Turbofan

Re-engine the Boeing 707-320 'E-3A Sentry'

Report

Project group A2k

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Table of contents

Summary

The North Atlantic Treaty Organization has given project group A2K the assignment to investigate the possibilities to re-engine the Airborne Warning And Control System fleet. The engines now installed, the TF33, do not comply with the high standards for these days anymore. The fuel consumption of these engines is very high compared to the present day engines, environmental aspects like the noise and gas pollution do not comply with the future regulations anymore.

To be able to re-engine the AWACS, all information must be collected about the AWACS itself, the currently used engines and the related systems.
The engine has the goal to generate a thrust force so the aircraft is able to move. The propulsion of the engine is generated because of the third law of Newton: Every action has an equal reaction in the opposite reaction. The airflow leaving the exhaust produces a force to the engine which generates an equal force applied in the moving direction.
The airflow first reaches the inlet, the distance between the first part of the engine and the gap is called the inlet. The inlet is used to provide the engine a straight airflow, even during different angels of attack, turbulence and all airspeeds.
The engine has the highest efficiency if the air is compressed and has a high temperature when it is combusted. Therefore the air has to go through the compressor. There are two kinds of compressors, the axial and the centrifugal flow compressor.
Then the airflow arrives in the combustion chamber, the air is there heated up, mixed with fuel and ignited. The hot airflow then goes trough the turbine, the turbine extracts energy from the hot airflow and powers the fan, compressor and gearboxes.
The rear opening of the engine is the jet nozzle or exhaust nozzle, the exhaust gases travel from the jet pipe to atmosphere via the convergent nozzle. This can increase the hot gas velocity to speeds of Mach 1.
Various kind of related systems are needed to operate and control the engine like a thrust reverser, bleed air system and a lubrication system. A gearbox is attached to drive several systems in the aircraft like the hydraulic and electrical systems.
An engine also produces vibrations, if the vibrations are too strong they can cause a serious hazard. Therefore vibration indicators are installed to indicate the vibration level.
The European Aviation Safety Agency and the International Civil Aviation Organization have drawn up strict regulations the aircraft have to comply with, for example about the noise pollution and the emission, this is one of the main reasons for the replacement of the TF33.

After all the necessary information is collected, a pre-selection can be made with the NATO demands. Three engines are selected, the PW6122, the CFM-56 7B22 and the V2524-A5. All the specifications of these engines are collected, their performance in different conditions is calculated and then they are compared to each other. Seven important aspects are used to compare the engines with each other and the old engines. It can be seen that the PW6122 scores best at almost all the aspects. Another advantage of the PW6122 is that it is from the same manufacturer as the TF33, this makes it easier to connect the engine and the maintenance staff needs less training to maintain the new engine. Therefore the engine that has to replace the TF33 is the PW6122.

After the PW6122 is chosen to be the best engine to replace the TF33, there has to be looked at the modification aspects. One of the problems in the modification aspect is the larger size of the new engines, this problem can be solved by making the pylons shorter. The old engine has more mechanical components which has to be replaced by new digital components.
There are also other systems in the aircraft depending on the engines, for example the pneumatic system and the hydraulic system. Because the PW6122 is from the same manufacturer as the TF33 some systems can be connected without complicated changes. Some systems however, like the bleed air and the lubrication system are to different and have to be modified.
Because the new engine is from the same manufacturer the maintenance staff will not have to be re-trained completely, however there has to be a training for the maintenance staff to learn how this new engine has to be maintained. There are two kinds of maintenance, on-wing and overhaul maintenance. Because in an overhaul maintenance check the engine is completely removed, the replacement will take place during this kind of maintenance, this is usually done during a D-check.
If all the different costs are put together, it becomes clear that it costs more than 38 million Euro to equip one aircraft with new engines. To re-engine the complete fleet of twenty aircraft will therefore cost over 760 million Euro. With a benefit of 1.4 million Euro compared to the old engine, the brake-even point is at about 27 years. The AWACS however will be replaced in about 15 years. It is therefore recommended not to modify the aircraft but to look at the possibility to buy complete new aircraft. That is because the present engines do not comply with the strict future environmental laws.

Introduction

The second project of the second year is about an engine of an aircraft. The project group consists of seven second years students of Aviation Engineering. The project group has been assigned by the NATO to re-engine the AWACS E-3A. The current TF33-PW-100A engines become old and has a low efficiency and are not fuel efficient compared to the nowadays engines. The current engine also has high noise level and no thrust reversers. The NATO still wants to fly for about fifteen years with the AWACS. The demand is that the new engines produces the same amount of thrust and has at least the same endurance of the TF33. The new engines must also have a lower fuel consumption.

This report will be divided into three chapters, each with their own logical structure. The first chapter is the definition phase, followed by a development phase and the last chapter is the design phase.

To start with the development phase it is necessary to know which components and regulations are involved with an engine. First an overview of thermodynamic laws and the AWACS E-3A will be given followed by a description of the TF33 engine. Forces and vibrations are an issue to design an engine. The engine has to comply with the several regulations made by international organisations and must be certified when the engine will be replaced **(1)**.
In the second chapter it is important to make the demands of the NATO clear before three engines can be chosen to replace the TF33. The TF33 and the three chosen engines will be calculated, so the three engines can be compared with the TF33. When the advantages and disadvantages have been made clear, one engine can be chosen to replace the TF33 **(2)**.
To make it possible to replace the engines of the AWACS some modification must be done to place the new engines. This is done for the engine and the involved subsystems. With the new engine the maintenance must be changed and will be easier because of the more modern engine. The most important aspects are the costs and benefits. To conclude the report these factors will be summed up and a recommendation to the board of directors of the NATO will be given **(3)**.

Main sources for this project are Scholder Projectboek Voortstuwingsinstallatie (2007) and the Rolls Royce –The Jet Engine 2nd edition (1996). Other sources can be found in the literature list on page 36 The abbreviations are written between straight parenthesis and can be found in the abbreviations list on page 35 The most important appendices are the project assignment **(Appendix I)**, the engine calculations **(Appendix XIV)**, the effort list **(Appendix XVII)** and the process report **(Appendix XVIII)**.

1 General purpose (TF33)

An engine is a complex system which combines several physical laws. Especially the gas turbine jet engine, such as the TF33, uses these laws in specific manners. To know how these laws apply best on the certain engine, the operational aspects of the aircraft should be reviewed first **(1.1)**. The basics of the jet engine relies on the known ‘suck, squeeze, bang’. When the air is sucked in the air will be compressed and finally be ignited. The application of these physical laws comes with difficulties, since it is propelled by accelerating the airflow **(1.2)**. By this method the air is accelerated through the engine. This is the actual thrust force which is generated. Because the engine relies on the principles of aerodynamic flow through the engine, the engine has lots of moving parts. These generate large vibrations in the engine **(1.3)**. Because the engine is such a delicate system, the engine is bounded to certain laws, which applies differently in every country. The AWACS will operate specifically in Europe; the European laws should be implemented in the jet engine design. Important aspect is the difference between the military and civil laws **(1.4)**. When all the engine aspects are revised, a complete summary of the TF33 can be made **(1.5)**.

1.1 Several engines and engine E-3A Sentry

The TF33 engines are the propulsion systems on the AWACS. This engine is a designed to achieve high performances. The engines on the AWACS rely on the same principles as any other engine, to propel an aircraft. These physics are a statement in engine design, which relies on the basic motion formulas **(1.1.1)**. To better understand the engine, this certain gas turbine engine should be reviewed. The gas turbine engine possesses certain features which can only be found on the gas turbine jet engine **(1.1.2)**. Even between all gas turbine jet engines there are differences in performance, which depends largely on the requirements of the costumers. By deciding which kind of engine is most suitable for the specific type of aircraft, aspects such as operation areas and operation purposes should be reviewed **(1.1.3)**.

1.1.1 Purpose of the jet-engine

All aircraft, either civil or military, contain a propulsion system. This propulsion system is necessary to move the aircraft. The force that the propulsion system is generating is called thrust. The thrust which is generated by the engine relies on several thermodynamic and physics principles. The main physical laws were described by Isaac Newton **(A)**. A different, but equally important theorem is the Bernoulli theorem, which states that the total amount of energy in an airflow is constant **(B)**. Eventually these physical laws are applied and the jet engine has a specific diagram to show these applied laws **(C)**.

A Newton stated the three laws of forces:

Newton’s laws of motions are:

1. Newton’s first law
2. Newton’s second law
3. Newton’s third law

Ad 1. Newton’s first law
Newton’s first law of motion is the law of inertia. This law could be described as: “a body in a state of rest remains at rest; a body in motion tends to remain in motion at a constant speed and in a straight line unless acted upon by some external force”. An object in rest will stay in place since there are no forces applied on it. But also an object in motion will remain to be in motion at a constant speed and a constant direction, unless an external force is applied. In everyday experience this will not occur due to the external force of gravity. Also friction could be described as an external force.

Ad 2. Newton’s second law
Newton’s second law of motion could be described as: “an unbalance of forces on a body produces or tends to produce an acceleration in the direction of the greater force; the acceleration is directly proportional to the force and inversely proportional to the mass of the body”. This law states that the acceleration of a body depends on the forces applied on the body. A larger force will result in a larger acceleration. Thus a larger applied force will result in a larger motion. An object in rest will have a total amount of forces which is equal to zero, since all forces in every direction will oppose the other. When a body is accelerating, the force in that direction is larger than the opposing force. The amount of force in a direction depends on the mass of the body and the acceleration in the direction. This is described in **Formula 1 page 6**, Newton’s second law.

Newton's second law: $F = m \times a$	F = Force [N] m = Mass [kg] a = Acceleration [m/s^2]	**1.** F in N m in kg a in m/s^2

Ad 3. Newton's third law
Newton's third law of motion could be described as: "Every action has an equal and opposite reaction". When a force is applied to a body, the body will exert an equal force, but in the opposite direction **(Formula 2)**. To visualize this theory the recoil of a rifle could be revised, when firing, a force will move the bullet to the front. The same amount force as exerted on the bullet will be exerted to the opposite direction. This will result in the recoil of the rifle. When practiced and put in perspective, the rifle could be considered the aircraft and the bullet could be considered the exhausting gas. By exhausting the gas with a certain force, aircraft will be propelled.

2. Newton's third law: $F_{action} = -F_{reaction}$

B Potential and Kinetic energy

This concludes that an additional force should be applied to the air passing through the jet engine, in order to accelerate the air. Newton's third law states that this will result in an opposite force, which is called thrust. This acceleration of air is done by the jet engine. This is done by compressing the air, which will give it a higher velocity. By stoking this compressed air, the volume of this gas will increase. This pressure will result in a thrust. This pressure is also referred as potential energy. This pressure will expand. When expanding, the air will move at a certain velocity. This change is the transformation from potential energy to kinetic energy. This is stated in Bernoulli's theorem **(Formula 3)**. Bernoulli's theorem states that the total amount of energy in a flowing gas is constant.

Bernoulli's Theorem: $P + \frac{1}{2}\rho v^2 + \rho g h = C$ Or simplified: $q + s = C$	v = speed of the gas g = gravitational acceleration h = Relative height of the gas P = External pressure ρ = Density of the gas Simplified: q = Dynamic pressure s = Static pressure	**3.** v in m/s g in m/s^2 h in meters P in Pa ρ in kg·m^{-3} Simplified: q in Pa s in Pa

When air is compressed, the volume of the air will decrease and the pressure will increase. When the volume increases, the pressure of the air is decreased. This applies when the temperature of the gas is constant. This is stated in Boyle's law **(Formula 4)**. A different, and equally important physical statement is Charles' law **(Formula 5 page 7)**, which states if any gas is held at a constant pressure, it is volume is proportional to the absolute temperature. These two formulas come from a very essential formula, called the combined gas law **(Formula 6 page 7)**. This law combines the knowledge of the relationship between the pressures of a volume with the temperature.

Boyle's law: $p \times V = C$	p = Pressure V = Volume	**4.** p in Pa V in m^3

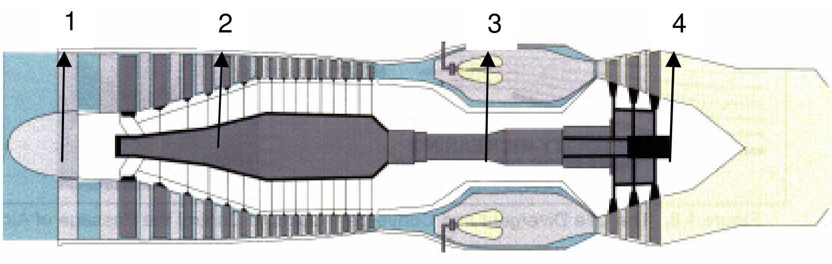
Charles' law: $\frac{V}{T} = C$	V = Volume T = Temperature	V in m^3 T in K **5.**

Combined gas law: $\frac{P \times V}{T} = C$	P = Pressure [N/m^2] V = Volume [m^3] T = Temperature [K]	P in N/m^2 V in m^3 T in K **6.**

This formula is crucial in the jet engine cycle, since the functioning of the engine relies on the principle of increasing the velocity of the gas flow, by decreasing the volume of the gas.

