operations [44]. Thus, a case study was carried out, as far as fuel consumption and extra time needed when a typical mission of an F-16 carrying an F110 engine carried out, manifesting the effects of compressor fouling in the overall effectiveness of an aircraft from the operational point of view.

As it was concluded from this case study the weight of the total fuel used increases linearly with increasing engine deterioration. The amount of extra fuel used, because of engine's deterioration is significant. For example, the amount of total fuel used to accomplish the complete mission A, with the engine suffering 6% deterioration is 1% higher (i.e. 2,889 kg of fuel instead of 2,859 kg) as compared with that for the clean engine. Moreover, what is also mentioned is that there is a linear rise in SFC and a corresponding linear reduction in fuel flow and Net Thrust, all for the same level of TET. For the mission profile considered in the present analysis, with increasing engine deterioration, the available Net Thrust is reducing and requires the engine to run at higher TET to meet the thrust requirements, in order to maintain the same aircraft performance. Finally, another significant point in this study is that in order to complete one of the two missions (mission A), an aircraft carrying an engine with 6% deterioration will take 83.84 sec more, compared with an aircraft with a clean engine. The importance of this advantage for an aircraft with a clean engine is well established and cannot be ignored from operational effectiveness point of view.

An economic analysis was also attempted, in order to quantify the effects of engine deterioration on the additional costs which arise, because of this specific deterioration. According to this analysis the total additional fuel that the Air Force will have to consume is 26,360.6 kg per aircraft per year. Assuming a hypothetical fuel price, it was concluded that Hellenic Air Force could pay, because of compressor fouling, as much as 1,850,550€ per year for the fleet of F-16s it possesses.

One of the best practices to nearly eliminate the effects of compressor fouling, particularly for aero gas turbine engines installed on aircrafts, is on–wing off–line cleaning. Compressor cleaning was presented and the effect of on-wing off-line cleaning on the performance of the F110 engine was manifested from a technical and economical standpoint. Frequent on–wing cleaning is established to improve efficiency, resulting, thus, in improved power output, fuel savings and prolonged aero engine life. Thus, another study was carried out, so as to investigate the effect of the implementation of compressor washing on the F110 engine, a decision that would make the choice of keeping the F110 engine in service a more economically and technically sound one. According to this study, it was verified that if, in order to keep the same level of thrust (and thus performance) the engine's TET was increased, the available HPT blade's creep life is significantly reduced. A detailed analysis was not, however, feasible, since many necessary technical details, were not publicly disclosed.

Finally, according to the results obtained, the optimal frequency of compressor washing was proposed, in order to eliminate safety compromises, improve performance and reduce the engine's life cycle cost.

7.2. Recommendations for Future Work

As most engineers know the process of any project cannot be considered as completed, since development is an on-going process and will always be progressive as long as both open minds and available tools exist.

The subjects covered in the present thesis are somehow restricted, due to the time limit allocated for the necessary research and writing. Therefore, some areas of interest and possible development are listed below:

- A complete creep life analysis (using LMP or any other engineering method) should be carried out, once the necessary technical data is acquainted by any reliable source, in order to demonstrate exactly the effects of the TET rise in the hot section's available life.

- A similar case study concerning the fuel consumption along with a mission analysis for the C–130 aircraft would be interested, since the C–130 is an aircraft with different philosophy and mission (cargo transport aircraft).

- An analogous technoeconomic study for the T–56 engine would be beneficial for anyone possessing a large number of C–130 aircrafts. This study would demonstrate the effects of compressor washing on fuel savings and on the T–56 hot section creep life.

- Finally, a preliminary design of an on–wing off–line compressor washing system especially for the F110 and the T–56 engine should be attempted, in order to trace possible difficulties or problems in the incorporation of such a system in the engine's maintenance plan.

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APPENDIX A

Turbomatch input file for the T56 engine simulation

In this section the Turbomatch input created and used by PYTHIA for the T56–A–15 engine, is presented.

```
!TURBOMATCH SCHEME DESIGN FILE
!ENGINE TYPE: T56
////
OD SI KE CT FP
-1
-1
INTAKE  S1,2        D1,2,3,4                          R300
COMPRE  S2,3      D5,6,7,8,9,10                    R301      V5 V6
PREMAS  S3,4,20  D12,13,14,15
DUCTER  S4,5       D16,17,18,19                    R302
BURNER  S5,6       D20,21,22                          R303
MIXEES  S6,20,7
TURBIN  S7,8        D23,24,25,26,27,28,29,30,301            V24
NOZCON  S8,9,1   D33                                   R304
PERFOR  S1,0,0   D23,35,36,37,304,300,303,0,0,0,0,0,0
CODEND
DATA////
1    0
2    0
3    0
4    0
5   -1.0
6   -1.0
7    9.30846
8    0.84382
9    0
10    5
12    0.95
13    0
14    1
15    0
16    0
17    0.042861
18    0
19    0
20    0.015478
21    0.9792
22   -1.0
23    3028000
24    0.7
25    0.7
26    0.87499
27   -1.0
28    1
29    6
30    1000
33   -1
35    0.95
36    0
37    0
-1
1 2 14.987
6 6 1283
-1
-1
```

APPENDIX B

Turbomatch input file for the F110 engine simulation

In this section the Turbomatch input file, created and used by PYTHIA for the F110–GE–129 engine, is presented.

```
!TURBOMATCH SCHEME DESIGN FILE
!ENGINE TYPE: F129
////
OD SI KE VA FP
-1
-1
INTAKE  S1,2          D1,2,3,4                          R300
COMPRE  S2,3          D5,6,7,8,9,10,11                  R301   V5   V6
PREMAS  S3,4,20       D12,13,14,15
COMPRE  S4,5          D16,17,18,19,20,21,22             R302   V16  V17
PREMAS  S5,6,22       D23,24,25,26
PREMAS  S22,23,24     D27,28,29,30
BURNER  S6,7          D31,32,33                         R303
MIXEES  S7,23,8
TURBIN  S8,9          D34,35,36,37,38,39,40,41,302,43          V35
MIXEES  S9,24,10
TURBIN  S10,11        D44,45,46,47,48,49,50,51,301,53          V45
DUCTER  S20,21        D54,55,56,57                      R304
MIXFUL  S11,21,12     D58,59,60
DUCTER  S12,13        D61,62,63,64                      R305
NOZDIV  S13,14,1      D65,66                            R306
PERFOR  S1,0,0        D67,68,69,70,306,300,303,0,0,305,0,0,0
CODEND
DATA////
1    0.0
2    0.0
3    0.0
4   -1.0
5   -1.0
6   -1.0
7    3.3
8    0.84
9    0.0
10   4.0
11   0.0
12   0.46
13   0.0
14   1.0
15   0.0
16  -1.0
17  -1.0
18   9.3
19   0.86
20   0.0
21   4.0
22   0.0
23   0.85
24   0.0
25   1.0
26   0.0
27   0.85
28   0.0
29   1.0
```

```
30    0.0
31    0.05
32    0.99
33   -1.0
34    100000
35   -1.0
36   -1.0
37    0.88
38   -1.0
39    2.0
40    5.0
41   -1.0
43    0.0
44    0.0
45   -1.0
46   -1.0
47    0.90
48   -1.0
49    1.0
50    5.0
51   -1.0
53    0.0
54    0.0
55    0.05
56    0.0
57    10000.0
58    1.0
59    1.0
60    0.40
61    1.0
62    0.05
63    0.90
64    100000.0
65    1.0
66   -1.0
67   -1.0
68   -1.0
69    0.0
70    0.0
-1
1 2 126.0
7 6 1735
-1
-3
```

