Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

Bachelorarbeit

Studiendepartment Fahrzeugtechnik und Flugzeugbau

Further investigation of engine performance loss, in particular exhaust gas temperature margin, in the CF6-80C2 jet engine and recommendations for test cell modifications to record additional criteria

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31. August 2011

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Abstract

The exhaust gas temperature (EGT) of civil jet engines is a major parameter to monitor and ensure safe engine operation and longer lifetime. Therefore EGT is limited to avoid damage to engine components. The difference between actual measured EGT and the defined limit is called EGT margin.

Since the end of 2008 General Electric CF6-80C2 jet engines which have been overhauled at LTQ Engineering achieve low EGT margin without recognising any reasons. Therefore engines overhauled before and after that date are compared in order to identify differences in performance. By analysing data of an engine performance estimation software and recorded data at the test cell as thrust specific fuel consumption, rotor speeds, thrust, fuel flow and pressure ratios, the problem is narrowed down to the fan and low pressure turbine. After isolating the problem, the blade tip to shroud clearance and the quantity of repair procedures of the fan module are analysed to order to detect any differences and possible reasons for low EGT margin. Both do not reveal any relationship to low EGT margin.

Finally recommendations are given at which engine stations additional test cell instrumentation should be implemented for subsequent test runs. The aim is to gain better knowledge of the performance of fan and low pressure turbine module. Therefore additional probes should be integrated in the secondary airflow behind the fan and in the exhaust nozzle behind the turbine. Hence a modification of the exhaust nozzle is necessary as no ports are available.

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Abbreviations and Acrynoms

Term	Definition
CPR	Compressor pressure ratio
EGT	Exhaust gas temperature
EGTM	EGT margin, exhaust gas temperature margin
EPR	Engine pressure ratio
GE	General Electric
HPC	High pressure compressor
HPT	High pressure turbine
HPTR	high pressure turbine rotor
HPTS	high pressure turbine stator
LPC	Low pressure compressor
LPT	Low pressure turbine
N1 rotor	Low pressure rotor
N2 rotor	High pressure rotor
SFC	(Uninstalled thrust) specific fuel consumption
SFCM	SFC margin, specific fuel consumption margin
TEMPER	Turbine Engine Module Performance Estimation Routine
w_f	Fuel flow

1 Introduction

The performance of jet engines is judged by several parameters. Most important is the generation of thrust in order to provide sufficient propulsion for the aircraft. Therefore engine parameters such as rotor speeds, fuel consumption and pressure and temperature across the engine are monitored in order to ensure safe engine operation. One of the most critical parameters is the exhaust gas temperature (EGT) and its margin to a certain limit. During normal operation, engine performance deteriorates which leads to an increase in EGT. The exposure of engine hardware, in particular of the high pressure turbine, to high gas temperatures leads to damage of components until they have to be overhauled.
This investigation focuses on the decrease of EGT margin in the General Electric CF6-80C2 jet engine which is shown in figure 1.1. The problem of low EGT margin arises after

Figure 1.1: General Electric CF6-80C2 [GE10]

full overhaul events in which the complete engine is disassembled, inspected, repaired if applicable and finally assembled and tested. Normally performance is restored and engines which have undergone such procedure should show high EGT margin.
With the change of overhaul vendor at the end of year 2008, engines no longer achieved desired EGT margin. Therefore this investigation alludes to pre-vendor engines with high EGT margin and post-vendor engines with low EGT margin. A previous investigation could not reveal any reasons; therefore it is necessary to extend the sample of engines and to take additional parameters into consideration in order to identify differences in engine performance and repair procedures of pre- and post-vendor engines.
LTQ Engineering is a joint venture of the Australian airline 'Qantas Airways' and the German maintenance, repair and overhaul company 'Lufthansa Technik'. Located in Melbourne, Australia, LTQ Engineering employs 200 people and provides overhaul services for CFM56 and CF6 jet engines.

2 Theoretical background

The complex configuration and functionality of a jet engine with its many components leads to many possible reasons for low EGT margin. Due to the available data and the complexity of the topic it is not possible to take every reason into account. Therefore, this literature review focuses on the key aspects of engine performance, explains the main parameters to assess performance and gives an understanding of overhaul and test procedures.

2.1 General Electric CF6-80C2

The General Electric (GE) CF6-80C2 jet engine is a dual-rotor turbofan powerplant with a high bypass ratio. It is designed for subsonic commercial airline service [GE90]. Introduced in October 1985, the CF6-80C2 is certified on 11 widebody aircrafts, including the Boeing 747 and 767, the McDonnell Douglas MD-11 and the Airbus A310 [GEA11]. Figure 2.1 shows the cross section of the engine with its major modules.

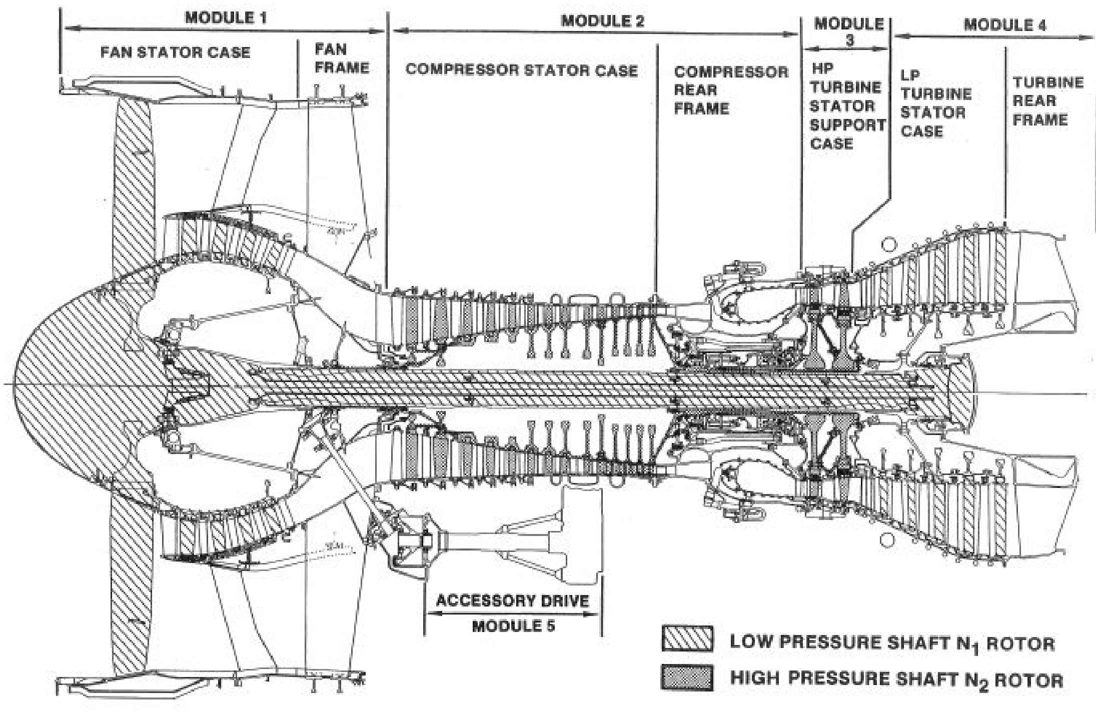

Figure 2.1: Cross section of the General Electric CF6-80C2 [GE02]

The dual-rotor engine has a low pressure rotor (N1 rotor) and a high pressure rotor (N2 rotor). The need for the dual-rotor configuration is based on the high compressor pressure ratio (CPR) and on the limitation of fan speed. To achieve the required pressure, a high rotation speed of the high pressure compressor (HPC) is necessary. At the same time, the fan speed is limited due to aerodynamics, strength and noise and requires a low rotation speed [BRÄ09]. Optimum design fan speed would be too slow for the HPC to compress enough air. Therefore the fan, the low pressure compressor (LPC, also called booster) and the low pressure turbine (LPT) rotate with a low speed on the N1 rotor. The N2 rotor is located between the fan and the LPT and consists of the HPC and the high pressure turbine (HPT). The combustion chamber is arranged between HPC and HPT [GE90]. In the further course of this investigation, engine data will be compared and it is important to know where this data is measured. Figure 2.2 shows the designation of the airflow stations of the CF6-80C2 according to GE. It has to be mentioned that only some of these parameters are recorded in a test run (refer to section 2.7 for further information). The numbers 11 to 19 represent stations of the secondary airflow, which is fan air exhausting through the fan nozzle. All other numbers belong to the primary airflow through the gas generator sections [GE90]. The ratio of secondary airflow and primary airflow is called bypass ratio and is the major parameter to increase the mass flow and consequently the thrust [SRCS09].

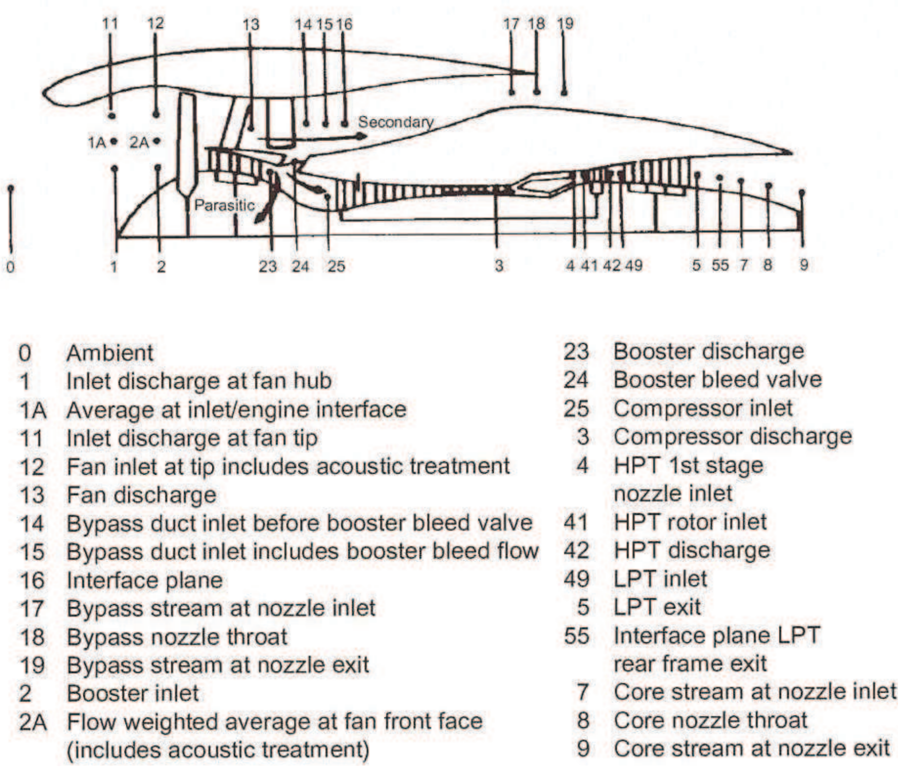

Figure 2.2: Airflow station designation [GE02]

This investigation focuses on the CF6-80C2B6 jet engine. 'CF' is an abbreviation for 'commercial fan', '6' stands for the original bypass ratio. '80' represents the time when it entered service, here the 1980s. It belongs to the engine series 'C', which defined the thrust rating and '2' represents the version within the engine series. The supplement 'B' reveals that the engine is used on a Boeing aircraft and '6' stands for the modification level.

2.2 Exhaust gas temperature

The exhaust gas temperature (EGT) is a key engine parameter used to monitor and analyse gas turbine performance. As one of the most critical parameters, the EGT acts as an indicator of the HPT inlet temperature, which is the highest temperature of the gas path (refer to station 4 in figure 2.2) [GIA09]. Due to the high energy gas stream (with temperatures around 1300 °C [BRÄ09]) right behind the combustion chamber, it is not possible to measure the HPT inlet temperature directly. The temperature is too high for the type of instrumentation available and leads to an increased error in measurement. For dual-rotor engines it is more common to record the temperature between HPT and LPT [SRCS09]. In GE CF6-80C2 engines, the LPT inlet temperature (station 49 in figure 2.2) is measured and designated as the EGT.
Excessive turbine temperatures and high rotation speeds result in an increased level of creep, oxidation and hot corrosion, which leads to a shorter lifetime of the components or, in the worst case, to a catastrophic failure. Creep is a permanent deformation that occurs to loaded components which are exposed to high temperatures, even if the stress level is below the yield strength (Hooke's law). The occurrence of creep or other failure modes cannot be avoided in the operating life of a jet engine and becomes relevant when the ratio of absolute material temperature to absolute melting temperature exceeds 0.5. In particular the HPT is exposed to temperatures above this value and therefore the effects are the greatest [SRCS09] [GIA09]. The relationship between creep and metal temperature is also shown on the left side of figure 2.3.

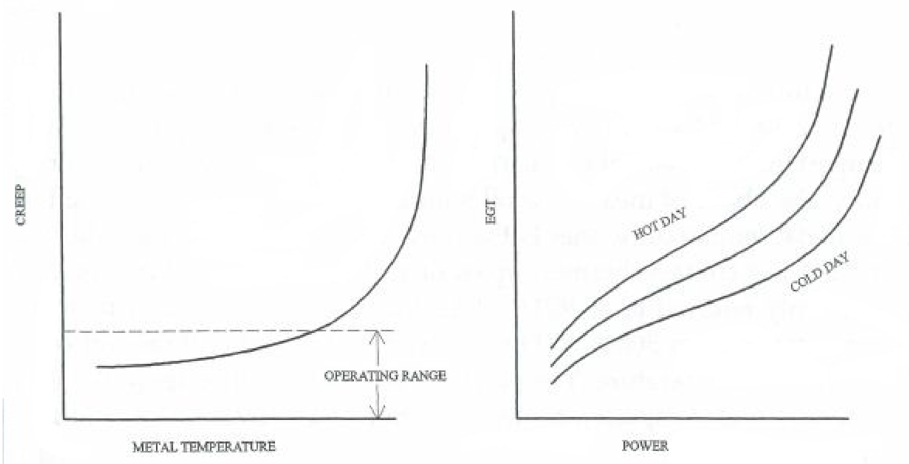

Figure 2.3: EGT correlations [GIA09]

The chart on the right side of figure 2.3 gives a description of the correlation between EGT and power output (thrust). One possibility to decrease the EGT is to reduce the engine thrust. According to this, high thrust leads to high EGT for a given engine architecture [GIA09]. To keep negative effects such as creep to a minimum, the EGT has to be limited.

Above the limit, serious damage to the turbine and other hardware must be expected. Therefore, EGT is one of the engine parameters which is monitored during operation and indicated in the flight deck. The unit of measurement is degree Celsius [°C]. The difference between the measured temperature and the EGT limit is called exhaust gas temperature margin (EGT margin or EGTM) and is one of the main parameters used to assess the quality of an overhaul. The limit is based on mechanical properties of the used material, in particular of turbine blade metal; for example single crystal nickel superalloys are more durable for high temperatures than directional solidified blades [BRÄ09] [GIA09]. GE recommends an EGT margin of 35 °C, however engines with a lower EGT margin can be released to service with approval of the operator.
The engine operator is generally concerned with the EGT margin. Due to changes in component quality as blade surfaces, size, material properties or clearances (refer to chapter 2.9), EGT increases over time in service (e.g. CF6-6D engines show a 17 °C increase in EGT after 4000 flight hours), but should be restored to its former condition after an overhaul. With this in mind, low EGT margin results in a shorter time in service until the next overhaul which causes higher costs for the operator [LHP78].

2.3 Fuel consumption

In addition to EGT, fuel consumption is another important engine parameter. The mass of fuel which is burnt in the combustion chamber during operation is usually measured in pounds weight of fuel per hour [lb/h] [MHP02] and will be named fuel flow (w_f) in the following. Although it has no direct effect on safe engine operation, the fuel flow has a great influence on the operational costs of an aircraft. Low fuel flow results in a longer range and/or increased payload [MAT05]. In this context it makes sense to introduce an additional parameter, the (thrust) specific fuel consumption (SFC). This describes how much fuel is burnt to produce a certain amount of thrust [BRÄ09]. Thereby the thrust and fuel flow data of an uninstalled engine (uninstalled = engine in test cell) is used to calculate the SFC because thrust is not measured in flight operations [WF98]. The unit of measurement for SFC is pounds weight of fuel per hour per pound force of thrust [lb/(lb_f·h)] [MHP02].The equation below presents the mathematical relationship of the SFC:

$$SFC = \frac{Fuelflow}{Thrust} = \frac{w_f}{F}$$

SFC allows for a comparison between engine types with different thrust ratings, making it a good indicator for overall engine performance [FLA05]. GE has defined a limit for SFC to allow a calculation of the SFC margin (SFCM). The unit of SFC margin is percent [%] and the equation to calculate it is shown below.

$$SFCM = \frac{measured\ SFC - SFC\ limit}{SFC\ limit} \cdot 100$$

The chart on the left side of figure 2.4 shows the relationship between SFC and EGT margin. Normally high SFC results in low EGT margin and low SFC in high EGT margin which is presented by the expected band. If SFC is high, the engine burns more fuel to generate a certain amount of thrust or generates insufficient thrust for its fuel flow. If an engine is located in the area of high SFC and high EGT margin and outside of the expected band, an error in measurement of thrust or fuel flow is very likely. The chart on the right side of figure 2.4 displays fuel flow as a function of EGT. An increase in fuel flow results in a temperature rise due to the additional energy in the gas path [GE02]. Unfortunately it is not possible to determine one component for a high fuel flow or SFC, probable causes may lay in a poor fan, LPT, HPC and/or HPT performance [GE10]. Therefore it is necessary to have a look at other parameters to isolate the fault.

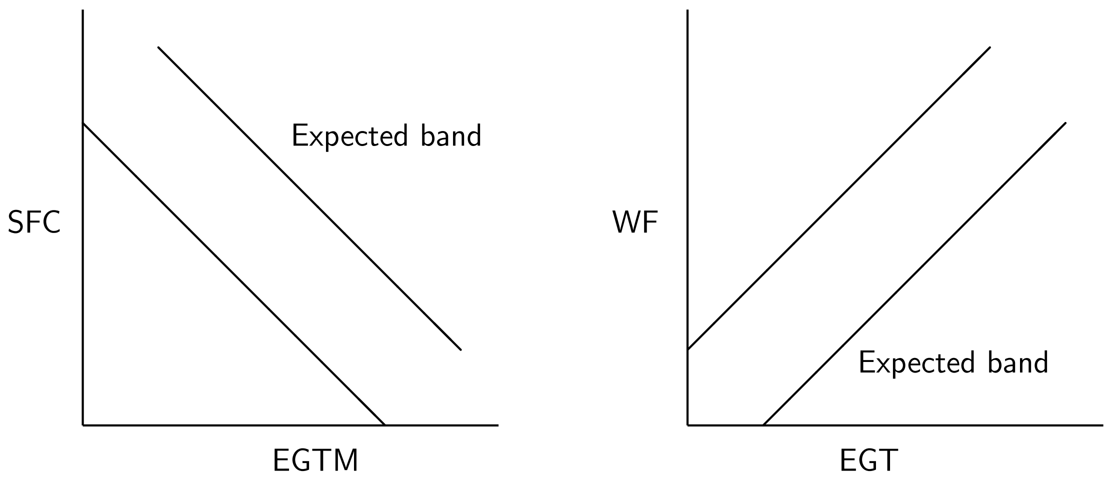

Figure 2.4: Relation between SFC and EGT margin and fuel flow and EGT [GE02]

In the further course of this investigation, EGT and SFC and their margins are the parameters which are used to assess the quality of an overhaul. High EGT (low EGT margin) and low SFC (high SFC margin) stand for poor engine performance; low EGT (high EGT margin) and high SFC (low SFC margin) are indicators for good engine performance.

2.4 Thrust

The capability to generate thrust is the most important characteristics of a jet engine. If an engine does not meet or exceed the required thrust level, it cannot be released into service [GE10]. To gain a general understanding of how thrust is generated, figure 2.5 shows a schematic diagram of a propulsive duct. The air flow $\dot{m}$ enters the intake with a velocity C_a and leaves with the velocity C_j. For this simple explanation it is not necessary to know what happened between these two stations.

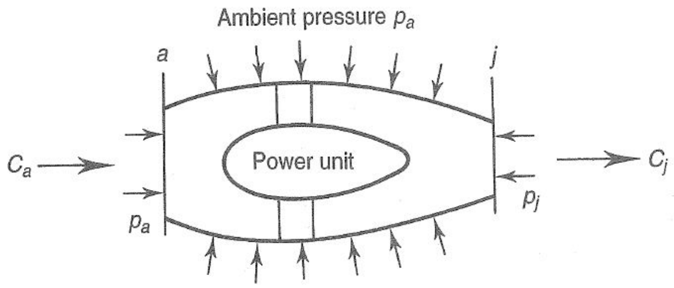

Figure 2.5: Propulsive duct [SRCS09]

Due to Newton's second law, the thrust F is summarised by:

$$F = \dot{m} \cdot (C_j - C_a)$$

For simplicity it is assumed that the exit pressure p_j of the exhaust gas equals the intake pressure p_a (the gas expands completely to p_a in the propelling nozzle). Otherwise it would be necessary to take an additional pressure thrust into account [SRCS09].
As explained in section 2.1, a turbofan engine has a primary and a secondary airflow. With the assumption of complete expansion and the simplification of no parasitic airflow, e.g. air for airfoil cooling, air conditioning or anti ice, it yields to the general thrust equation for turbofan engines. $\dot{m}_I$ represents the primary airflow, $\dot{m}_{II}$ is the secondary airflow. The intake velocities C_{aI} and C_{aII} are equal, only the discharge velocities C_{jI} and C_{jII} are different. With a bypass ratio of $\mu = \frac{\dot{m}_{II}}{\dot{m}_I} = 5,31$ for the CF6-80C2 nearly 85% of the intake air goes through the secondary air path [BRÄ09].

$$F = [\dot{m}_I \cdot (C_{Ij} - C_{Ia})] + [\dot{m}_{II} \cdot (C_{IIj} - C_{IIa})]$$

The first part of the equation represents the thrust generated through the core nozzle. This primary airflow provides about 20% of the engine thrust. The thrust generated through the secondary airflow can be calculated with the second part of the equation and amounts to 80% [GE90]. Although the discharge velocity of the secondary path is lower than the primary path ($C_{Ij} > C_{IIj}$), more thrust is generated because of the higher air flow ($\dot{m}_{II} > \dot{m}_I \cdot$). Therefore the fan is regarded as the main component to generate thrust [BRÄ09] and should be analysed if engine thrust is very high. The unit of thrust is pound force of thrust [$\mathrm{lb_f}$] ($1\,\mathrm{lb_f} = 4.44822\,\mathrm{N}$).
The generation of more thrust means an additional exposure for the engine components due to higher fuel consumption and EGT. It is desirable that an engine generates just as much thrust to meet or exceed the thrust limit in a performance acceptance test (refer to section 2.7 for further information) [GE10].

2.5 Pressure ratios

The pressure ratio between two airflow stations is a good indicator for component performance [MHP02]. Usually the ratio of discharge pressure to intake pressure is used, whereat it is important to differentiate between compressor and turbine. Low compressor pressure ratio means poor component performance because of a small pressure increase through the compressor. In contrast, a low turbine pressure ratio stands for an effective energy extraction of the turbine and good component performance [GE02].

Engine pressure ratio (EPR) is usually measured between booster inlet and HPT outlet (between station 2 and 49, refer to figure 2.2). In the CF6-80C2, fan inlet pressure (P12) is used instead of booster inlet pressure due to availability [GE10]. Observing EPR has the advantage that it is directly proportional to engine thrust. A change of 1% in EPR results in a 1% change in thrust [BRÄ09]. Higher EPR results in higher thrust generation, which leads to a higher fuel consumption and therefore to an increase in EGT as explained in chapter 2.3. The chart on the left side of figure 2.6 shows the relationship between EPR and EGT.

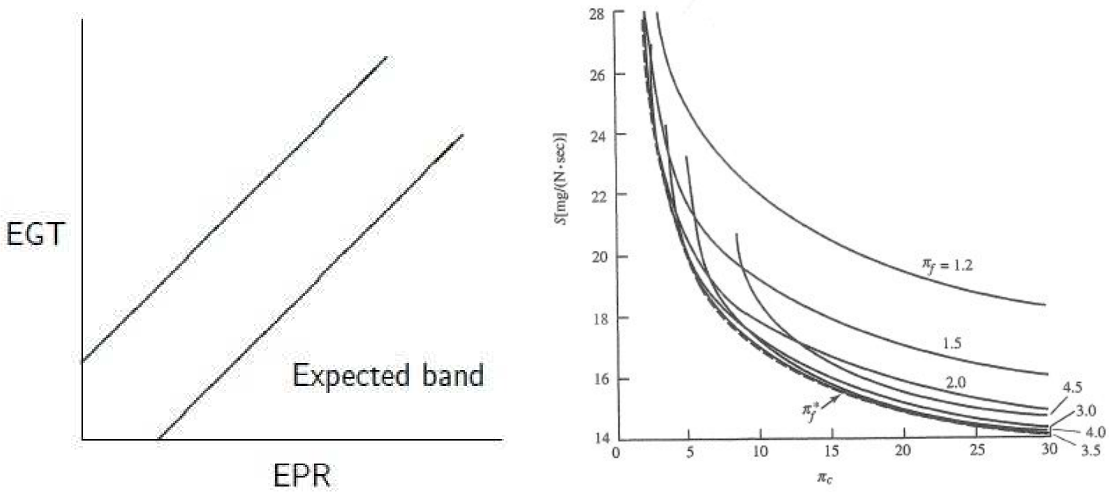

Figure 2.6: EPR relation to EGT (left side)[GE02] and to SFC (right side)[MAT05]

A comparison of EPR of different engines shows the performance of the high pressure systems. An engine has poor HPC or HPT performance if it is not located in the expected band [GE02].