C The Brayton Cycle

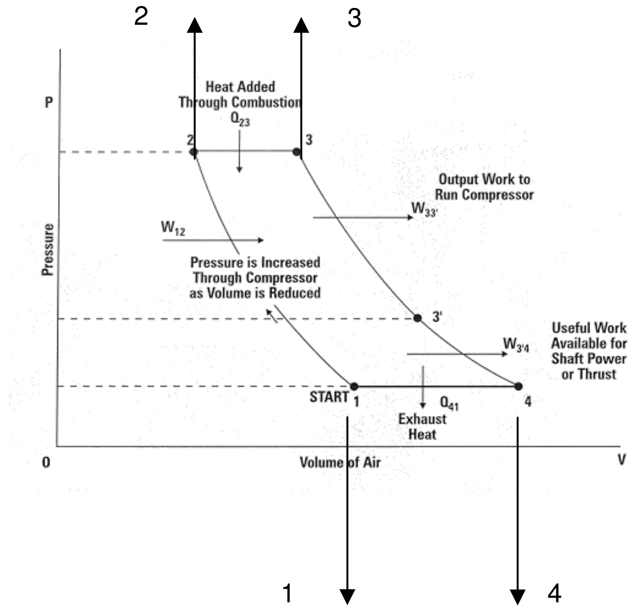
This cycle of events in the jet engine is stated in 'The Brayton Cycle'. The Brayton cycle is the thermodynamic cycle in a jet engine and knows four states in the jet engine cycle ***(Figure 1.1)***. Intake, compression, expansion and exhaust. The velocity and volume of the gas is variable, in order to accelerate or to decelerate the gas flow, but the pressure in of the gas is constant. This cycle is also referred as the continuous-combustion cycle. The intake (1) of the engine is diverging. This will cause the air flow to slow down and increase slightly in pressure. The air will be passed through to the compressor where the air will be compressed (2). This compressor will decrease the volume of the air and thereby increase the pressure of the air. The expansion of the air will be carried out by the combustion chamber (3). The air will be mixed with ignited fuel. Because of the generated heat the air will expand and will remain at the same pressure and according to Charles' law, which stated that the an increase in temperature will increase the pressure, the volume, the volume will increase. Therefore the velocity will increase. The gasses, with an increased velocity will be transferred to the turbine assembly where the velocity energy will be transformed to mechanical energy. The exhausts of these gasses are carried out by the exhaust (4). This is the actual propulsion for the jet engine.



1. Inlet
2. Compression
3. Combustion
4. Exhaust

Fig. 1.1: Jet engine order

This cycle for the jet engine is also referred as the thermo-dynamical cycle of events. This cycle of events are shown in the Brayton cycle diagram ***(Figure 1.2 page 8)***. This cycle is an idealized cycle. In point 1 the air has entered through the inlet. From point 1 to point 2 the air is compressed and the pressure will increase such as the diagram shows. The volume of air will decrease due to the compression. When the air is heated by the combustion chamber (2-3), the volume of the gas will increase while the pressure will remain constant. When the gas passes out of the combustion chamber, the pressure will decrease and the volume will increase since the gas is allowed to expand. The resulting volume (4) and pressure is the available work power to deliver the thrust. When the gas passes through the exhaust (4-1), the temperature will decrease and thereby the volume of gas will decrease.



1. Inlet
2. Compression
3. Combustion
4. Exhaust

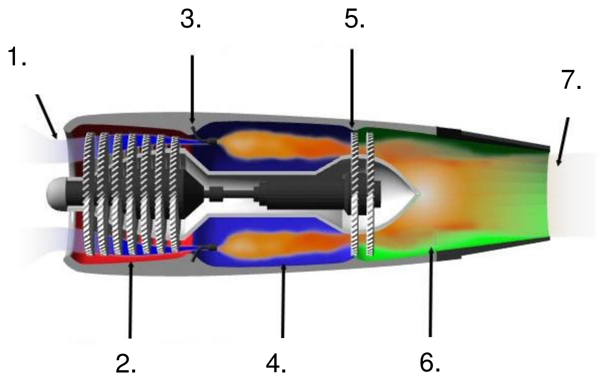
Fig. 1.2: The Brayton cycle

1.1.2 Gas turbine engines

There are several engines used in the aviation industry. One of these is the turbo jet engine. This can be divided in three different types: The turbojet **(A)**, the turbo engine with after burner **(B)** and the turbofan **(C)**.

A Turbojet

The thrust which is delivered by a turbojet engine ***(Figure 1.3)*** is coming from the exhaust of the core engine. In the front of the engine cold air goes inside the inlet (1) of the engine. A compressor (2) compresses air which is blown on high pressure into the combustion chamber (3). In the combustion chamber fuel is injected and ignited. Behind the combustion chamber a turbine (4) is placed which is driven by hot, high pressure exhaust gases, which are also used to deliver thrust, coming out of the combustion chamber. The turbine drives a shaft which actuates the compressor. At the end of the engine a convergent exhaust nozzle (5) to increase the speed of the exhaust gases, to deliver more thrust.

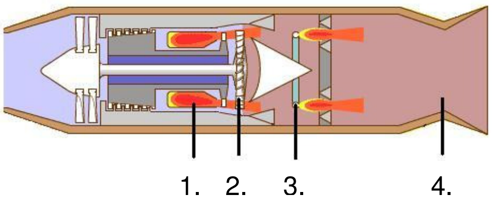


1. Inlet
2. Compressor
3. Fuel injector
4. Combustion chamber
5. Turbine
6. Exhaust nozzle
7. Hot exhaust gases

Fig: 1.3: Turbojet engine

B Turbo engine with afterburner

To deliver more thrust an afterburner ***(Figure 1.4 page 9)*** can be placed on a jet engine. Afterburning consists of injecting an igniting fuel between the turbine and exhaust nozzle. In this process the exhaust gas temperature will increase, which increases the velocity of the exhaust gases leaving the exhaust nozzle and delivers more thrust.

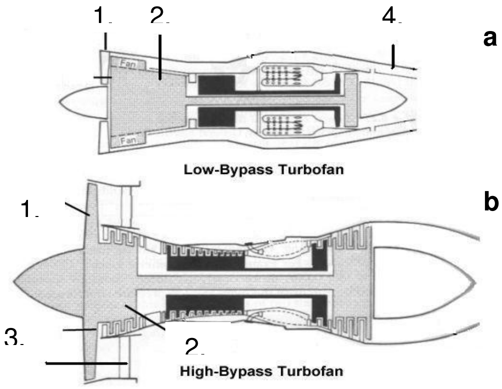


1. Combustion chamber
2. Turbine
3. Afterburner
4. Exhaust nozzle

Fig: 1.4: Turbo engine with afterburner

C Turbofan engines

The principle of the turbofan engine is almost the same as the principle of the turbojet engine **(A)**. The turbofan engine has a fan in the inlet which rotates linear with the compressor. The fan blows cold air through the bypass of the engine and delivers thrust and sometimes extra cooling for the core engine.
A difference can be made between high bypass engines and low bypass engines. If the most thrust of the engine is generated by the fan, the engine can be called a high bypass engine ***(Figure 1.5a)***. If the most thrust of the engine is generated by the exhaust gases of the core engine, the engine can be called a low bypass engine ***(Figure 1.5b)***. Mostly this is related to the size and the number of stages of the fan.



1. Inlet
2. Compressor
3. Fan
4. Fan exhaust

Fig. 1.5: Turbofan engines

1.1.3 The E-3A Sentry

To get an overview of the AWACS E-3A the main purpose is described and the operation area will be analyzed **(A)**. The used engine and the specifications will be investigated **(B)**.

A AWACS

The AWACS are developed from the Boeing 707-320 series by the NATO. The main purpose is to improve the air defence by scanning the area and alert the NATO early. These scans are done by a 30ft radar mounted on top of the fuselage ***(Figure 1.6)***. This radar rotates every 10 seconds 360 degrees and can scan an area of 312,000 km^2, to scan an area that size the AWACS must fly at an altitude of 30,000 ft. The AWACS have a flight crew of fourteen people to operate optimal during flight. The main base of the AWACS is at Geilenkirschen in Germany. When an AWACS starts a mission it can continue over 10 hours without refuelling, when there is fuel needed the AWACS can be re-fuelled in the air. There are more specifications in **Appendix II**

Fig. 1.6: AWACS with radar

B Engines of the AWACS

The NATO has installed four Pratt & Whitney TF33 100A engines on the AWACS. These are the first generation by-pass engines and there are no thrust-reversers installed. This means that an AWACS needs a long runway to land. The engines are old, produce much noise and have a low By-pass ratio. The fuel consumption is also too high. This relatively makes them less effective than modern engines.

1.2 Description engine E-3A Sentry

During the most intensive maintenance check the whole aircraft shall be disassembled. Also the engine of the aircraft is attended during the check. In this paragraph the engine also shall be disassembled for a clear view of all involved components. The components will be discussed in order from front to rear. The first component, where the airflow is passing, is the inlet **(1.2.1)**. The air shall directly be compressed in the compressor for an ideal combustion **(1.2.2)**. The combustion in the combustion chamber gives the aircraft the propulsion **(1.2.3)**. Some energy of the combustion is needed to provide some components intern and extern the engine. This energy in form of an airflow will be received by the turbine **(1.2.4)**. The airflow is leaving the engine in the exhaust **(1.2.5)**. Fuel is an important aspect to have the engine run **(1.2.6)**. By using the engine as propulsion of the aircraft, no other energy producers are needed to provide energy to the external subsystems **(1.2.7)**.

1.2.1 Inlet

The front gap in the housing is used to guide the airflow into the engine. The distance between the first part of the engine (compressor) and the gap is called the inlet. The inlet is not a part from the engine itself, the inlet is a part of the front nacelle installation or housing. The inlet has an aerodynamical advantag, this is described as the purpose **(A)**. The use of the inlet on the TF33 engine is described as the application **(B)**.

A Purpose

The inlet is used to provide the engine a straight airflow, even during different angels of attack, turbulence and all rational airspeeds. This to prevent harmful effects in the compressor. The inlet also has another function. The shape of a modern turbofan inlet duct causes an air velocity decrease therefore a temperature and pressure increase, this phenomenon is called ram recovery and has a positive impact on the thrust without using more fuel, the pressure and temperature increasing occurs by flying faster than Mach 0.2. There are several formulas to calculate the inlet values of temperature, pressure and airspeed in contrast with the outside temperature, pressure and airspeed. The first aspect that has to be solved for proving that the inlet has a positive effect on the efficiency, is the temperature in the inlet duct. The temperature (T_{01}) from the airflow in the first stage of the inlet depends on the air velocity (c_l), compression velocity (c_p) and Outside Air Temperature [OAT] (T_{am}) **(Formula 7)**.

$T_{01} = T_{am} \dfrac{c_l^{\ 2}}{2 \cdot C_p}$	T_{01} = The inlet temperature T_{am} = OAT c_l = Air velocity c_p = Compression velocity	T_{01} & T_{am} in Kelvin c_l & c_p in m/s	**7.**

To calculate the efficiency of the inlet duct one other variable is needed, the temperature at the rear of the inlet duct (T'_{01}), therefore the pressure of the airflow at the rear of the inlet duct must be estimated. For this calculation the outside air pressure is needed (p_{am}) and the air gas constant (γ) **(Formula 8)**.

$P_{01} = P_{am} (\dfrac{T'_{01}}{T_{am}})^{\frac{\gamma}{\gamma - 1}}$	P_{01} = Air pressure rear of inlet P_{am} = Outside air pressure T'_{01} = Temperature rear of inlet γ = Gas constant (1,4 for air)	P_{01} & P_{am} in Pascal T'_{01} in Kelvin	**8.**

The final step to indicate the advantage for inlet duct use is to calculate the efficiency (η_{inl}) **(Formula 9)**.

$\eta_{inl} = \dfrac{T'_{01} - T_{am}}{T_{01} - T_{am}}$	η_{inl} = Efficiency of the inlet	η_{inl} in %	**9.**

B Application

Fig. 1.7: TF33 variable inlet valves

The TF33 has also an inlet duct. This inlet also has valves in the housing assembly to variable the inlet temperature and pressure ***(Figure 1.7)***. Titanium inlet case is provided to prevent Foreign Object Damage [FOD]. The case and the hollow housing vanes of the TF33 are provided with small holes connected to a warm air system to de-ice the engine if necessary.

1.2.2 Compressor

According to the working cycle of Brayton the combustion is done with high efficiency when the air for the combustion is compressed and has a high temperature. The compression can be done by a compressor. There are different ways to compress the air in an engine. Using a centrifugal flow compressor is an efficient way to compress the air **(A)**.
The most efficient compressor, when flying with higher speeds, is the axial flow compressor **(B)**. The TF33 has an axial flow compressor, the pressure ratio describes the efficiency of this engine **(C)**.

A Centrifugal flow compressor

The centrifugal flow compressor consists of several single or double-sided disk stages (impellers) mounted on one axle driven by a turbine **(Appendix III.A)**. The air that is leaving the inlet duct collide to the centre of these impellers **(Appendix IV)**. The rotating impeller increases the air velocity and pressure during the centrifugal action that moves the air from the centre to the rim of the impeller. At the rim of the impeller the air is been captured by a diffuser. The diffuser leads the compressed air to the next impeller that is increasing the pressure once more. Also this diffuser has an divergent nozzle, this means an increasing of the pressure. In every stage 50% of the pressure rise is done by the diffuser and 50% by the impeller. In contrary to the high efficiency, the centrifugal flow compressor cannot be used for higher speeds, this because this compressor can convert less air in a higher pressure as the axial compressor with the same frontal surface.