APPENDIX C

Operational Effectiveness Analysis

In this appendix, the step–by–step calculations, in order to produce the necessary results for the two different missions are presented. The methodology followed is the one described in reference [43], and all the expressions and engineering data, necessary for determining the aircraft's data are taken from references [54] and [57].

Mission A

i. Take-Off

The maximum lift coefficient for an aircraft is quite difficult to estimate. Values range from about 1.2 to 1.5 for a plain wing with no flaps to as much as 5.0 for a wing with large flaps immersed in the jetwash. The maxim lift coefficient for an aircraft designed for short take-off and landing applications will be typically around 3.0. In the absence of exact value of C_{LMAX} for the aircraft under consideration, a take-off Mach of 0.3 and take-off lift equal to 1.05 times the weight of the aircraft can be assumed, which is true for a typical fighter aircraft.

During the ground roll, the forces of the aircraft are the thrust, drag and rolling friction of the wheels, the last being expressed as a rolling friction coefficient μ times the weight of the wheels (W–L). A typical μ value for rolling resistance on a hard runway is 0.03 to 0.05. The resulting acceleration of the aircraft can be expressed in terms of the aerodynamic coefficients by the following expression:

$$a = g\frac{[T_{av} - D_{av} - \mu(W - L_{av})]}{W}$$

Since the thrust, drag and the lift vary during the ground roll, an average value must be used. The average values for these can be calculated as follows:

$$T_{av} = \frac{T_{ts} + T_{tf}}{2}$$

where T_{av}= Total average thrust

T_{ts}= Total thrust at the start of the stage

T_{tf}= Total thrust at the end of the stage

The same applies for L_{av} (average Lift) and D_{av} (average Drag). As in this case the Mach No. at the start of the take-off roll is zero, therefore L_{ts} and D_{ts} will be both zero. Hence $L_{av} = L_{tf}/2$, $D_{av} = D_{tf}/2$ and $L_{tf} = 1.05 * W$.

Substituting, we get $L_{tf} = 1.05x12000x9.81 = 123606N$ (since $1kg = 9.81N$)

and $L_{av} = \frac{123606}{2} = 61803N$.

Drag can be calculated as follows:

$$D_{tf} = \frac{1}{2}\gamma PM^2 SC_D$$

Where
$$\gamma = 1.4$$
$$P = 101523N/m^2$$
$$M = 0.3$$
$$S = 27.88m^2$$
and

$$C_D = C_{D_0} + KC_L^2$$

where $C_{D_0} = 0.015$ for a typical fighter aircraft for subsonic flight and $K = 1/\pi Ae$ where the Aspect Ratio A is $A = b^2/S$ (b being the wing span and S the wing surface area) and e=0.70-0.85 typical range, assume e=0.80. Hence,

$$K = \frac{1}{(\pi * 3.2 * 0.80)} = 0.1242$$

and C_L can be determined as follows:

$$C_L = \frac{1.05W}{1/2 \gamma PM^2 S} = \frac{1.05 * 12000 * 9.81}{1/2 * 1.4 * 101523 * 0.3^2 * 27.88} = 0.69317$$

Therefore, $C_D = 0.015 + 0.1242 * 0.69317^2 = 0.0746$ and

$$D_{tf} = \frac{1}{2}\gamma PM^2 SC_D = \frac{1}{2} * 1.4 * 101523 * 0.3^2 * 27.88 * 0.0746 = 13302.6N$$

Hence $D_{av} = \frac{13302.6}{2} = 6651.3N$

Now, putting the values of lift, drag, weight, g and μ=0.04 in the expression of acceleration above, we get:

$$a = \frac{9.81 * [T_{av} - 6651{,}3 - 0.04(W * 9.81 - L_{av})]}{12000 * 9.81} \Rightarrow a = \frac{T_{av} - 8887.98}{12000}$$

The velocity at take-off can be expressed as follows:

$V_f = V_s + at \Rightarrow V_f = at$ (since the velocity at the start of the T.O. roll is zero as Mn is zero).

Also, $V_f = M_f \sqrt{\gamma RT} = 0.3 * \sqrt{1.4 * 287 * 288} = 102 m/s$

Therefore, $t = \frac{V_f}{a} \Rightarrow t = \frac{102}{a}$

Average fuel flow can be expressed as $F_{av} = \frac{F_s + F_f}{2}$,

where F_S = fuel flow at start of the take-off roll

F_f = fuel flow at the end of the take-off roll

The fuel weight (FW) consumed during the take-off roll can be expressed as follows:

$$FW = F_{av} * t$$

The performance results for the take-off stage of mission A for the "clean" and for the 6% deteriorated engine are given below in Table C1.