Due to availability of engine data (refer to chapter 2.7), it is not possible to provide the pressure ratio of each component. In addition to EPR, the ratio between discharge static and inlet total pressure of the HPC (PS3/P25) is used in this investigation [MHP02]. The pressure ratio of discharge static pressure of the HPC and fan inlet pressure (PS3/P12) indicates the performance of the full compressor. On the right site of figure 2.6, SFC (S) is plotted versus the compressor pressure ratio (CPR, π_c) for different fan pressure ratios

(π_f). SFC decreases with an increase in CPR at constant fan pressure ratio [MAT05]. The correlation can be applied to the HPC pressure ratio as it is the second module of the full compressor; high HPC pressure ratio leads to decreased SFC.

2.6 Rotor speed

As mentioned earlier, the CF6-80C2 engine has two rotors which operate with different speeds. The monitoring of rotor speeds to control the engine performance is used in almost all gas turbines [GIA09]. But the examination of the N1 and N2 rotor speed on their own is not very significant. In an acceptance test run the engine must meet or exceed all requirements at the same N1 rotor speed. Therefore a comparison of N1 rotor speeds is not possible [GE10]. The analysis of N2 rotor speed is used to assess the performance of HPC and HPT. A fast spinning HPT is more efficient which results in higher rotation speed of the N2 rotor and therefore higher pressurisation of the HPC. Comparably low pressure ratio and high core speed indicate a lack of efficiency for the compressor. Low N2 speed can be the result of deterioration of the HPC or HPT [GE02]. Figure 2.7 displays the relationship between rotor speeds and output power for a dual-rotor engine.

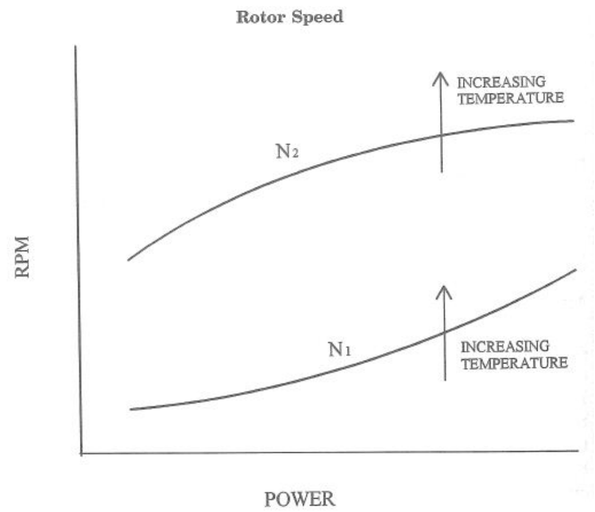

Figure 2.7: Rotor speeds and power output [GIA09]

To achieve a higher thrust level for a given engine architecture, rotor speeds have to be increased. An increase in outside air temperature at constant power output results in higher rotor speeds as well [GIA09].

2.7 Performance acceptance test

After repair or overhaul, every engine is tested to ensure that it meets operational and performance standards. The procedure is called performance acceptance test and normally consists of two phases; in the first phase, engine functions such as variable stator vane and variable bypass valve tracking (both used on low performance levels to ensure a stable compressor operation [BRÄ09]) are tested and vibration limit and operational response checks are performed. In the second phase, the engine has to demonstrate that it meets certified thrust within its operational limits [GE10]. Figure 2.8 displays these limits for both power settings on standard and hot day. The engine has to meet or exceed limits for

80C2B6

POWER SETTING N1K (RPM)	FLAT RATE TEMP. °F (°C)	BAND	STANDARD DAY THRUST LBS	STANDARD DAY EGT °F (°C)	STANDARD DAY CORE SPEED RPM	STANDARD DAY FUEL FLOW PPH	STANDARD DAY EPR RATIO	HOT DAY EGT °F (°C)	HOT DAY CORE SPEED RPM
TAKEOFF 3470	86 (30)	MAX	61905	1608(876)	10569	22016	7.75	1701 (927)	10841
		MIN	59100	1508(820)	10348	20879	7.46		
MCT 3340	77 (25)	MAX	57270	1558(848)	10371	19875	7.17	1618 (881)	10550
		MIN	54640	1449(787)	10150	18738	6.86		

Figure 2.8: Limits of performance acceptance test [GE10]

takeoff and maximum continuous thrust at certain N1 rotor speed, below the limits of EGT, fuel flow, EPR and N2 rotor speed [GE10]. The highest thermal and mechanical stresses occur during takeoff conditions on a hot day, thus deterioration effects can be detected at the earliest [EFWZ11] and margins are smaller, therefore data from this power setting is collected and analysed in this investigation. Only EGT and N2 rotor speed change on hot day conditions, the limits for thrust, fuel flow and EPR are the same as on standard day condition. Both ambient conditions are referred to sea level, whereby standard day represents 15 °C and hot day 30 °C air temperature [GE10].
Due to different weather conditions (temperature, pressure and humidity) and to allow a comparison between the tested engines, all recorded data has to be corrected to the same power setting and ambient condition [GE10]. The GE engine shop manual and performance estimation program TEMPER (Turbine Engine Module Performance Estimation Routine) provide these correction factors. It has to be mentioned that the performance acceptance test is much more limited than production testing in the development stage due to reduced instrumentation. The following data is measured during an engine test run:

- N1 rotor speed (fan speed) [rpm]
- N2 rotor speed (core speed) [rpm]
- thrust [lb]
- fuel flow [lb/h]
- barometric pressure [psia]

- absolute humidity [grains/lb]
- fan inlet temperature (T12) [°C]
- fan inlet total pressure (P12) [psia]
- LPC inlet temperature (T25) [°C]
- LPC inlet total pressure (P25) [psia]
- LPC discharge temperature (T3) [°C]
- LPC discharge static pressure (PS3) [psia]
- LPT inlet temperature (EGT)(T49) [°C]
- LPT inlet total pressure (P49) [psia]

Different from the static pressure, the total pressure takes the movement of the air into account. It is the sum of static pressure and velocity pressure [GIA09]. Both are measured in pounds per square inch absolute [psia], which is the pressure relative to a vacuum. The abbreviations for pressure measurement used in this investigation are 'P' for total pressure and 'PS' for static pressure followed by the station number where pressure is recorded. In terms of accuracy, the measurement of static pressure causes more problems than of total pressure. Difficult conditions such as high air speeds, turbulence and high temperatures falsify the measurement of static pressure. However both static and total pressure have to be measured to calculate the thermodynamic cycle. Measured temperatures are always total temperatures which consider the kinetic energy of the airflow [BRÄ09]. The barometric pressure and humidity are measured so that test data can be referred to either standard day or hot day conditions. Although the effect of humidity upon engine performance is very small, it is not negligible because it causes changes in basis properties of specific heat and gas constant. It is described as the ratio of mass of water to the mass of dry air and the unit is grains per pound (1 grain = 1/7000 pound) [grains/lb] [GE02] [WF98].

2.8 Performance estimation

General Electric offers customers the option to submit their engine test data to a performance diagnostics software. This computer program is called TEMPER, an abbreviation for Turbine Engine Module Performance Estimation Routine and is used to assign the deviation in EGT margin and SFC margin to the engine components (fan, LPC, HPC, HPT stator (HPTS), HPT rotor (HPTR), LPT and MEAS. MEAS is an abbreviation for measurement and deviations which cannot be assigned to a component are listed in this category. For instance, if a pressure probe (e.g. P49) is not installed or has a high error in measurement, the TEMPER software has problems to differentiate between HPT and LPT. Therefore the deviation is put into the MEAS category. Figure 2.9 shows a flow-chart of the TEMPER process and which input data is needed. In the first step, the customer has to provide a test cell correlation report which defines the facility adjustment parameters. Furthermore the customer stipulates his preferred parameter units. GE provides a baseline engine model (e.g. factory new engine or average of engines) to which test data is compared. Regarding this information the personalised TEMPER program is set up. The customer submits the

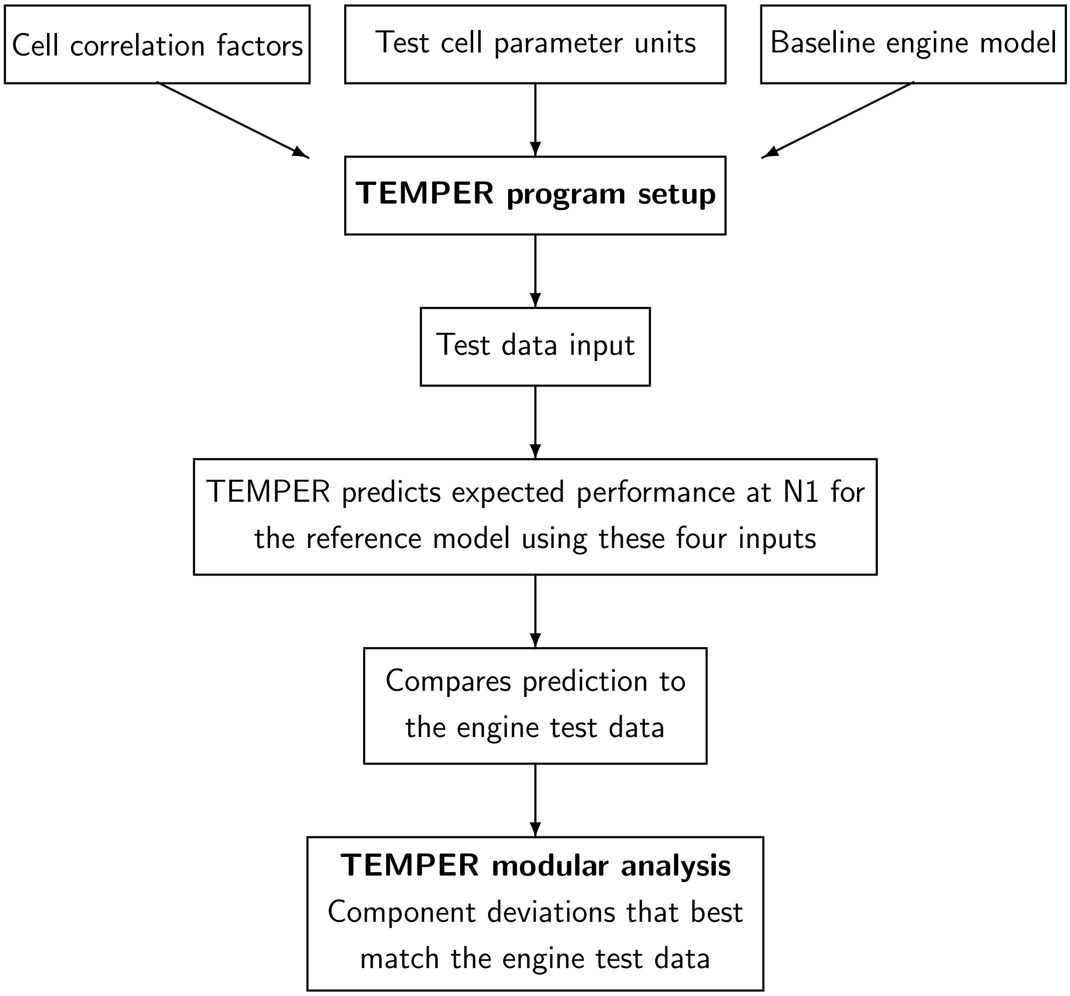

Figure 2.9: Flow-chart of the TEMPER process [GE02]

engine test data via email to the TEMPER program which calculates the entire thermodynamic cycle for both power settings (takeoff and maximum continuous) by using the measured fan speed (N1 rotor speed), fan inlet temperature and total pressure (T1A and P1A), barometric pressure and humidity. This prediction is compared to the engine test data and deviations are identified. Finally the TEMPER program creates the thermodynamic model by using the method of least-squares to provide component deviation which matches the test data at its best. The final report includes the effects of each module on EGT margin and SFC margin, deviation of the test cell data from the prediction before and after module assessment and the deviation of component flow and efficiency from reference baseline [GE02]. Appendix A.2 shows a TEMPER report for further information.
Related to the TEMPER data this investigation concentrates on the deviation of EGT

margin and SFC margin per module. This data gives a first impression of the abnormal performing component, although it is not possible to identify the reasons for deterioration. Therefore it is necessary to analyse additional test cell data to gain more information about each component.

2.9 Performance deterioration

During the operating period, engine performance decreases because of deposits on the compressor blades (compressor fouling), increased tip clearances and corrosion or erosion of the blades. A decrease in power generation, an increase in turbine operating temperature and increased fuel consumption are the consequences. Although takeoff and landing are only a short period of the flight duration, performance deterioration is the greatest at this time. Pollen, tree-sap and insects are drawn into the engine and form sticky deposits on the compressor blades. Hard particles such as sand cause erosion and change the airfoil shape and the ingestion of chemical particles due to pollution or salty atmosphere cause corrosion, especially of the turbine blades due to the high operating temperature. The cross section of a turbofan engine in figure 2.10 displays loads and failure modes for each component.

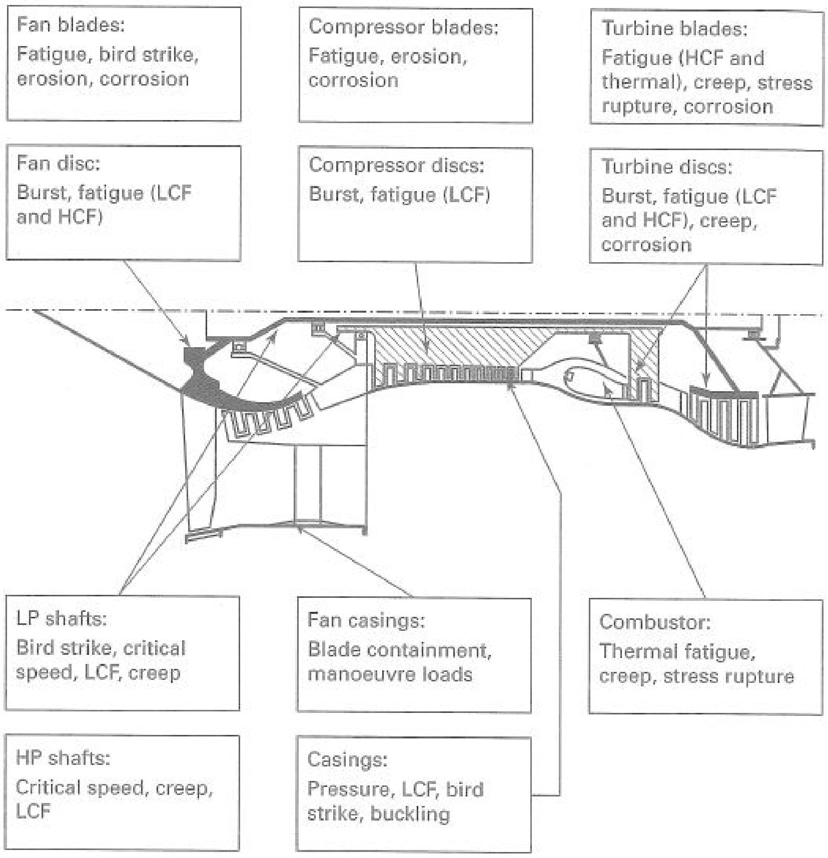

Figure 2.10: Loads and failure modes [SRCS09]

All these failure modes have an effect on the size, surface, clearance and material properties of the engine components [SRCS09]. It has to be mentioned that after a complete overhaul, all dimensions should be within their limits and engine performance shall be restored. The effects on EGT at takeoff and SFC in cruise for each module are shown in table 2.1 to 2.4. All effects are based on experience according to General Electric and represent the worst case. They can be classified in two categories which are external and internal performance losses. External losses are leakage airflows and mechanical friction losses in bearings and seals [BRÄ09]. Higher seal clearances enable higher parasitic airflow and result in decreased total airflow through the engine. Friction losses caused by boundary layer growth over the blade profile and higher clearances between rotor and stator stages or between blade tip and case are called internal losses [SRCS09]. Clearances between rotor blades and case (tip clearance) or rotor and stator (interstage clearance) have an effect on the efficiency of a component. With a high overtip leakage the pressure increase of the compressor is lower and the turbine extract less work from the gas flow [WF98]. More fuel has to be burnt in order to reach required N1 rotor speed. Therefore higher clearances of LPC, HPC, HPT and LPT cause an increase in EGT (and lower EGT margin). Higher fan blade to case clearance leads to lower EGT instead. The efficiency of the fan drops with higher fan blade tip clearance. The core modules do not have to work as hard to achieve the required N1 rotor speed which results in less fuel consumption [GE06] [GE02]. Therefore EGT decreases (and EGT margin increases), but the engine achieves higher SFC due to less thrust generation of the secondary flow path [BRÄ09]. The effect of component efficiency due to tip clearance is shown in figure 2.11. Due to the angle of incidence and shape of the

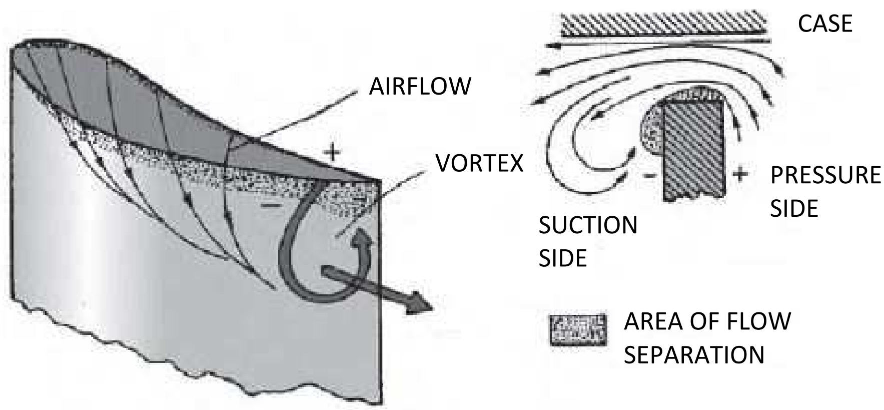

Figure 2.11: Effect of clearances [BRÄ09]

airfoil, blades and vanes have a suction side and a pressure side and an airflow occurs from high pressure to low pressure. It runs against the main flow direction and causes vortices to be generated leading to flow separation on the airfoil and a decrease in efficiency [BRÄ09]. Component efficiency is also influenced by airfoil roughness (quality in surface finish). The area near the airfoil surface where flow velocity is reduced due to viscous friction is called the boundary layer. There are two types of boundary layers; laminar and turbulent. Figure 2.12 shows the two types of layers. When the air flows along the surface, the boundary layer grows and changes from laminar to turbulent with increased distance to the leading edge. Higher surface roughness leads to an early transition from a laminar to a turbulent

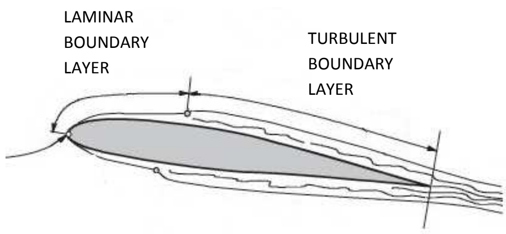

Figure 2.12: Boundary layer [BRÄ09]

boundary layer [SCH09]. Due to higher drag of turbulent boundary layers, the efficiency of the blades is reduced which leads to poorer pressurisation for compressors or poorer work extraction for turbines. The same effects as described before occur with a decrease in component efficiency; EGT and SFC increase for the affected module.

Table 2.1: Deterioration effects on EGT and SFC for the fan/booster module [GE06]

	SFC [%]	EGT [°C]
increase of fan blade tip clearance (for each 0.02-inch clearance)	0.09	-0.90
fan blade leading edge erosion	0.41	0.80
fan surface finish (60 microinches versus 22 microinches)	0.035	0.672
fan blade pitting	0.04	0.12
fan blade dirt	0.11	0.35
splitter erosion	0.05	-0.06
OGV leading edge erosion	0.05	-0.06
booster airfoil surface finish (50 microinches versus 24 microinches)	0.015	0.3
booster shroud erosion (for each 0.02-inch clearance)	0.07	1.0

Table 2.2: Deterioration effects on EGT and SFC for the HPC module [GE06]

	SFC [%]	EGT [°C]
increase of blade to case clearances (for each 0.01-inch clearance for all stages)	0.185	3.80
increase of vane to spool clearances (for each 0.01-inch clearance for all stages)	0.121	2.48
airfoil surface finish (all blades and vanes, 60 microinches versus 22 microinches)	0.641	15.0
decrease of airfoil chord length (for each 0.03-inch chord length loss for all stages)	0.185	3.80
increase of CDP seal clearance (for each 0.01-inch clearance)	0.39	4.7
increase of 4R vent seal clearance	0.17	1.0

Table 2.3: Deterioration effects on EGT and SFC for the HPT module [GE06]

	SFC [%]	EGT [°C]
airfoil surface finish (stage 1, 120 mircoinches versus 33 microinches)	0.17	3.21
increase of blade tip clearance (stage 1 blade and stage 2 blade and vane)	0.305	6.19
interstage seal clearance (for each 0.01-inch clearance)	0.04	0.9

Table 2.4: Deterioration effects on EGT and SFC for the LPT module [GE06]

	SFC [%]	EGT [°C]
increase of blade to case clearance (for each 0.01-inch clearance for all stages)	0.078	0.69
airfoil surface finish (all blades and vanes, 150 microinches versus 55 microinches)	0.575	8.22
increase of interstage seal clearance	0.225	2.11

2.10 Jet engine overhaul

To maintain engine performance and to secure a safe operation, it is necessary to overhaul jet engines after a certain period of time. The most common reasons for removal are the

achievement of life limit of engine parts or reduced EGT margin. Life limited parts have to be replaced after a certain number of cycles [FAR11]. One cycle contains of all stages of the flight mission as idle, take-off (full thrust), cruise and landing [WF98]. Parts are life limited because not every failure mode (e.g. change in material properties) is detectable during inspection. Another reason for removal is the decrease in EGT margin. It indicates poor engine performance and higher hardware exposure [FAR11]. An example for an engine monitoring report of a CFM56 jet engine is presented in the appendix A.1.
As engine data such as EGT and life limits are monitored, the operator sets the time for an overhaul event. There are three different types of overhaul:

- Minimum workscope
- Performance workscope
- Full overhaul workscope

The minimum workscope is performed when a not predictable but minor defect occurs, e.g. change of fan blades or gearbox. These maintenance procedures are performed without a complete disassembly of all engine modules. The average turnaround time at LTQ Engineering is 25-30 days depending on the defect. If a drop in EGT margin or SFC margin is detected, the engine is overhauled in accordance with the performance workscope. This concentrates mainly on the high pressure modules as HPC and HPT and takes around 60-70 days. The remaining modules are not disassembled. It has to be mentioned that this workscope is not used at LTQ Engineering anymore due to the age of engines which are maintained. The overhaul of the high pressure modules is not sufficient to restore performance for older engines. The full overhaul workscope consists of the disassembly, inspection, overhaul and assembly of all engine parts. This overhaul event takes up to 90 days and restores performance for all engine modules [FAR11].
Therefore only engines which have undergone full overhaul are investigated. These engines should reach the required performance limits and permit an expedient comparison.

2.11 Results of preceding investigation

As the problem of low EGT margin has existed since the end of 2008, an investigation was carried out in 2010 to find possible reasons for the performance deterioration. This investigation was based on test cell and TEMPER data, in which the same sample of pre-vendor engines was used. However, the sample of post-vendor engines only included five. Therefore the validity was limited due to data availability. The HPC module was identified as the faulty component and the investigation focused on different reasons for low EGT margin.
The analysis of HPC seal clearances (CDP and 4R vent seal) showed that post-vendor engines have a smaller clearance which theoretically results in lower EGT and SFC (refer to

section 2.9). Therefore the seal clearances do not reveal any reason that accounts for the lack in EGT margin or SFC margin.

Considering the blade to case clearance of HPC stages, the pre-vendor engines achieved a greater clearance; post-vendor engines showed smaller HPC stage clearance. The magnitude of EGT and SFC increase are shown in table 2.5. They were determined by measuring the variation of clearance from the performance target for each HPC stage. Each variation was multiplied by an influence factor on EGT and SFC (based on GE) and led to the shown results. The blade to case clearance justified an increase in EGT of 2.87 °C for

Table 2.5: Effect of blade to case clearance on EGT and SFC [TRA10]

	EGT [°C]	SFC [%]
pre-vendor engines	+2.87	+0.13
post-vendor engines	+2.30	+0.11

pre-vendor and only 2.30 °C for post-vendor engines. This trend was seen as evidence that post-vendor engines achieve a greater performance restoration for the HPC than pre-vendor engines. Hence the difference in HPC blade to case clearance was eliminated as the reason for low EGT margin.

The result of the analysis of vane to rotor clearance was that post-vendor engines have a bigger clearance than pre-vendor engines; however, the effect on EGT and SFC was very small. Therefore it has minor significance for a comparison between pre- and post-vendor engines. The results are shown in table 2.6 and have been determined in the same way as in table 2.5. Due to the great effect of HPC surface finish on EGT and SFC, the performed

Table 2.6: Effect of vane to rotor clearance on EGT and SFC [TRA10]

	EGT [°C]	SFC [%]
pre-vendor engines	+0.87	+0.04
post-vendor engines	+1.15	+0.06

blade repairs have been analysed. Although this investigation could not show the magnitude of EGT and SFC increase (no data regarding surface roughness was available), the result was that the HPC blades of post-vendor engines have undergone a less efficient restoration. This means that less repairs have been performed and less blades were replaced with new. In turn, this was seen as an indicator for lack of performance of post-vendor engines.

For future investigations it was recommended that the sample of engines should be increased and that the composition of blade material in the HPC and the implication of repairs may be a field of interest [TRA10].