B Axial flow compressor

The most used compressor in the modern engines is the axial flow compressor. An axial flow compressor is in respect of all others an efficient compressor. However there are several types of axial flow compressors, from less efficient, like the straight engine, up to extremely efficient, like the high by-pass engine. An axial flow compressor consists of one or more rotor blade assemblies mounted on its own axle **(Appendix III.B)**. The turbine is rotating this axle. The rotor blades are fitted on the axle under an angle. The rotor blades are scooping the air and convert the kinetic energy of the air into a pressure and air velocity increases. Like the diffuser of the centrifugal flow compressor, fixed stator blades are fitted between each disk of rotor blades to lead the airflow to the next disk of rotor blades. The stator blades are necessary to maintain a constant air velocity as the density of the air increases. In the early years one turbine rotated one rotor blade assembly that compressed the air as long as needed for the combustion. This compressors where long installations and less efficient as a twin spool compressor. A twin spool compressor has for every rotor blade assembly an own axle with an own turbine. The axles are integrated in each other and can rotating with its own velocity because of the ball and roller bearings. Difference between these velocities can be made. The front compressor turns with a low velocity and is called the Low Pressure Compressor [LPC]. The rear compressor turns with a high velocity and is called the High Pressure Compressor [HPC]. The velocity difference has a great impact on the efficiency of the engine. A higher velocity means a higher pressure increasing.
Twin spool compressors can be used to design a by-pass engine. The airflow in the inlet of a by-pass engine is spited up in two directions. One part of the airflow enters the core engine for compression and combustion and an other part of the airflow is passing the exterior of the engine but intern housing. The relation between the by-pass flow and the flow that entered the engine is called the By-Pass Ratio [BPR]. A high BPR means a higher efficiency and less noise. The pressure and temperature difference between the exhaust gasses and the outside temperature and pressure is high. Because a by-pass engine is increasing the pressure and temperature of the by-pass flow the difference between the variables at the exhaust of the engine will be fewer when comparing with the engine exhaust variables.
To give the by-pass flow a higher pressure and temperature a second rotor blade assembly must be required. In the LPC the air will be compressed and will be separated before entering the HPC into an engine flow and by-pass flow **(Appendix III.C)**. For even better results a multi spool compressor can be used. This compressor exists of a LPC, HPC and an Intermediate Pressure Compressor [IPC]. The turbine form the LPC is turning a fan that provides the airflow a temperature and pressure increasing. This multi

spool compressor system is used on high by-pass engines **(Appendix III.D)**. A normal value at the high by-pass engines is 80% will pass the by-pass core and the other 20% will pass the engine core.
The rotor blades (vanes) are free fitted on the rotor disks, this concerning the vibrations and leisure during maintenance. The vanes are also twisted, the airflow will increase at the edge of the vane up to 1500ft. sec. this causes turbulence in the engine. In some operating conditions the engine and the airflow are not tuned to each other. When the compressor is turning but the airflow will not be sucked in the engine, because the vanes will not produce much lift, the engine can be flooded. This phenomenon is called stall. Another phenomenon is when the compressor is turning on a lower speed, for example throttle push back, but the air still is entering the engine core with a high velocity. The engine can not process the air and the airflow will find its way back in a reverse direction. This phenomenon is called surge and can damage the vanes. To prevent these failures, Variable Stator Vanes [VSV] are used. These vanes can change its angle to increase lift suction and process more air when necessary.

C TF33 Compressor

The axial flow compressor of the TF33 engine is provided with a twin-spool of rotor blade assemblies. The LPC guides 10% along the by-pass core and 90% along the engine core.

1.2.3 Combustion Chamber

When the air comes out of the compressor it is ready to be ignited. To ignite the fuel in the engine a combustion chamber is needed **(A)**. For ignition different parts are needed **(B)**, than the combustion chamber that is used at the TF – 33 is shown **(C).**

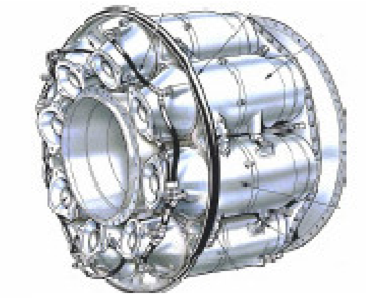


Fig. 1.8: Tube annular combustion chamber

A Purpose

There are two kinds of combustion chambers, the tube annular ***(figure 1.8)*** and the annular combustion chamber ***(Figure 1.9)***. The annular combustion chamber is the most common used because of the low production costs. The combustion chamber will mix the air from the compressor with a spray of fuel. This will lead to an ignition of the fuel. Because the temperature of the ignited fuel of ignition can be too high for the surrounding materials so it can cause damage, therefore there is air used to cool the combustion chamber. From the total air that comes out of the compressor only 20 percent will be ignited and the other 80 percent is needed to cool the chamber.
The amount of fuel that must be ignited depends on the desired kinetic energy raise that is needed. The air will be heated up in the combustion chamber between 850 and 1700 degrees Celsius, the air from the compressor has a temperature of 200 to 550 degrees Celsius. The amount of heat needed to reach the acquired temperature can be achieved by the amount of fuel that will be ignited. The air pressure in the combustion chamber can be calculated with **(formula 10)**.

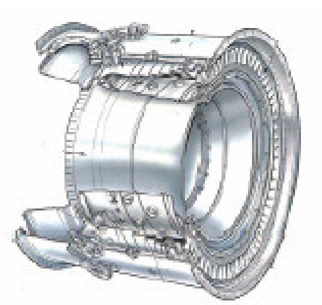
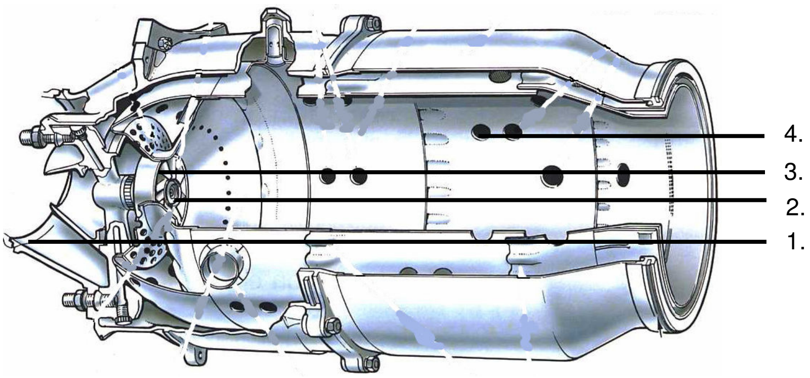


Fig. 1.9: Annular combustion chamber

$p_{04} = p_{03} - \Delta p$	$p_{03=}$ Air pressure rear of compressor $p_{04=}$ Air pressure rear of combustion chamber $\Delta p_{=}$ Air pressure difference	**10.**

B Operation

The combustion chamber ***(Figure 1.10 page 13)*** consists out of different parts. The air comes out of the compressor through the snout (1). To insert fuel there are Fuel Spray Nozzles [FSN] (2), these will spray fuel in the combustion chamber. Because the speed of the air out of the compressor is too high there are swirl fans (3), these fans slow the air down so it can be ignited. The air that is needed to cool the combustion chamber will be created by the dilution holes (4), these holes consist air that is not heated.



1. Snout
2. Fuel Spray Nozzle
3. Swirl Fans
4. Dilution Holes

Fig. 1.10: Combustion chamber

C TF33 Combustion Chamber

The TF33 has an eight tube annular combustion chamber, this means that there are eight tubes surrounding the combustion chamber.

1.2.4 Turbine

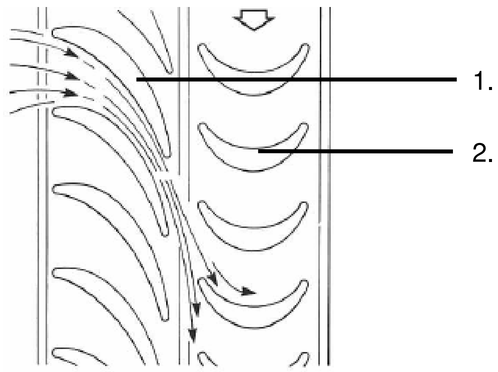
A turbine is used to provide the power to drive the compressor and gearboxes **(A)**. This is done by extracting energy from the hot gases released from the combustion system and expanding them to a lower pressure and temperature **(B)**.

A Purpose

The turbine extracts energy from the hot gasses that flow through it and converts the energy into mechanical energy which is used to drive the compressor and gearboxes. The taken energy will be mainly from potential energy and heat energy. On modern turbofan engines, the fan produces the greatest amount of thrust. As the turbine is driving the fan, it is delivering the energy to produce this massive airflow.

B Operation

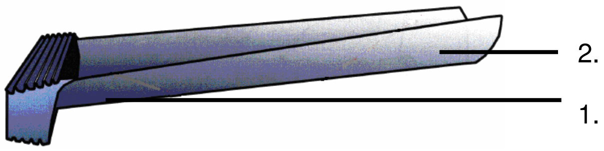
A turbine ***(Figure 1.11)*** consists of one row stationary nozzle guide vanes (1) and one row of rotating turbine blades (2). At the base, nozzle guide vanes are convergent, so they increase the velocity and decrease the pressure of the air.



1. Stationary nozzle guide vanes
2. Rotating turbine blades

Fig. 1.11: Turbine driven by the impulse of the gas flow

The twist in the blades ***(Figure 1.12)*** is used to distribute the workload evenly along the blade length by keeping the exit pressure and velocity uniform from the base to the tip.



1. Impulse
2. Reaction

Fig. 1.12: Twisted turbine blade

At the base, impulse blades are used. Closer to the tips more and more wrong is used to distribute the workload along the blade ***(Figure 1.13 page 14)***.

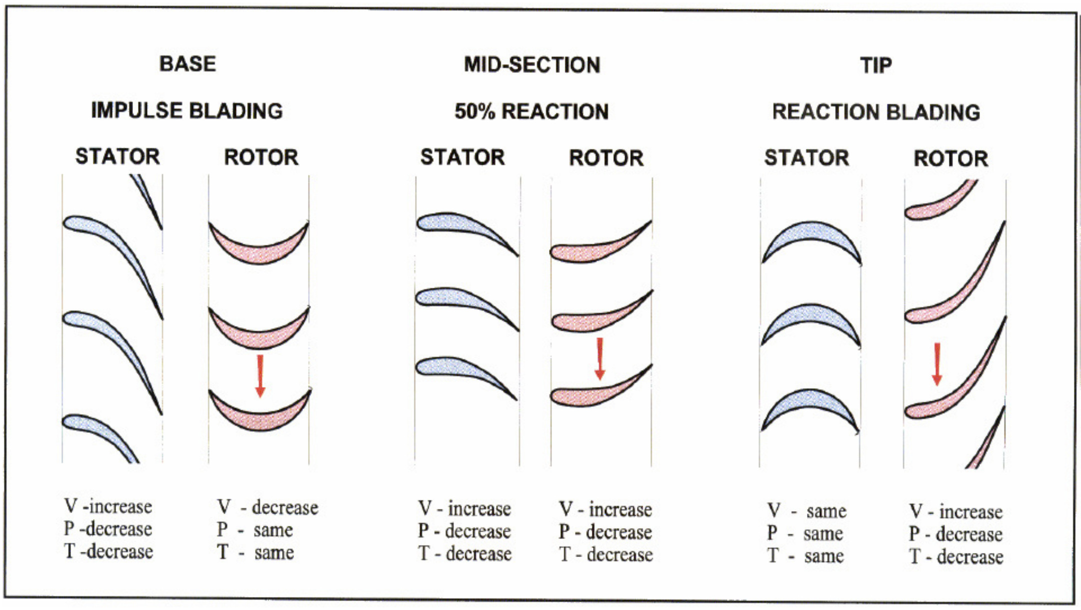
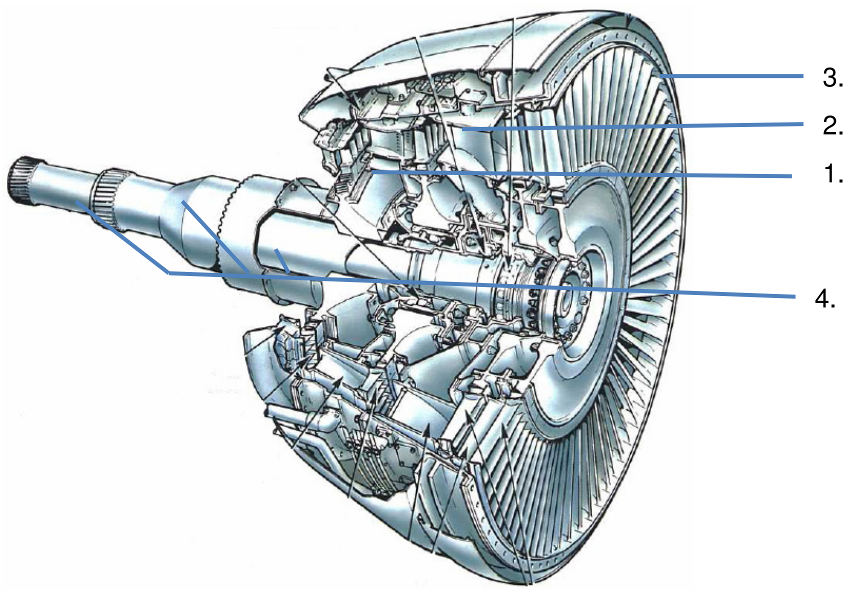


Fig. 1.13: The twist of the blades changes from action to reaction

In the following example ***(Figure 1.14)***, there is a turbine with three stages. A high pressure turbine (1), as well as an intermediate pressure turbine (2) and a low pressure turbine (3) are present. Each turbine rotates at its own speed and drives its own turbine shaft (4). Potential energy of the airflow will be absorbed by the turbine and decreases with each stage. The low pressure turbine, rotating at the lowest speed, is interconnected with the low pressure turbine shaft and drives the fan.