Table C.1.Performance results for "Take-off" stage (Mission A)

	0%	**6%**
W_{gs} (kg)	12000	12000
T_{ts} (N)	141070	131195
T_{tf} (N)	133270	123941
T_{av} (N)	137170	127568
α (m/sec^2)	10,69	9,89
t (sec)	9,54	10,32
F_s (kg/sec)	7,77	7,21
F_f (kg/sec)	7,92	7,35
F_{av} (kg/sec)	7,845	7,28
FW (kg)	74,84	75,13
W_{gf} (kg)	11925,15	11924,9

ii. Climb from S.L. to 8000 m Accelerating from M=0.3 to M=0.8

The time to climb can be estimated by using the following expression:

$$t = \frac{W}{V_{av}} \frac{(h_f - h_s)}{(T_{es} - T_{ef})} \ln \frac{T_{es}}{T_{ef}}$$

where W = aircraft weight at the end of the T.O. stage

h_s = start altitude = 0 m

h_f = final altitude = 8000 m

T_{es} = Excess thrust at the start of the climb

T_{ef}= Excess thrust at the end of the climb

V_{av}= Average velocity

Average velocity can be determined as follows:

$$V_{av} = \frac{V_s + V_f}{2}$$

where $V_s = M_s \sqrt{\gamma RT} = 0.3 * \sqrt{1.4 * 287 * 288} = 102.05 m/s$

and $V_f = M_f \sqrt{\gamma RT} = 0.8 * \sqrt{1.4 * 287 * 236} = 246.35 m/s$

hence $V_{av} = \frac{V_s + V_f}{2} = \frac{102.05 + 246.35}{2} = 174.2 m/s$

Since the Drag D_s is the same as the end of the T.O. stage

$$T_{es} = T_{ts} - D_s = T_{ts} - 13302.6$$

Since $C_{Lf} = \frac{1.05W}{\frac{1}{2}\gamma PM^2 S} = \frac{1.05 * 11925.15 * 9.81}{\frac{1}{2} * 1.4 * 35800 * 0.8^2 * 27.88} = 0.2747$

then $C_{Df} = C_{D_0} + KC_{Lf}^2 = 0.015 + (0.1242 * 0.2747^2) \Rightarrow C_{Df} = 0.0243$

and $D_{tf} = \frac{1}{2}\gamma PM^2 SC_{Df} = \frac{1}{2} * 1.4 * 35800 * 0.8^2 * 27.88 * 0.0243 = 10894.16 N$

hence $T_{ef} = T_{tf} - D_{tf} = T_{tf} - 10894.16$

Now putting the values of h_s, h_f and V_{av} the time expression can be written as follows:

$$t = \frac{8000 * 9.81}{174.2 * (T_{es} - T_{ef})} \ln \frac{T_{es}}{T_{ef}}$$

The fuel consumed during the climb stage can be determined as $FW = F_{av} * t$

The distance covered horizontally towards target while climbing can be given as:

$$D = V_{av} * \cos[\sin^{-1} \frac{(h_f - h_s)}{V_{av} * t}]$$

and the cumulative time

t_{cum}=time to T.O. + time to climb

The performance results for the "Climb and Accelerate" stage of mission A, for the "clean" and for the 6% deteriorated engine, are given below in Table C.2.

Table C.2.Performance results for "Climb & Accelerate" stage (Mission A)

	0%	**6%**
W_{gs} (kg)	11925,15	11924,9
T_{ts} (N)	67610	62877
T_{tf} (N)	34856	32416
T_{es} (N)	54307,4	49574,4
T_{ef} (N)	23961,84	21518,19
t (sec)	144,8	159,8
F_s (kg/sec)	1,39	1,29
F_f (kg/sec)	0,84	0,78
F_{av} (kg/sec)	1,115	1,035
FW (kg)	161,45	165,39
D_{climb} (km)	23,92	26,662
t_{cum} (sec)	154,34	170,15
W_{gf} (kg)	11763,75	11759,21

iii. Acceleration from 0.8M to 1.5M at 8000 m

The time to accelerate can be estimated by using the following expression:

$$t = \frac{W}{g}\frac{(V_f - V_s)}{(T_{es} - T_{ef})}\ln\frac{T_{es}}{T_{ef}}$$

where W = aircraft weight at the end of the “climb” stage

V_s = velocity at the start of the stage = 246.35m/s

V_f = velocity at the end of the stage i.e.

$V_f = M_f\sqrt{\gamma RT} = 1.5*\sqrt{1.4*287*236} = 461.9m/s$

T_{es} = Excess thrust at the start of the stage

T_{ef}= Excess thrust at the end of the stage

Since the Drag D_s is the same as the end of the climb stage

$$T_{es} = T_{ts} - D_s = T_{ts} - 13302.6$$

Since $C_{Lf} = \frac{W}{\frac{1}{2}\gamma PM^2S} = \frac{11763.75*9.81}{\frac{1}{2}*1.4*35800*1.5^2*27.88} \Rightarrow C_{Lf} = 0.0734$

hence, $C_{Df} = 0.021$ from a typical curve for a fighter aircraft during supersonic flight.

Therefore, $D_{tf} = \frac{1}{2}\gamma PM^2SC_{Df} = \frac{1}{2}*1.4*35800*1.5^2*27.88*0.024 = 33012N$

hence $T_{ef} = T_{tf} - D_{tf} = T_{tf} - 33012$

Now putting the values of V_s, V_f and W, the time expression can be written as:

$$t = \frac{W*(461.9-246.35)}{9.81*(T_{es}-T_{ef})}\ln\frac{T_{es}}{T_{ef}} = \frac{W*215.55}{9.81*(T_{es}-T_{ef})}\ln\frac{T_{es}}{T_{ef}}$$

The fuel consumed during the acceleration stage can be determined as:

$$FW = F_{av} * t$$

The acceleration during this stage can be estimated by using the following expression:

$$V_f = V_s + at \Rightarrow a = \frac{V_f - V_s}{t} = \frac{215.55}{t}$$

The distance covered horizontally towards target while accelerating can be given as:

$$D = V_s t + \frac{1}{2}at^2 = 246.35 * t + \frac{1}{2}at^2$$

Whereas, Cumulative Distance towards target = D_{climb} + $D_{acceleration}$ and the cumulative time

t_{cum}=time to T.O. + time to climb+ time to accelerate

The performance results for the “Acceleration” stage of mission A for the “clean” and for the 6% deteriorated engine, are given below in Table C.3.