3 Analysis of TEMPER data

The effects of module performance on EGT margin and SFC margin of pre- and post-vendor engines are presented in this chapter. As mentioned in section 2.8, the TEMPER software presents the deviation in EGT margin and SFC margin on a modular basis. All engines in this investigation have passed through a full overhaul, therefore performance should be refurbished. The overall sample of engines consists of 29, whereby 10 are pre-vendor and 19 are post-vendor engines. Figure 3.1 and figure 3.2 compare pre- and post-vendor engines related to EGT margin and SFC margin. The blue bars are the pre-vendor engines, the red bars stand for the post-vendor engines. To allow a better comparison, each engine is allocated to a number. The numbers are assigned in chronological order to the time of overhaul. The pre-vendor engines have an average EGT margin of 39.4 °C, the post-vendor engines of 30.9 °C. It has to be mentioned that three pre-vendor engines (#4, #5 and #8) have a low EGT margin and four post-vendor engines (#16, #20, #24 and #28) a high EGT margin. However it is noticeable that the EGT margin has dropped with the change of the overhaul vendor. As the aim of this investigation is to find reasons for the performance deterioration and to identify possible changes in repair procedures, a comparison of pre- to post-vendor engines is more significant than of engines with high and low EGT margin. 70 % of pre-vendor engines reach the required EGT margin of 35 °C whereby it is only 21 % for post-vendor engines.

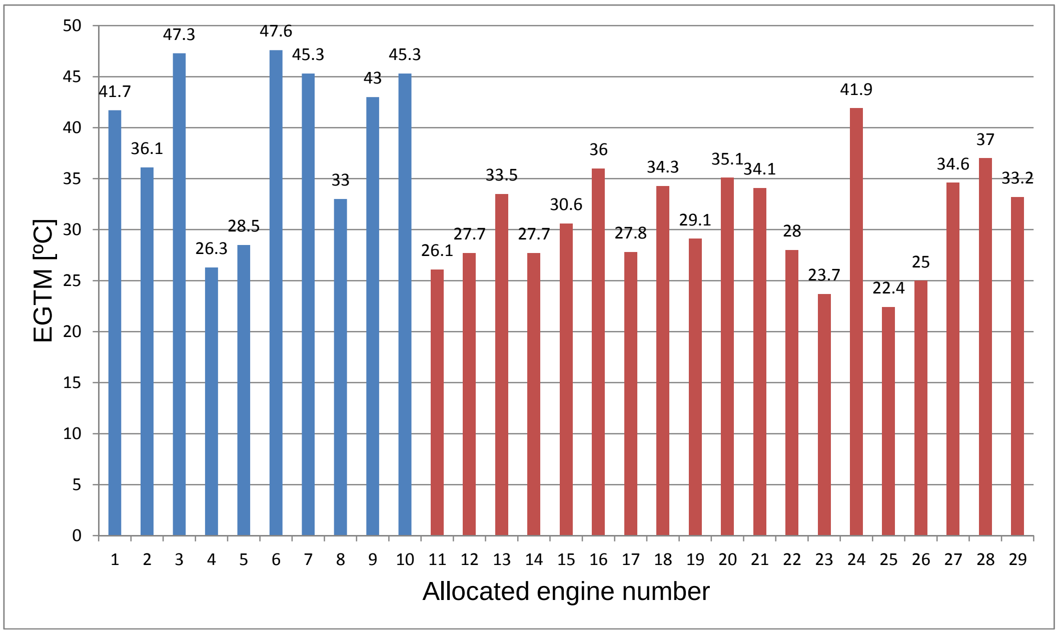

Figure 3.1: Comparison of EGT margin

Figure 3.2 displays the SFC margin for pre- and post-vendor engines. The average SFC margin of pre-vendor engines is 5.72 % and of the post-vendor engines is 5.92 %. As mentioned in section 2.3, higher SFC results in higher EGT (lower EGT margin); this relationship cannot be confirmed considering the engines in this investigation. Although post-vendor engines show slightly lower SFC (higher SFC margin) than pre-vendor engines, their EGT margin is low as well. A detailed analysis of EGT margin and SFC margin will be carried out later.

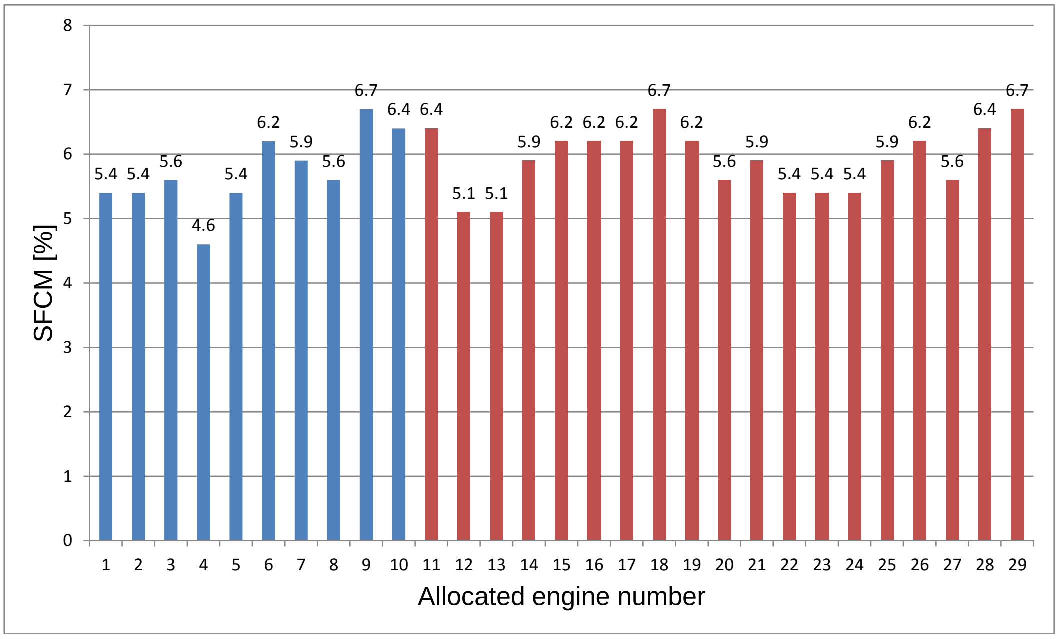

Figure 3.2: Comparison of SFC margin

3.1 EGT margin deviation per module

Figure 3.3 compares the deviation for pre-vendor (blue dots) and post-vendor engines (red dots) overhauled by LTQ Engineering. The '0 °C line' represents the baseline model which is defined by General Electric. Positive deviation from this baseline indicates higher module efficiency and therefore a gain in EGT margin. Negative deviation shows that the module performs lower than the baseline model which results in EGT margin loss. It has to be mentioned that this relationship is inverse for the fan module in terms of efficiency and blade to case clearance as described in section 2.9. However, characteristics such as EGT margin, thrust rating, SFC margin or condition (factory new or overhauled) of the baseline model are unknown. Therefore a comparison to the baseline is not very significant especially for the purpose of this investigation. The chart gives the costumers the opportunity to compare their engines and discover trends in performance.
This chart is used to identify differences in module efficiency between pre- and post-vendor engines. Due to higher EGT margin of pre-vendor engines, the spread for each module is judged as normal and engines which are not grouped in this population show an abnormal

performance. This can be considered as an indicator for a change in repair procedures for this module between pre- and post-vendor overhaul. The fan and LPT modules for

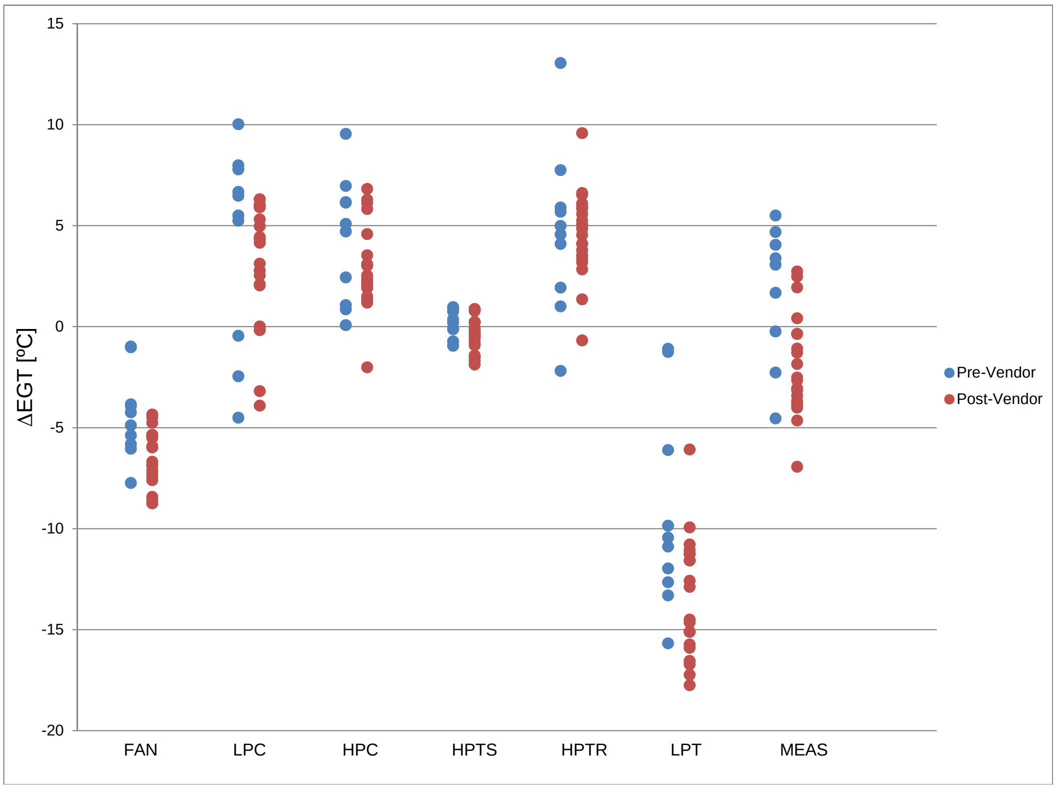

Figure 3.3: Deviation of EGT margin per module

pre-vendor engines show a negative deviation. The LPC, HPTS and HPTR modules and the MEAS category are spread around the baseline with a tendency to positive deviation and the HPC module has a positive deviation.
For the LPC and HPTR modules, the post-vendor engines are located in the same range as pre-vendor engines. This leads to the conclusion that a change in repair procedures is very unlikely or at least, the change has no influence on LPC and HPTR efficiency and EGT. Considering the HPC module and MEAS category, only one post-vendor engine is out of the range of the pre-vendor engines. Noticeable are the deviations of EGT margin for the fan, HPTS and LPT modules. Four post-vendor engines have a greater loss of EGT margin for the fan module; four engines are out of range for the HPTS module and six engines for the LPT module.
As stated before, not all pre-vendor engines have a high EGT margin and not all post-vendor engines suffer from a low EGT margin. Therefore it makes sense to highlight these engines and assess whether a certain pattern can be identified. Figure 3.4 is similar to figure 3.3, although pre-vendor engines with low EGT margin are marked yellow whereas post-vendor engines with high EGT margin are marked black. It has to be mentioned that one pre-vendor engine with low EGT margin (#4) is not displayed in the MEAS category due to

high positive deviation of 31.8 °C. The pre-vendor engines with a low EGT margin show a

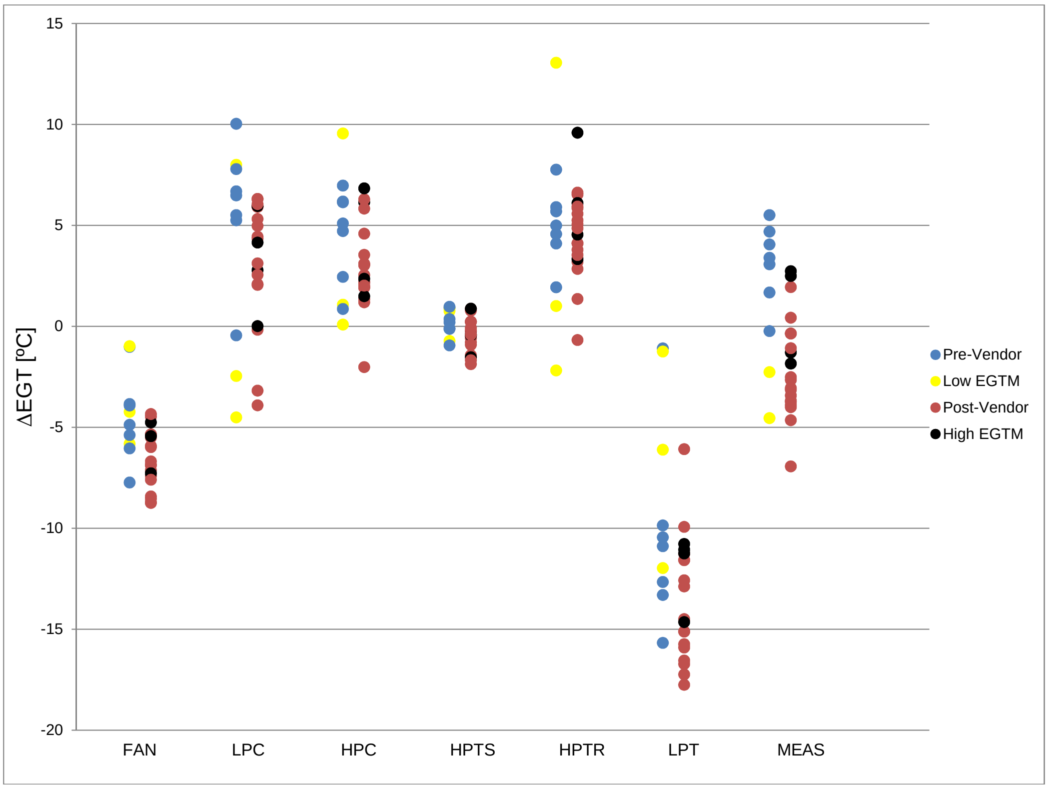

Figure 3.4: Deviation of EGT margin per module with marked engines

big spread across the normal range, e.g. for HPC module; two engines are located right over the baseline, the third has a positive deviation of nearly 10 °C. It is not noticeable that these pre-vendor engines all have the same pattern, therefore it is very hard to identify one module as a reason for the low EGT margin. The same problem arises with the post-vendor engines with a high EGT margin. Although the spread is smaller, they are located in the normal range of the pre-vendor engines and it is not possible to exclude one module from the investigation.

3.2 SFC margin deviation per module

In addition to EGT margin, the modular deviation of SFC margin for pre- and post-vendor engines is compared in figure 3.5. The structure of this chart is similar to figure 3.3, although the deviation in SFC margin per module instead of EGT margin is presented. A result of negative 1 % leads to a decrease in SFC margin of 1 %. Given this relationship, positive 1 % results in an increase of SFC margin. The fan and LPT modules show a decrease in SFC margin for all engines. The LPC, HPC and HPTR modules are located around the baseline with a tendency to positive deviation and finally the HPTS module has a slight tendency to negative deviation. This indicates that both the fan and the LPT module are responsible for a decrease in SFC margin whereby the performance of the remaining modules leads to an improvement or at least to no change in SFC margin. Again the spread of pre-vendor engines is judged as normal.

The post-vendor engines are located in the range of pre-vendor engines for the LPC and HPTR modules. The fan and HPC modules show normal behaviour for the post-vendor engines with just one engine beyond the range of pre-vendor engines. The greatest difference between pre- and post-vendor engines is shown in the HPTS and LPT modules. Five post-vendor engines are located outside the range of pre-vendor engines for the LPT module and four engines for the HPTS module, whereby the deviation is very small.

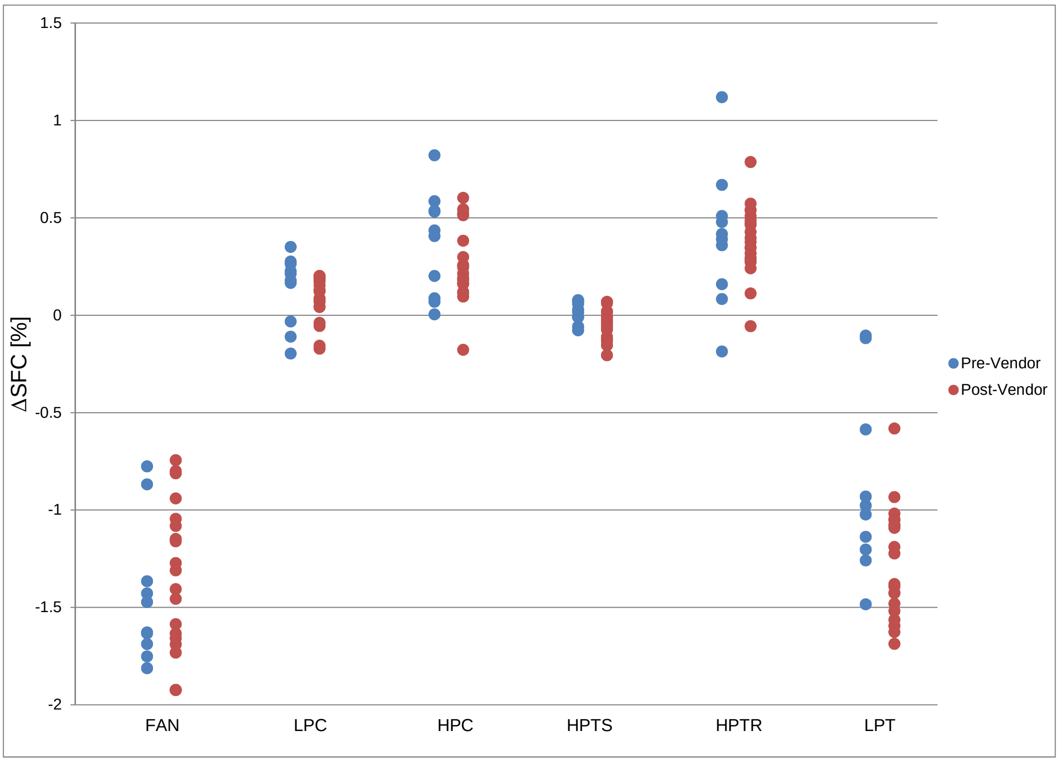

Figure 3.5: Deviation of SFC margin per module

3.3 Results of the analysed TEMPER data

Considering the TEMPER data of figure 3.3 and figure 3.4, this investigation identified abnormalities for the fan, HPTS and LPT. For these modules the deviation in EGT margin for some post-vendor engines is not located in the range of pre-vendor engines. For the remaining modules, the post-vendor engines are located in the range of the pre-vendor engines; hence there is no indication that these modules show any abnormality. The comparison of deviation in SFC margin shows the same trend. The deviation in SFC margin (refer to

figure 3.5) is mostly caused by the fan and LPT modules whereby the post-vendor engines are not located in the population of pre-vendor engines for HPTS and LPT module.
In figure 3.6 the six engines with an abnormal EGT margin deviation in the LPT module are marked yellow. These engines also have the highest fan module deviation of all post-vendor engines. High negative deviation in EGT margin for the fan module indicates good fan efficiency in terms of fan blade clearance as described in section 2.9. As the fan and the LPT are located on the same rotor (N1 rotor), it is consistent that the LPT module has a high deviation in EGT margin as well. In order to keep N1 speed constant, the LPT has to work harder and more fuel is needed to provide the energy.

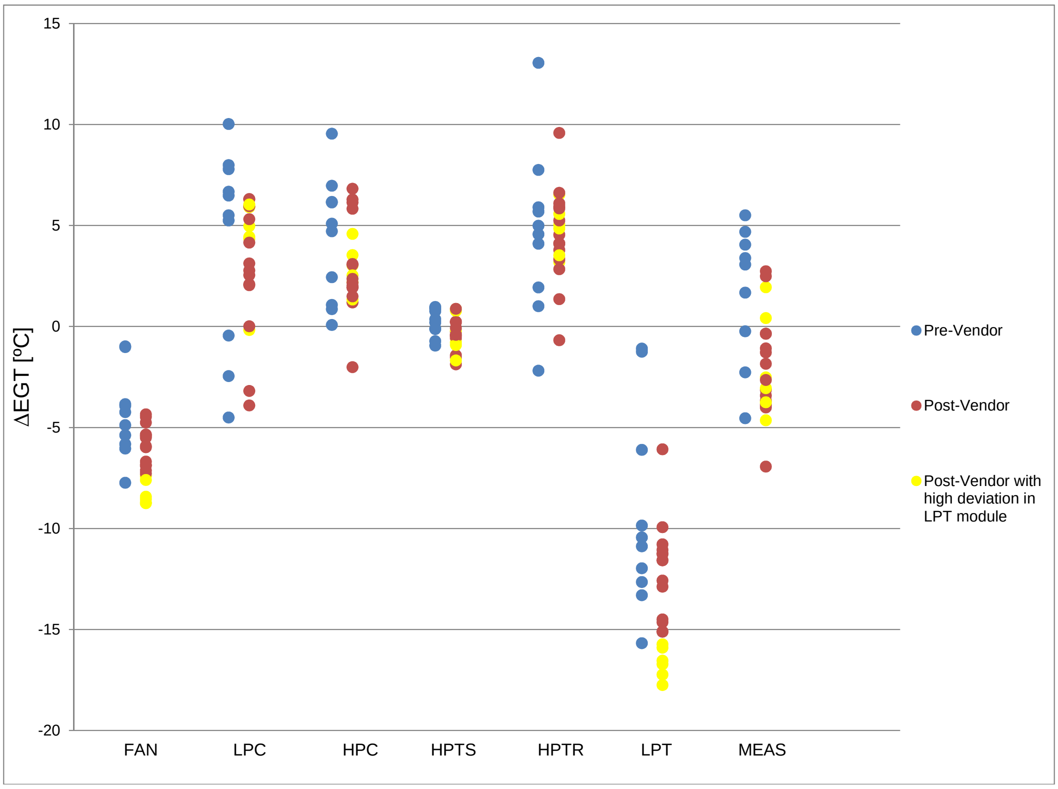

Figure 3.6: Deviation of EGT margin per module with marked engines of low LPT module performance

The same engines are marked yellow again in figure 3.7 to identify their effect on SFC margin. They show the highest deviation for the LPT module. This relationship is consistent because high SFC (and therefore negative deviation in SFC margin) leads to high EGT (and negative deviation in EGT margin). However, it is noticeable that these engines have small deviation in SFC margin for the fan module. This can be explained by the fact that higher fan efficiency leads to higher thrust and therefore smaller deviation in SFC margin.
The relationship between fan and LPT module and their effect on EGT margin and SFC margin suggest that part of this investigation should focus on the fan and LPT. Both modules show abnormal behaviour compared to pre-vendor engines, therefore it might be

possible to identify any changes in repair procedures.

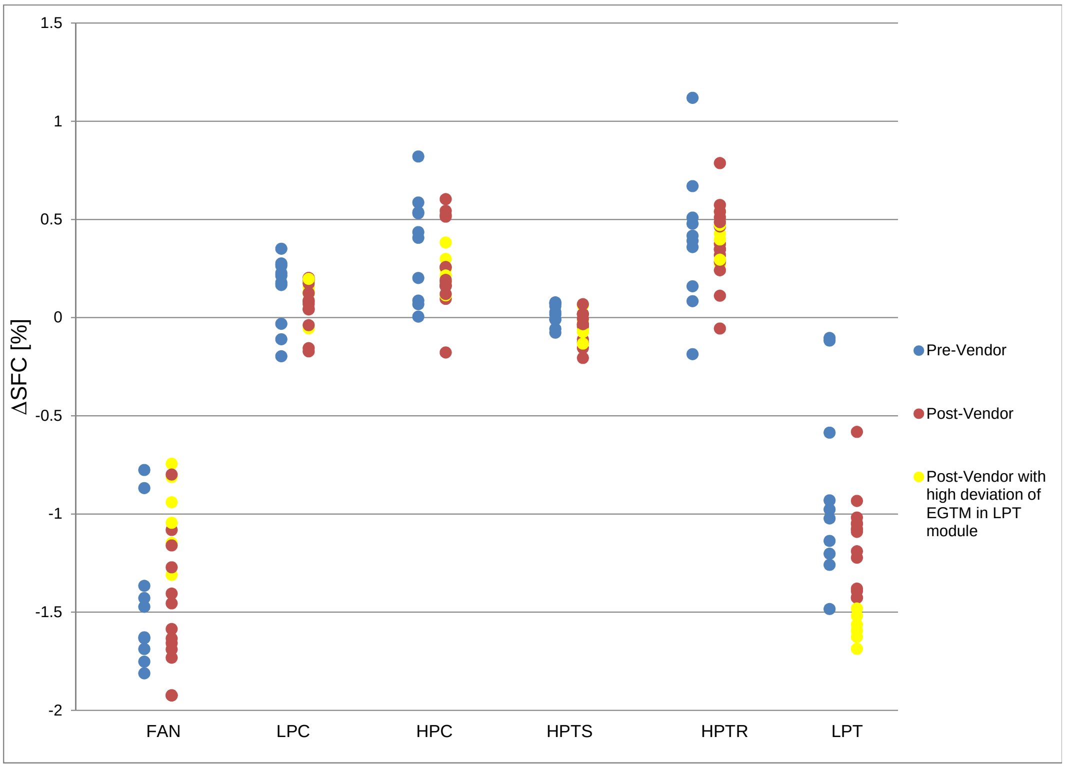

Figure 3.7: Deviation of SFC margin per module with marked engines of low LPT module performance

Unfortunately this is only a possible explanation for low EGT margin for six post-vendor engines. The remaining post-vendor engines do not show abnormal behaviour in any module. With this in mind it is necessary to analyse additional engine data to find possible reasons. In section 2.11, it is recommended to focus on the HPC module. With a greater sample of engines, there is no longer an indication that the HPC module of post-vendor engines shows different behaviour than pre-vendor engines. In addition to this, the previous investigation of clearances and repair procedures did not indicate a relationship between HPC module and low EGT margin.