1. High pressure turbine
2. Intermediate pressure turbine
3. Low pressure turbine
4. Turbine shafts

Fig. 1.14: Turbine

1.2.5 Exhaust system

The rear opening of engine is the jet nozzle or exhaust nozzle. The nozzle acts as an orifice, the size of which determines the velocity of gases as they emerge from the engine. In most subsonic aircraft, it is fixed at the time of manufacture.

A Purpose

Gas turbine engines are equipped with an exhaust system which passes the gases discharged from the turbine, to the atmosphere at a velocity, and in the right direction, to provide resultant thrust. The velocity and pressure of the exhaust gases create the full amount of thrust on turbo-jet engines. In turbo-fan engines only a small amount of thrust is contributed by the exhaust gases, because most energy is absorbed by the compressor for driving the fan. The design of the exhaust system is important for the engines performance;

the areas of the jet pipe and outlet nozzle affect the turbine entry temperature, the mass airflow and the velocity and pressure of the exhaust jet.

B Operation

The exhaust gases travel from the jet pipe to atmosphere via the convergent nozzle. This increases the hot gas velocity to speeds of Mach 1 in a turbo-jet engine at virtually all throttle settings above idle. At this velocity, the nozzle is chocked. That means that no further increase in velocity is possible, unless the gas stream temperature is increased. In turbofan engines ***(Figure 1.15)***, there are two streams of air, the hot exhaust gases and the cold by-pass airflow. These streams are usually exhausted separately in high by-pass ratio engines, so that each nozzle can be designed to obtain maximum efficiency. A hot air nozzle (1) and a cold air nozzle (2) are then used.

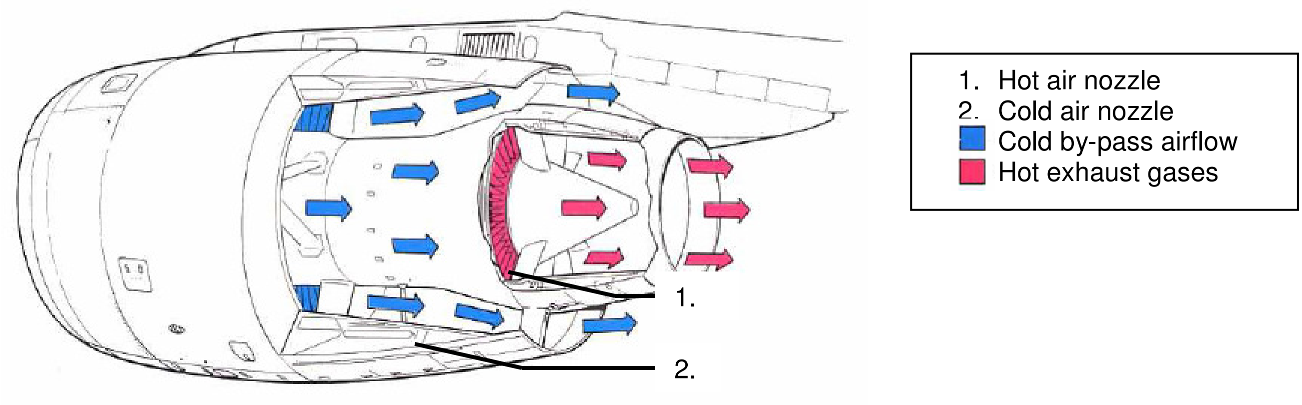


Fig. 1.15 Separated gas streams

1.2.6 Fuel system

Fuel is a liquid mixture of crude oil and other substances. Fuel is needed to be ignited in the combustion chamber, so the pressure will rise up rapidly and drive the turbine. The fuel system consists of a number of components from tank to fuel spray **(A)**. To result in better fuel economy and longer engine life, an aircraft can be equipped with a supervisory Electrical Engine Control system **(B)** or a Full Authority Digital Engine Control System [FADECS] **(C)**. The TSFC is used to determine if the engine has a high efficiency **(D)**.

A System components

Fuel is not directly inserted to the fuel spray nozzles, but is flown through a lot of components ***(Figure 1.16 page 16)***. The text has the same order as the figure. The fuel is stored in various fuel tanks. When one fuel tank has a leak, not all the fuel is wasted because of the other fuel tanks. A set of booster pumps pass the fuel via non-return valves through a fuel shut off valve. The valve is closed when the pilot pulls the fire lever, so the fuel can be isolated from the engine. The fuel enters the low pressure pump. The pump is driven by the gearbox. The low pressure pump has also a back-up function for the booster pump. The low pressure pump will then suck the fuel from the fuel tanks. The aircrafts Menimum Equipment List [MEL] must be consulted to prevent vaporizing of fuel due to high altitude, also called cavitations. From the low pressure pump the fuel is flow to a fuel cooled oil cooler. The fuel is cooled and then heated to eliminate ice crystals. The heater uses compressor air to maintain a predetermined fuel temperature. Fuel temperature is sensed and can be indicated in the cockpit. A filter is installed to filter the fuel, so dirt cannot reach the rest of the system and the engines. Fuel pressure is sensed and can be indicated, so the pilot can verify if the filter is clogged. The high pressure pump is driven by the engine high pressure shaft through the gearbox. The fuel raises the pressure and flow which is required for the engine thrust setting. Mostly this is an axial piston type pump or a spur gear type high pressure pump. After the high pressure pump another filter is installed. The fuel control unit controls the fuel flow for a given thrust setting. Air intake pressure, altitude control, acceleration control, Exhaust Gas Temperature [EGT] limitation, power limiter and a Rounds per Minute [RPM] limiter are used to adjust the fuel flow. After the fuel control unit, the fuel is flown through a high pressure fuel cock valve. This valve is normally open to start the engine and closes to stop the engine. The valve is mechanically controlled by a lever in the cockpit. The flow meter measures the fuel flow in gallons/hour or kilograms/hour. The flow meter also include an integrator to sum the total amount of fuel used since the engines where started. This part is indicated in the cockpit. Finally the fuel enters the fuel spray nozzles and sprays the fuel into the combustion chamber. A drain tank collects fuel which is not ignited when the engine is shut down or after a failed start. When the engine is running normal, the drain tank is isolated by a drain valve.

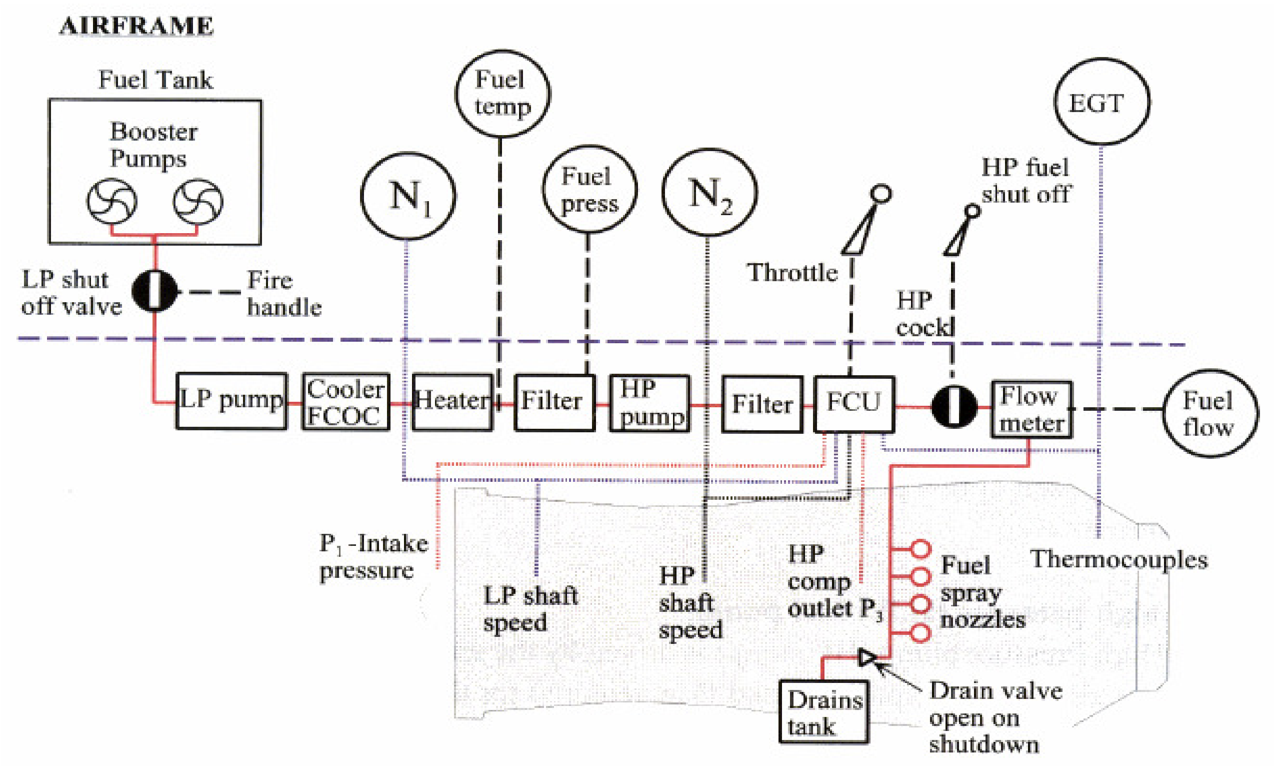


Fig. 1.16: Schematic fuel system

B Supervisory Electrical Engine Control system

The supervisory Electrical Engine Control [EEC] uses a computer which receives inputs of engine parameters and controls a standard hydro mechanical Flight Control Unit [FCU]. The FCU responds to the supervisory EEC command and performs a function, like more thrust, which is necessary for the engine operation and protection. The computer monitors throttle lever angle, Mach number, inlet pressure and inlet temperature. The computer also provides a constant thrust when a change occurs in air pressure, temperature and flight environment.

C Full Authority Digital Engine Control system

A FADEC is a computer based digital control system for the engines. The computer controls the N2 RPM to the desired RPM of N1 which is set by the pilot. The FADEC also report the engine conditions. When the pilot moves the throttles to adjust the r.p.m, the FADEC will execute this by sending signals to the engine. The FADEC does not sent signals only, but also receive. It receives digital and analogue data. Digital data can be taken from the Air Data Computer [ADC] such as altitude and speed. Digital data can also be taken from the FQMC such as, amount of fuel. Analogue data are data from the engine such as N1 and N2 r.p.m, inlet temperature and fuel temperature. Data from the aircraft (position of thrust lever, thrust reverser) and data from the other FADEC are analogue. The FADEC is thus connected with the aircraft, engine and a power supply. Each engine uses two FADEC's; one active and a stand-by FADEC. The two FADEC's are connected with each other via a crosstalk cable. The stand-by FADEC can now control the active one because the date from the engine is sent to both FADEC's. If the active FADEC fails, the stand-by FADEC can now be active. The FADEC is also connected to two power supplies, also one for back-up. When a power supply fails, the FADEC automatically switches in 0.8 s, so this does not affect the engine.

D Thrust Specific Fuel Consumption

The efficiency of an engine can be measured by calculating the Thrust Specific Fuel Consumption [TSFC] **(Formula 11)**. The outcome is how much fuel the engine burns in one hour per Newton thrust. A low TSFC means high engine efficiency and a high TSFC means thus low engine efficiency. Aircraft designers try to tend for the lowest TSFC possible, because the fuel costs are lower.

$TSFC = \frac{m_f \times 3600}{F_t}$	$TSFC$ = Thrust Specific Fuel Consumption m_f = Fuel mass F_t = Trust	$TSFC$ in kg/N.hr m_f in kg/s F_t in N	**11.**

1.2.7 Related systems

Various kind of related systems are needed to operate and control the engine. Most aircraft use a thrust reverser to slow down faster when the aircraft lands **(A)**. The engine must be cooled **(B)** and lubricated **(C)**. An auxiliary gearbox is mounted on the engine to drive several aircraft systems **(D)**. There are two common ways to start the engine **(E)**.

A Thrust reverser

A thrust reverser is a separate part of the engine and is not required on an aircraft. The function of the thrust reverser is to reverse the gas flow after touchdown. The advantage of a thrust reverser is the shorter stop distance when the aircraft is braking after landing. The thrust reverser works maximum when the pilot lands on a wet or icy runway, because the brake friction is poor in those conditions. The pilot can operate the thrust reverser by pulling the throttles upwards **(Appendix V)**. There are three types of thrust reversers;

1. Clamshell doors
2. Bucket doors
3. Blocker doors

Ad. 1 Clamshell doors
Clamshell doors are usually pneumatic operated and uses high pressure to operate. The pneumatic rams move the door from its stowed position **(Appendix VI)** to deployed position **(Appendix VII)**. When the doors close, cascade vanes are revealed. The normal exhaust gas exit is now closed and the gas leaves the cascade vanes in a component in the same direction as the aircraft movement and opposes the aircraft motion.