Table C.3.Performance results for “Accelerate” stage (Mission A)

	0%	**6%**
W_{gs} (kg)	11763,75	11759,21
T_{ts} (N)	34856	32416
T_{tf} (N)	36878	34297
T_{es} (N)	21553	19113,4
T_ef (N)	3685	499
t (sec)	250,65	496,4
α (m/sec^2)	0,86	0,434
F_s (kg/sec)	0,84	0,78
F_f (kg/sec)	1,07	1
F_{av} (kg/sec)	0,995	0,89
FW (kg)	239,37	441,79
D_{accel} (km)	88,762	175,759
D_{cumul} (km)	112,682	202,421
t_{cum} (sec)	405	666,55
W_{gf} (kg)	11524,37	11317,41

iv. Cruise to Target with 1.5M at 8000m

While cruising,

T = D and L = W

As the cruise Mach number is 1.5, the cruise velocity can be given as follows:

$$V = M\sqrt{\gamma RT} = 1.5 * \sqrt{1.4 * 287 * 236} = 461.9 m/s$$

In cruise the drag on the aircraft is the same as the D_{tf} of the last (acceleration) stage:

$$D = 33012N$$

In case the total thrust available is more than the drag, the throttle will be retarded back to make it equal to drag. The actual throttle setting can be given as follows:

$$T.S.(\%) = \frac{33012 * 100}{T_t}$$

The distance to reach the target (400 km away from home base) is given as:

D_t = 400 – D_{cum}(till last stage)

The time (in seconds) to reach the target is given as:

$$t = \frac{D_t * 1000}{461.9}$$

As in this case the throttle will be retarded back to make the total available thrust equal to the drag, therefore, the fuel flow will not be the same as at 100% throttle setting. The effective fuel flow can be given as follows:

$$F_{eff} = \frac{F * TS}{100}$$

Now, the total fuel consumed during cruise stage can be found in the same way as in previous stages, as follows:

$$FW = F_{eff} * t$$

The performance results for the "cruise" stage of mission A for the "clean" and for the 6% deteriorated engine, are given below in Table C.4.

Table C.4.Performance results for "Cruise" stage (Mission A)

	0%	6%
W_{gs} (kg)	11524,37	11317,41
T_t (N)	36878	34297
TS (%)	89,51	96,25
D_t (km)	287,318	197,579
t_t (sec)	622,035	427,752
F (kg/sec)	1,07	1
F_{eff} (kg/sec)	0,9577	0,9625
FW (kg)	595,722	411,712
t_{cum} (sec)	1027,035	1094,3
W_{gf} (kg)	10928,64	10905,69

v. Air Combat While Descending from 8000m to 3000m

The time and the average Thrust-to-Weight Ratio $(T/W)_{av}$ specified in this case is as follows:

t = 3 minutes = 180 seconds

$(T/W)_{av}$ = 0.75

The total thrust required can be given as follows:

$$T_{t\ req} = 0.75 * 9.81 * \text{weight of the aircraft}$$

whereas the total fuel flow can be found as follows:

$$F_t = T_{treq} * SFC_{av}$$

where $$SFC_{av} = \frac{SFC_{8000} + SFC_{3000}}{2}$$

The performance results for “Air Combat” stage of mission A for the “clean” and for the 6% deteriorated engine, are given below in Table C.5.

Table C.5.Performance results for “Air Combat” stage (Mission A)

	0%	**6%**
W_{gs} (kg)	10928,64	10905,69
T_{t8000} (N)	97928	91073
T_{t3000} (N)	121970	113432
T_{av} (N)	109949	102252,5
sfc_{8000} (mg/Nsec)	58,71	59,6
sfc_{3000} (mg/Nsec)	63,75	64,71
sfc_{av} (mg/Nsec)	61,23	62,155
T_{treq} (N)	80803	80238
t (sec)	180	180
F_t (kg/sec)	4,947	4,987
FW (kg)	890,46	897,7
W_{weapon} (kg)	981	981
t_{cum} (sec)	1207,035	1274,3
W_{gf} (kg)	10038,18	10007,98

vi. Re – Climb from 3000m to 8000m at 0.8M

The time to re-climb can be estimated by using the following expression:

$$t = \frac{W}{V_{av}} \frac{(h_f - h_s)}{(T_{es} - T_{ef})} \ln \frac{T_{es}}{T_{ef}}$$

where W = aircraft weight at the end of the "air combat" stage
h_s = start altitude = 3000 m
h_f = final altitude = 8000 m
T_{es} = Excess thrust at the start of the re-climb
T_{ef}= Excess thrust at the end of the re-climb
V_{av}= Average velocity

Average velocity can be determined as follows:

$$V_{av} = \frac{V_s + V_f}{2}$$

where $V_s = M_s \sqrt{\gamma RT} = 0.8 * \sqrt{1.4 * 287 * 268} = 262.52 m/s$

and $V_f = M_f \sqrt{\gamma RT} = 0.8 * \sqrt{1.4 * 287 * 236} = 246.35 m/s$

hence $V_{av} = \frac{V_s + V_f}{2} = \frac{262.52 + 246.35}{2} = 254.4 m/s$

The lift coefficient at 3000 m is given by the expression:

$$C_{L3000} = \frac{1.05 * W}{\frac{1}{2} \gamma P M^2 S} = \frac{1.05 * 100038.18 * 9.81}{\frac{1}{2} * 1.4 * 70116 * 0.8^2 * 27.88} = 0.118$$

Then

$$C_{D3000} = C_{D_0} + KC_{L3000}^2 = 0.015 + (0.1242 * 0.118^2) \Rightarrow C_{D3000} = 0.01672$$

and $$D_{3000}=\frac{1}{2}\gamma PM^2SC_{D3000}=\frac{1}{2}*1.4*70116*0.8^2*27.88*0.01672=14650N$$

hence $$T_{es}=T_{ts}-D_s=T_{ts}-14650$$

Similarly $$C_{L8000}=\frac{1.05*W}{\frac{1}{2}\gamma PM^2S}=\frac{1.05*10038.18*9.81}{\frac{1}{2}*1.4*35800*0.8^2*27.88}=0.23123$$

then $$C_{Df}=C_{D_0}+KC_{L8000}^2=0.015+(0.1242*0.23123^2)\Rightarrow C_{Df}=0.02164$$

and $$D_{tf}=\frac{1}{2}\gamma PM^2SC_{Df}=\frac{1}{2}*1.4*35800*0.8^2*27.88*0.02164=9676.33N$$

hence $$T_{ef}=T_{tf}-D_{tf}=T_{tf}-9676.33$$

Now putting the values of h_s, h_f and V_{av} the time expression can be written as follows:

$$t=\frac{5000*9.81}{254.43*(T_{es}-T_{ef})}\ln\frac{T_{es}}{T_{ef}}$$

The fuel consumed during the climb stage can be determined as $FW=F_{av}*t$

The distance covered horizontally towards target while climbing can be given as:

$$D=V_{av}*\cos[\sin^{-1}\frac{(h_f-h_s)}{V_{av}*t}]$$

and the cumulative time t_{cum}=time to re-climb + $time_{cum}$(till last stage)

The performance results for the “Re-Climb” stage of mission A for the “clean” and for the 6% deteriorated engine, are given below in Table C.6.