4 Analysis of test cell data

The analysis of TEMPER data in chapter 3 identified the fan and LPT module performance as possible reasons for low EGT margin. However it only provides an explanation for six post-vendor engines (32 %), therefore additional engine data such as fuel flow, thrust, N2 rotor speed and pressure ratios are analysed in this chapter. The presented data in figure 4.1 through 4.5 compares these parameters of both pre-vendor (blue dots) and post-vendor engines (red dots) to ascertain any differences in engine performance. The spread of pre-vendor engines is considered as normal based on experience at LTQ Engineering, therefore post-vendor engines which are not located within the population of pre-vendor engines show abnormal behaviour. The charts in this chapter are recommended by General Electric as part of the diagnostics technique to assess engine performance. To simplify the description and to allow a better comparison the allocated engine numbers are plotted next to the dots.

4.1 SFC margin versus EGT margin

In figure 4.1 SFC margin is plotted versus EGT margin at take-off and hot day conditions and is used as an indicator for overall engine performance. Normal performance variation is considered to occur within the two blue lines which represent the normal spread of pre-vendor engines. The lines are defined by calculating a linear trend line for the pre-vendor engines and moving it to the outermost located points. Engines which are located in that band show normal behaviour, i.e. if an engine has high SFC margin it also achieves high EGT margin because of less fuel burnt. In contrary, engines with low EGT margin have low SFC margin. This relationship is explained in section 2.3. It is noticeable that ten of nineteen post-vendor engines are not located in this band. Although most of them have high SFC margin (low SFC), their EGT margin is not in the required limit (except for engine #28). This abnormality can be explained by two possible reasons; these ten engines achieve an abnormal low fuel flow or generate more thrust than necessary. Both reasons lead to low SFC and therefore to high SFC margin. In the next step, an analysis of fuel flow and thrust is necessary to determine reasons for poor engine performance. An error in measurement provides a third possible explanation, whereby it is unlikely that this occurs to 53 % of post-vendor engines.

As described in section 3.3, six post-vendor engines show abnormal EGT margin deviation for LPT and fan modules in comparison to pre-vendor engines. These six engines (#14, #15, #17, #18, #25 and #26) are part of the population beyond the expected band. The remaining engines are located in the normal band of pre-vendor engines but achieve low EGT margin except for engine #16, #20 and #24. Low EGT margin is an indicator for poor core performance.

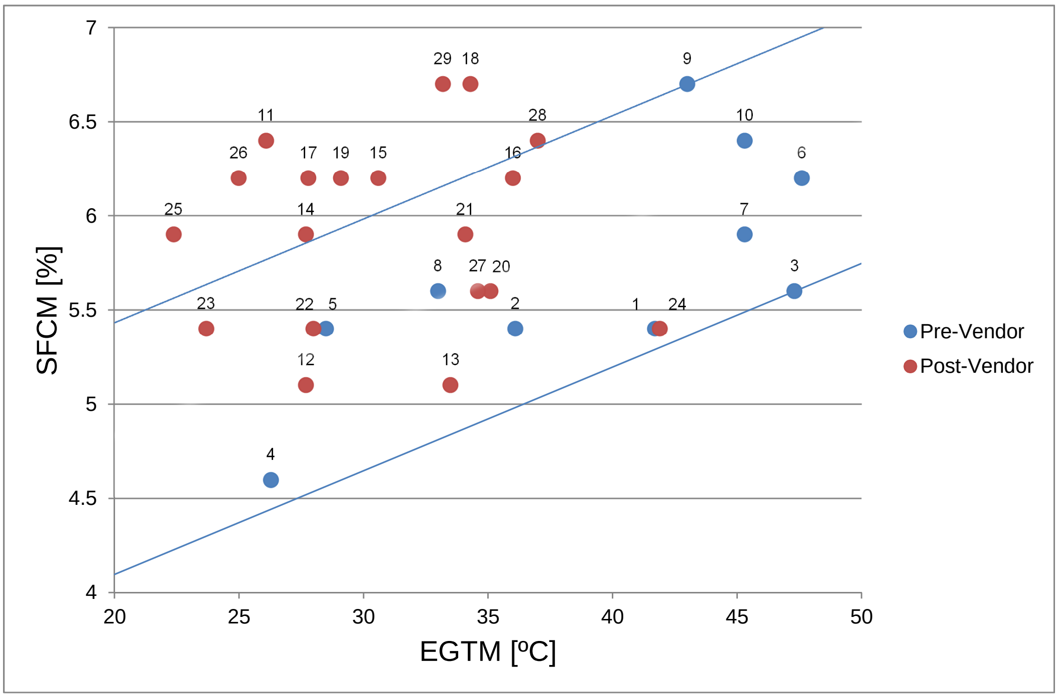

Figure 4.1: SFC margin versus EGT margin

4.2 Fuel flow versus thrust

As nine post-vendor engines show abnormal high SFC margin and low EGT margin at the same time, it is necessary to analyse the two parameters which are used to calculate SFC; per definition, SFC is the amount of fuel that the engine burns per hour divided by the amount of thrust that the engine generates. This helps to evaluate whether fuel flow or thrust are responsible for the low SFC (high SFC margin) and to exclude an error in measurement as an explanation. Figure 4.2 shows fuel flow versus thrust for pre- and post-vendor engines. Pre-vendor engines generate 60761 lb_f thrust in average whereby the amount for post-vendor engines is 61141 lb_f. This represents higher thrust generation for post-vendor engines of 0.62 %. The same trend applies to fuel flow. Post-Vendor engines burn 0.69 % more fuel than pre-vendor engines (21737 lb/h to 21588 lb/h).

The yellow dots are the same post-vendor engines which are located beyond the normal band of pre-vendor engines in figure 4.1. Except for engine #28, they all have high SFC margin but do not reach the desired EGT margin of 35.0 °C. By comparing the two parameters, it becomes significant that most of them show higher thrust and fuel consumption. This explains the higher SFC margin but lower EGT margin; the high fuel consumption leads to high EGT, however the increased thrust generation results in low SFC and therefore high SFC margin. The position of engine #28 beyond the normal band of pre-vendor engines is explained by lower fuel flow but nevertheless higher thrust generation compared to engines in the same range. The same phenomena occurs to engine #19.

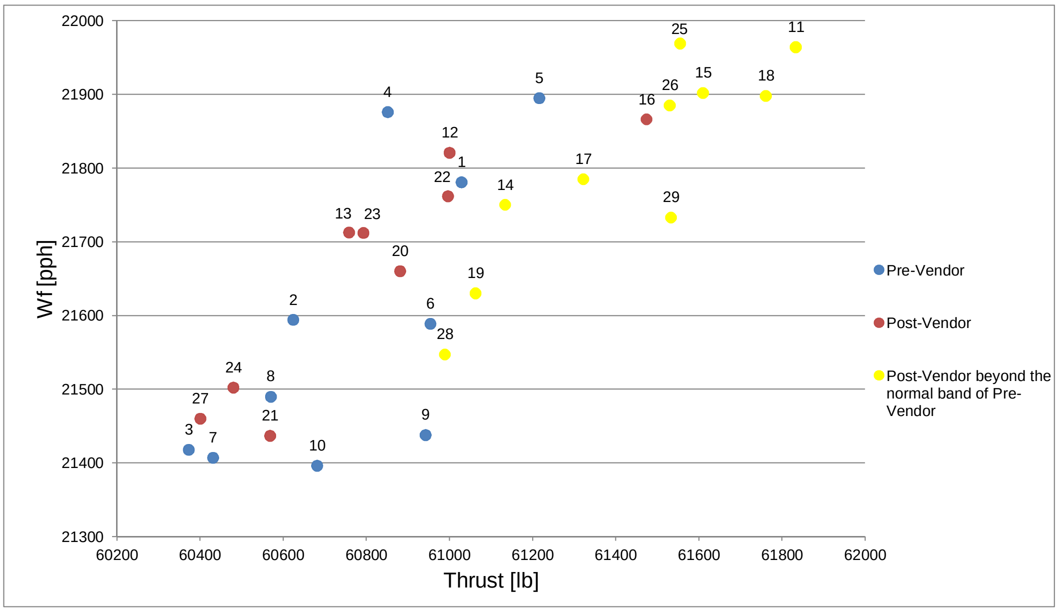

Figure 4.2: Fuel flow versus thrust

Furthermore two additional engines show a different behaviour; pre-vendor engine #5 and post-vendor engine #16 which are both located in the normal band in figure 4.1. Engine #5 achieves lower SFC margin of 5.4 % as well as low EGT margin of only 28.5 °C. The opposite behaviour applies to engine #16. Although it generates high thrust by high fuel flow, it has an EGT margin of 36.0 °C and SFC margin of 6.2 %. It is also noticeable that the engines #14, #15, #17, #18, #25 and #26 which show abnormal deviation in EGT margin for the fan and LPT module in figure 3.6 are assigned to high thrust and fuel flow. The remaining engines show lower thrust levels.
This chart indicates a relationship between high thrust and high fuel flow which causes high EGT except for engine #26. It is consistent that a higher thrust generation leads to higher fuel flow, because engine modules have to work harder and therefore need more energy. However it is not possible to determine whether the fan module or the core modules are responsible for higher thrust generation.

4.3 Thrust versus EGT margin

As described in the previous section, there is a correlation between high thrust and high fuel consumption. In figure 4.3, thrust is plotted against EGT margin for pre- and post-vendor engines. Although this chart does not provide any further explanations, it underlines the importance of thrust generation on EGT margin in this investigation. It is significant that engines with a thrust level beyond 61100 lb_f achieve EGT margin under 35.0 °C. Only engine #16 fulfils this requirement. The high thrust generation might be an explanation for low EGT margin for pre-vendor engine #5 and post-vendor engines #11, #14, #15,

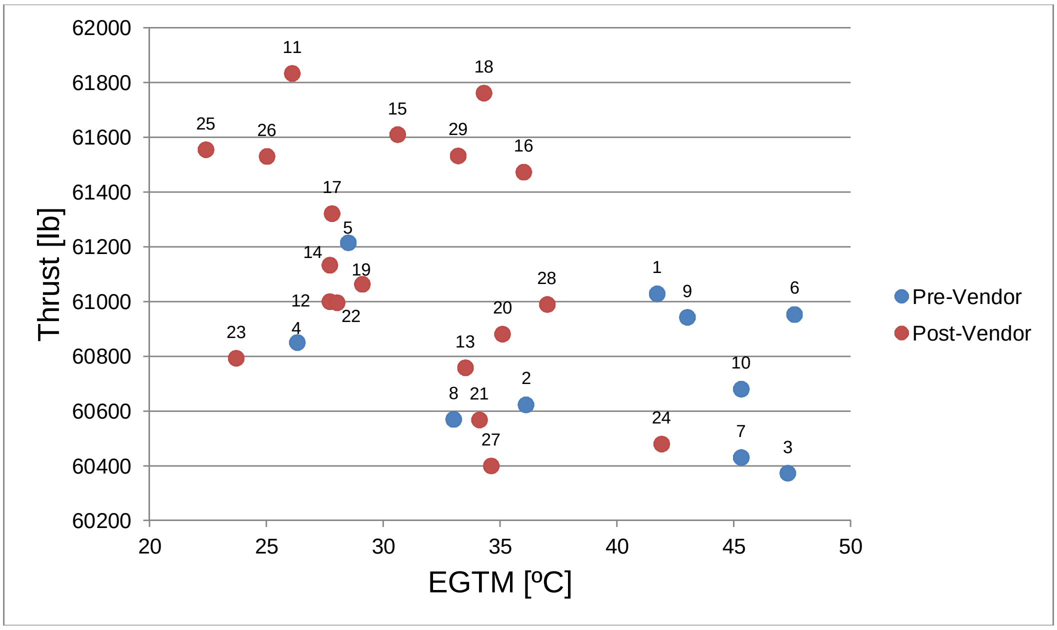

Figure 4.3: Thrust versus EGT margin

#17, #18, #19, #25, #26 and #29. In the further course of this investigation these engines are referred to as 'high thrust engines'. As the fan produces most of the thrust, it is reasonable to focus on this module whether any changes in repair procedures have taken place between pre- and post-vendor engines.

The remaining engines show a lower thrust generation, whereby the EGT margin ranges from 23.7 °C for engine #23 to 47.6 °C for engine #6. A correlation between thrust and EGT margin is not significant for these engines.

4.4 EPR versus EGT margin

Engine pressure ratio is an indicator for the core performance of an engine. It is defined as the ratio between LPC inlet and HPT outlet pressure. Figure 4.4 shows EPR against EGT margin. It has to be mentioned that pre-vendor engine #8 is not shown due to data availability.

Pre-vendor engines are located between an EPR of 7.46 to 7.56 and achieve an average EPR of 7.51. With an average EPR of 7.50 for post-vendor engines, there is no significant difference detectable. However, it is noticeable that engines with almost the same EPR achieve different EGT margin as shown by engines #4 and #10. This big spread must be accepted as normal. The high thrust engines show a tendency to higher EPR (except for engine #29). High EPR means poor LPT performance whereby two possible reasons have to be taken into account. Due to deterioration of turbine blades and/or higher tip clearances (refer to section 2.9) the LPT needs more energy and therefore higher inlet pressure in order to keep N1 speed constant. Another explanation for high EPR is highlighted by the fan module. High fan efficiency due to small tip clearances or poor fan blade quality demands more energy extraction of the LPT because it is harder to spin the fan. On the other side low EPR and low EGT margin are indications of poor HPC/HPT or combustion module performance. This may be a possible explanation for low EGT margin of engine #22.

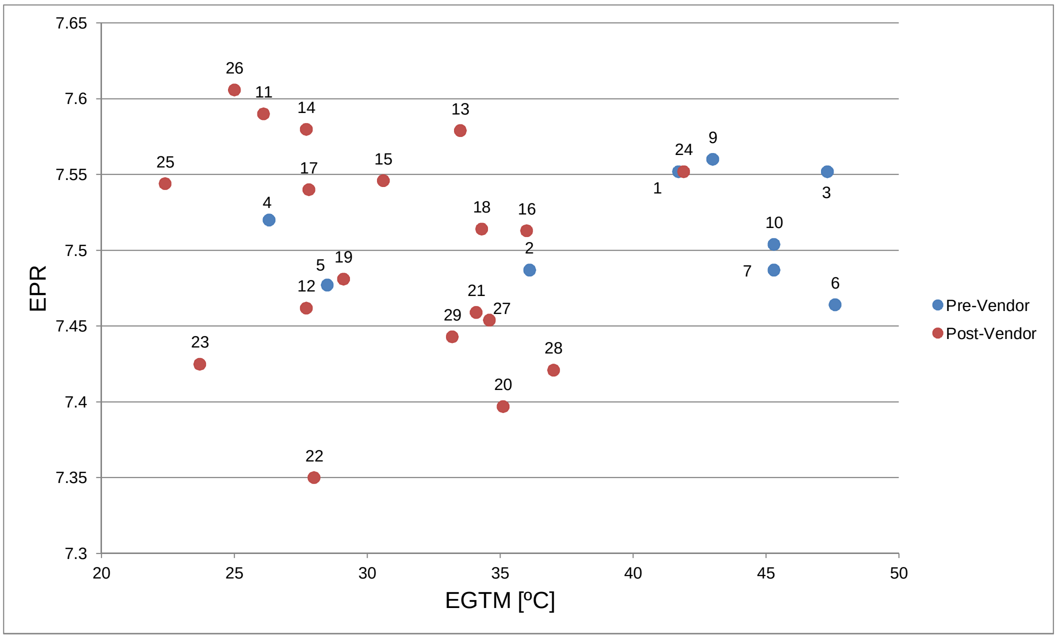

Figure 4.4: EPR versus EGT margin

4.5 N2 speed versus HPC pressure ratio

An effective method to assess HPC performance is to plot N2 rotor speed versus the ratio of HPC discharge static and HPC inlet total pressure (PS3/P25). Higher N2 rotor speed usually leads to higher pressurisation across the HPC. High pressure ratio also indicates an effective working HPC which results in lower EGT. Regarding the N2 rotor, low speed signifies poor HPC and/or HPT performance. Poor fan and/or LPT module performance is indicated by high rotor speed.

The two parameters are shown in figure 4.5. Due to data availability, engine #19 is not presented in this chart. The data is unlike previous charts corrected to standard day and not to hot day conditions. But as all engine data is provided for the same power setting, a comparison between pre- and post-vendor engines is still meaningful.

The spread of pre-vendor engines is very broad; it ranges from low N2 speed and low pressure ratio as engine #6 to high N2 speed and high pressure ratio as engine #1. This relationship is consistent because low N2 speed means that the HPC turns more slowly which results in low pressurisation. In contrast, high N2 rotor speed leads to high pressurisation across the compressor. In figure 2.6 the relationship between SFC and CPR is

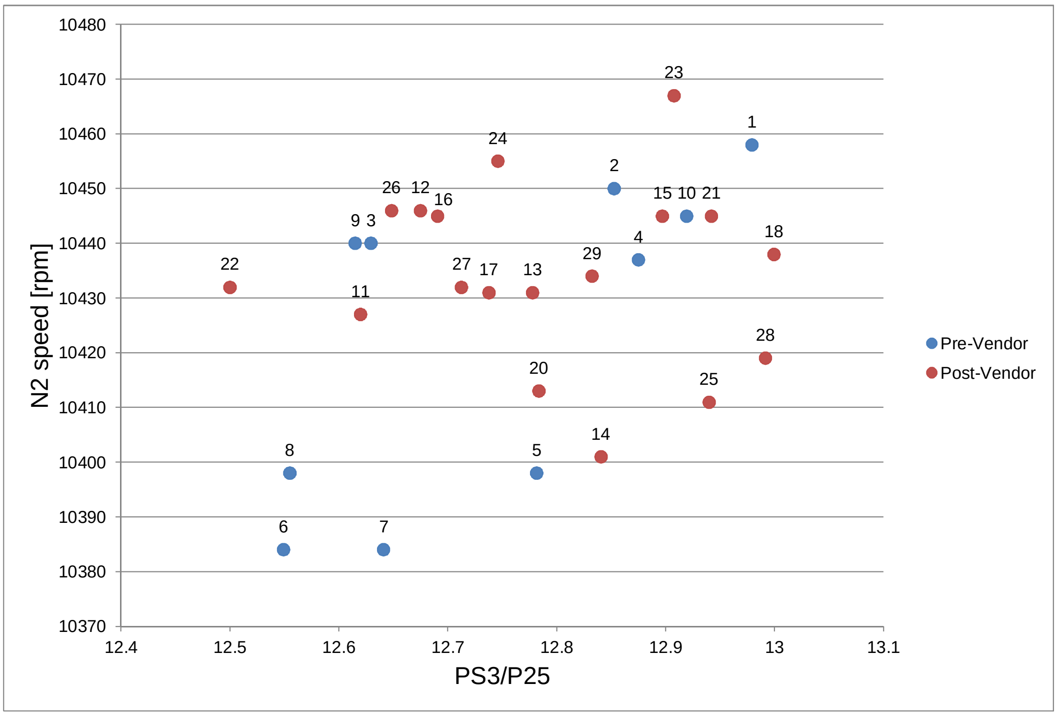

Figure 4.5: N2 rotor speed versus PS3/P25

shown. The trend, that higher pressure ratio leads to less fuel consumption, cannot be recognised as engines with high pressure ratio achieve low EGT margin (e.g. # 23 and # 25).

The average HPC pressure ratio of post-vendor engines is 12.79 and therefore 0.4 % higher than of pre-vendor engines (12.74). The comparison of average N2 rotor speed only shows a difference of 0.1 % (10423 rpm for pre-vendor and 10434 rpm for post-vendor engines).

An interesting comparison is provided by engine #18 and #22. Both operate at nearly the same N2 rotor speed, therefore the same pressurisation or same pressure ratio is expected. However engine #18 shows 4 % higher pressure ratio compared to engine #22 and consequently better HPC performance. A similar conclusion can be drawn by comparing engine #23 and #25. Although both engines achieve nearly the same pressure ratio, engine #25 operates at lower N2 rotor speed which means higher HPC efficiency. However, it has to be mentioned that the difference in N2 rotor speed is 0.5 %. Therefore the significance is limited.

The preceding investigation focused on the HPC as the main module responsible for low EGT margin. This trend cannot be confirmed by analysing the data graphed in figure 4.5. Only engine #22 shows a significant poorer HPC performance. By comparing the remaining pre- and post-vendor engines no differences in HPC performance are detectable which give reasons for focusing on the HPC.

4.6 Results of the analysed test cell data

This chapter focused on the analysis of test cell data to identify differences between pre- and post-vendor engines. However the investigation is limited by availability of engine data. The most significant difference is shown in figure 4.3. Nine of nineteen post-vendor engines (#11, #14, #15, #17, #18, #19, #25, #26 and #29) generate more thrust by achieving low EGT margin. These engines burn more fuel which is graphed in figure 4.2. Engines with high deviation in EGT margin for the fan and LPT module are highlighted in figure 3.6. These six engines belong to the sample of high thrust engines. As the fan is the main module of thrust generation, the conclusion can be drawn that a change in fan performance is a reason for the difference between pre- and post-vendor engines. Higher fan efficiency due to smaller tip clearance results in higher EGT and lower EGT margin as described in section 2.9. Therefore the analysis of fan module repairs as the next step might obtain an explanation for low EGT margin.

However this relationship does not apply to all post-vendor engines. A comparison of EPR is presented in figure 4.4. High thrust engines show a tendency to higher EPR which again indicates poor fan and LPT module performance. As the LPT module shows high deviation in EGT margin as described in section 3.3, an analysis of repair procedures of the LPT module might be an area of interest in the further course of the investigation. Besides that engine #22 has an abnormal low EPR by achieving low EGT margin. The engine core or the combustion chamber are possible reasons for poor engine performance.

The analysis of N2 rotor speed and HPC pressure ratio in figure 4.5 shows normal behaviour for post-vendor engines compared to pre-vendor engines. Poor HPC performance is only detectable for engine #22 which is consistent to the comparison of EPR.

5 Analysis of performed repairs

Based on the analysis in chapter 3 and 4, the performance of the fan and LPT modules have been identified as possible reasons for low EGT margin. In this part of the investigation repair procedures for the fan module are analysed to ascertain differences between pre- and post-vendor engines. The effects of component quality on EGT and SFC are presented in section 2.9. They provide the basis for analysed repair procedures in this chapter. It has to be mentioned that it is not possible to analyse all performance effects. The airfoil surface finish is determined by measuring the airfoil roughness. Small roughness represents better surface finish due to lower friction. As blade repairs are not performed by LTQ Engineering itself, no data about airfoil roughness is available. Therefore alternative analyses of the effect of airfoil finish are required. Furthermore deterioration like erosion, pitting and contamination with dirt are removed after overhaul and cannot be taken into consideration for high EGT and SFC. Only clearances are recorded after an overhaul to avoid damage to blades and cases and to guarantee safe and efficient engine operation.

5.1 Fan tip clearance

The effect of fan blade tip clearance on EGT and SFC is determined by General Electric and based on experience. Besides the influence on engine performance, the clearance must be controlled to ensure safe and efficient engine operation. The fan consists of 38 titanium blades whose dovetail joints are mounted into the fan disk. It is a lose fitting without any fasteners. The inner fan case is sealed with an abradable shroud. The first layer consists of a backing sheet of fabric glass, followed by a honeycomb core of phenolic reinforced polyamid fiber and a lightweight phenolic mircoballon filler. Figure 5.1 displays a part of the forward fan case and its main components.

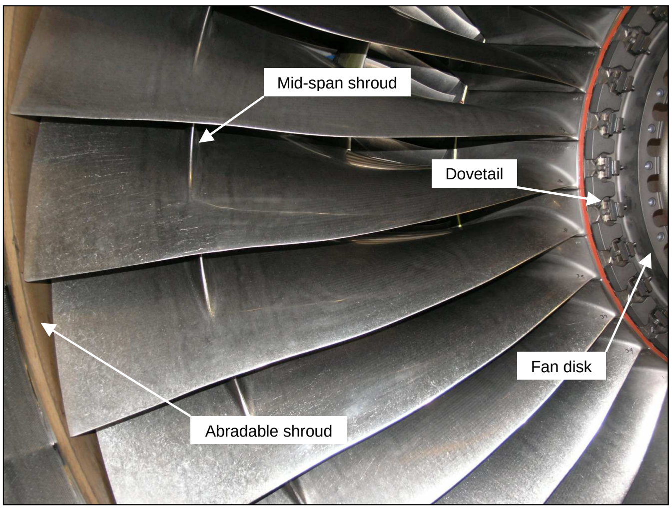

Figure 5.1: Forward fan case

Due to the wear of dovetail coating, the loose fitting and the radial forces caused by the high rotation speed, the fan blades move outwards and decrease the fan blade tip clearance during operation. Additionally, aerodynamic forces lead to a slight untwist of the blades. The mid-span shroud is necessary in order to keep the untwist to an minimum. These two effects lead to grinding of the abradable shroud by the fan blade tips during operation. Smaller fan blade tip clearance leads to higher fan efficiency, but also an increase in abrasion. Therefore it is harder to spin the fan. A perfect installation shows minimum tip clearance without touching the shroud.
As part of the inbound inspection prior to engine overhaul, the fan tip clearance is measured at two positions; E12 is located in a distance of 10.4 in (264 mm) from the forward flange of the fan forward casing, E13 has a distance of 13.4 in (340 mm). To simulate engine operation, both dimensions are measured with the fan blade at 6:00 o'clock position. Due to the loose fit and gravity force, the blades are seated to their operational position as close as possible [GE10]. Figure 5.2 displays the positions of E12 and E13.