Ad. 2 Bucket doors
The bucket doors are hydraulically actuated and use bucket type doors to reverse the exhaust gas. In the stowed position **(Appendix VIII)** the bucket doors form the nozzle of the engine. When deployed **(Appendix IX)** the gas has a component in the direction of the aircraft motion and opposes the aircraft motion.

Ad. 3 Blocker doors
Blocker doors are only used on a by-pass engine and only the air of the by-pass is reversed. Blocker doors are actuated by an air motor or hydraulic rams. When the translating cowl is stowed it closes the engine **(Appendix X)**. When deployed **(Appendix XI)**, the translating cowl is moved backwards which able the blocker doors to deploy and close the by-pass nozzle. The by-pass air leaves the cascade vanes in a component in the same direction of the aircraft movement and opposes the aircraft motion.

B Bleed air

Bleed air is used to internally cool the engine and externally used for other aircraft systems such as, air condition, anti-icing and fuel tank pressurisation. Bleed air can be taken from two sources. The air can be taken from the outlet of the low pressure compressor and can be filled up with air from the outlet of the high pressure compressor. Low pressure bleed is used in combination with high power operation. In low power operation the low pressure bleed will drop and the high pressure valve will open to maintain the pressure. The high pressure valve will also open as the pilot selects anti-icing, because high pressure bleed has a high temperature, which is needed to prevent icing. Bleed air can be shut off the engine when, for example, the fire handle is operated to prevent smoke in the cabin. The valve must also be closed during de-icing on the ground to prevent toxic fumes in the cabin. Internal air must be drained in the early stage of the compressor to maintain its function. When the air finishes off cooling, it is dumped overboard or added in the main gas stream to compensate the drainage.

C Lubrication

There are a couple reasons for a lubricant in an engine. Primary to reduce friction of components, so they will not get stuck. The oil can also clean the engine. When dirt runs in the engine, the oil carries the dirt to the oil filter where it is been filter out. Most of the bearings are made of steel and will oxidise itself. The oil will also minimise corrosion by a liberal coating of oil around the bearings. Another reason to use oil is to cool the bearings, especially around the hot end of the engine. The reasons for oil are thus; to reduce friction and corrosion, cleaning and cooling. There are two basic recirculatory systems;

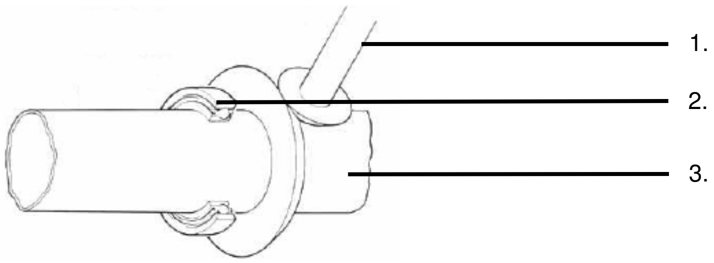
1. Pressure relief valve system
2. Full flow system

ad 1 Pressure relief valve system
The oil flow to the bearing chambers is controlled by a spring loaded valve. The valve opens at a pressure which is the same as the idling speed of the engine and gives a consequently constant feed pressure. Oil from the oil tank is filtered first before it enters the engine. When the oil has flown through the engine it will fall in a collection compartment. From the compartment the oil is cooled by an oil cooler. There are two types of coolers: a fuel cooled oil cooler and an air cooled oil cooler. The next step is the de-aerator tray where bubbles are allowed to escape. The cycle is now completed and the oil will flow into the oil tank. Any air pressure that is build up in the lubrication system (leakage seals or through the de-aerator) must escape. When the pressure is just vented to the atmosphere it contains not only pressure, but also oil mist what will pass the atmosphere. Consequence is that the oil content will decrease. To prevent this, the oil mist is vented by a centrifugal breather.

ad 2 Full flow system
The oil pressure pump directly supplies the oil without the use of a pressure relief valve. The advantage of this system is the smaller pressure because the volume of the oil passed is less than that in the pressure relief valve system. This happens because of the large amount of oil which is spilled back to the tank by the pressure relief valve at high engine speed. Just like the pressure relief valve system the oil flows through a filter. It flows along a couple of sensors which measures the temperature and quantity of the oil. When the oil has done its task it is collected, cooled, flown through the de-aerator and finally flows into the oil tank.

D Auxiliary gearbox

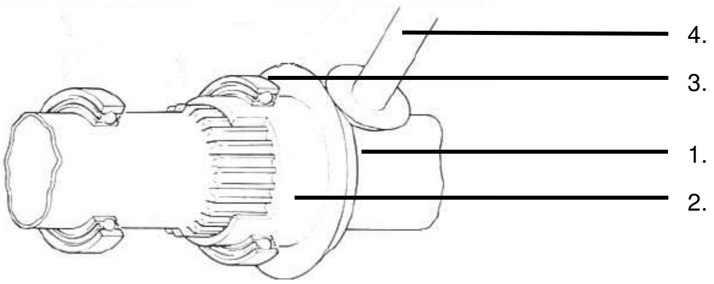
An auxiliary gearbox is an accessory drive which is located in the engine. The power source for the gearbox is usually taken via the high compressor shaft. From the compressor shaft the translation is transmitted by a radial driveshaft. The radial driveshaft is connected to the gearbox and drives the accessory. The auxiliary gearbox provides the power for hydraulic, pneumatic and electrical mechanisms for the engine and other aircraft systems. The auxiliary gearbox provides also power for fuel pumps and oil pumps. Movement of the compressor shaft and the radial driveshaft, caused by axial movement of the compressor shaft must be prevented. A method to prevent this ***(Figure 1.17)*** is to mount the radial driveshaft (1) as close as possible to the compressor shaft bearing (2) which holds the compressor shaft (3).



1. Radial driveshaft
2. Bearing
3. Compressor shaft

Fig. 1.17: Direct drive

Alternatively ***(Figure 1.18)***, a compressor shaft bevel gear (1) can be mounted on a stub shaft (2) which has internally cut teeth and its own location bearing (3). The stub shaft is splined into the compressor shaft which allows axial movement within movement of the radial driveshaft (4).



1. Bevel gear
2. Stub shaft
3. Location bearing
4. Radial driveshaft

Fig. 1.18: Stub shaft drive

An idler gear drive is a more complex system ***(Figure 1.19 page 19)***. A straight gear (1) is placed upon the compressor shaft (2). The idler gear shaft (3) is connected to the straight gear and bearings (4). The radial driveshaft (5) is driven by a bevel gear (6) mounted on the idler gear shaft.

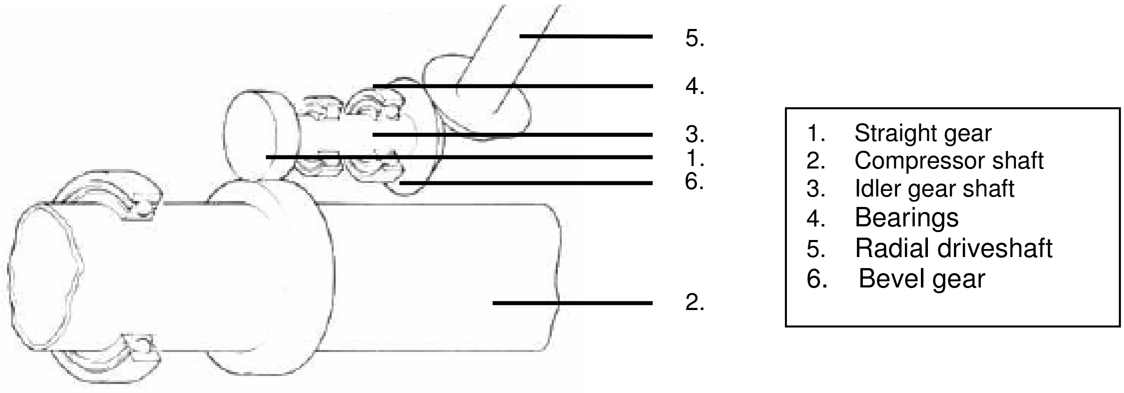


Fig. 1.19: Idler gear drive

To prevent disturbing of the airflow in the engine, the diameter of the driveshaft must be very small. When the diameter is smaller it must rotate faster to transmit the power. This results in stress and vibrations of the shaft. The solution is to mount a roller bearing halfway the shaft. This allows in a rotational speed of 25.000 RPM with a shaft diameter of less than 4 centimetres.

E Engine starting

To start the engine there must be a few requirements the engine has to comply with. First, the compressor must be rotated to get air in the combustion chamber. Fuel must also be provided in the combustion chamber and the air/fuel mixture must be ignited. The two most common methods to start the engine are,

1. The air starter motor
2. Electric starter motor

ad 1 The air starter motor
The air starting system has a couple of advantages; it is comparatively light, simple and economical to operate. The air starter motor is connected to the accessory gearbox **(Appendix XII)**. The air that is needed to drive the motor comes from the Auxiliary Power Unit [APU] or a ground power unit. The APU is located at the rear part of the tail and is a kind of a small gas turbine. The APU powers the most important aircraft systems such as hydraulic, electrical and pneumatic devices without starting the main engines. This is especially an advantage when the aircraft is on the ground. The APU's turbo shaft is started with an electric starter motor which is connected to the aircraft battery. The air is controlled by a pressure valve, which is open when the pilot pushes the engine start button and will closed when a predetermined speed is reached. The air from the APU drives the turbine of the air starter motor, which will rotate the reduction gear and the engine drive shaft will be rotated **(Appendix XIII)**. The ignition is started at the same time the pilot pushes the engine start button. The engine should light up and is indicated by monitoring the EGT. When the engine is accelerating to idle speed a mechanism called sprag clutch ratchet prevent the air starter motor to rotate even faster. When this happens the air starter motor can fail due to the centrifugal forces. This cycle works the same with the ground power unit. The air is now directly inserted to the air starter motor.

ad 2 Electric starter motor
The electric starter motor is usually a DC motor connected to the engine with a reduction gear and a ratchet mechanism. When the engine reaches a self-sustaining speed the mechanism will disengage. The electric starter motor is connected to the gearbox and drives the compressor when it rotates. The voltage passed through relays and resistances to build up the starter gains speed. The electric starter motor provides also power for the ignition system.

1.3 Forces and vibrations acting on an engine

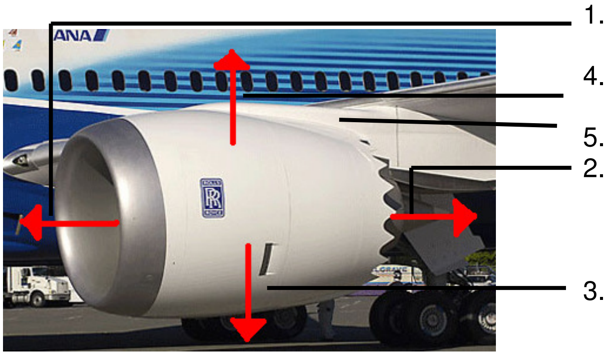
There are many forces working on an engine, on the outside and the inside, all these forces have to be controlled and must be transmitted to the aircraft construction **(1.3.1)**.
Vibrations occur in different parts of the engine, they can cause serious damage and the pilots need to be warned if the vibrations are too strong **(1.3.2)**.

1.3.1 Forces on the engine

The forces that act on the engine can be divided in the forces acting on the construction and the forces acting inside the engine. The forces on the outside are for example thrust and weight **(A)**. The forces inside the engine are for example produced by the turbine shaft and the airflow **(B)**.

A Forces outside the engine

In total there are four forces acting on the construction of the engine ***(Figure 1.20)***, the thrust, drag, lift and weight. Because of the acceleration of the air through the engine, propulsion or thrust (1) is produced, the reaction of the air force to the engine pulls the engine forwards. Because the engine has a large frontal surface it also causes drag (2). The weight of the engines on short haul aircraft is between 2000 and 3000 Kg per piece (3) it is important that the wings can carry that extra load (4), therefore by the search for a new engine it is important to be aware of the mass of that new engine.
All these forces are transmitted to the aircraft construction through the attachment pylon (5). This pylon must be strong enough to withstand these forces. This pylon is stretched out along the length of the engine so the thrust force is spread and the stress equally distributed. The pylon is attached to the wing with three bolts placed in a triangle, this is the best way to distribute the forces and vibrations to the wing. If more bolts are used the construction will be too rigid and the vibrations would be too high for the wing to handle.



1. Thrust
2. Drag
3. Weight
4. lift
5. pylon

Fig. 1.20: Forces on the engine construction

B Forces inside the engine

There are several important forces present inside an engine: aerodynamic forces on the different spinning blades, pressure force in the combustion chamber and centrifugal forces due to the movement of different components
The different blades in the engine have the same shape as a wing profile to raise the pressure. This means that there are forces working on the blades. The higher the rotation speed of the blades the higher the pressure difference and forces on the blades.
In the compressor the pressure of the airflow is dramatically increased, when it reaches the combustion chamber the pressure and the heat are so intense that this combustion chamber has to withstand very high forces. The combustion chamber must therefore be build from endurable materials and because of the heat heavy materials like metal must be used instead of composites.
As a result of the spinning blades and the turbine shaft at a very high rotation speed, centrifugal forces and tension in the blades occurs. Therefore the attachment places between the blades and the shaft must be build strong enough to withstand these forces.
Because of the rotation of the shaft at high speeds torsion occurs. And the thrust generated pushes the shaft forwards, radial and axial forces are hereby created. The shaft is therefore attached to a ball bearing that absorbs the radial and axial forces. The axial forces are led through the construction to the pylon that attaches the engine to the wing so the thrust force forward is distributed along the aircraft structure.