Table C.6.Performance results for “Re-climb” stage (Mission A)

	0%	**6%**
W_{gs} (kg)	10038,18	10007,98
T_{ts} (N)	51105	47258
T_{tf} (N)	34854	32414
T_{es} (N)	36455	32878
T_{ef} (N)	25177	22755
t (sec)	63,51	70,14
F_s (kg/sec)	1,27	1,18
F_f (kg/sec)	0,84	0,78
F_{av} (kg/sec)	1,055	0,98
FW (kg)	67	68,73
$D_{re\text{-}climb}$ (km)	15,363	17,128
t_{cum} (sec)	1270,5	1344,44
W_{gf} (kg)	9971,17	9939,25

vii. Re – Acceleration From M 0.8 to M 1.5 at 8000 m

The time to re-accelerate can be estimated by using the following expression:

$$t = \frac{W}{g}\frac{(V_f - V_s)}{(T_{es} - T_{ef})}\ln\frac{T_{es}}{T_{ef}}$$

where W = aircraft weight at the end of the “re-climb” stage

V_s = velocity at the start of the stage = 246.35m/s

V_f = velocity at the end of the stage i.e.

$$V_f = M_f\sqrt{\gamma RT} = 1.5 * \sqrt{1.4 * 287 * 236} = 461.9 m/s$$

T_{es} = Excess thrust at the start of the stage

T_{ef}= Excess thrust at the end of the stage

Since the Drag D_s is the same as the end of the re-climb stage

$$T_{es} = T_{ts} - D_s = T_{ts} - 9676.33$$

Since $$C_{Lf} = \frac{W}{\frac{1}{2}\gamma PM^2 S} = \frac{9971.17*9.81}{\frac{1}{2}*1.4*35800*1.5^2*27.88} \Rightarrow C_{Lf} = 0.0622$$

hence, $C_{Df} = 0.020$ from a typical curve for a fighter aircraft during supersonic flight as shown in figure 8.39 [ ]

Therefore, $$D_{tf} = \frac{1}{2}\gamma PM^2 SC_{Df} = \frac{1}{2}*1.4*35800*1.5^2*27.88*0.020 = 31440N$$

hence $$T_{ef} = T_{tf} - D_{tf} = T_{tf} - 31440$$

Now putting the values of V_s, V_f and W, the time expression can be written as follows:

$$t = \frac{W*(461.9-246.35)}{9.81*(T_{es}-T_{ef})}\ln\frac{T_{es}}{T_{ef}} = \frac{W*215.55}{9.81*(T_{es}-T_{ef})}\ln\frac{T_{es}}{T_{ef}}$$

The fuel consumed during the acceleration stage can be determined as follows:

$$FW = F_{av}*t$$

The acceleration during this stage can be estimated by using the following expression:

$$V_f = V_s + at \Rightarrow a = \frac{V_f - V_s}{t} \Rightarrow a = \frac{215.55}{t}$$

The distance covered horizontally towards target while re-accelerating can be given as:

$$D = V_s t + \frac{1}{2}at^2 = 246.35*t + \frac{1}{2}at^2$$

Whereas, Cumulative Return Distance towards target = $D_{re\text{-}climb}$ + $D_{re\text{-}accelerate}$

and the cumulative time t_{cum}=$time_{cum(till\ last\ stage)}$ + time to re-accelerate

The performance results for the "Re-acceleration" stage of mission A for the "clean" and for the 6% deteriorated engine, are given below in Table C.7.

Table C.7.Performance results for "Re-accelerate" stage (Mission A)

	0%	6%
W_{gs} (kg)	9971,17	9939,25
T_{ts} (N)	34856	32416
T_{tf} (N)	36878	34297
T_{es} (N)	25179,67	22757
T_{ef} (N)	5438	2857
t (sec)	166,86	223,4
α (m/sec^2)	1,29	0,964
F_s (kg/sec)	0,84	0,78
F_f (kg/sec)	1,07	1
F_{av} (kg/sec)	0,955	0,89
FW (kg)	159,35	198,82
$D_{re\text{-}accel}$ (km)	59,064	79,09
D_{ret_cumul} (km)	74,427	96,218
t_{cum} (sec)	1437,36	1567,84
W_{gf} (kg)	9811,82	9740,43

viii. Cruise-Back to Descend Point With 1.5M at 8000 m

Again, in cruise phase,

$$T = D \quad \text{and} \quad L = W$$

As the cruise Mach number is 1.5, the cruise velocity can be given as follows:

$$V = M\sqrt{\gamma RT} = 1.5 * \sqrt{1.4 * 287 * 236} = 461.9 m/s$$

In cruise the drag on the aircraft is the same as the D_{tf} of the last (re-acceleration) stage:

$$D = 31440N$$

In case the total thrust available is more than the drag, the throttle will be retarded back to make it equal to drag. The actual throttle setting can be given as follows:

$$T.S.(\%) = \frac{31440 * 100}{T_t}$$

The distance to reach the descend point (45 km away from home base) is given as:

$$D_{desc.point} = 400 - 45 - D_{return\_cum}(\text{till last stage})$$

The time (in seconds) to reach the descent point is given as:

$$t_{des.po} = \frac{D_{dec.po} * 1000}{461.9}$$

As in this case the throttle will be retarded back to make the total available thrust equal to the drag, therefore, the fuel flow will not be the same as at 100% throttle setting. The effective fuel flow can be given as follows:

$$F_{eff} = \frac{F * TS}{100}$$

Now, the total fuel consumed during “cruise to descend point” stage can be found in the same way as in previous stages, as follows:

$$FW = F_{eff} * t_{desc.poi}$$

The performance results for the “cruise-back to descend point” stage of mission A for the “clean” and for the 6% deteriorated engine, are given below in Table C.8.