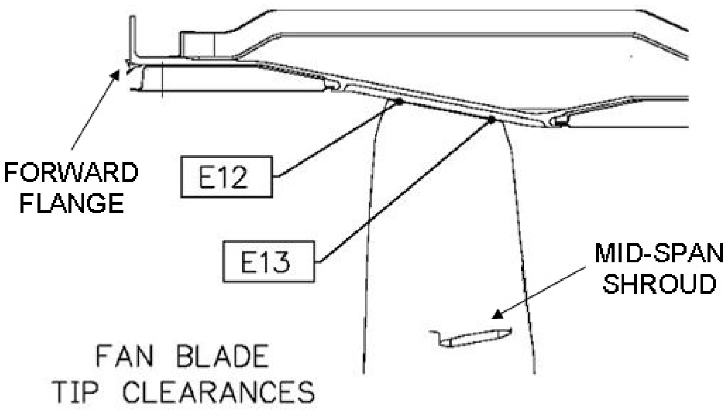

Figure 5.2: Position of E12 and E13 [GE10]

If the dimensions for E12 and E13 are within limits and the abradable does not show any damage at the inbound inspection, no repairs are performed. Only the fan blades are removed and overhauled according to the engine shop manual. The limit for E12 and E13 position are displayed in table 5.1. The old limit is based on the GE manual. LTQ Engineering has the allowance of its costumer to exceed this value at 15 %.

Table 5.1: Limits for E12 and E13 fan tip clearance [GE10]

Position	**Old minimum**	**Old maximum**	**New maximum**
E12	0.115 in (2.92 mm)	0.198 in (5.03 mm)	0.228 in (5.78 mm)
E13	0.156 in (3.96 mm)	0.236 in (5.99 mm)	0.271 in (6.89 mm)

After measuring E12 and E13 clearance for each blade, the 38 values for each position are averaged and represent the fan blade tip clearance. The fan tip clearance does not change if the same set of blades is refitted and no repairs on the abradable shroud are performed. In this situation no clearances are recorded in the outbound inspection and the measurements of the inbound inspection are used. Figure 5.3 and 5.4 compares E12 and E13 tip clearance and EGTM margin for pre- and post-vendor engines.

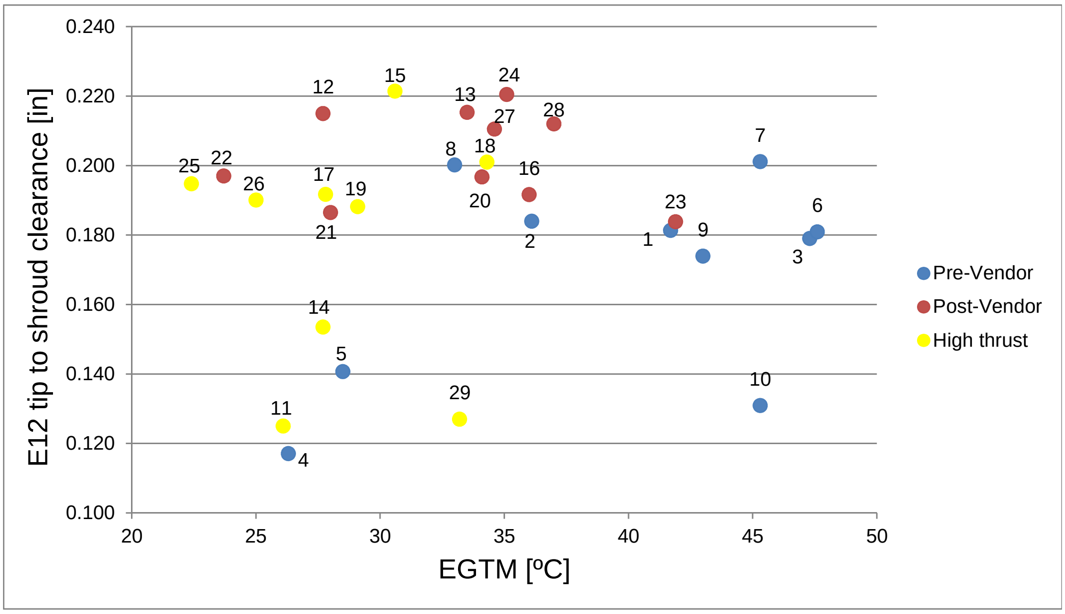

Figure 5.3: E12 fan blade tip clearance versus EGT margin

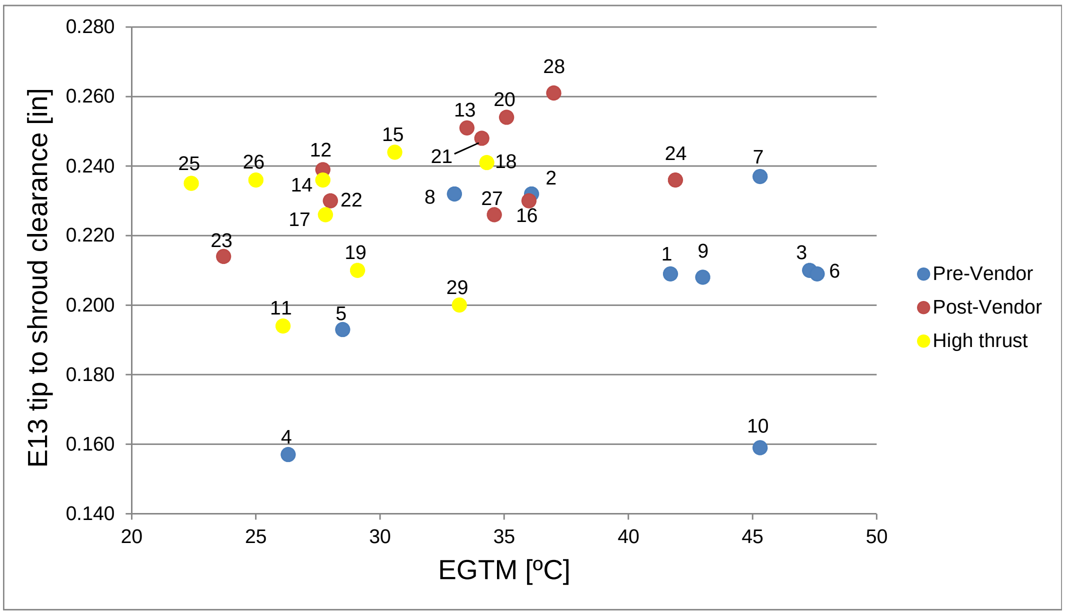

Figure 5.4: E13 fan blade tip clearance versus EGT margin

The blue dots represent the pre-vendor engines, red and yellow dots are post-vendor engines whereby the yellow ones are high thrust engines. As described in section 2.9, an increase of

0.02 inch in fan blade tip clearance results in decrease of 0.9 °C in EGT. Considering the pre-vendor engines in figure 5.3 this numerical relationship cannot be confirmed. One example is given by the comparison of engines #2 and #6. By having almost the same clearance, these engines show a difference in EGT margin of more than 10 °C. Other demonstrative examples are the comparison between #7 and #10 or between #5 and #10. This broad spread of pre-vendor engines makes it difficult to find a relationship between EGT margin and fan blade tip to shroud clearance.
In section 4.3 a relationship between high thrust and small clearance due to higher fan efficiency is assumed. Considering the yellow dots no confirmation is seen, which becomes evident by comparing engine #11 with #18. Although both engines almost generate the same thrust, the difference in clearance amounts to 0.08 in or 66.7 %. Altogether post-vendor engines show a tendency to higher fan blade tip to shroud clearance which should result in higher EGT margin instead in lower than pre-vendor engines.
The same relationship is recognised by analysing the E13 clearance in figure 5.4. The spread is very similar to the previous chart, but it is still not possible to draw a conclusion. Engines #1 to #3 and #6 to #9 show E13 tip to shroud clearance of 0.20 inch to 0.24 inch and higher EGT margin. The post-vendor engines in the same range of E13 clearance achieve low EGT margin at the same time.
By comparing the fan blade tip to shroud clearance it becomes evident that there is no or just minor effect on EGT margin noticeable. Most of post-vendor engines are located in the same range as the pre-vendor engines for both measuring points. The remaining engines show even bigger tip clearance which should lead to higher EGT margin based on experience of GE. As the post-vendor engines do not show great differences in fan blade tip clearance compared to pre-vendor engines, this can be eliminated as a reason for low EGT margin. The only significant difference between pre- and post-vendor engines is related to the fan blades. By collecting the E12 and E13 clearances, it was also recorded whether the original fan blades were refitted or replaced. Pre-vendor engines have always been equipped with the same set of blades. In contrast, fan blades of post-vendor engines are more often replaced with blades from other engines. However, all fitted fan blades have been repaired, therefore a coincidence between refitted or replaced blades and low EGT margin is difficult to proof.

5.2 Condition of fan blades

The blade condition has a significant effect on the fan performance. As described in section 2.9, high airfoil roughness, leading edge erosion, pitting and dirt lead to poor fan efficiency and therefore to increase in EGT and SFC. In order to identify differences between pre- and post-vendor engines, the repairs of fan blades are analysed.
As part of the engine disassembly, fan blades are cleaned to remove lubricant, dirt or other

contaminations and after that inspected in two ways. A fluorescent-penetrant inspection is carried out to discover small surface defects such as cracks which may not be visible under normal white-light. Thereto the fan blades are etched and fluorescent penetrating oil is applied to the parts. Excessive oil is removed and a developer is applied after that. The developer absorbs the oil and remains in small cracks after water washing. The blade is inspected under ultraviolet light and defects become visible. The second inspection is visual and it is performed in order to detect nicks, dents, scratches or dimensional changes.
If defects are within the repairable limits, the appropriate repair is performed to restore the fan blade. The engine shop manual includes 18 different repair procedures for fan blades. If a defect is beyond the repairable limit, the part has to be scrapped. After an overhaul small defects can remain on the blade as long as they are within serviceable limits. It has to be mentioned that fan blade repairs have not been performed by LTQ Engineering itself. Therefore no data concerning the airfoil roughness or dimensions is available.
Some repairs have never been performed neither on pre- nor on post-vendor engines. Therefore they are not described in this investigation. To improve the understanding, figure 5.5 labels the different parts of a fan blade. Table 5.2 shows, how many fan blades have un-

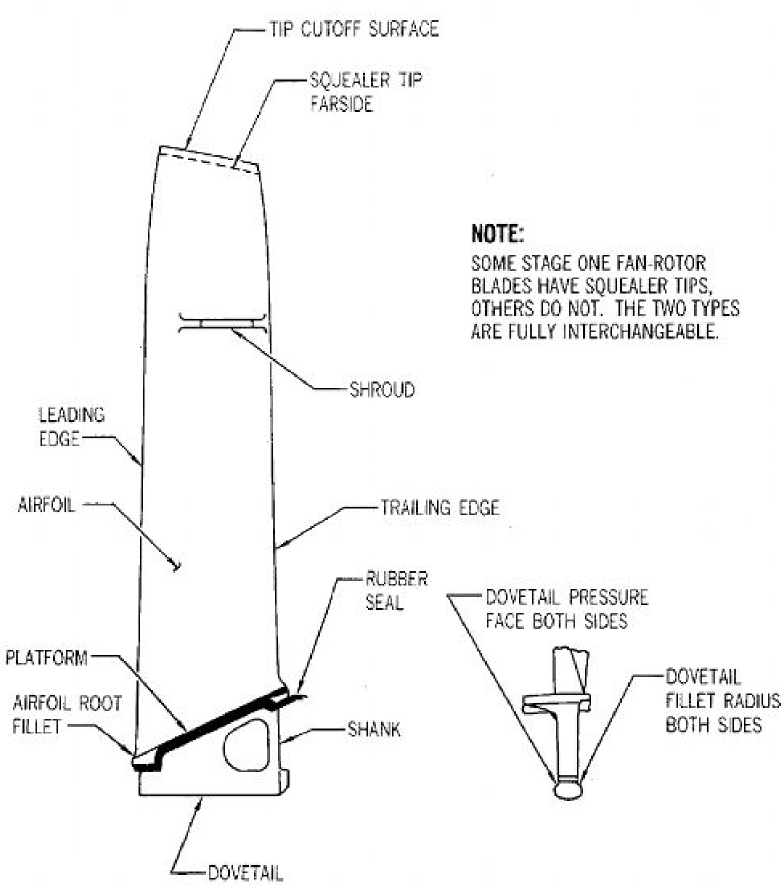

Figure 5.5: Nomenclature of a fan blade[GE10]

dergone each repair. The first ten engines are pre-vendor, the remaining are post-vendor engines. Four repairs have always been performed on pre- and post-vendor engines; polishing (repair 003), shotpeening (repair 004), blending of airfoil, platform and shank (repair 005) and replacement of dovetail coating (repair 007). The polish and shotpeen repair are used to improve the surface finish by decreasing the roughness. The blend repair is performed to remove nicks, dents or scratches with a fine file, silicon carbide cloth or abrasive stone by not exceeding the maximum blend limits. After that the blades are shotpeened with steel shot at 15 psi pressure. The surface finish should show an average roughness of 22 microinches. If it does not meet the requirements, the polish repair has to be performed. A vibratory container with abrasive charged pellets is used and the repair is carried out in two phases; in the first phase the fan blade is covered in coarse abrasive media for 3 hours. After that it is inspected and the average surface finish must be at least 35 microinches. If not, the repair has to be performed again. In the second phase the fan blade is polished by finish abrasive media for 1 hour. The final surface finish has to be at least 22 microinches [GE10]. These three repairs are used in order to restore surface finish. As they have been performed on all pre- and post-vendor engines, airfoil surface finish is eliminated as a reason of low EGT margin for post-vendor engines.

Repair 007 stipulates the replacement of copper-nickel-indium dovetail coating and solid-film lubricant. The coating is used as an antifretting surface on the contact areas of the dovetail. The copper-nickel-indium coating powder is applied to the part by thermal spraying (plasma arc or flame spraying). Finally the dovetail is covered with solid-film lubricant. It is not very likely that this repair procedure has any effect on EGT or SFC. The coating is used to minimize dovetail wear and does not affect the airflow. An elimination as a reason of low EGT margin is additionally justified by the fact that the repair has been performed on all pre- and post-vendor engines.

Repair 002 (repair of mid-span shroud hardcoat), repair 006 (dovetail/platform seal replacement) and repair 016 (moment-weigh procedure) are performed on most engines. Repair 016 is carried out to determine the moment-weight of a fan blade. The moment-weight is important for trim balance of the fan rotor assembly. The procedure has been performed on engines with low as well as high EGT margin. The only exceptions are engines #1, #11 and #20. Therefore there is no indication that it has any effect on EGT.

The repair of mid-span shroud hardcoat (repair 002) is similar to repair 007 (replacement of dovetail coating) and has been performed on some pre- and post-vendor engines. An effect of the hardcoat on EGT is not mentioned by GE, therefore this repair is eliminated as a reason. The same applies to repair 006; there is no indication that it has been performed only on engines with low or high EGT margin.

The remaining repairs (008 to 012) have been performed a few times on both pre- and post-vendor engines. Therefore there is no justification to assign one of these repairs as a reason for low EGT margin.

Considering the fan blade repairs, no significant differences between pre- and post-vendor engines are noticeable. All blades have undergone airfoil surface finish restoration (repair 003, 004 and 005). Therefore this is eliminated as a reason for low EGT margin although no airfoil roughness data is available. The remaining repairs are performed on some pre- and post-vendor engines. These procedures cannot be considered as a reason for low EGT margin either because they have been performed on engines with high as well as low EGT margin. There is no difference in fan blade repairs noticeable between pre- and post-vendor engines.

Table 5.2: Quantity of fan blades which have been repaired

Engine	Rep. 002	Rep. 003	Rep. 004	Rep. 005	Rep. 006	Rep. 007	Rep. 008	Rep. 009	Rep. 010	Rep. 011	Rep. 012	Rep. 016
1		38	38	38		38						
2	38	38	38	38	38	38		2				38
3	38	38	38	38	38	38			3			38
4		38	38	38	2	38						38
5	38	38	38	38		38						38
6	38	38	38	38	9	38		4				38
7	38	38	38	38	38	38						38
8		38	38	38		38				38		38
9	38	38	38	38	7	38				38		38
10	1	38	38	38	1	38		1		38	1	38
11		38	38	38		38						
12	38	38	38	38	3	38		31				38
13	38	38	38	38	38	38		3		38	1	38
14		38	38	38		38						38
15		38	38	38		38						38
16		38	38	38	22	38		18				38
17		38	38	38		38						38
18	38	38	38	38	7	38		9				38
19	4	38	38	38	4	38						38
20		38	38	38		38						
21		38	38	38		38						38
22	26	38	38	38	24	38	1	2	1		2	38
23	38	38	38	38	38	38	7	14			8	38
24	38	38	38	38	38	38		4			3	38
25	38	38	38	38	38	38		11			2	38
26	38	38	38	38	38	38		1			2	38
27		38	38	38		38						38
28	38	38	38	38	38	38						38
29	38	38	38	38	38	38		7				38

6 Discussion of the analysis

The objective of this multi faceted investigation was to identify differences in module performance and repair procedures of pre- and post-vendor engines to determine possible reasons for low EGT margin. As pre-vendor engines show higher average EGT margin, their engine data is judged normal. Deviations were seen as an indicator for performance changes and potential changes in repair procedures.

In the first step an analysis of TEMPER data has been performed. Pre-vendor engines achieve an average EGT margin of 39.4 °C; the average EGT margin of post-vendor engines is 30.9 °C. However it was noticeable that post-vendor engines show lower SFC. Figure 3.6 displayed that six post-vendor engines have an abnormal EGT margin deviation for the LPT module and show the highest deviation for the fan module. This was the first indicator that this investigation should focus on these two modules. Furthermore four post-vendor engines revealed higher deviation for the HPTS module than pre-vendor engines. Due to the small effect of the HPTS on EGT margin, this module was not analysed in the further course of the investigation. It has to be mentioned that the significance of TEMPER data is limited; for all engine test data which has been submitted to the TEMPER software, the measurement of the LPT inlet pressure (P49) was judged abnormal, indicated by a warning in the TEMPER report. This warning is shown due to the high deviation to the baseline model. A malfunction of the pressure probes can be eliminated as the probes had been replaced. A possible explanation could be the condition of the baseline model; it is unknown whether this model is based on factory new or overhauled engines. Therefore the comparison to the baseline is not meaningful. As the warning was given for both pre- and post-vendor engines, it has to be accepted as normal. Furthermore it has to be mentioned that it is an analysis probe which does not have any control functions on the engine. An additional problem arises by considering the MEAS category. Variations of EGT which cannot be attributed to a particular module are listed in this category. Post-vendor engines show negative deviation up to 7.0 °C. An accurate conclusion can only be drawn if the deviations are allocated to the engine modules and not to the MEAS category (deviations should be around 0 °C).

The same trend was discovered by analysing SFC margin deviation per module in figure 3.7. Post-vendor engines show abnormal deviation for the HPTS and LPT modules. It was noticeable that the same post-vendor engines which show high deviation in EGT margin for the LPT module have the highest negative deviation in SFC margin for the LPT module as well. On the other side these engines achieve the smallest deviation in SFC margin for the fan module. As described in section 2.9, high fan efficiency due to small fan blade to shroud tip clearance increases EGT. At the same time, thrust generation is increased which leads to small SFC (high SFC margin). Therefore the relationship between deviation in EGT margin and SFC margin for these engines was seen as consistent and confirms focusing on

the fan module.
In chapter 4 test cell data was analysed in order to identify further differences between pre- and post-vendor engines and to find reasons for high deviation in EGT margin for the fan and LPT modules. It has to be mentioned that this part of the investigation was limited by data availability. Therefore it was not possible to assess performance for each module; especially performance estimation of the combustion chamber was not feasible because no data can be measured due to high temperatures. Differences between pre- and post-vendor engines caused by this module could not be noticed in this investigation. The flame profile (shape of the flames in the combustion chamber) has great effect on engine performance. The combustion chamber of a CFM56 jet engine is shown on the left side of figure 6.1. On the right side the dome angle (angle VF) is displayed in detail. It is the angle between combustion chamber and a virtual horizontal axis. The effect of dome angle change in a

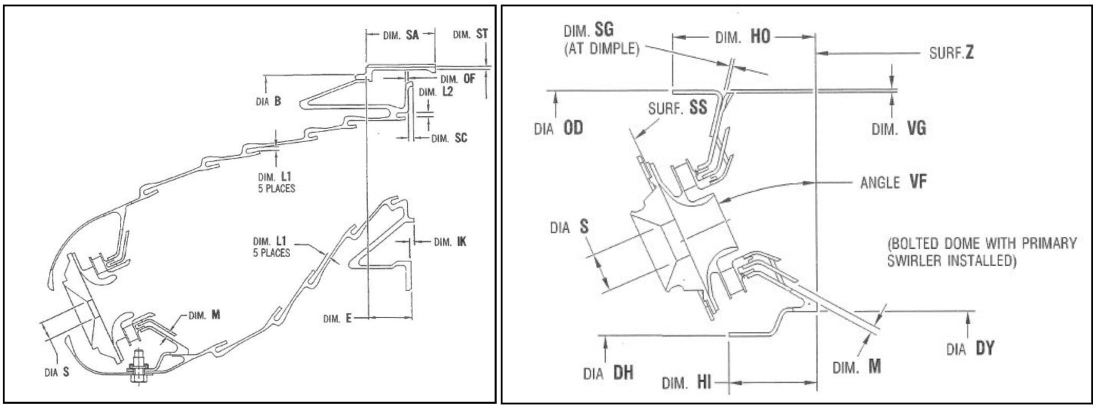

Figure 6.1: Combustion chamber (left) and dome angle (right) of the CFM56 [CFM10]

CFM56-7 is shown in figure 6.2. Small changes in dome angle could cause hot spots in the combustion chamber which leads to performance drop. The dome can be installed with an angle of 22° to 26° according to the manufacturer. Performance differences caused by this variation cannot be assessed and provide a possible explanation for low EGT margin.
In addition, engine data was restricted by correction factors. Not all parameters were corrected to the same power setting and condition (hot or standard day). However it was regarded that a comparison was only done with parameters of the same correction level.
Figure 4.1 displayed that nine post-vendor engines show high SFC margin by achieving low EGT margin. They are located beyond the expected band of pre-vendor engines. It was noticeable that all engines with high deviation in EGT margin for the fan and LPT modules show this abnormality. Again this was interpreted as a confirmation to focus on the fan module as high fan efficiency in terms of blade to case clearance leads to increase in EGT (decrease in EGT margin) but decrease in SFC (increase in SFC margin). This is a possible explanation why these engines are located beyond the normal band.
As SFC is defined as the ratio of burnt fuel to generated thrust, these two parameters were

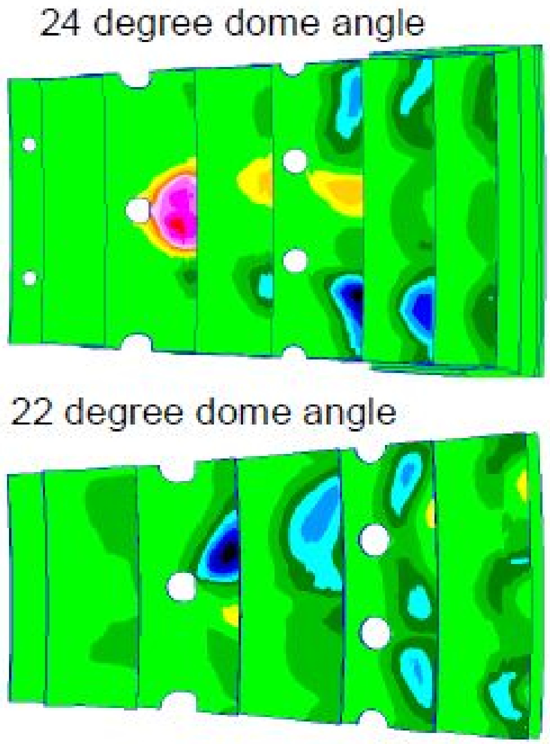

Figure 6.2: Hot spots due to change in dome angle [NEW11]

plotted in figure 4.2. It revealed that some post-vendor engines show high fuel consumption but generate more thrust at the same time. This leads to low SFC and accordingly to high SFC margin. An interesting relationship was displayed in figure 4.3, where thrust was plotted against EGT margin. Nearly 50 % of post-vendor engines generate more thrust than pre-vendor engines. As the fan is the main module of thrust generation and the TEMPER data revealed that some post-vendor engines have higher deviation in EGT margin for the fan module, the conclusion was drawn that a closer look at the fan module could provide explanations.

The chart presented in figure 4.4 confirmed that the fan and LPT may be the poor performing modules due to the tendency to higher EPR of high thrust post-vendor engines. However it has to be mentioned that an overall trend could not be identified; engines with the same EPR achieve high and low EGT margin (e.g. engines #24 and #25) or achieve the same EGT margin by having different EPR (e.g. engines #14 and #22). This problem arises for all comparisons; post-vendor engines show broad spread, hence it was not possible to identify a clear trend. Moreover the test data itself has to be seen critically; as mentioned earlier, the TEMPER report gives a warning for all engines that the P49 measurement was judged abnormal. This has an effect on EPR as it represents the ratio of P49 to P12. An abnormal P49 measurement leads to defective EPR and therefore reduced significance. To assess the HPC performance, N2 speed versus PS3/P25 was plotted in figure 4.5. It was not possible to identify a clear trend either due to the great spread in HPC pressure ratio. Only one post-vendor engine shows poorer HPC performance. However all engines achieve nearly the same N2 rotor speed which indicates that a change in HPC and/or HPT performance is very small.