1.3.2 Vibrations

Vibration is the oscillation with a certain frequency of an object around an equilibrium position. Vibrations can cause serious hazard to the different components in the engine. There can be different causes of vibrations **(A)**. To indicate the vibration of the engine a vibration indicator is installed **(B)**.

A Types of vibration

Low cycle fatigue occurs when the temperature varies in a short period of time, this can be caused if the throttle is changing during for example the take-off. The main place where this problem occurs is the fan, if the rotation speed is increased, the outside of the blades heats up quicker than the inside because the speed is higher on the outside. This causes temperature tension in the blades and vibrations. These vibrations in the fan blades can be subdued by midspans placed on the middle of the blades.
High cycle fatigue occurs because of the hot gas stream that flows through the blades of the turbine, this can cause the blades to vibrate.
Torsion vibration always occurs in rotating systems where a tool is driven by an axis. In an engine this is the turbine that drives the compressor through a shaft. The thrust of the turbine is transported to the

compressor through this shaft. The torsion in the shaft because of the masses of the turbine and compressor causes vibrations.
Blade flutter occurs when vibration is generated with the same frequency as the characteristic frequency of a certain component. This is called resonance and it occurs in the fan blades, this destructs an engine within a few minutes.

B Vibration indication

To warn the pilots if serious vibration occur electrical vibration indicators are installed. A proximity transducer is a non contact vibration sensor. It exists of an ac powered coil. If this coil is placed at a distance of several millimetres from a rotating axis made of electricity conductive material, an electrical flow will run proportional to the distance. If vibrations occur and the distance to the coil and the axis changes frequently, a voltage difference is noticed proportional to the distance variation. The vibration sensing device is attached to the transmitter. A vibration transmitter is mounted on the engine casing and electrically connected to the amplifier and indicator. On a multi spool engine a crystal transmitter is used giving a more reliable vibration indication. A system of filters in the electrical circuit to the gauge makes it possible to compare the vibration obtained against a known frequency range and so locate the vibration source. If the vibration level is unacceptable a warning light turns on, the pilot can then shut down the engine and prevent serious damage.

1.4 Regulations

To be sure an engine is safe enough for use on an aircraft and for environmental aspects, the are a few organisations over the world to make regulations for the engines and for other parts of the aircraft. These organizations also conduct inspections and inspect announced and unannounced whether or not entrepreneurs and individuals obey the laws. The modified aircraft have to comply with these regulations to be certified and be able to fly legaly.
The engine requirements applicable for this project are mainly provided by the European Aviation Safety Agency (EASA) and the International Civil Aviation Organization (ICAO).
The EASA regulations concern mostly the technical aspects of the legislation **(1.4.1)**. The environmental aspects are mostly described by ICAO **(1.4.2)**.

1.4.1 Technical regulations

The EASA has made some documents, called Certification Specifications (CS). These documents shows the technical specifications an aircraft has to satisfy too to be airworthy, are described. Each subject has its own chapter. The technical certification specifications for engines are described in CS-E. CS-E is the part or the CS that describes the engine certification demands. These are all technical and operational demands in order to guarantee the safety of the engine during the flight cycle. This also includes maintenance aspects. To get a certification first all data of the engine parts and suspension has to be shown in complete detail. The engine will have to be tested with special testing equipment and should be tested while operating. The CS-E states that the turbine engine should comply with several demands which are divided in subparts of the CS-E. These can be described as chapters. The turbine engine has to comply with general engine demands **(A)** and specific turbine engine demands **(B)**.

A General technical demands

The general demands the engine has to deal with are the demands which applies to all aircraft engines. These chapters are divided in subchapter with each a different subject. These subchapters with subjects are shown below:

- CS-E 10 Applicability Describes where the CS-E is applicable
- CS-E 15 Terminology Describes terms used in chapters to follow
- CS-E 20 Engine configuration and Interfaces Describes engine configuration and settings
- CS-E 25 Instructions to continued airworthy Describes the aspects to keep airworthy
- CS-E 30 Assumption Assumptions made when installing the engine
- CS-E 40 Ratings Describes the power and thrust ratings
- CS-E 50 Engine control system Describes the control system demands
- CS-E 60 Provision for instruments Describes instruments installation demands
- CS-E 70 Manufacturing methods Describes durability of materials and engine
- CS-E 80 Equipment Describes equipment installed on the engine
- CS-E 90 Prevention of corrosion Describes prevention of corrosion
- CS-E 100 Strength Describes minimum strength of engine parts

- CS-E 110 Drawings of parts — Describes the demand of proper manuals
- CS-E 120 Identification — Describes the engine must comply with IR 21A.801
- CS-E 130 Fire protection — Describes the fire-protection on the engine
- CS-E 140 Test – Engine configuration — Describes the engine configuration for tests
- CS-E 150 Test – General conduct of tests — Describes how the tests should be performed
- CS-E 160 Test – History — Describes the logs of the tests should be kept
- CS-E 170 Engine system verification — Describes components should perform adequate

B Specific turbine engine demands

The CS-E also has regulations which are related only for the turbine engine, such as the TF-33. These are also described in the same way as the general CS-E. These are a lot more and are shown in **Appendix XIV**.

1.4.2 Environmental regulations

There are very strict regulations about the emission and noise pollution of aircraft at this moment to protect the environment. ICAO is the main organisation concerning the environmental aspects of the law. The two most important environmental aspects are:

1. Noise pollution
2. Emission

ad 1 Noise pollution
The CS-36 about the noise regulations directs through to annex 16 from ICAO. The noise is calculated only by annex 16 in EPNdB (Effected Perceive Noise level). Before the EPNdB can be calculated noise data has to be collected. The specifications about the measurement of these noise is described in annex 16 chapter three. The noise has to be measured in approach, take-off and in fly-over conditions.

- During approach, a microphone has to be place at the extended centreline, at an altitude of 120 m the noise level may not exceed 108 EPNdB.
- During take-off a microphone is placed at 650 m from the extended centreline, this point measures a maximum noise level during take-off.
- The point where the fly over is measured is placed 6500 m from the start of the take-off on the extended centreline this noise may not exceed 108 EPNdB.

After these measurements are done, these values can be used to calculate the noise pollution, this is explained in chapter four of annex 16.

ad 2 Emission
The emission produced by the jet engines is a very delicate subject nowadays due to the green house effect. The emission data of the jet engines can be found in the ICAO Engine Exhaust Emission Databank. This databank also provides the maximum allowed emissions. The Smoke Number (SN) is a dimensionless number which indicates the mass of the exhaust smoke. This can be calculated by a simple formula **(Formula 12)**. This formula shows the calculation of the smoke number. The SN is not allowed to be less than 50.

SN formula $$83.6 \times (F_{00})^{-0,274}$$	F_{00} = Maximum thrust available	F_{00} in Newtons **12.**

There is also the gaseous emission. This is only applicable for engines which have thrust larger than 26.7 kN. This also has a mathematical formula which allows to calculate the maximum gaseous emission allowed. This is shown in **formula 13**.

Hydrocarbons (HC): $D_p/F_{00} < 19,6$ Carbon monoxide (CO): $D_p/F_{00} < 118$	D_p = Mass of pollutioning material F_{00} = Maximum thrust available	**13.** D_p in kilograms F_{00} in Newtons

1.5 Summary TF33

The TF33 is a low by-pass turbofan engine. The engine works according to the Brayton cycle. The pressure and temperature variations are possible by the inlet, compressor stages, combustion chamber, turbine and the nozzle. The TF33 exist of two compressor stages, the LPC and the HPC. The airflow after the LPC is spitted-up in a by-pass airflow and a core engine airflow. The HPC causes another pressure and temperature increasing for the tube annular combustion chamber. After the ignition the hot gasses are passing the engine trough the turbine and exhaust. The turbine drives the compressors and related systems, like fuel pumps, electrical generators for instance. The main purpose of the TF33, like all jet engines is to propel the aircraft. One engine is not enough to propel the aircraft. There are 4 TF33 needed to propel the aircraft. The combustion causes an action, therefore action is reaction, and combustion forces will pass the forces to the attachment bolts, the wings, and the whole aircraft.

2 Engine Selection

All parts of the engine are investigated and with this information a new engine can be chosen. There are very much engines to choose from, so there must be some aspects where can be looked at. First the demands of the NATO must be known. **(2.1)**
When the demands are clear there can be a pre-selection where three engines are selected out of all the engine possibilities, in this selection there must be considered that the engine will fit at the AWACS and that the thrust is enough. **(2.2)**
There are three engines selected and with the specifications of these engines a choice is made, the engine that is best of these three for the AWACS will be the final engine. **(2.3)**

2.1 NATO demands

To decide which engine is most suitable for the AWACS, some operational aspects should be taken into consideration. Even more important are the applied NATO demands. The NATO has given specific demands. Some are preferred demands, and others are obliged demands. It is very important to make sure that the engines are capable of powering the aircraft. Also, additional operating functions, such as a thrust reverser, should be installed **(A)**. Because the current engines are not very efficient this replacement should be an opportunity to install less polluting, less noise generating and more efficient engines **(B)**. This modification should be tested under the worst circumstances in order to guarantee the safety. Also a deciding factor is the maintenance. All demands can be summed up **(C)**.

2.1.1 Performance

To certify the aircraft's new engine, the engines should proof that the performance are adequate to power the aircraft in even the most severe conditions. A safe engine should be guaranteed. Before this can be proven in practice, first in theory all the specifications of the engine should be able to power the aircraft. With these theoretical specifications, a prediction of the actual performances can be established. The performance, such as TSFC, take-off distance required and landing distance required are all very important performance factors. The performance of the engines should be tested under different circumstances, with both practical tests and theoretical tests. The aircraft should be able to take off and land in every possible weather situation. This includes hail, heavy rain and heavy snow. This also includes a take-off and landing on a 'hot day'. Also, the Specific Fuel Consumption [SFC] should be low enough to make the aircraft fly ten hours straight without refuelling, with a True Air Speed [TAS] of 500kts. Unlike the current engines the new engines should be equipped with thrust reversers to minimize the landing distance required. Although the thrust reverser is a very delicate part of the engine housing, it should have excellent performance and durability. The thrust reversers are required to land the aircraft on even the shortest runways.

2.1.2 Efficiency

Because the current engines, TF33, are somewhat inefficient, the fuel consumption is relatively high. To achieve a better efficiency, the new engine should be equipped with a larger bypass ratio. This will improve the efficiency of the engine concerning fuel consumption. Also, the main problem is the noise generation of the current engine. This is an important aspect in the engine selection. Although the engines should produce less noise and use less fuel, it should achieve at least the same thrust as the current engines, in order to guarantee an improvement. Also, most important is the reliability of the engine. The reliability is also an essential factor.
Different, but equally important, aspect is the durability of the engine. The tear and wear of the engine should be as low as possible. Also, it should be easy to maintain the new engine, since the military has a tight maintenance schedule. Troubleshooting should take a minimum amount of time and also replacing a part of the engine should be made as easy as possible. This will save precious time. This can be established by easy access points to the parts of the engine for the maintenance crew.

2.1.3 Summed up demands

All the requirements summed up:

- Theoretical proof that the engine can power the aircraft and all subsystems in all conditions
- The safety of the engine should be proved
- Reliability of the engine is crucial
- Performance capabilities are crucial

- The aircraft should be able to take-off and land in all possible conditions
- The engine should generate less pollution, should be more quiet and more efficient
- The engine housing should be equipped with a thrust reverser
- The aircraft should be able to land at an altitude of 6000 ft.
- The engine should be able to fly ten hours straight without refuelling, at a TAS of 500kts.
- The engine should be very durable and easy to maintain

2.2 Engine Possibilities

With the knowledge of the demands from the NATO, the possible new engine can be chosen. To know which engine is good for the AWACS there are three engines from different producers selected to compare them with each other **(2.2.1)**. All the specifications of these three engines are separated in a table to see which engine is the right one to replace the TF33 **(2.2.2)**.
With all the information of these engines there are calculations made to see the performance of the selected engines **(2.2.3)**. When these calculations are done there advantages and disadvantages of the selected engines are investigated **(2.2.4)**.

2.2.1 Engine Possibilities

With the requirements of the NATO, there can be three engines selected which are theoretical possible to replace the TF33. To select these, there engines there has been looked at the performance and the size, because the engine must fit under the wing of an AWACS. Each engine is from another engine manufacture so it is possible to compare them well with each other. The engines will be the Pratt & Whitney PW 6122 **(A)**, the CFM 56 7B22 **(B)** and the V2524 – A5 **(C)**.

A PW 6122

Pratt & Whitney created the PW 6122 ***(Figure 2.1)***, this engine is used at the Airbus A318-121. It gives 22.000lbs thrust at sea level and with a diameter of 60,0 inches it is 7,0 inches wider than the TF33. The static bypass ratio is 4,90 and has an annular combustion chamber.