Table C.8.Performance results for "Cruise back" stage (Mission A)

	0%	**6%**
W_{gs} (kg)	9811,82	9740,43
T_t (N)	36881	34299
TS (%)	85,24	91,66
D_{desc_point} (km)	280,573	258,782
t_{desc_point} (sec)	607,43	560,25
F (kg/sec)	1,07	1
F_{eff} (kg/sec)	0,912	0,9166
FW (kg)	554,01	513,53
t_{cum} (sec)	2044,79	2128,09
W_{gf} (kg)	9257,81	9226,9

ix. Decelerate and Descend to Land

In this stage the start Mach number is 1.5 and the end Mach number is 0.3, therefore:

$$V_s = M_s \sqrt{\gamma RT} = 1.5 * \sqrt{1.4 * 287 * 236} = 461.9 m/s$$

and $$V_f = M_f \sqrt{\gamma RT} = 0.3 * \sqrt{1.4 * 287 * 288} = 102 m/s$$

hence $$V_{av} = \frac{V_s + V_f}{2} = \frac{461.9 + 102}{2} = 281.95 m/s$$

In this stage the throttle is continuously retarded to reduce thrust to decelerate as the thrust available at the same throttle setting increases with reduction in altitude. The throttle cannot be retarded below 35% throttle setting (because of the requirement of other systems such as hydraulic, pneumatic, electrical etc), although the available thrust will keep on increasing with decreasing altitude. Therefore, from this point onward the descend speed and angle is maintained by the application of aerodynamic brakes etc. In this stage the aerodynamic loads on the aircraft can be expressed by the following equation:

$T = D - W \sin\gamma$ where γ is the descent angle

$$\frac{T}{W} = \frac{D}{W} - \sin\gamma$$

Assuming constant thrust-to-weight ratio of 0.22 and an angle of descent of 10.08 degrees, the time to descent and the weight ratio can be given as follows:

$$time\_to\_descent = \frac{8000}{V_{av} * \sin(10.08)}$$

and $$\frac{W_{gf}}{W_{gs}} = 1 - SFC_{av} * time\_to\_descent * \frac{T}{W}$$

where $$SFC_{av} = \frac{SFC_{8000} + SFC_{S.L.}}{2}$$

Now the weight of fuel consumed during this stage can be given as follows:

$$FW = W_{gs} - W_{gf}$$

The performance results for “Deceleration and Descend to Land” stage of mission A for the “clean” and for the 6% deteriorated engine, are given below in Table C.9.

Table C.9.Performance results for “Decelerate and Descend to land” stage (Mission A)

	0%	**6%**
W_{gs} (kg)	9257,81	9226,9
sfc_{8000} (mg/Nsec)	29,12	29,56
sfc_{SL} (mg/Nsec)	20,63	20,9
sfc_{av} (mg/Nsec)	24,875	25,23
FW (kg)	111,093	110,72
t_{cum} (sec)	2206,9	2920,2
W_{gf} (kg)	9146,71	9116,17

x. Landing and Switch-Off

The resulting deceleration of the aircraft during landing roll can be expressed in terms of the aerodynamic coefficients by the following expression in same way as in the take-off stage:

$$a = g\,\frac{[T_{av} - D_{av} - \mu(W - L_{av})]}{W}$$

The average thrust, lift and drag can all be estimated in the same way as in the take-off stage.

Since the Mach number at the end of the landing roll is zero, both L_f and D_f will also be zero, hence:

$$L_{av} = \frac{L_s}{2} \qquad \text{and} \qquad D_{av} = \frac{D_s}{2}$$

where $L_s = (L_f)_{T.O.} * \frac{(W_{gs})_{land}}{(W_{gs})_{T.O.}} = 1.05*12000*9.81*\frac{9146.71}{12000} \Rightarrow L_s = 94215.68N$

therefore, $L_{av} = \frac{94215.68}{2} = 47107.84N$

and $C_{L\,s} = (C_{L\,f})_{T.O.} * \frac{(W_{gs})_{land}}{(W_{gs})_{T.O.}} = 0.69317*\frac{9146.71}{12000} \Rightarrow C_{L\,s} = 0.5283$

therefore, $C_{D\,s} = 0.015 + (0.1242*0.528^2) = 0.04967$

Since $D_s = (D_f)_{T.O.} * \frac{(C_{Ds})_{land}}{(C_{Df})_{T.O.}} = 13302.6*\frac{0.049679146.71}{0.0746} \Rightarrow D_s = 8857.31N$

then $D_{av} = \frac{D_s}{2} \Rightarrow D_{av} = \frac{8857.31}{2} \Rightarrow D_{av} = 4428.65N$

The rolling resistance will be greatly increased by the application of the brakes. Typical μ values for a hard runway surface are about 0.3 – 0.5.

Now putting the values of lift, drag, weight, g and μ=0.5 in the deceleration expression above, we get:

$$a = 9.81 * \frac{[T_{av} - 4428.65 - 0.5 * (9146.71 * 9.81 - 47107.84)]}{9.81 * 9146.71} \Rightarrow a = \frac{T_{av} - 25739.34}{9146.71}$$

The thrust term is the idle thrust (35% T.S.). Assuming that the aircraft is equipped with thrust reversers, the thrust will be a negative value approximately equal to 50% of the maximum forward thrust at that throttle setting (35%).

Therefore, the average thrust in this stage will be as follows:

$$T_{av} = -(\frac{T_t}{2} * 0.35 * 0.50)$$

The velocity at touch – down can be expressed as follows:

$$V_s = M_s \sqrt{\gamma RT} = 0.3 * \sqrt{1.4 * 287 * 288} = 102 m/s$$

$V_f = V_s + at \Rightarrow -V_s = at$ (since the velocity at the end of the landing roll is zero as Mn is zero).

Therefore, $t = -\frac{V_s}{a} \Rightarrow t = -\frac{102}{a}$

Average fuel flow can be expressed as $F_{av} = \frac{F_s + F_f}{2}$,

where F_s = fuel flow at start of the landing roll

F_f = fuel flow at the end of the landing roll

The fuel weight (FW) consumed during the landing roll can be expressed as follows:

$$FW = F_{av} * t$$

The performance results for the landing stage of the mission A, for the “clean” and for the 6% deteriorated engine, are given below in Table C.10.

Table C.10.Performance results for “Landing” stage (Mission A)

	0%	**6%**
W_{gs} (kg)	9146,71	9116,17
T_{ts} (N)	67610	62877
T_{tf} (N)	77559	72130
T_{av} (N)	-12702	-11813,11
α (m/sec^2)	-4,202	-4,109
t (sec)	24,269	24,82
F_s (kg/sec)	1,39	1,29
F_f (kg/sec)	1,37	1,27
F_{eff} (kg/sec)	0,2415	0,224
FW (kg)	5,86	5,559
t_{cum} (sec)	2231,16	2315
W_{gf} (kg)	9140,84	9110,61

Mission B

i. Take – off

The procedure for the T.O. stage of the mission B is exactly the same as for the T.O. stage of the mission A. However, the aircraft gross weight in this role is 15000 kg, instead of 12000kg as was in mission A. Due to the change in weight, the values of the following parameters also differ from that of mission A and will be used as follows:

$$C_{Lf} = 0.8664 \qquad C_{Df} = 0.1082$$

$$D_f = 19302.133N \qquad D_{av} = 9651.06N$$

$$L_f = 154507.5N \qquad L_{av} = 77253.75N$$

and $$a = \frac{T_{av} - 12446.916}{15000}$$

The performance results for the T.O. stage of the mission B, for the “clean” and for the 6% deteriorated engine, are given below in Table C.11.