It has to be mentioned that the difference between highest and lowest values of a parameter is around 2.5 % in average. The difference between the highest value of a pre-vendor engine and the highest value of a post-vendor engine is less than 1.0 % for all parameters. Therefore the significance is restricted. Table 6.1 shows absolute and percentage deviation between highest and lowest values and demanded instrument accuracy for main engine parameters. By assessing engine performance, deviation in terms of accuracy has to be taken into account. It is obvious that the deviations cannot be explained only by measurement errors. However it has to be considered that inaccuracy in the measurement system can skew the conclusions, especially if only small differences between pre- and post-vendor engines appear. Due to the complexity of jet engines, small deviations can have several reasons and it

Table 6.1: Deviation of engine parameters and instrument accuracy [GE10]

Parameter	**Absoulte deviation**	**Percentage deviation**	**Instrument Accuracy**
N2 rotor speed	83 rpm	0.8 %	±5 rpm
Thrust	1460 lb_f	2.4 %	±140 lb_f
Fuel flow	537 lb/h	2.7 %	±0.5 % of point
EGT	25.2 °C	113 %	±3.0 °C

is difficult to detect which module operates in a different way. Furthermore the approach to identify reasons for low EGT margin only provides a limited view of the problem. The aim of the investigation was to find reasons for low EGT margin of post-vendor engines. Based on GE recommendations, TEMPER data and selected engine parameters have been analysed to identify differences between pre- and post-vendor engines. It is possible that reasons for low EGT margin are based on small changes in each component and not on great change in one or two components as assumed in this investigation. These small differences are hardly noticeable but lead to high deterioration of EGT margin in total.

Furthermore it is conceivable that friction of seals and bearings affect EGT and engine performance. Their influence does not appear in changes in engine parameters and therefore it is difficult to discover. However the drag produced by seals and bearings is very small, which is shown by spinning the N1 rotor. Not much force is needed to set the fan and LPT modules in motion by hand and the rotor rotates for a long time before coming to rest. Therefore it is justified that friction effects of seals and bearings are neglected. Additionally the gearbox (includes fuel pump, hydraulic pump, lube and scavenge pump, starter and generator) causes drag. As the gearboxes for one engine model are the same and only small differences in drag occur, the effect on engine performance is insignificant. These two examples show the complexity of engine performance. Numerous small changes in component performance lead to low EGT margin in total, but it is nearly impossible to detect them. Moreover the data availability restricts the investigation, e.g. additional drag of the gearbox is not measured.

Another approach would have been to examine each engine on its own. However as the problem of low EGT margin is more significant for post-vendor engines, a comparison to pre-vendor engines is more meaningful. Besides that a detailed analysis of each engine would require more time and greater resources.

Concentrating only on repair procedures without analysing TEMPER and test cell data would have been another conceivable approach especially since no clear trends could be discovered. The effects of each module on EGT and SFC are presented in section 2.9 and provide a basis for that kind of investigation. However this approach is associated with the risk that no differences are detected as all repairs are performed according to manual requirements and dimensions are within limits. To allow a comparison, the behaviour of pre-vendor engines was judged normal due to high EGT margin of most pre-vendor engines. All conclusions are based on this assumption although three pre-vendor engines show low EGT margin. This approach is justified by the fact that a sudden and significant drop in EGT margin occurred with the change of the overhaul vendor.

It is evident that the possible reasons for low EGT margin are numerous and complex. The generation of more thrust and the relationship between low EGT margin but high SFC margin was the most significant difference between pre- and post-vendor engines. Therefore this investigation focused on the fan as the main module for thrust generation.

Smaller fan blade tip to shroud clearance lead to higher fan efficiency and therefore higher thrust, but lower EGT margin at the same time. Tip clearances are represented by two measurements called E12 and E13 and were analysed in section 5.1. It was expected that engines with higher thrust and low EGT margin have smaller tip clearance. This trend could not be confirmed as seen in figures 5.3 and 5.4. Due to the broad spread it was not possible to identify a relationship between high thrust/ low EGT margin and small tip clearance. Both pre- and post-vendor engines have almost the same clearance by achieving different EGT margin. Hence the conclusion was drawn that this is not the reason for low EGT margin. Post-vendor engines show a tendency to higher tip to shroud clearance which should result in lower EGT (higher EGT margin). As the achievement of required thrust level has never been a problem, it is recommended that fan blades should be installed with clearance as big as possible within the limits.

Based on experience, the condition of the fan blades is an issue in terms of EGT and SFC. Therefore quantity of repair procedures has been analysed in section 5.2. It became evident that airfoil surface restoring repairs were performed on every engine, so the effect on EGT

and SFC is the same for pre- and post-vendor engines. It has to be mentioned that no roughness data of the blades is provided, which would represent a better estimation of the airfoil surface condition. The remaining repairs were performed on some engines, but it is unlikely that the replacement of coating on the dovetail or shroud has a great effect on engine performance. Besides that these repairs were performed on engines with both high and low EGT margin.
Both analyses do not reveal any relationship between low EGT margin and repair procedures or clearances. The assumption that higher thrust is caused by changes in the fan rotor assembly could not be confirmed. However a possible explanation may be based on the shape of the fan blade airfoil, e.g. leading edge contour, which cannot be detected by analysing the quantity of repairs. Although dimensions are within limits, it is possible that different overhaul vendors perform the same repair with different results. This is very hard to proof and requires more data and time.
Finally it has to be mentioned that jet engines are not designed for diagnostics; the available instrumentation is used in order to ensure safe engine operation and not to assess module performance. The same problem arises with recorded dimensions; only security relevant data as clearances are measured. Therefore it is very difficult to identify reasons for low EGT margin, especially if no obvious changes have occurred.

7 Recommendations for test cell modifications

Due to the limited availability of engine data it is difficult to assess performance of all engine modules. Therefore it is reasonable to implement additional test cell instrumentation to record more data. This chapter gives a description of instrumentation and stations where it is measured. Furthermore recommendations are given how to install the instrumentation and which modifications are necessary.
To assure safe engine operation, the performance acceptance test is performed in 'on-wing condition'. Therefore a cowling for the secondary airpath and an exhaust nozzle behind the LPT module are fitted to the engine. Additionally a bellmouth inlet is used which substitutes the engine flight inlet and keeps flow losses due to friction and turbulence to a minimum [BRÄ09]. Figure 7.1 pictures the three components in the test cell.

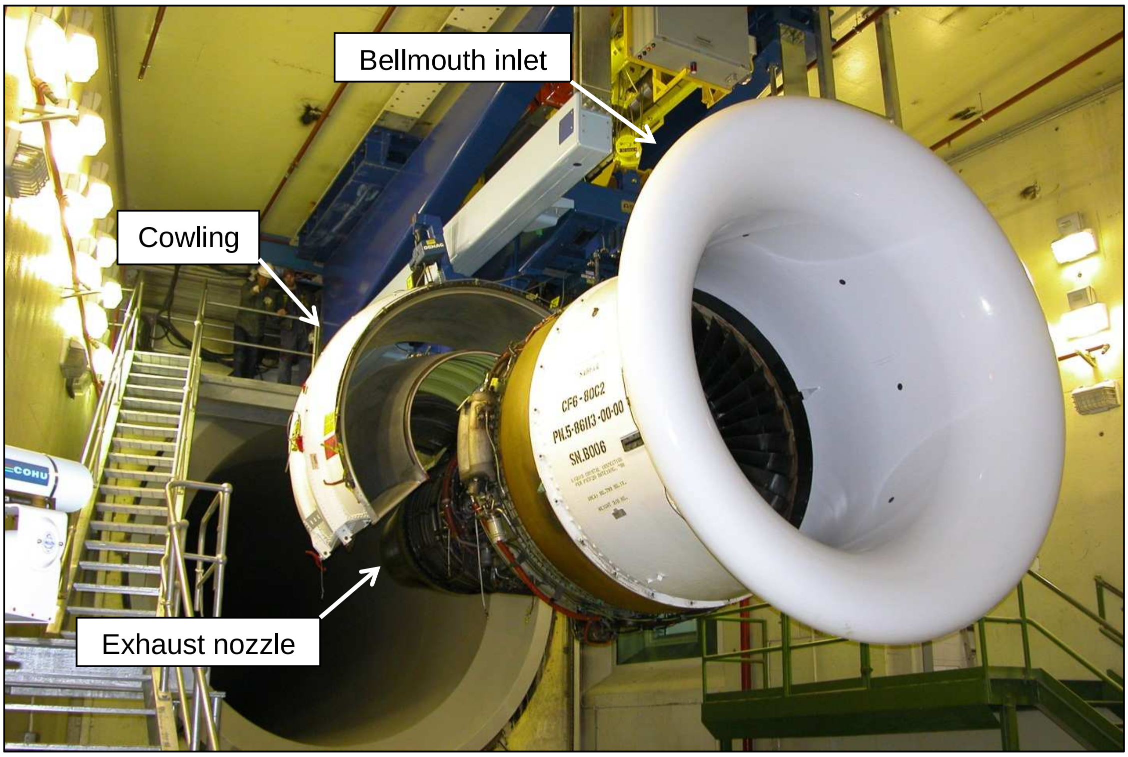

Figure 7.1: Engine installation in the LTQ test cell

7.1 Additional measuring points

The TEMPER data reveals that the fan and LPT modules show high deviation in EGT margin. Due to data availability it is not possible to assess performance of these two components. Therefore pressure and temperature data at inlet and outlet of the modules has to be recorded. The ratio of inlet and outlet pressure represents efficiency of pressurisation or work extraction. The temperature ratio is needed to calculate the thermodynamic cycle and is used to judge how the component performs compared to the ideal cycle. The measurements which are recorded in the test cell at LTQ Engineering are mentioned in section 2.7. Both pressure and temperature are recorded at the fan inlet (P12 and T12). However these are the only measurements which are taken in the secondary airpath. To assess fan performance it would be necessary to record parameters behind the fan module. As the fan is the only rotating part, it is less important where the additional criteria in the secondary airpath are recorded. However it has to be mentioned that the airflow is affected by struts and cowling. This leads to pressure decrease and temperature increase in consequence of friction. The temperature increase (dissipation) only affects the boundary layer and is very small compared to temperature change due to compression, energy extraction and combustion. Therefore friction losses are solely described by a decrease in total pressure when the thermodynamic cycle is calculated [BRÄ09]. As the changes in pressure and temperature should be the same on all engines due to same cowling, the additional measurements can be taken anywhere in the secondary airpath. Figure 7.2 shows the CF6-80C2 cowling which is used at LTQ Engineering. The cowling provides four ports (two on each side) for pressure

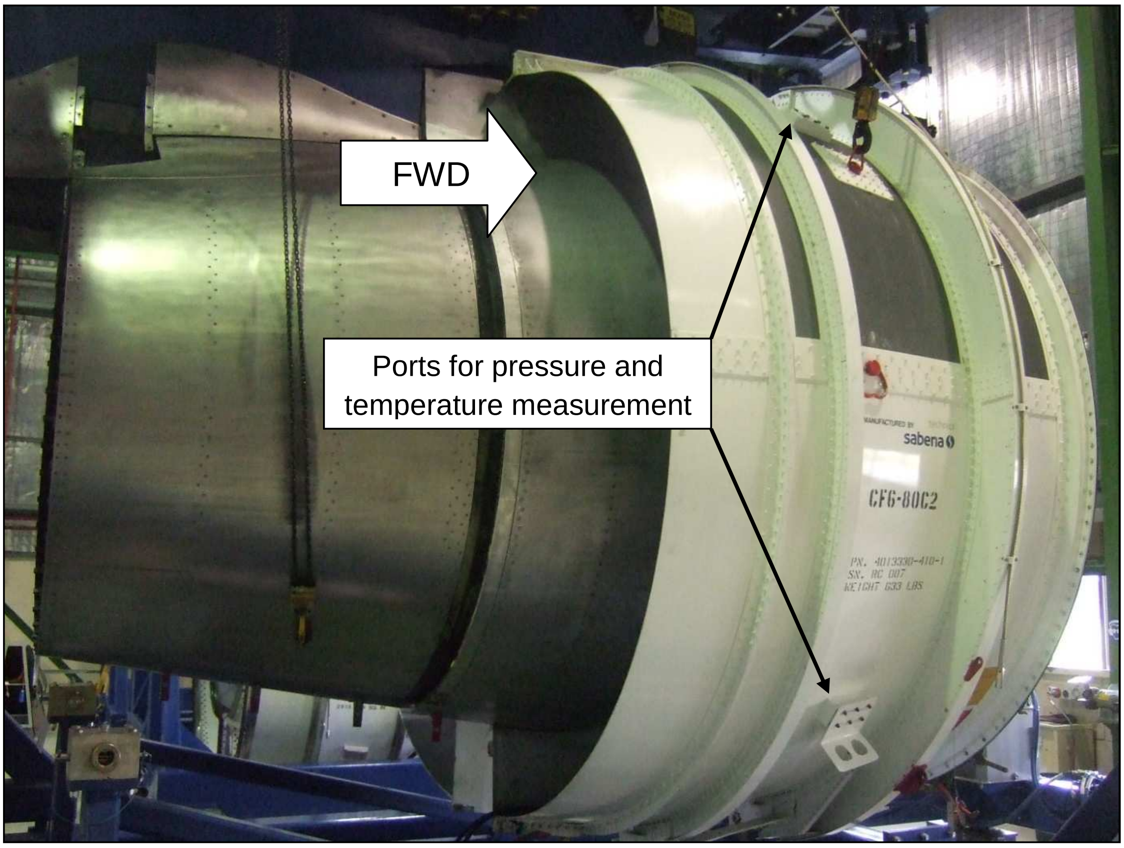

Figure 7.2: CF6-80C2 test cell cowling(right side)

and temperature measurement. These ports can be used to record the additional criteria in the secondary airpath and no modifications are necessary. This position matches station

17 (nozzle inlet) in figure 2.2. The number of probes which should be used depends on the pressure and temperature uniformity at the station. More locations and greater coverage lead to more accurate results but demands more time and effort, e.g. for installation, calibration and overhaul of the instrumentation. Non-uniform pressure distribution is likely for the fan downstream, therefore more coverage should be employed [WF98]. With this in mind all four ports should be equipped with instrumentation.
To assess the performance of the LPT module, pressure and temperature measurements at the component inlet and outlet are necessary. Again both measurements are already taken at the inlet of the LPT (P49 and T49). Figure 7.3 shows both engine sides and the available ports for measuring instruments. The only available port behind the LPT is for a

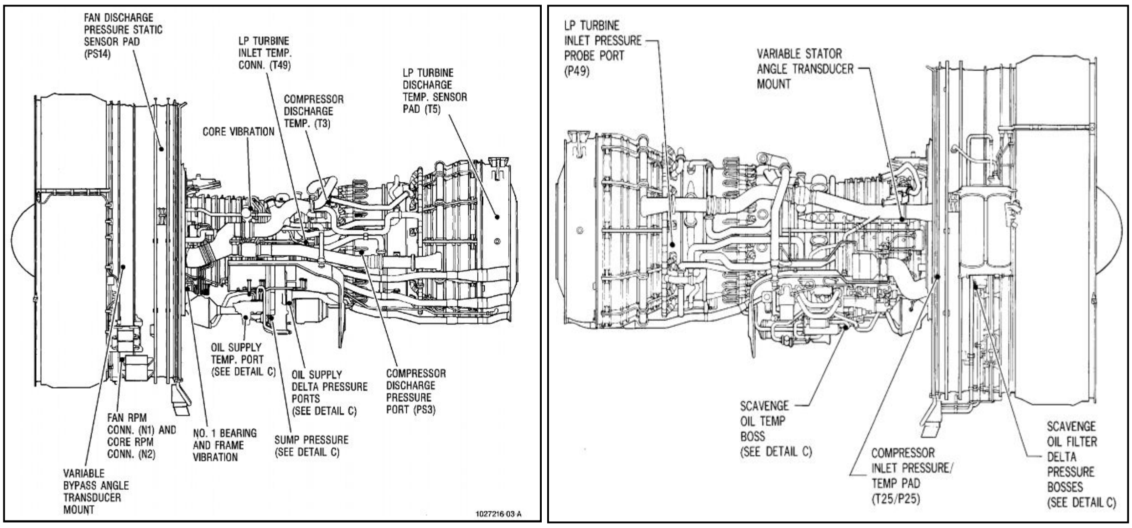

Figure 7.3: Available ports on the CF6-80C2 [GE10]

temperature sensor at station 5 (top right on the left picture). Due to significant swirl at the hot end greater coverage with more than one probe is needed [WF98]. Therefore the only possible location for additional instrumentation to assess LPT performance is in the exhaust nozzle (stations 55 to 9). However this requires a modification of the nozzle as no ports are provided from manufacture.

7.2 Instrumentation

For measurement of pressure and temperature, both sensors are installed in rakes. An example of the rakes which should be used on the CF6-80C2 engines are shown in figure 7.4. The rake includes six pressure and/or temperature sensors and it is installed with its axis towards the direction of the gas flow. The six heads are called Kiel heads and they assure effective measurements despite greater incidence angles. However due to their size and small wall thickness, they are susceptible to damage during installation and removal [WF98]. Thermocouple sensors or resistance temperature detectors are the most common

Figure 7.4: Rake for temperature and pressure measurement

methods to measure temperatures in jet engines whereby they are applicable for different temperature regions. Thermocouple sensors are temperature sensing devices which use voltage generation due to temperature difference and different metal alloys. As the temperature at the measuring point increases or decreases, the millivolt value of the sensing elements increase or decreases accordingly [GE03]. Figure 7.5 shows a schematic diagram of a thermocouple sensor. The Type K thermocouple sensors are the most common type

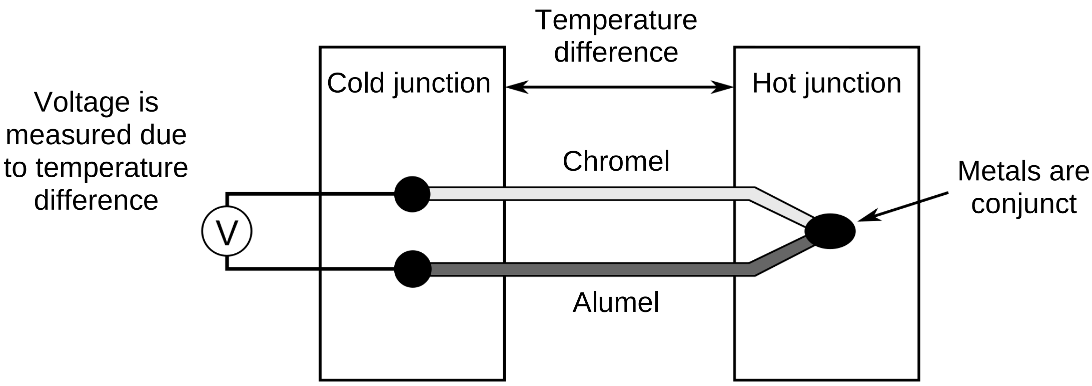

Figure 7.5: Schematic assembly of a thermocouple sensor (Type K) [WIK11]

for industry applications and are made of chromel and alumel alloy conductors. The functionality is based on the thermoelectric effect or Seebeck effect; a conductor generates emf whenever it is exposed to gradient in temperature. A second conductor is needed to form a closed circuit in order to measure this emf. By using dissimilar wires, different voltage generation is achieved by the conductors and can be measured at the free ends and related to a temperature due to the linear relationship. It has to be mentioned that the magnitude of the emf is a function of temperature difference between both junctions and the type of material. Furthermore the temperature difference is referred to the cold junction; therefore the reference temperature of the cold junction has to be known or compensation has to be

used in order to receive an absolute temperature measurement [CHI01].
Thermocouple sensors are the standard instrument to measure temperatures up to 1400 °C whereby they are less accurate than resistance temperature detectors [RAT07]. Furthermore they are characterised by fast response time by temperature changes. Due to high temperature and exposure to reactive atmosphere, the lifetime of thermocouple sensors is limited and the simple relationship between temperature and voltage falsifies with time [CHI01]. The CF6-80C2 jet engine uses eight Type K thermocouple sensors to measure EGT [GE10].
Resistance temperature detectors are used for smaller temperature range up to 600 °C [RAT07]. They are characterised by high accuracy and high resistance against corrosion and chemical atmosphere. Their functionality is based on electrical resistance change of a metal wire (usually platinum) due to temperature change. The platinum wire is wounded around a ceramic insulator or encapsulated in glass [CHI01]. As the temperature increases or decreases, the resistance value of the sensing elements increases or decreases accordingly. In contrast to thermocouple sensors, these detectors require a power source to operate. By providing constant power supply the resistance change is measured by a change in voltage. PT200 resistance temperature detectors (platinum wire and resistance of 200 Ω at 0 °C) are used for measuring the HPC inlet temperature on the CF6-80C2 jet engine [GE97].
For measuring the temperature behind the LPT the use of thermocouple sensors due to their higher temperature range is recommended. With temperature around 550 °C they are the preferred measurement device for high temperatures although resistance temperature detectors would be the better choice in terms of chemical resistance and accuracy. In the secondary airpath (station 17) temperature should be measured with resistance temperature detectors such as PT100 due to lower temperature around 180 °C and higher accuracy. It has to be mentioned that the choice of temperature measurement sensors is only based on operating range and accuracy and on recommendations by GE. Other determining factors such as size of the measuring device, time response to temperature changes, stability, self heating or calibration have not been considered as the temperature range is the most important criterion [CHI01].
Pitot tubes are used to record total pressure and are installed in rakes as well. A pitot tube is a simple tube whose tapping points towards the direction of the airflow. The air comes to rest at the end of the tube and its pressure can be measured. Usually the measured pressure is an average of several pitot tubes. Therefore the capillary tubes are brought together in a manifold where its pressure is measured by sensor [WF98]. On the left side of figure 7.6 the rake for fan inlet pressure on a CFM56 is shown. The pressure is determined by the average of two measurements. The right side displays the capillary tubes which connect the pitot tube with the manifold (not shown).
Pressure transducers are the most common device to measure pressure. They are electromechanical devices which convert pressure to an electrical signal. The sensor consists

of two chambers which are separated by a thin, elastic diaphragm. Usually they are made of beryllium, copper, phosphor bronze or stainless steel sheets. The pressure difference between both chambers (total pressure of the airflow on one side and barometric pressure on the other) causes movement of the diaphragm. This displacement is amplified using a mechanical, electrical, electronic, or optical system [RAT07]. Figure 7.7 shows a schematic pressure capsule with strain gauges mounted to the diaphragm.

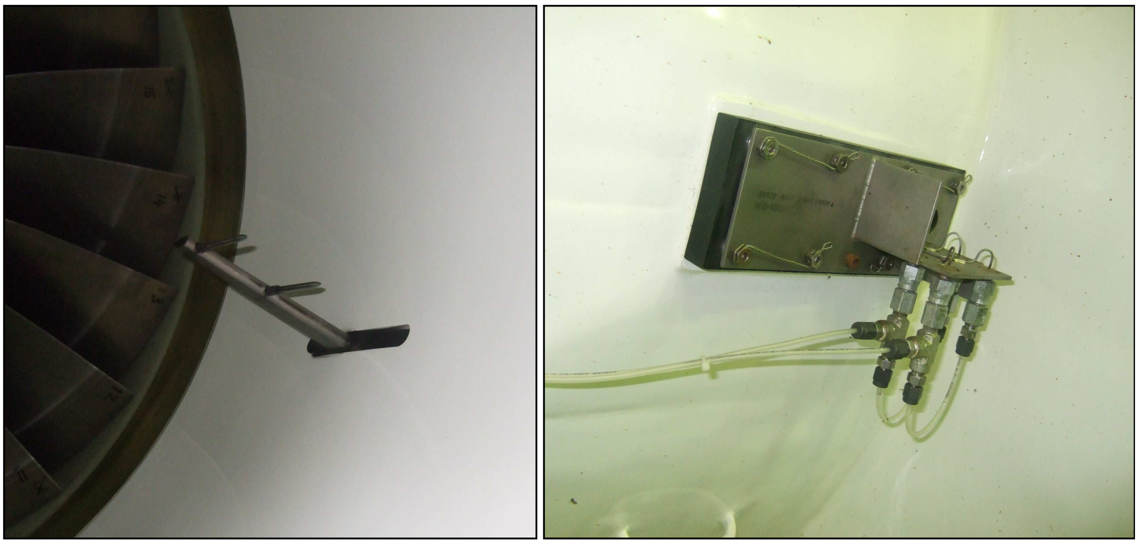

Figure 7.6: Pressure rake (left) and capillary tubes (right)

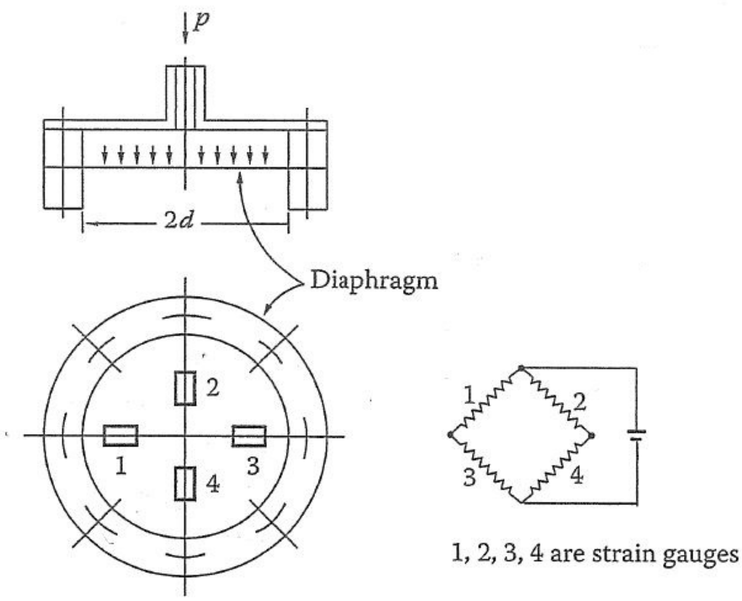

Figure 7.7: Pressure transducer (strain-gauge-type) [RAT07]

7.3 Modifications

After determination of measurement stations and description of instrumentation, this section gives recommendations and instructions as to which modifications have to be performed to record additional criteria. As mentioned before the recording of pressure and temperature in the bypass (station 17) does not require any modifications due to the use of existing ports. However recording additional criteria behind the LPT requires hardware changes. As modifications on the engine itself are not allowed due to certification regulations, only test cell equipment such as the exhaust nozzle can be modified for the implementation. Figure 7.8 shows the exhaust nozzle of the CF6-80C2 which is used at the LTQ test cell.
A similar modification has been performed on the CFM56-5C jet engine exhaust nozzle at Lufthansa Technik in Hamburg. Eight additional rakes have been implemented in the exhaust nozzle to measure temperature at station 55. Based on experience which has been gained during several test runs, pressure measurement behind the LPT causes problems in terms of accuracy due to significant swirl and pressure differences. Therefore the results of pressure measurement are not meaningful and cannot be used to calculate the thermodynamic cycle or to assess module performance. Besides that the pressure value is not required to calculate the thermodynamic model if all other measurements are taken into account. Hence only additional thermocouple sensors at station 55 should be integrated in the CF6-80C2. Measurements have shown that the four rakes should be enough to achieve satisfying and significant results if only temperature is measured. The integration of additional instrumentation does not pose a problem in terms of spare channels or connectors in the test cell. However there are some points which should be considered before performing any modifications. Due to the high temperature behind the LPT, the connectors of the sensors should not be located in this area. Therefore cables must be long enough to reach connectors in the cooler areas of the engine.