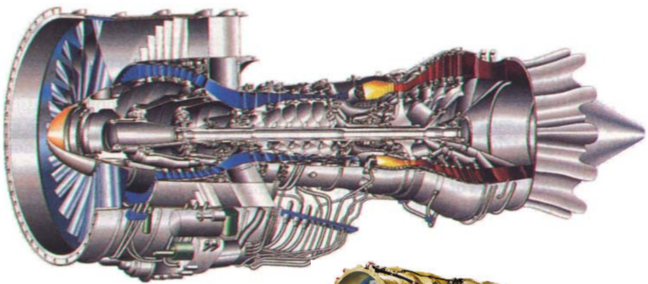


Fig. 2.1: PW 6122

B CFM 56 7B22

The CFM 56 7B22 ***(Figure 2.2)*** is used on the Boeing 737-600/-700/-700BBJ/-800/-800BBJ2, this type of CMF engines is one of the most used types. It delivers a thrust of 22.000lbs at sea level. The diameter of the CFM is 65,0 inches, this is 12,0 inches wider than the old TF33 and it has a bypass ratio of 5,40. The compressor is an axial one, with three low pressure stages and nine high pressure stages.

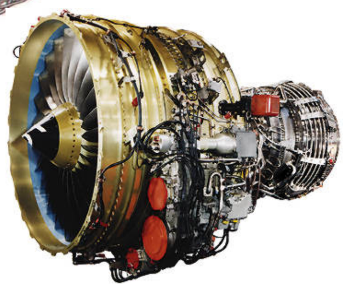


Fig. 2.2: CFM 56 7B22

C V2524 – A5

International Aero Engines AG is a joint venture with among the shareholders Pratt & Whitney and Rolls Royce. The V2524 – A5 ***(Figure 2.3)*** is operational since 1997 and is used at the Airbus A319. This engine delivers 22,000lbs of thrust at sea level and has a bypass ratio of 4,90. It has an axial compressor, with four low pressure stages and ten high pressure stages.

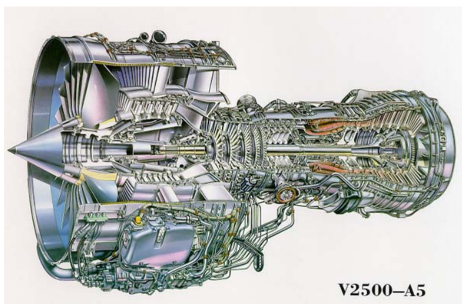


Fig. 2.3: V2524 – A5

2.2.2 Engine Specifications

To choose the best engine of the three selected engines, the specifications of the engines must be looked at thoroughly. In a table the specifications, given by the manufacturers, of the TF33-PW-100A, PW6122, CFM56-7B22 and V2524-A5 are represented to give a good survey of the differences **(Appendix XV)**. The next specifications are described in the table:

- **Manufacturer and model** (In the first and second column respectively the manufacturer and the type of the engine will be described.)
- **Thrust** (Thrust is the maximum power of the engine at MSL, given in lbs.)
- **SFC** (SFC means Specific Fuel Consumption in lb/lbs x hour.)
- **Airflow** (Static airflow is the mass of air which flows through the engine, given in lb/second.)
- **BPR** (BPR is the bypass ratio. It is the ratio between the thrust given by the core engine and the thrust given by the fan. The BPR is a bearing number.)
- **Cruise speed** (The cruise speed is the speed the engine has the highest efficiency, given in Mach. Mach is the ratio between the speed of sound on altitude and the TAS. Mach is a bearing number.)
- **Cruise altitude** (The cruise altitude is the altitude, from MSL, where the engine has the highest efficiency, given in feet.)
- **Fan stages** (The fan stages are the number of fan rotor discs in the engine.)
- **LPC stages** (The LPC stages are the number of rotor discs in the low pressure compressor.)
- **HPC stages** (The HPC stages are the number of rotor discs in the high pressure compressor.)
- **HPT stages** (The HPT stages are the number of rotor discs in the high pressure turbine.)
- **LPT stages** (The LPT stages are the number of rotor discs in the low pressure turbine.)
- **Fan diameter** (Fan diameter is the diameter of the fan in inches.)
- **Length and diameter** (The length and the diameter are the sizes of the complete engine, given in inches.)
- **Dry weight** (The dry weight is the weight of the complete engine, without liquids like lubricating oil etcetera. This is given in lb.)

2.2.3 Engine calculations

In first instance the manufacturer of the aircraft will present some main performances. Other performances during different flight phases can be calculated. Performances that are in relation with the air velocity, air pressure and air temperature. The variables may change during different stages of an engine. For each engine the efficiency and range become the final answer. The engines will be calculated and represent in **Appendix XVI**. From the current engine the PW TF33 **(A)** and the chosen engines: PW-6122, CFM56-7B22 and V2524-A5 **(B-D)** the efficiency and range will be calculated during operation in a standard day with Mean Sea Level [MSL] variables, in a hot day with a high temperature and low pressure, in a cold day International Standard Atmosphere [ISA] with a low temperature and low pressure, on a 6000ft. All formulas for the calculations are represented in **Appendix XVII**. *The most important source that is attended during the calculations is: Aircraft gas-turbines by Rob Scholder 2007.*

A Current engine: TF33

The PW TF33 engine itself has particular performances. The performances are calculated to find an engine with at least the same performances. The most important performances of the new engines are the TSFC, endurance, maximum thrust and its range during different flight phases. To improve these performances, the performances of the old engine must be known. The variables during the calculations for each engine are accepted to equal. The Thrust and SFC of the TF33 are given in **Table 1**.

Operation	Thrust [kN and lbs]	SFC [lb/lbf hr]
Standard day conditions (ISA)	57,28kN / 12862lbs	0,53
Cold day (273K)	60,67kN / 13622lbs	0,524
Hot day (300K)	53,53kN / 12019lbs	0,535
Standard day, on 6000ft. elevation	48,77kN / 10950lbs	0,70

Table 1: Thrust and SFC of TF33

The range and endurance of the TF33 are represented in **Table 2**.

Operation	Range [nm]	Endurance [hr]
Standard day conditions (ISA)	4481nm	10,02hr
Cold day (273K)	4494nm	10,05hr
Hot day (300K)	4465nm	9,99hr
Standard day, on 6000ft. elevation	4877nm	10,05hr

Table 2: Range and endurance of TF33

B PW-6122

In the most ideal way, the range and endurance from the possible engines are better than the current engine, with a lower SFC. The thrust of all engines must be equal in the most ideal way. For the chosen engines also the operation performances are calculated with the same variables. The relative small engine, the PW-6122, has a high BPR, and can operate in general 1000nm more. Also the endurance is more with less thrust. The results are given in **Table 3**.

Operation	Thrust [kN and lbs]	SFC [lb/lbf hr]
Standard day conditions (ISA)	36,71kN / 8243lbs	0,36
Cold day (273K)	37,89kN / 8508lbs	0,355
Hot day (300K)	29,04kN / 6520lbs	0,367
Standard day, on 6000ft. elevation	30,23kN / 6787lbs	0,52

Table 3: Thrust and SFC of PW-6122

The range and endurance of the PW-6122 are represented in **Table 4**.

Operation	Range [nm]	Endurance [hr]
Standard day conditions (ISA)	5491nm	12,28hr
Cold day (273K)	5636nm	12,60hr
Hot day (300K)	4787nm	10,71hr
Standard day, on 6000ft. elevation	5606nm	12,54hr

Table 4: Range and endurance of PW-6122

C CFM56-7B22

This engine has in general a range of 5400nm this is an improvement in contrast to the range from the TF33. Despite of all, this engine must have its benefits from its high endurance, instead of its thrust performances. The CFM56-7B22 has a high thrust that means a high value of the SFC. The results are presented in **Table 5**.

Operation	Thrust [kN and lbs]	SFC [lb/lbf hr]
Standard day conditions (ISA)	42,66kN / 9579lbs	0,38
Cold day (273K)	45,41kN / 10195lbs	0,371
Hot day (300K)	34,75kN / 7803lbs	0,388
Standard day, on 6000ft. elevation	36,48kN / 8190lbs	0,53

Table 5: Thrust and SFC of CFM56-7B22

The range and endurance of the CFM56-7B22 are represented in **Table 6**.

Operation	Range [nm]	Endurance [hr]
Standard day conditions (ISA)	5165nm	11,55hr
Cold day (273K)	5197nm	11,63hr
Hot day (300K)	5510nm	12,32hr
Standard day, on 6000ft. elevation	5192nm	11,61hr

Table 6: Range and endurance of CFM56-7B22

D V2524-A5

The last chosen engine, the V2524-A5, has variable results. The engine has a high by-pass ratio, so it can perform long range with a low value of thrust. The results are presented in **Table 7**.

Operation	Thrust [kN and lbs]	SFC [lb/lbf hr]
Standard day conditions (ISA)	28,82kN / 6472lbs	0,36
Cold day (273K)	34,89kN / 7834lbs	0,355
Hot day (300K)	kN / lbs	0,367
Standard day, on 6000ft. elevation	27,53kN / 6181lbs	0,52

Table 7: Thrust and SFC of V2524-A5

The range and endurance of the V2524-A5 are represented in **Table 8**.

Operation	Range [nm]	Endurance [hr]
Standard day conditions (ISA)	4601nm	10,29hr
Cold day (273K)	5410nm	12,10hr
Hot day (300K)	nm	hr
Standard day, on 6000ft. elevation	5309nm	11,87hr

Table 8: Range and endurance of V2524-A5

2.2.4 Advantages and disadvantages

After the three possible engines are analyzed and the performance of each one is calculated, the advantages and disadvantages of each engine will be investigated. There are several important aspects the engines will be judged for. For every aspect an engine will get a rating; ++ means excellent, + means good, +/- means satisfactory, - means unsatisfactory and -- means bad. These ratings of the three engines are compared to each other to get a clear view about the differences so the best possible engine can be picked to replace the old TF33 engines.
The aspects the engines are judged for are:

1. TSFC
2. Thrust
3. Weight
4. Range
5. Endurance
6. Emission
7. Noise

Ad 1 TSFC
It is important to look at the TSFC of each engine because the TSFC tells a lot about the fuel consumption per hour which is relating to the operational costs. The TSFC has also effect on the range of the aircraft, it is therefore important that the TSFC is as low as possible.
All the three engines have the same TSFC, 0.036 Kg/N hr. The old engine, the TF33 has a TSFC of 0.056 Kg/N hr so all the engines are a big improvement. All the engines are therefore good enough for the replacement compared to the old ones.

Ad 2 Thrust
The thrust of each engine is examined because the thrust the engine generates tells something about the maximum speed of the aircraft and the take-off distance required.
The thrust the CFM 56-7B22 can generate at cruise speed is 22.700 lb. the PW6122 can deliver 22.000 lb. The V2524-A5 can deliver 24.000 lb. compared to the old engine, which delivers 22.000 lb this is a little more. The V2524-A5 delivers the most thrust and is therefore the best rated for this aspect. The other two engines are satisfactory.

Ad 3 Weight
Weight is an important aspect in the engine choice because each wing must be able to withstand the force of two engines. And of course the higher the engine weight the higher the fuel consumption is.
The CFM 56-7B22 has a weight of 2368Kg. the PW6122 has a weight of 1866 Kg. And the V2524-A5 has a weight of 2331 Kg. It is clear that the PW6122 has a much lower weight than the other two engines that makes that this engine is rated excellent in weight compared to the other two.

Ad 4 Range
The range of the engines is very important because the AWACS must be able to operate in large distances. Equipped with the old engines the AWACS had a range of about 4500 nm as can be seen in chapter 2.2.3. As can be seen in chapter 2.2.3 the engine that has the largest range on a standard day is the PW6122 with a range of about 5500 nm, this range is much larger than the TF33 and the engine is therefore rated ‘excellent’ at this aspect. The CFM-56 7B22 has a little larger range as the TF33 and is therefore rated ‘good’. The V2524-A5 has a range of 4600 nm which is the lowest range of the three engines and just a little more than the TF33, it is therefore rated ‘satisfactory’.

Ad 5 Endurance
The endurance of the new engine is very important because the AWACS has a surveillance goal and therefore needs to be able to spend at least 10 hours in the air with a TAS of 500 Knots. That is the time the old engines could stay in the air without refuelling.

All the engines have the possibility to stay in flight for 10 hours without refuelling. The PW6122 has however the longest endurance of over 12 hours and is therefore rated ‘excellent’. The CFM56-7B has an endurance of 11.5 hours and is therefore rated ‘good’. The V2524-A5 has a range that is about the same as the TF33 and is therefore rated ‘satisfactory’.

Ad 6 Emission

Nowadays the environmental health is a big issue all over the world, the aviation industry has to comply with a lot of rules concerning for example the engine emission. The old TF33 engines have too much emission of toxic gasses to be allowed to operate much longer. Therefore the new engines must be much cleaner.
The CFM 56-7B22 has a dual annular combustor especially designed for a minimum emission. Pratt & Whitney is also investing in low NOx emission by means of the development of the Technology for Advanced Low NOx [TALON] combustors installed on the PW6122. These two engines are therefore rated excellent and the V2524-A5 is rated satisfactory.

Ad 7 Noise

Most of the airports around the world have very strict noise restriction laws. It is therefore important that the replacing engine meets all the present laws of noise emission.
Pratt & Whitney has developed the Geared TurboFan [GTF] technology which reduces the noise with five till ten decibels. Therefore the PW6122 is rated ‘excellent’. Because the noise levels of the other two engines are well within the limits, these are rated ‘good’.