Table C.11.Performance results for “take-off” stage (Mission B)

	0%	**6%**
W_{gs} (kg)	15000	15000
T_{ts} (N)	141070	131195
T_{tf} (N)	133270	123941
T_{av} (N)	137170	127568
α (m/sec^2)	8,314	7,674
t (sec)	12,26	13,29
F_s (kg/sec)	7,77	7,21
F_f (kg/sec)	7,92	7,35
F_{av} (kg/sec)	7,845	7,28
FW (kg)	96,18	96,75
W_{gf} (kg)	14903,8	14903,2

ii. Climb from S.L. to 200 m with acceleration from 0.3 M to 0.8 M

The procedure for this stage is exactly the same as for the climb stage of the mission A. However, in this case, the altitude at the end of the climb is 200 m, instead of 8000 m, therefore, the following parameters will vary from that of the mission A and the values will be used as follows:

$$C_{Lf} = 0.01266 \qquad C_{Df} = 0.015$$

$$V_f = 271.5 m/\sec \qquad V_{av} = 186.75 m/\sec$$

$$D_s = 19302 N \qquad D_f = 18562.6 N$$

The performance results for the “climb” stage of mission B, for the “clean” and for the 6% deteriorated engine, are given below in Table C.12.

Table C.12.Performance results for “climb” stage (Mission B)

	0%	**6%**
W_{gs} (kg)	14903,8	14903,2
T_{ts} (N)	67610	62877
T_{tf} (N)	50551	47012
T_{es} (N)	48308	43575
T_{ef} (N)	31989	28449,4
t (sec)	3,955	4,41
F_s (kg/sec)	1,39	1,29
F_f (kg/sec)	1,4	1,29
F_{av} (kg/sec)	1,395	1,29
FW (kg)	5,517	5,693
D_{climb} (km)	0,711	0,798
t_{cum} (sec)	16,215	17,7
W_{gf} (kg)	14898,2	14897,5

iii. High speed/low level cruise to target with 0.8 M at 200 m

The procedure is exactly the same as for the “cruise to target” stage of the mission A, except for the following which differ and will be used as follows:

$$D_t = 800 - D_{c\lim b} \qquad D = 18562.6N$$

$$V = 271.5m/\sec \qquad t = \frac{D_t * 1000}{271.5}$$

The performance results for the “cruise to target” stage of the mission B, for the “clean” and for the 6% deteriorated engine, are given below in Table C.13.

Table C.13.Performance results for “cruise to target” stage (Mission B)

	0%	**6%**
W_{gs} (kg)	14898,2	14897,5
T_t (N)	50551	47012
TS (%)	36,72	39,48
D_t (km)	799,289	799,202
t_t (sec)	2943,97	2943,65
F (kg/sec)	1,4	1,315
F_{eff} (kg/sec)	0,514	0,519
FW (kg)	1513,45	1528,23
t_{cum} (sec)	2960,18	2961,35
W_{gf} (kg)	13384,7	13369,36

iv. Air combat over battle zone

The procedure is exactly the same as for the “Air combat” stage of mission A, except for the following which differ and will be used as follows:

$t = 2\min = 120\sec$ and $(T/W)_{av} = 0.70$

The performance results for the “air combat” stage of the mission B, for the “clean” and for the 6% deteriorated engine, are given below in Table C.14.

Table C.14.Performance results for "cruise to target" stage (Mission B)

	0%	6%
W_{gs} (kg)	13384,7	13369,36
T_{av} (N)	117760	109516
T_{treq} (N)	91912,7	91807,39
sfc (mg/Nsec)	66,92	67,58
t (sec)	120	120
F_t (kg/sec)	6,15	6,2
FW (kg)	738,09	744,52
W_{weapon} (kg)	400	400
t_{cum} (sec)	3080,18	3081,35
W_{gf} (kg)	12246,6	12224,8

v. Low Level Pass over Target

The procedure is exactly the same as for the "cruise to target" stage, except for the following which differ and will be used as follows:

$$t = 20\sec \qquad V = 322.04 m/\sec$$

$$C_{Lf} = 0.0689 \qquad C_{Df} = 0.0156$$

$$D_f = 27170 N$$

The performance results for the "low level pass over target" stage of mission B, for the "clean" and for the 6% deteriorated engine, are given below in Table C.15.

Table C.15.Performance results for "low-level pass" stage (Mission B)

	0%	6%
W_{gs} (kg)	12246,6	12224,8
T_t (N)	46615	43351
TS (%)	58,28	62,67
t_t (sec)	20	20
F (kg/sec)	1,4	1,32
F_{eff} (kg/sec)	0,816	0,827
FW (kg)	16,32	16,55
W_{weapon} (kg)	5200	5200
t_{cum} (sec)	3100,18	3101,35
W_{gf} (kg)	7030,2	7008,25

vi. Cruise – Back to Descend Point with 0.85 M at 200 m

The procedure is exactly the same as for the "cruise to target" stage, except for the following which differ and will be used as follows:

$$V = 288.14 m/\sec \qquad C_{Lf} = 0.005$$

$$C_{Df} = 0.015 \qquad D = 20932.15 N$$

$$D_{dec.point} = 800 - 3.0 \qquad t_{dec.p.} = \frac{797 * 1000}{288.14}$$

The performance results for the "cruise-back to descend point" stage of mission B, for the "clean" and for the 6% deteriorated engine, are given below in Table C.16.

Table C.16.Performance results for "cruise back" stage (Mission B)

	0%	6%
W_{gs} (kg)	7030,2	7008,25
T_t (N)	49318	45866
TS (%)	42,44	45,63
t_t (sec)	2766,01	2766,01
F (kg/sec)	1,4	1,31
F_{eff} (kg/sec)	0,594	0,597
FW (kg)	1643,45	1653,39
t_{cum} (sec)	5866,19	5867,36
W_{gf} (kg)	5386,74	5354,85

vii. Decelerate and Descend to Land

The procedure is exactly the same as for the "decelerate and descend to land" stage of mission A, except for the following which differ and will be used as follows:

$$V_s = 288.14 m/\sec \qquad V_f = 102 m/\sec$$

$$V_{av} = 195.07 m/\sec \qquad \gamma = 3.81 \deg$$

The performance results for the "decelerate and descend to land" stage of mission B, for the "clean" and for the 6% deteriorated engine, are given below in Table C.17.