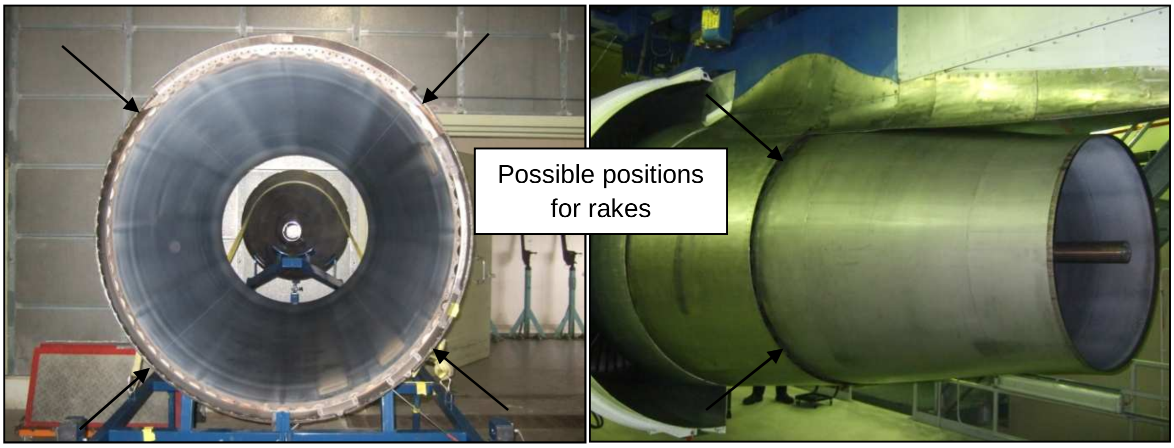

Figure 7.8: CF6-80C2 exhaust nozzle uninstalled (left side) and installed (right side)

Furthermore it should be possible to seal the ports for the rakes if the additional equipment

is not used in order to avoid parasitic airflow through the exhaust nozzle. Additionally a flush surface inside of the nozzle should be provided; otherwise vortices could appear and affect engine performance.
Another problem arises with cables of the temperature sensors. As the exhaust nozzle does not provide any channels to cover the cables, it has to be avoided that they interfere with the secondary airflow. It may be possible to hide the cables in the small cavity between outer and inner nozzle cover as seen in figure 7.8 and 7.9 in more detail. Additionally the

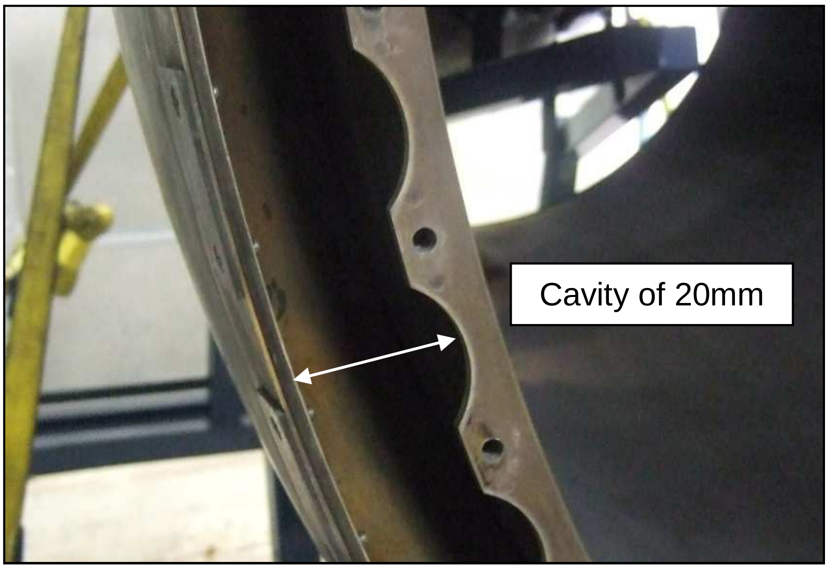

Figure 7.9: Exhaust nozzle cable installation

installation of the base plates of the rake could cause problems due to wall thickness. The inner exhaust nozzle wall is very thin and as a result is easily damaged or cracked. This is even more likely due to high temperature gradient. Perhaps reinforcement of the wall in the cavity can solve the problem.
These recommendations are based on experience of previous modifications and assessment of the exhaust nozzle. As there are no drawings, rakes or additional data available, it is difficult to predict possible issues.

8 Further examinations

It is recommended that future work focuses on the reasons for higher thrust generation as this is the most obvious difference between pre- and post-vendor engines. With recording pressure and temperature behind the fan it should be possible to determine whether higher thrust is based on fan performance as assumed in this investigation. As fan blade tip to shroud clearance and repair procedures did not reveal any substantial reasons for high thrust and low EGT margin, additional monitoring and documenting of fan blade parameters such as chord length, leading edge contour or surface roughness may be useful.

Due to time and complexity it was not possible to analyse repair procedures for the LPT module. As this module shows high negative deviation it would be interesting to consider whether it is possible to identify any correlations between LPT and low EGT margin. Therefore conceivable examinations are clearance and airfoil surface finish of LPT blades. The data availability is the same as for the fan module; clearances are always recorded, although no data concerning airfoil quality is provided. Hence other methods have to be used to assess the airfoil quality. Furthermore additional information are gained as a result of test cell modifications. Although pressure cannot be measured behind the LPT due to accuracy, the recording of temperature allows better understanding of the thermodynamic cycle and a more accurate calculation.

The modification of the exhaust nozzle should be the next step in order to gain additional data as soon as possible. It is reasonable to manufacture samples of the cut out in order to find the best way and avoid damage to the nozzle.

Appendix

A.1 Engine monitoring report

The following pages show the 'on wing' history and monitoring report of a CFM56-3C-1 jet engine which is provided by the engine operated. The report includes general information about the engine as date and reason for removal, time since new (TSN), cycles since last visit (CSLV) and last test results. The 'on wing' history (pages 1 and 2) contains performed maintenance work and warnings which have occurred during operation. The numerous warnings of high EGT (and therefore reduced EGT margin) have been the reason for removal. The tabular report lists monitored engine data of the last days before removal for takeoff (page 3) and cruise conditions (page 5). A graphic representation of the data is given on page 4 (takeoff) and page 6 (cruise).

[redacted] [redacted] [redacted]

DATE REMOVED: 11 October 2005

REASON: Reduced EGT Margin.

TSN: 43961 CSN: 26096 TSI: 5273 CSI: 3323

TSLV: 5273 CSLV: 3323 (Check times with CAMSYS)

PREVIOUS REMOVAL: HPT BLADE CAMPAIGN.

LAST TEST RESULTS: EGT Margin: 43.9° C @ TO, 55.3° C @ MC.

Operating Line: N/S units.

ON WING HISTORY :

13DEC03	Engine installed. During post engine change ground runs/starts N2 rotor failed to rotate on one occasion. Suspect N2 rotor bow. Engine allowed to cool was normal.
19DEC03	Crew report engine failed to start with no N2/N1 rotation. Suspect rotor bow. Subsequent engine start was normal.
17JAN04	HPT and Combustor Borescope performed, nil defects noted.
20FEB04	ACARS message due high EGT during take-off. Peak EG 926.5° C for 16 seconds above 920° C.
21MAY04	HPT Borescope performed, nil defects noted.
02AUG04	Fan Blade No.17 blended to remove leading edge damage. NDI check performed and nil defects noted.
27NOV04	Fan Blade No7 blended to remove leading edge damage. NDI check performed and nil defects noted.
08APR05	ACARS message due to high EGT during take-off. Peak EGT 924° C for 2 seconds above 920° C.
15MAY05	ACARS message due to high EGT during climb. Peak EGT 895° C for 300 seconds.
16MAY05	Engine fire system failed test. MEL 26-2 applied.
27MAY05	HPT Borescope performed, nil defects noted.
16JUN05	Crew reported engine Generator tripped off line during taxi. Reset was carried out ok. Unable to fault after clearing HV light on M238 panel.
03JUL05	ACARS message due high EGT during take-off. Peak EGT 924° C for 2 seconds above 920°C.
25JUL05	HPT Borescope performed, nil defects noted.
03AUG05	EGT indication system test carried out and nil defects were reported as no report was received.
04SEP05	ACARS message due high EGT during climb. Peak EGT 859° C for 300 seconds above 895° C.
16SEP05	ACARS message due high EGT during climb. Peak EGT 859° C for 300 seconds above 895° C.
23SEP05	ACARS message due high EGT during take-off. Peak EGT 924° C for 2 seconds above 920° C.
25SEP05	ACARS message due high EGT during take-off. Peak EGT 930° C for 2 seconds above 930° C. HPT Borescope carried out, nil defects noted.
29SEP05	ACARS message due high EGT during climb. Peak EGT 859° C for 300 seconds above 895° C.
30SEP05	ACARS message due high EGT during climb. Peak EGT 859° C for 300 seconds above 895° C.

04OCT05	Crew noted with no engine bleed take-off with OAT 37° C, engine EGT exceeded 942° C for 2 seconds until thrust was retarded after take-off. Then returned within limits and operation normal after that. DFDAU interrogated for engine exceedances and indicated 930° C for 2 seconds. Nil action required. ACARS message indicated 931° C for 2 seconds above 930° C. ACARS message due high EGT during climb. Peak EGT 895° C for 300 seconds above 895° C.
05OCT05	ACARS message due high EGT during climb. Peak EGT 895° C for 300 seconds above 895° C. ACARS message due high EGT during take-off. Peak EGT 931° C for 2 seconds above 930° C.
06OCT05	ACARS message due high EGT during climb. Peak EGT 895° C for 300 seconds above 895° C.
11OCT05	Engine removed due to reduced EGT margin. Suspect HPT Blade tip rub.

Trend Monitoring at removal showed:

Take-off Data: EGTM: -13.1° C, SLOATL: 26.1° C.
Cruise Delta: EGT: 38.9° C, N2: -2.6 %, FF: 1.4 %

INBOUND TEST:

WORK CONTENT SUMMARY:

SHOP FINDINGS:
DEFECT CONFIRMED:

ENGINE ACCEPTANCE TEST:

AIRCRAFT	POS	ESN	INSTALLED	ENGINE TYPE	N1MOD	EGT SHUNT	TCC TIMER	THRUST RTG
[redacted]	[redacted]	[redacted]	14-DEC-2003	CFM56-3C-1	-	-	ACTIVE	23.5

DATE	TIME	TAT °C	ALT FT	MACH	AGW TNS	CORR N1 %	THRUST DERATE %	FAN DERATE %	EGT_HOT_DAY_MARGIN RAW °C	EGT_HOT_DAY_MARGIN SMTH °C	SEA_LEVEL_OATL RAW °C	SEA_LEVEL_OATL SMTH °C	BLDS 1234	PKS 123	AI EW	IV 12
05[illegible]04	0813 I									39.6		42.3				
01MAY05	0153 C									3.4		31.0				
01JUN05	0217 C									2.9		30.9				
01JUL05	0447 C									-3.8		28.9				
01AUG05	0212 C									0.8		30.3				
01SEP05	0020 C									-1.7		29.5				
28SEP05	0007	24.5	173	.269	64	95.0	2.1	0.7	-8.8	-5.0	27.4	28.5	00	11	10	0
28SEP05	0407	30.5	527	.266	60	95.5	1.7	0.6	-4.7	-4.9	28.6	28.5	00	11	10	0
28SEP05	0756	24.5	245	.267	55	90.7	15.4	5.1	-5.0	-5.0	28.5	28.5	00	11	10	0
28SEP05	1031	22.5	454	.277	57	94.0	6.0	2.0	1.8	-3.6	30.6	28.9	00	11	10	0
28SEP05	2240	20.3	571	.279	56	96.0	0.3	0.1	-1.2	-3.1	29.6	29.1	00	11	10	0
29SEP05	0044	26.8	235	.268	57	92.7	9.5	3.1	-8.1	-4.1	27.6	28.8	00	11	10	0
29SEP05	0304	12.8	2328	.292	56	97.5	-0.2	-0.1	9.2	-1.5	32.8	29.6	01	11	10	1
29SEP05	0530	25.8	402	.287	61	94.2	5.1	1.7	-4.3	-2.0	28.7	29.4	00	11	10	0
29SEP05	2108	30.5	406	.272	60	94.4	4.6	1.6	-14.2	-4.4	25.8	28.7	00	11	10	0
30SEP05	0005	28.8	173	.276	63	95.2	1.5	0.5	-5.0	-4.5	28.5	28.7	00	11	10	0
30SEP05	0315	33.0	1890	.274	54	92.7	10.3	3.4	0.2	-3.6	30.0	28.9	00	11	10	0
30SEP05	0620	31.5	302	.274	60	93.7	6.6	2.2	-14.2	-5.7	25.8	28.3	00	11	10	0
30SEP05	0907	24.8	232	.279	60	93.5	7.0	2.3	-8.7	-6.3	27.4	28.1	00	11	10	0
01OCT05	0042	19.5	370	.271	56	91.9	12.3	4.1	-15.2	-8.1	25.5	27.6	00	11	10	0
01OCT05	0307	24.0	843	.274	54	91.8	13.5	4.6	-14.0	-9.3	25.9	27.3	00	11	10	0
01OCT05	0434	21.0	2152	.274	54	96.6	1.5	0.7	1.7	-7.1	30.5	27.9	00	11	10	0
01OCT05	0642	25.5	825	.273	52	91.1	15.5	5.3	-11.1	-7.9	26.7	27.7	00	11	10	0
01OCT05	0836	23.8	400	.281	57	92.9	9.3	3.1	-7.7	-7.8	27.7	27.7	00	11	10	0
01OCT05	1052	22.8	831	.285	53	91.3	15.0	5.1	-10.0	-8.3	27.0	27.5	00	11	10	0
01OCT05	2346	20.3	2120	.265	48	92.9	11.9	4.3	-3.2	-7.3	29.0	27.8	00	11	10	0
02OCT05	0119	29.0	342	.276	57	93.7	6.5	2.2	-12.2	-8.2	26.4	27.6	00	11	10	0
02OCT05	0319	26.0	289	.270	58	92.7	9.5	3.1	-9.4	-8.5	27.2	27.5	00	11	10	0
02OCT05	0538	29.0	395	.271	56	92.2	11.4	3.8	-9.8	-8.7	27.1	27.4	00	11	10	0
02OCT05	0831	28.5	461	.270	57	92.2	11.6	3.9	-9.6	-8.9	27.1	27.4	00	11	10	0
03OCT05	0743	18.0	582	.268	53		14.3	4.8		-8.9		27.4	00	11	10	0
03OCT05	0901	24.5	2144	.266	49	92.4	13.5	4.8	3.6	-6.4	31.1	28.1	00	11	10	0
03OCT05	1048	14.8	524	.268	57		10.4	3.5		-6.4		28.1	00	11	10	0
03OCT05	2306	15.3	1911	.266	51	94.0	8.6	3.1	3.0	-4.5	30.9	28.7	00	11	10	0
04OCT05	0113	20.3	35	.279	59	93.8	5.6	1.9	-14.7	-6.5	25.7	28.1	00	11	10	0
04OCT05	0514	39.3	1895	.274	61	94.3	0.5	0.1	-5.5	-6.3	28.3	28.1	01	11	10	1
04OCT05	0934	19.8	35	.277	52		15.2	5.0		-6.3		28.1	00	11	10	0
04OCT05	2313	25.8	58	.281	60	94.9	2.2	0.8	-10.8	-7.2	26.8	27.9	00	11	10	0
05OCT05	0219	35.5	1361	.276	58	95.5	0.1	0.0	-3.2	-6.4	29.0	28.1	01	11	10	0
05OCT05	0535	26.3	211	.275	60	93.6	6.7	2.2	-8.0	-6.8	27.6	28.0	00	11	10	0
05OCT05	0821	16.0	673	.266	54	93.0	9.4	3.2	-7.2	-6.8	27.9	28.0	00	11	10	0
05OCT05	2304	21.5	339	.270	57	91.8	12.6	4.2	-7.9	-7.1	27.6	27.9	00	11	10	0
06OCT05	0245	29.0	278	.270	62	95.3	1.6	0.6	-8.5	-7.4	27.5	27.8	00	11	10	0
06OCT05	0611	20.5	421	.259	49		17.9	6.1		-7.4		27.8	00	11	10	0
06OCT05	0731	19.3	2226	.276	54	97.0	0.7	0.3	-5.0	-6.9	28.5	28.0	00	11	10	0
06OCT05	0945	28.8	432	.270	56	92.0	12.0	4.0	-6.4	-6.8	28.1	28.0	00	11	10	0
06OCT05	2229	30.5	402	.289	63	94.6	4.0	1.4	-8.7	-7.2	27.4	27.9	00	11	10	0
07OCT05	0156	16.3	613	.278	64	95.1	3.0	1.1	-6.4	-7.0	28.1	27.9	00	11	10	0
07OCT05	0612	19.3	45	.267	61	94.4	3.8	1.3	-11.0	-7.8	26.7	27.7	00	11	10	0
07OCT05	0932	15.3	609	.296	56	91.7	13.6	4.5	-4.1	-7.1	28.8	27.9	00	11	10	0
07OCT05	2253	25.3	466	.280	60	93.8	6.5	2.2	-12.2	-8.1	26.4	27.6	00	11	10	0
08OCT05	0128	15.8	2642	.290	56	96.6	2.3	1.0	-11.7	-8.8	26.5	27.4	00	11	10	0
08OCT05	0415	28.0	666	.286	60	94.0	6.4	2.2	-7.2	-8.5	27.9	27.5	00	11	10	0
10OCT05	0116	22.0	370	.269	56	92.8	9.6	3.2	-25.5	-11.9	22.5	26.5	00	11	10	0
10OCT05	0644	20.3	335	.257	53	92.0	12.0	4.0	-15.8	-12.7	25.3	26.3	00	11	10	0
10OCT05	0855	20.3	802	.271	55	92.4	11.7	4.0	-14.9	-13.1	25.6	26.1	00	11	10	0
10OCT05	1036	14.8	2113	.258	46		14.3	5.1		-13.1		26.1	00	11	10	0

END

[redacted] TAKEOFF EGT MARGIN AND SLOATL - SMOOTHED TREND PLOT REPORT

AIRCRAFT	POS	ESN	INSTALLED	ENGINE TYPE	N1MOD	EGT SHUNT	TCC TIMER	THRUST RTG
[redacted]	[redacted]	[redacted]	14-DEC-2003	CFM56-3C-1	-	-	ACTIVE	23.5

DATE TIME	CORR N1	THRUST DERATE	FAN DERATE	TAKEOFF EGT HOT DAY MARGIN (°C) -10....0...10...20...30...40...50...60...70...80...90..100	SLOATL (°C) 20...30...40...50...60
09[illegible]04 0813 I				. H	. S
01[illegible]05 0153 C				. H	. S
01JUN05 0217 C				. H	. S
01JUL05 0447 C				H .	. S
01AUG05 0212 C				H	. S
01SEP05 0020 C				H.	. S
28SEP05 0007	95.0	2.1	0.7	H .	. S
28SEP05 0407	95.5	1.7	0.6	H .	. S
28SEP05 0756	90.7	15.4	5.1	H .	. S
28SEP05 1031	94.0	6.0	2.0	H .	. S
28SEP05 2240	96.0	0.3	0.1	H .	. S
29SEP05 0044	92.7	9.5	3.1	H .	. S
29SEP05 0304	97.5	-0.2	-0.1	H.	. S
29SEP05 0530	94.2	5.1	1.7	H.	. S
29SEP05 2108	94.4	4.6	1.6	H .	. S
30SEP05 0005	95.2	1.5	0.5	H .	. S
30SEP05 0315	92.7	10.3	3.4	H .	. S
30SEP05 0620	93.7	6.6	2.2	H .	. S
30SEP05 0907	93.5	7.0	2.3	H .	. S
01OCT05 0042	91.9	12.3	4.1	H .	. S
01OCT05 0307	91.8	13.5	4.6	H .	. S
01OCT05 0434	96.6	1.5	0.7	H .	. S
01OCT05 0642	91.1	15.5	5.3	H .	. S
01OCT05 0836	92.9	9.3	3.1	H .	. S
01OCT05 1052	91.3	15.0	5.1	H .	. S
01OCT05 2346	92.9	11.9	4.3	H .	. S
02OCT05 0119	93.7	6.5	2.2	H .	. S
0[illegible]05 0319	92.7	9.5	3.1	H .	. S
02[illegible]05 0538	92.2	11.4	3.8	H .	. S
02OCT05 0831	92.2	11.6	3.9	H .	. S
03OCT05 0743		14.3	4.8	H .	. S
03OCT05 0901	92.4	13.5	4.8	H .	. S
03OCT05 1048		10.4	3.5	H .	. S
03OCT05 2306	94.0	8.6	3.1	H .	. S
04OCT05 0113	93.8	5.6	1.9	H .	. S
04OCT05 0514	94.3	0.5	0.1	H .	. S
04OCT05 0934		15.2	5.0	H .	. S
04OCT05 2313	94.9	2.2	0.8	H .	. S
05OCT05 0219	95.5	0.1	0.0	H .	. S
05OCT05 0535	93.6	6.7	2.2	H .	. S
05OCT05 0821	93.0	9.4	3.2	H .	. S
05OCT05 2304	91.8	12.6	4.2	H .	. S
06OCT05 0245	95.3	1.6	0.6	H .	. S
06OCT05 0611		17.9	6.1	H .	. S
06OCT05 0731	97.0	0.7	0.3	H .	. S
06OCT05 0945	92.0	12.0	4.0	H .	. S
06OCT05 2229	94.6	4.0	1.4	H .	. S
07OCT05 0156	95.1	3.0	1.1	H .	. S
07OCT05 0612	94.4	3.8	1.3	H .	. S
07OCT05 0932	91.7	13.6	4.5	H .	. S
07OCT05 2253	93.8	6.5	2.2	H .	. S
08OCT05 0128	96.6	2.3	1.0	H .	. S
08OCT05 0415	94.0	6.4	2.2	H .	. S
10OCT05 0116	92.8	9.6	3.2	-H .	. S
1[illegible]05 0644	92.0	12.0	4.0	-H .	. S
10[illegible]05 0855	92.4	11.7	4.0	-H .	. S
10OCT05 1036		14.3	5.1	-H .	. S

END

[redacted] CRUISE PERFORMANCE DELTAS - TABULAR REPORT

AIRCRAFT	POS	ESN	INSTALLED	ENGINE TYPE	N1MOD	EGT SHUNT	TCC TIMER	THRUST RTG
[redacted]	[redacted]	[redacted]	14-DEC-2003	CFM56-3C-1	-	-	ACTIVE	23.5