Table C.17.Performance results for “decelerate and descend to land” stage (Mission B)

	0%	**6%**
W_{gs} (kg)	5386,74	5354,85
sfc_{200} (mg/Nsec)	28,42	28,63
sfc_{SL} (mg/Nsec)	20,63	20,9
sfc_{av} (mg/Nsec)	24,525	24,765
FW (kg)	5,38	5,42
t (sec)	15,42	15,42
t_{cum} (sec)	5881,61	5882,78
W_{gf} (kg)	5381,35	5349,43

viii. Land and Switch – Off

The procedure is exactly the same as for the “landing” stage of mission A, except for the following which differ and will be used as follows:

$$L_s = 55430.59N \qquad L_{av} = 27715.29N$$

$$D_s = 4814.54N \qquad D_{av} = 2407.27N$$

and $$a = \frac{T_{av} - 14945.14}{5381.35}$$

The performance results for the “landing” stage of mission B, for the “clean” and for the 6% deteriorated engine, are given below in Table C.18.

Table C.18.Performance results for “landing” stage (Mission B)

	0%	**6%**
W_{gs} (kg)	5381,35	5349,43
T_{ts} (N)	66610	62877
T_{tf} (N)	77559	72130
T_{av} (N)	-12614,7	-11813,1
α (m/sec^2)	-5,121	-4,985
t (sec)	19,91	20,45
F_s (kg/sec)	1,39	1,29
F_f (kg/sec)	1,37	1,27
F_{eff} (kg/sec)	0,2415	0,224
FW (kg)	4,8	4,58
t_{cum} (sec)	5901,52	5903,3
W_{gf} (kg)	5376,5	5344,84

The overall performance results for both missions are given in Table C.19 and C.20.

Table C.19.Overall performance results for Mission A

MISSION A		
	clean engine	**6% deterioration**
$FW_{TAKE-OFF}$ (kg)	74,84	75,13
FW_{CLIMB} (kg)	161,45	165,39
$FW_{ACCELERATE}$ (kg)	239,37	441,79
FW_{CRUISE} (kg)	595,722	411,712
$FW_{AIR\ COMBAT}$ (kg)	890,46	897,7
$FW_{RE-CLIMB}$ (kg)	67	68,73
$FW_{RE-ACCELERATE}$ (kg)	159,35	198,82
$FW_{CRUISE\ BACK}$ (kg)	554,01	513,53
$FW_{DEC-DESC-TO-LAND}$ (kg)	111,093	110,72
FW_{LAND} (kg)	5,86	5,559
TFW_A (kg)	2859,155	2889,081
ΔFW_A (kg)		29,926
ΔFW_A (%)		**1,047**
t_{cumA} (sec)	2231,16	2315
Δt_{cumA} (sec)		**83,84**

Table C.20.Overall performance results for Mission B

MISSION B		
	clean engine	**6% deterioration**
$FW_{TAKE-OFF}$ (kg)	96,179	96,75
FW_{CLIMB} (kg)	5,517	5,693
$FW_{HIGH\ SPEED\ CRUISE}$ (kg)	1513,45	1528,23
$FW_{AIR\ COMBAT}$ (kg)	738,09	744,52
$FW_{LOW\ LEVEL\ PASS}$ (kg)	16,32	16,55
$FW_{CRUISE\ BACK}$ (kg)	1643,45	1653,39
$FW_{DEC-DESC-TO-LAND}$ (kg)	5,38	5,42
FW_{LAND} (kg)	4,8	4,58
TFW_B	4023,186	4055,133
ΔFW_B		31,947
ΔFW_A(%)		**0,794**
t_{CumA} (sec)	5901,52	5903,3
Δt_{cumB} (sec)		**1,78**

APPENDIX D

Thesis Gant Chart

ID	Task Name	Start	Finish
1	**Master of Research PROJECT**	Mon 1/10/07	Sun 12/10/08
2	**LECTURES AND LITERATURE REVIEW**	Mon 1/10/07	Fri 7/12/07
3	Literature review	Mon 1/10/07	Fri 7/12/07
4	GT Technology for Operation and Maintenance Engineers	Mon 26/11/07	Fri 30/11/07
5	**GAS TURBINE PERFORMANCE DETERIORATION**	Tue 2/10/07	Tue 18/12/07
6	**PYTHIA DIAGNOSTICS**	Tue 2/10/07	Mon 15/10/07
7	Familiarisation with existing PYTHIA diagnostics	Tue 2/10/07	Mon 15/10/07
8	**GAS TURBINE DETERIORATION ANALYSIS**	Mon 15/10/07	Tue 18/12/07
9	**T56-A-15 DETERIORATION**	Mon 15/10/07	Tue 30/10/07
10	Compressor fouling	Mon 15/10/07	Sat 20/10/07
11	Turbine fouling	Sat 20/10/07	Thu 25/10/07
12	Turbine erosion-corrosion	Thu 25/10/07	Tue 30/10/07
13	**F110-GE-129 DETERIORATION**	Thu 1/11/07	Thu 15/11/07
14	Compressor fouling	Thu 1/11/07	Mon 5/11/07
15	Turbine fouling	Tue 6/11/07	Sat 10/11/07
16	Turbine erosion-corrosion	Mon 12/11/07	Thu 15/11/07
17	**ANALYSIS OF RESULTS ACQUIRED**	Mon 19/11/07	Tue 18/12/07
18	T56	Mon 19/11/07	Sat 1/12/07
19	F110	Mon 3/12/07	Tue 18/12/07
20	**TECHON-ECONOMIC STUDY OF COMPRESSOR WASHING**	Fri 25/1/08	Sat 28/6/08
21	**TECHNICAL STUDY**	Fri 25/1/08	Tue 15/4/08
22	F110 mission analysis	Fri 25/1/08	Tue 15/4/08
23	Effect on fuel consumption and extra mission time	Wed 20/2/08	Sun 6/4/08
24	**ECONOMIC STUDY**	Sun 20/4/08	Sat 28/6/08
25	Effects on fuel savings and creep life	Sun 20/4/08	Thu 29/5/08
26	Compressor washing frequency optimization	Sun 18/5/08	Sat 28/6/08
27	**MRes REQUIREMENTS**	Thu 20/12/07	Sun 12/10/08
28	**ADMINISTRATION**	Thu 20/12/07	Sun 12/10/08
29	5month review	Thu 20/12/07	Sun 20/1/08
30	5month review presentation	Fri 29/2/08	Fri 29/2/08
31	Thesis Writing	Sun 29/6/08	Sun 28/9/08
32	Thesis Examination	Sun 12/10/08	Sun 12/10/08