DATE	TIME		TAT °C	ALT FT	MACH	AGW TNS	DELTA_EGT RAW °C	DELTA_EGT SMTH °C	DELTA_N2 RAW %	DELTA_N2 SMTH %	DELTA_FF RAW %	DELTA_FF SMTH %	MXCN_EGTMGN RAW °C	MXCN_EGTMGN SMTH °C	MXCN_N2_MGN RAW %	MXCN_N2_MGN SMTH %	BLDS 1234	PKS 123	AI EW	IV 12
08[illegible]4	0952	I						10.9		-2.6		0.1		40.1						
01JUN05	0036	C						29.1		-2.4		0.6		21.9						
01JUL05	0501	C						31.2		-2.6		1.0		19.8						
01AUG05	0228	C						29.8		-2.6		0.5		21.2						
01SEP05	0036	C						33.5		-2.4		0.8		17.5						
01OCT05	0101	C						35.4		-2.5		1.4		15.6						
03OCT05	2317		2.5	20990	.662	50	34.7	30.0	-1.8	-2.3	0.7	0.8	16.3	21.0			11	11		0
04OCT05	0129		-7.0	27965	.777	58	33.2	30.6	-2.4	-2.3	1.3	0.9	17.8	20.4			11	11		0
04OCT05	0133		-7.0	27968	.776	58	33.7	31.2	-2.6	-2.4	1.0	0.9	17.3	19.8			11	11		0
04OCT05	0533		-15.8	32959	.752	59	30.1	31.0	-2.8	-2.4	0.8	0.9	20.9	20.0			11	11		0
04OCT05	0538		-16.3	32961	.745	59	31.4	31.1	-2.6	-2.5	0.9	0.9	19.6	19.9			11	11		0
04OCT05	0947		0.5	26002	.777	51	39.2	32.7	-2.2	-2.5	1.3	0.9	11.8	18.3			11	11		0
04OCT05	1013		0.0	26004	.774	49	49.4	36.1	-2.3	-2.4	2.8	0.9	1.6	14.9			11	11		0
04OCT05	2038		-25.3	34999	.743	55	25.0	36.1	-2.3	-2.4	0.5	0.9	26.0	14.9			11	11		0
04OCT05	2052		-26.0	35000	.741	54	36.0	36.0	-2.7	-2.5	1.5	0.9	15.0	15.0			11	11		0
04OCT05	2333		-16.5	31968	.737	58	30.8	35.0	-2.4	-2.5	1.3	1.0	20.2	16.0			11	11		0
05OCT05	0013		-17.8	33970	.737	56	37.8	35.6	-2.5	-2.5	1.7	1.1	13.2	15.4			11	11		0
05OCT05	0238		-16.3	32991	.746	56	25.7	35.6	-2.5	-2.5	0.3	1.0	25.3	15.4			11	11		0
05OCT05	0239		-16.3	32987	.746	56	30.7	34.6	-2.5	-2.5	1.3	1.0	20.3	16.4			11	11		0
05OCT05	0552		-3.3	27997	.771	59	42.1	36.1	-2.3	-2.4	1.8	1.1	8.9	14.9			11	11		0
05OCT05	0604		-3.0	28002	.780	58	49.9	38.9	-2.7	-2.5	1.5	1.1	1.1	12.1			11	11		0
05OCT05	0841		-22.8	34984	.752	52	27.8	38.9	-2.5	-2.5	-0.3	1.1	23.2	12.1			11	11		0
05OCT05	0847		-23.0	34971	.742	52	36.6	38.4	-2.6	-2.5	1.1	1.1	14.4	12.6			11	11		0
05OCT05	2110		-9.0	30006	.748	57	27.0	36.1	-2.3	-2.5	0.1	1.0	24.0	14.9			11	11		0
05OCT05	2324		-19.8	33992	.756	55	28.7	34.7	-2.6	-2.5	1.2	1.0	22.3	16.3			11	11		0
05OCT05	2326		-20.0	33997	.754	55	29.8	33.7	-2.8	-2.6	0.9	1.0	21.2	17.3			11	11		0
06[illegible]05	0307		-12.5	32959	.745	60	37.9	34.5	-3.0	-2.6	1.7	1.1	13.1	16.5			11	11		0
06[illegible]05	0309		-12.5	32967	.743	60	40.9	35.8	-3.0	-2.7	2.0	1.2	10.1	15.2			11	11		0
06OCT05	0622		5.5	19986	.664	49	32.0	35.0	-2.1	-2.7	0.5	1.1	19.0	16.0			11	11		0
06OCT05	0749		-25.3	34975	.732	53	29.3	33.9	-2.5	-2.7	1.4	1.1	21.7	17.1			11	11		0
06OCT05	1005		-17.8	34001	.739	54	30.7	33.3	-2.2	-2.7	1.5	1.2	20.3	17.7			11	11		0
06OCT05	1010		-18.3	34000	.746	54	34.5	33.5	-2.5	-2.6	0.9	1.2	16.5	17.5			11	11		0
06OCT05	2023		-13.8	32966	.743	56	42.6	35.3	-2.8	-2.7	1.6	1.2	8.4	15.7			11	11		0
06OCT05	2038		-11.0	32967	.768	56	49.8	38.2	-3.0	-2.7	2.3	1.3	1.2	12.8			11	11		0
06OCT05	2245		-1.5	27979	.760	61	45.2	39.6	-2.7	-2.7	1.9	1.4	5.8	11.4			11	11		0
06OCT05	2247		-1.3	27974	.765	61	35.2	38.7	-2.4	-2.6	0.6	1.3	15.8	12.3			11	11		0
07OCT05	0215		-4.3	25969	.766	63	48.6	40.7	-2.4	-2.6	2.4	1.4	2.4	10.3			11	11		0
07OCT05	0230		-3.0	25976	.772	62	56.0	43.8	-2.8	-2.6	2.0	1.5	-5.0	7.2			11	11		0
07OCT05	0632		-22.3	33011	.737	60	33.8	43.8	-2.5	-2.6	1.8	1.5	17.2	7.2			11	11		0
07OCT05	0755		-17.5	33006	.741	56	49.8	45.0	-2.7	-2.6	2.0	1.5	1.2	6.0			11	11		0
07OCT05	0954		-17.3	34957	.740	54	43.2	44.6	-2.6	-2.6	1.9	1.6	7.8	6.4			11	11		0
07OCT05	0955		-17.5	34964	.740	54	40.4	43.8	-2.7	-2.6	1.4	1.6	10.6	7.2			11	11		0
07OCT05	2048		-19.8	34972	.755	51	34.0	43.8	-2.5	-2.6	1.0	1.5	17.0	7.2			11	11		0
07OCT05	2105		-21.0	34971	.740	51	44.2	43.9	-2.7	-2.6	0.9	1.5	6.8	7.1			11	11		0
07OCT05	2313		-17.5	33979	.737	58	42.4	43.6	-2.6	-2.6	2.6	1.6	8.6	7.4			11	11		0
07OCT05	2315		-17.0	33998	.747	58	44.6	43.8	-2.9	-2.7	2.3	1.6	6.4	7.2			11	11		0
08OCT05	0146		-14.0	33001	.749	55	41.7	43.3	-2.3	-2.7	1.6	1.6	9.3	7.7			11	11		0
08OCT05	0200		-15.0	32997	.742	54	45.3	43.7	-2.7	-2.7	1.3	1.6	5.7	7.3			11	11		0
08OCT05	0434		-11.0	32015	.763	59	43.7	43.7	-2.7	-2.7	2.2	1.7	7.3	7.3			11	11		0
08OCT05	0457		-10.5	31995	.762	58	56.1	43.7	-2.9	-2.7	2.7	1.8	-5.1	7.3			11	11		0
09OCT05	2145		-27.0	34001	.742	54	32.3	43.7	-2.3	-2.7	1.4	1.7	18.7	7.3			11	11		0
09OCT05	2219		-24.3	34000	.752	53	43.5	43.7	-2.9	-2.8	1.4	1.7	7.5	7.3			11	11		0
10OCT05	0134		-23.5	32976	.745	55	32.6	43.7	-2.4	-2.8	0.7	1.6	18.4	7.3			11	11		0
10[illegible]5	0153		-23.5	34972	.742	54	45.1	44.0	-3.0	-2.8	1.5	1.6	5.9	7.0			11	11		0
10[illegible]05	0705		-26.5	33997	.746	52	34.2	42.0	-2.6	-2.8	0.7	1.5	16.8	9.0			11	11		0
10OCT05	0913		-18.3	30971	.784	54	31.5	39.9	-2.3	-2.8	0.6	1.4	19.5	11.1			11	11		0
10OCT05	1050		-23.3	33972	.754	45	34.7	38.9	-2.5	-2.6	1.1	1.4	16.3	12.1			11	11		0

END

AIRCRAFT	POS	ESN	INSTALLED	ENGINE TYPE	N1MOD	EGT SHUNT	TCC TIMER	THRUST RTG
[redacted]	[redacted]	[redacted]	14-DEC-2003	CFM56-3C-1	-	-	ACTIVE	23.5

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                          DELTA EGT (°C)                      DELTA N2 (%)                        DELTA  FF (%)
  DATE  TIME -20..-10....0...10...20...30...40...50 -3...-2...-1....0....1....2....3 -6...-4...-2....0....2....4....6....8
08??N04 0952 I           .     G                       2            .                                F
0????05 0036 C           .             G                2           .                                . F
01JUL05 0501 C           .              G              2            .                                .  F
01AUG05 0228 C           .             G               2            .                                . F
01SEP05 0036 C           .               G              2           .                                . F
01OCT05 0101 C           .                G            2            .                                .   F
03OCT05 2317             .             G                 2          .                                . F
04OCT05 0129             .              G                2          .                                . F
04OCT05 0133             .              G               2           .                                . F
04OCT05 0533             .              G               2           .                                . F
04OCT05 0538             .              G               2           .                                . F
04OCT05 0947             .               G              2           .                                . F
04OCT05 1013             .                G             2           .                                . F
04OCT05 2038             .                G             2           .                                . F
04OCT05 2052             .                G             2           .                                .  F
04OCT05 2333             .                G             2           .                                .  F
05OCT05 0013             .                G             2           .                                .  F
05OCT05 0238             .                G             2           .                                .  F
05OCT05 0239             .                G             2           .                                .  F
05OCT05 0552             .                G             2           .                                .  F
05OCT05 0604             .                  G           2           .                                .  F
05OCT05 0841             .                  G           2           .                                .  F
05OCT05 0847             .                 G           2            .                                .  F
05OCT05 2110             .                G             2           .                                .  F
05OCT05 2324             .                G             2           .                                .  F
05OCT05 2326             .               G             2            .                                .  F
06OCT05 0307             .                G            2            .                                .  F
0???T05 0309             .                G           2             .                                .  F
0???T05 0622             .                G           2             .                                .  F
06OCT05 0749             .               G             2            .                                .  F
06OCT05 1005             .               G             2            .                                .  F
06OCT05 1010             .               G             2            .                                .  F
06OCT05 2023             .                G            2            .                                .  F
06OCT05 2038             .                 G           2            .                                .  F
06OCT05 2245             .                  G          2            .                                .   F
06OCT05 2247             .                  G          2            .                                .  F
07OCT05 0215             .                   G         2            .                                .   F
07OCT05 0230             .                    G        2            .                                .   F
07OCT05 0632             .                    G        2            .                                .   F
07OCT05 0755             .                     G       2            .                                .   F
07OCT05 0954             .                     G       2            .                                .   F
07OCT05 0955             .                    G        2            .                                .   F
07OCT05 2048             .                    G        2            .                                .   F
07OCT05 2105             .                    G        2            .                                .   F
07OCT05 2313             .                    G        2            .                                .   F
07OCT05 2315             .                    G        2            .                                .   F
08OCT05 0146             .                    G        2            .                                .   F
08OCT05 0200             .                    G        2            .                                .   F
08OCT05 0434             .                    G        2            .                                .   F
08OCT05 0457             .                    G       2             .                                .    F
09OCT05 2145             .                    G       2             .                                .    F
09OCT05 2219             .                    G       2             .                                .   F
10OCT05 0134             .                    G       2             .                                .   F
10OCT05 0153             .                    G       2             .                                .   F
1????05 0705             .                   G        2             .                                .   F
10??T05 0913             .                  G         2             .                                .   F
10OCT05 1050             .                  G          2            .                                .   F
END
```

A.2 TEMPER report

As part of this investigation is based on TEMPER reports, the results of the takeoff power setting estimation for engine # 28 are presented on the following pages. Usually TEMPER reports provide additional results for the maximum continuous power setting. However they are not shown because they are not analysed in this investigation.
On the first two pages the measured engine data and its corrections are listed. This data was used in chapter 4 to identify additional reasons for low EGT margin. The bar chart on page 2 shows the deviation in EGT margin as it was presented in section 3.1. The deviation in SFC margin is given on the top of page 3. Additionally the 'hardware and measurement status' are illustrated on that page. Both results have not been used in this investigation. The input data which has been submitted to the TEMPER software is shown on page 4 and top of page 5. The value '-5555' means that no data was provided. The second half of page 5 presents the values for deviation in SFC and EGT margin. The column 'CRSFC' lists the values for SFC margin deviation; EGT margin deviation is shown in column 'HDEGT'.

```
++++++++++++++ TEMPER Processing Results Wed May 11 18:10:59 EDT 2011 ++++
+++++++++++++++            TEMPER Processing Results          ++++++++++
The results of an E-mail Test Cell TEMPER run should look similar in format
to TEMPER output you have received in the past.  If your e-mail software
uses proportional font, the TEMPER output may be incorrectly aligned (it
may look compressed to the left side of the paper) when the file is
printed.  To correct the alignment problem simply reformat, or save, the
output in a fixed format font.
+++++++++++++++        End of Reformatting Instructions         +++++++++
++++++++++++++ Process results for TEMPER Data File 20110511180727.604 +++
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
                    *** POWER SETTING---TKOF ***

                                JTS

               CF6-80C2B6   ENGINE PERFORMANCE ANALYSIS
           READING    1.     ENGINE [redacted]     DATE  110511

                         *** MEASURED DATA ***
         XN1     XN2    PT49     T49F     WF      FN      PT12
        3440.  10298. 106.31  1491.8  20041.  54660.  14.261

        T12F    PSW     T25F     T3F   PSB3      PT25   T54
        43.8  10.660    214.9  1004.  458.6     35.3 -5555.

        VSVD    VBVI    PT54     PBAR     PS14   HUM    XLHV  SHUNT
        2.360  0.024-5555.0  14.493******** 88.   18603.  60.

        *** CALCULATED DATA CORRECTED TO STANDARD DAY ***
        XN1K    T25XF   T49K    ETAC    ETAT    ETAROT   GHP
        3475.   215.0    840.   0.896   0.873   0.885   1633.

         FNK     WFK    XN2K    PS3QP2    P3Q49     EPR
        56340. 20986.  10419.   32.158    4.314    7.455

         W2K    DVSV   DVBVP  T49Q25  T3QT2   T49X
        1762.  0.582  0.024   3.028  2.907   2024.

    *** INLET CONDENSATION CORRECTION AND FACILITY ADJUSTMENTS ***
    TRISEI  RELHUM   CELLF   SWFF    SEGTF   SN2F    SEPRF    SW2F
     15.4   200.2   1.0517  0.9753  0.9906  0.9974  0.9827  1.0000

    *** ATC DATA CORRECTED TO STD DAY,DRY & FACILITY MODIFIERS ***
       FNKATC   SFCATC    W2KATC  WFKATC   N2KATC  EGTATC  XN1K
        59253.   0.345    1762.   20468.   10391.   824.  3459.

                            *** FTC DATA ***
       FNKFTC   SFCFTC    W2KFTC  WFKFTC   N2KFTC  EGTFTC
        60626.   0.353    1757.   21373.   10519.   839.

      *** FTC DATA AT N1K OF 3470. RPM STD DAY ***
       FNKAN1   W2KAN1   WFKAN1   N2KAN1  EGTAN1   SFCAN1 EPRAN1
       60989.    1762.   21547.   10536.    841.   0.3533  7.421
```

*** FTC DATA AT RATED THRUST OF 59100. LBS, STD DAY ***

XN1AFN	W2KAFN	WFKAFN	XN2AFN	EGTAFN	SFC	LIMIT	MARG.
3410.	1738.	20630.	10448.	827.	0.349	0.373	6.4%

*** HOT DAY CONDITIONS AT N1K= 3470.,T2 = 86.F ***

FNAN1	LIMIT	MARG.	HDEGTC	LIMIT	MARG.	HDN2	LIMIT	MARG.
60989.	59100.	3.2%	890.	927.	37.0C	10807.	10841.	0.32%

1

ACCEPTANCE TEST-
Test Cell Data for [redacted] CF6-80C2B6

CF6-80C2B6 TEST CELL TEMPER TAKE OFF
8CA 44L

JTS CF6-80C2B6 [redacted] TEST DATE 110511

ESTIMATED DELTA EGT (DEG C) FOR MODULE REPLACEMENT

```
        FAN      LPC      HPC      HPTS     HPTR      LPT      MEAS
    ..............................................................
    .                                                            .
    .                                                            .
 20.                                                             .
    .                                                            .
    .                                                            .
    .                                                            .
    .                                                            .
 10.                                        010                  .
    .                                       XXX                  .
    .                                       XXX                  .
    .                                       XXX                  .
    .                     002               XXX                  .
  0.             000      XXX      001      XXX                  .
    .   XXX                                          XXX    002  .
    .   XXX                                          XXX         .
    .   005                                          XXX         .
    .                                                XXX         .
-10.                                                 XXX         .
    .                                                011         .
    .                                                            .
    .                                                            .
    .                                                            .
-20.                                                             .
    .                                                            .
    .                                                            .
    ..............................................................
```

ESTIMATED PERCENT DELTA SFC FOR MODULE REPLACEMENT

FAN	LPC	HPC	HPTS	HPTR	LPT
-1.5	0.0	0.2	0.1	0.8	-1.1

THE MEASUREMENT P49 IS JUDGED ABNORMAL

1

HARDWARE STATUS

	PCT XHAT	XH/SIG
FAN FLOW	-0.436	-1.453
FAN EFF.	-2.782	-1.987
LPC FLOW	0.147	0.588
LPC EFF.	-0.207	-0.345
HPC FLOW	-0.221	-0.552
HPC EFF.	0.334	0.446
HPT FLOW	-0.493	-0.704
HPT EFF.	1.058	1.763
LPT FLOW	-0.078	-0.776
LPT EFF.	-1.346	-2.070

MEASUREMENT STATUS

	VALUE	PCT DELTA	PCT ERROR	ERR/SIG
PS	1			
RDG	1.00000			
P25	35.3000	-2.494	-0.367	-0.815
T25	101.630	0.340	0.847	2.822
XN25	10298.0	0.590	0.000	0.000
PS3	458.600	2.395	0.273	0.546
T3	539.800	0.697	0.036	0.180
WF36	20041.0	-2.448	-2.259	-2.823
P49	106.310	4.171	3.191	5.803
T49	811.000	-0.874	0.150	0.272
PS1A	10.6600	0.607	0.128	0.640
FN	54660.0	-0.982	-0.277	-0.616
XN12	3440.00			
T1A	6.54300			
P1A	14.2610			
PBAR	14.4930			
HUM	87.5900			
VBV	0.170000			
VSV	2.36000			

INPUT VARIABLES

CASE	1.00000	SFLT	1.00000	PRNT	1.00000
CTRL	4.00000	ADPT	1.00000	AGEB	4000.00
AGEC	4000.00	AGEF	4000.00	AGEH	4000.00
AGEL	4000.00	CELL	1.00000	CNFG	1.00000
DATE	110511.	FHV	18603.0	MODL	800.900
RTYP	1.00000	ESN	695283.	SHNT	60.0000

PERCENT PROBABILITY = 0.0
RESIDUAL ERROR = 66.5

1 PROPRIETARY

GEM 13.0 CF6-80C2B6 ENGINE

GEM 13.0 CF6-80C2B6 ENGINE G0119B-44L

JTS

INPUT

CASE	1.0000	SFILT	1.0000	SPRINT	1.0000
SWCTRL	4.0000	SWOILC	-5555.0000	SWTEMP	-5555.0000
ZA41	-5555.0000	ZADAPT	1.0000	ZAGEB	4000.0000
ZAGEC	4000.0000	ZAGEF	4000.0000	ZAGEH	4000.0000
ZAGEL	4000.0000	ZCELL	1.0000	ZCELLF	-5555.0000
ZCONFG	1.0000	ZCOWL	-5555.0000	ZDATE	110511.0000
ZFHV	18603.0000	ZINLET	-5555.0000	ZMODEL	800.8999
ZRTYPE	1.0000	ZSG	-5555.0000	ZSN	695283.0000
ZTFF	-5555.0000	EGTSHN	60.0000	ZBAROM	14.4930
ZFN	54660.0000	ZHUM	87.5900	ZP14	-5555.0000
ZP17	-5555.0000	ZP1A	14.2610	ZP25	35.3000
ZP49	106.3100	ZP495	-5555.0000	ZP5	-5555.0000
ZP5V	-5555.0000	ZPS	1.0000	ZPS14	-5555.0000
ZPS1A	10.6600	ZPS25	-5555.0000	ZPS3	458.5999
ZRDG	1.0000	ZT1A	6.5430	ZT25	101.6300
ZT3	539.7998	ZT49	811.0000	ZT495	-5555.0000
ZT5	-5555.0000	ZT5V	-5555.0000	ZTARE	-5555.0000
ZTCC	-5555.0000	ZVBV	0.1700	ZVSV	2.3600
ZWF36	20041.0000	ZXN12	3440.0000	ZXN25	10298.0000

OUTPUT

NSI = 202 0 0 0 0 0 0 0 0 0

TEMPI	0.0000	XN12SE	3440.0000	XN25SE	10298.0000
P49SE	106.3100	T49F	1491.7998	WF36SE	20041.0000
FNSE	54660.0000	PT2ACC	14.2610	T12F	43.7773
PS2ACC	10.6600	T25F	214.9338	T3F	1003.6396
PS3SE	458.5999	P25SE	35.3000	T5F	-5555.0000
VSVSE	2.3600	VBVSE	0.0236	P5SE	-5555.0000
PBAR	14.4930	P14SE	-5555.0000	HUMACC	87.5900
FHV	18603.0000	XN1KAC	3475.1875	T25XF	214.9712
T49K	839.9485	ETAC	0.8965	ETAT	0.8731
ETAROT	0.8848	GHP	1633.3113	FNKACC	56339.9609
WFMKAC	20986.1680	XN2KAC	10418.5195	PS3QP2	32.1576
P3Q49	4.3138	EPRACC	7.4546	W2KACC	1761.5654
DVSVAC	0.5819	DVBVAC	0.0236	T49Q25	3.0280
T3QT2	2.9066	T49X	2024.2686	TRISEI	15.4453
RHACC	200.1581	CELLF	1.0517	SWFACC	0.9753
SEGTAC	0.9906	SXN2AC	0.9974	SEPRAC	0.9827

SW2KAC	1.0000	FNKATC	59253.0352	SFCATC	0.3454
W2KATC	1761.5654	WFKATC	20467.9727	XN2ATC	10391.4727
EGTATC	823.7854	XN1RAC	3458.7629	XN1REF	3470.0000
FNKAN1	60988.5664	W2KAN1	1761.6575	WFKAN1	21546.9414
XN2AN1	10535.8164	EGTAN1	840.9875	SFCAN1	0.3533
EPRAN1	7.4207	FNREF	59100.0000	XN1AFN	3410.4636
W2KAFN	1738.0945	WFKAFN	20629.6445	XN2AFN	10447.9531
EGTAFN	827.1145	SFCAFN	0.3491	SFCREF	0.3730
SFCMAR	6.4343	FNREF1	59100.0000	T2REF	86.0000
FNMAR	3.1955	HDEGTC	889.9690	EGTREF	927.0000
EGTMAR	37.0310	XN2KHD	10806.5625	XN2REF	10841.0000
XN2MAR	0.3177	EGTKF	-459.6699		

0 PROPRIETARY

1 PROPRIETARY

GEM 13.0 CF6-80C2B6 ENGINE

GEM 13.0 CF6-80C2B6 ENGINE G0119B-44L

JTS

OUTPUT CASE = 1.0000

	CRSFC	G0	HDEGT	ZERR	ZO	ZQSIG
1	-1.4556	0.0000	-5.4360	-0.3666	-2.4938	-0.8148
2	-0.0386	0.0000	0.0163	0.8467	0.3398	2.8225
3	0.1926	0.0000	2.3575	-0.0001	0.5901	-0.0003
4	0.0687	0.0000	0.8781	0.2728	2.3952	0.5457
5	0.7868	0.0000	9.5865	0.0359	0.6966	0.1796
6	-1.0521	0.0000	-11.0639	-2.2588	-2.4475	-2.8235
7	0.0000	0.0000	0.0000	3.1915	4.1714	5.8026
8	0.0000	0.0000	0.0000	0.1495	-0.8741	0.2719
9	0.0000	0.0000	0.0000	-5555.0000	-5555.0000	-5555.0000
10	0.0000	0.0000	0.0000	-5555.0000	-5555.0000	-5555.0000
11	0.0000	0.0000	0.0000	-5555.0000	-5555.0000	-5555.0000
12	0.0000	0.0000	0.0000	0.1281	0.6068	0.6403
13	0.0000	0.0000	0.0000	-0.2772	-0.9822	-0.6160
14	0.0000	0.0000	0.0000	-5555.0000	-5555.0000	-5555.0000
15	0.0000	0.0000	0.0000	-999.0000	-999.0000	-999.0000
16	0.0000	0.0000	0.0000	-999.0000	-999.0000	-

999.0000
17 0.0000 0.0000 -1.8441 -999.0000 -999.0000 -
999.0000
18 0.0000 0.0000 0.0000 -999.0000 -999.0000 -
999.0000
19 0.0000 0.0000 0.0000 -999.0000 -999.0000 -
999.0000
20 0.0000 0.0000 0.0000 -999.0000 -999.0000 -
999.0000

	XHAT	XQSIG	IALERT
1	-0.4358	-1.4527	36265
2	-2.7816	-1.9869	0
3	0.1471	0.5884	0
4	-0.2073	-0.3454	0
5	-0.2207	-0.5518	0
6	0.3342	0.4456	0
7	-0.4927	-0.7039	0
8	1.0581	1.7635	0
9	-0.0776	-0.7756	0
10	-1.3457	-2.0703	0
11	0.0000		

PCN1AR	PROB	X2J	ICODE
106.4550	0.0000	66.4515	0

0 PROPRIETARY
1

*** POWER SETTING---MXCN ***

JTS

CF6-80C2B6 ENGINE PERFORMANCE ANALYSIS
READING 2. ENGINE [redacted] DATE 110511

*** MEASURED DATA ***

XN1	XN2	PT49	T49F	WF	FN	PT12
3310.	10133.	98.75	1437.8	18235.	51214.	14.275

T12F	PSW	T25F	T3F	PSB3	PT25	T54
43.6	10.970	202.8	971.	426.8	33.3	-5555.

VSVD	VBVI	PT54	PBAR	PS14	HUM	XLHV	SHUNT
2.940	0.024	-5555.0	14.495	********	88.	18603.	60.

*** CALCULATED DATA CORRECTED TO STANDARD DAY ***

XN1K	T25XF	T49K	ETAC	ETAT	ETAROT	GHP
3344.	202.8	809.	0.900	0.869	0.885	1453.

FNK	WFK	XN2K	PS3QP2	P3Q49	EPR
52736.	19090.	10253.	29.898	4.322	6.918

W2K DVSV DVBVP T49Q25 T3QT2 T49X

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