After all the engines have been rated on seven important aspects the results are placed in a table so it becomes easy to see the differences between the three engines **(Table 9)**.

	CFM 56-7B22	V2524-A5	PW6122
TSFC	+	+	+
Thrust	+/-	+	+/-
Weight	+	+	++
Range	+	+/-	++
Endurance	+	+/-	++
Emission	++	+/-	++
Noise	+	+	++

Table 9: engine comparison

2.3 Engine selection

One engine type must be chosen to replace the old engines on the AWACS. Of course the new engine must have at least the same performance as the TF33. After all the demands of the NATO are put together, three engines can be picked with the right sizes and a performance that complies with the NATO demands. These three possible engines are the PW6122 from Pratt & Whitney, the CFM56-7B from General electric and the V2524-A5 from Rolls Royce and Pratt & Whitney.
The specifications of these engines are analyzed and the performance of these engines in calculated under different conditions so the engines could be compared to each other. The engines are compared to each other at seven important aspects; TSFC, thrust, weight, range, endurance, emission and noise. The results of that investigation are placed in a table so it becomes clear which engine scores the best at each aspect and which engine is the best to replace the TF33.
In table 2.x (chapter 2.2.4) can be seen that not one of the engines has a negative rating for any aspect. Every engine is capable of replacing the old TF33 and is even much more economical. There is however one engine that is compared to the other two the best to replace the old engines. The total points every engine has can be counted if every ‘+’ is worth one point, every ‘-‘ is minus one point and the ‘+/-‘ is neutral. Counting the points of every engine, it can be seen that the V2524-A5 scores the least points (4). The CFM-56 7B22 has three points more but the PW6122 from Pratt & Whitney scores eleven points. This means that the PW6122 is by far better than the other two engines for the NATO and is therefore the best engine to replace the old TF33. The PW6122 scores the best at almost every aspect. Another advantage of the PW6122 is that it has the same manufacturer as the TF33, what means that it will probably be easier to connect the new engine to the systems in the aircraft.

3 Modification aspects

After having chosen the new engine, it is to have a close look at the additional matters.
At first there must be looked at the technical modification aspects **(3.1)**.
The place and the engine pylons must be adapted to be compatible with the PW6122 engine. Also must be investigated if some subsystems, like fuel systems etc., must be adapted, updated or replaced.
Maintenance is also a very important component for the NATO. The engines must be easy in maintenance. The maintenance crew of the NATO must be retrained to get enough knowledge of the PW6122 to maintain it **(3.2)**.
The costs to re-engine an aircraft are very high and unpredictable, so there must be made a very detailed overview between the costs and benefits of re-engaging the AWACS. On the basis of the costs and benefits overview a recommendation, re-engine or do not re-engine, can be given to the NATO **(3.3)**.

3.1 Technical modification aspects

The current engine and subsystems design is from the 1960's. In the meantime there have been several advantages the design of engines and subsystems. To modify the E-3A it is necessary to get clarity about the replacement of the chosen engine **(3.1.1)**. Some subsystems must be replaced or upgraded, because they don't work together with the brand new PW6122 engine **(3.1.2)**.

3.1.1 Replacement of the chosen engine

As stated in the previous chapter, the TF33 engine will be replaced with a new PW6122. Thereby the size of the new engine **(A)** has to be taken into account, as well as the engine controls **(B)**. When these problems are overlooked, the modification can be reviewed **(C)**.

A. Engine size

To minimize damage during takeoff, landing and taxiing, a clearance between the engines and ground is needed. The current ground clearance of the E3-A inboard engine with the ground is 0,84m. Because the diameter of a new PW6122 engine is 0,27m larger, a new and smaller pylon has to be fitted. The old pylon is large enough to be shortened by 0,27m. The ground clearance and safety margin can therefore remain the same. The weight is reduced because of the smaller pylon.

B. Engine controls

The PW6122 is controlled and monitored by means of the FADEC system. This fully digital system is more advanced than the mechanical monitoring and control system which is now in use for the TF33 engine. Therefore the old system needs to be replaced by the FADEC-system of the PW6122. This also means that all the mechanical components from the old monitoring and control system have to be replaced by new digital components. For example, the mechanical transmission from the thrust levers used with the TF33 engine has to become digital to work with the FADEC system, which then regulates the power setting. Because the mechanical links are replaced with electric wires, a weight reduction can be arranged.

C. Replacement

The PW6122s weight is a little more than the old TF33 engine, but can be fitted with minimal structural customization. The location of the engines cannot be changed, because this change will affect the aerodynamic characteristics of the aircraft.
The D-check occurs approximately every four to five years of operating an aircraft, to keep the aircraft airworthy. During this check, more or less the entire aircraft will be taken apart for inspection. During this check the engines will also be removed from the aircraft. This is the best moment to replace the engines, because the aircraft is already out of service, in a hangar, with the engines removed.

3.1.2 Replacement of subsystems

An airplane has got a lot of subsystems depending on the engine. For each type of engine are specific subsystems. When a new type of engine is placed, some subsystems, has to be completely or partially, replaced or adapted. The subsystems are divided into hydraulic **(A)**, pneumatic **(B)**, avionics **(C)** and thrust reversers **(D)**.

A. Hydraulic subsystems

The hydraulic systems are driven by the engine gearbox, which is driven by the HPC shaft.
The hydraulic components are:

1. Fuel pumps
2. Lubrication
3. Other hydraulic systems

Ad 1 Fuel pumps
The fuel pumps are directly driven by the gearbox of the engine.
This is a mechanical connection, so it is easy to adapt. Because the PW6122 and the TF33 are both Pratt & Whitney products, there is a chance the mechanical connection fits instantly.

Ad 2 Lubrication
The new PW6122 engine has got its own integrated lubricating system. The TF33 lubricating is very divergent from the PW6122, so the new integrated system must be used.

Ad 3 Other hydraulic systems
Some other hydraulic systems like the systems for landing gear extension and flight controls are driven by the engine. These systems are pressured by engine driven pumps which are connected to the gearbox of the engine. Because this is a mechanical connection, it is easy to adapt. Because the PW6122 and the TF33 are both manufactured by Pratt & Whitney, there is a chance the mechanical connection fits instantly.

B. Pneumatic subsystems

The pneumatic subsystems are driven by air pressure coming from the engine, called:

1. Bleed air
2. Air starter motor

Ad 1 Bleed air
Some pneumatic systems are directly powered from air pressure, coming from the HDC and LDC. For example this can be anti-icing or the air conditioning system. The PW6122 has its own integrated bleed air system, so only the tubes to the subsystems have to be connected.

Ad 2 Air starter motor
In the PW6122 the air starter motor is integrated, so it is not necessary to use the TF33 air starter motor, which probably does not fit on the PW6122. The air starter motor is driven by air, coming from the APU or a ground power unit. Only the tube from the engine to the aircraft has to be connected.

C. Avionics

Some of the electronic components, or avionics, must be replaced or updated. These components could be to send signals or electricity to the engine, or vice-versa.
The avionics are:

1. Generator
2. FADEC

Ad 1 Generator
To supply the aircraft from electricity during flight and taxiing, a generator, called the integrated drive generator, is provided. This generator is mechanically driven by the gearbox of the engine. Because this is a mechanical connection, it is easy to adapt. Because the PW6122 and the TF33 are both manufactured by Pratt & Whitney, there is a chance the mechanical connection fits instantly.

Ad 2 FADEC
The FADEC is a very important computer which is tuned to the specific engine where it is made for. That means the FADEC used for the TF33 is not compatible with the PW6122. The FADEC must be replaced for a PW6122 compatible one.

D. Thrust reversers

To decrease the required landing distance, thrust reversers must be placed on the PW6122 engines. For this engine the "blocker doors" thrust reversers are the best option. This is because this type only reverses bypass air, so it does not damage by the hot exhaust gases. The there is a lot of bypass air available, so this is not a problem.
The thrust reverser has to be connected to a hydraulic system. Also the thrust levers have to be replaced or adapted. This is because the TF33 did not have thrust reversers, so the original thrust levers in the AWACS are not prepared for thrust reverse.

3.2 Maintenance

To keep the aircraft airworthy it is important that regular maintenance is done. The maintenance procedure and instructions of an engine is based on manufacturer's recommendations and approved by the airworthy authorities. Due to technical advances Pratt & Whitney has reduced the amount of parts in the PW6000 series what results in easier and cheaper maintenance. There can be two kinds of maintenance on the engine; if the engine stays on the wing during the maintenance action, it is called on-wing maintenance **(3.2.1)**. If the engine is removed completely from the wing for the maintenance action it is called overhaul maintenance **(3.2.2)**.

3.2.1 On-wing maintenance

The maintenance done when the engine is still fixed on the wing can be scheduled, the engine must be checked on regular basis to maintain the safety **(A)**. Due to for example a bird strike or a failure it can be possible that unexpected maintenance has to be applied, this is called unscheduled maintenance **(B)**.

A Scheduled maintenance

Scheduled maintenance includes the periodic checks that have to be applied in accordance with the aircraft maintenance schedule **(Appendix XVIII)**. In this maintenance schedule the item which has to be checked is written down, the period the maintenance has to be applied and the specific action that has to be applied. The time before the maintenance must be done is called the 'not exceed limit', usually calculated in aircraft flying hours of flight cycles. These checks vary from transit checks, which are not very complicated and have to be done after every flight cycle, to more complicated checks which have to be done within a certain amount of flight hours.

B Unscheduled maintenance

The unscheduled maintenance consists of actions that are not related to time limits. This necessary maintenance is unexpected and it is often important that the action is quick accomplished so the flight schedule of the aircraft gets no delays. The unscheduled maintenance is mostly caused by something like a bird strike, a strike of a lightning or heavy landing. It is also possible that a malfunction occurs or a rectification adjustment or replacement recommendation of the manufacturer has to be done.
Unscheduled maintenance often brings high costs if it takes too long to accomplish the specific actions it is therefore important that an engine is easy accessible, the amount of components is as least as possible and there are reliable condition monitoring systems. The PW6122 is therefore a large improvement compared to the old TF33 engine because Patt & Whtiney designed this engine with less components than any P&W engine.

3.2.2 Overhaul maintenance

After a specific time period (a certain amount of flight hours), recommended by the manufacturer and approved by the airworthy authorities, the engines have to be removed from the wing and certain components have to be replaced. The time an engine may fly without replacing these components is called 'Time Between Overhauls' [TBO]. The purpose of an overhaul is to restore the engine so it can continue it's life with new performance limitations and the same reliability. This is achieved by dismantling the engine in order that parts can be inspected for their condition and to determine the need for renewal or repair of the parts whose deterioration would reduce the performance of the engine.
To prevent that at a certain time a lot of the engines need an overhaul it is important to make a time schedule for all the engines in the fleet. It is important that the overhaul is not done exactly at the expiry date of the TBO to prevent that an aircraft is grounded because of an engine failure. To reduce the time an overhaul takes, the engine consists of different modules which all have a specific function. In the motor shop, where the overhaul takes place, the different modules are disassembled and complete modules are replaced.

3.3 Costs, benefits and recommendation

When deciding whether to perform the modification, or not, depends largely on the financial aspects. A good investigation of the costs is required to make sure a modification is realizable. An overview is required to sum up and explain all the costs of the modification. This summation is crucial to investigate the possibilities. Replacing the engines will take time and costs money **(3.3.1)**. Also equally important are the financial benefits which comes with replacing the engines **(3.3.2)**. This financial analyzes will result in a complete recommendation. This recommendation includes the benefits which are not value related. The recommendation also includes a complete summation of the financial aspects. This will also include a break-even table which will show the time it will take to recoup the investment **(3.3.3)**.

3.3.1 Costs

There are several costs that need to be taken into consideration. These costs are either material costs or non-material costs. The costs described are necessary to install and to operate the engine. The costs of the modification are admitted in tables. The purchasing of the engine, including the piston, cowling and related systems like thrust-reverser are calculated **(A)**. After purchasing the units, these units must be installed. The costs of the installation including the required equipment and tools are shown **(B)**. The technical service and the pilots are not trained to manage the new installation; therefore the staff must be re-schooled **(C)**. When the aircraft is reinstalled the documents and the aircraft are not valid and airworthy anymore, they must be adjusted for the new engines. The costs for the documents and the costs for the certification are shown **(D)**. The total costs of the whole modification are calculated **(E)**.

A Engine purchase

The engine and all related systems will have to be bought and installed. The purchase of the entire engine system consist of the engine itself, the cowling, the pylon, the thrust reversers, the hang-up pins, the control wiring, the databus, the symbol generator and the LCD screen. These are all required in different amounts, such as **Table 10** shows.

Unit	Unit amount	Unit costs [€]	Total price [€]
PW-6122 engine	4	8.000.000,-	32.000.000,-
Cowling	4	900.000,-	3.600.000,-
Pylon	4	150.000,-	600.000,-
Thrust-reverser	4	500.000,-	2.000.000,-
Hang-up pins	12	13.333,-	160.000,-
Control wire ring	1500m	10,-/m	15.000,-
Databus (ARINC 429)	2	4.000,-	8.000,-
Symbol generator	2	3.000,-	6.000,-
LCD-screen	2	8.000,-	16.000,-
			Total 38.405.000,-

Table 10: Purchase

B Engine installation

Once purchased, the engine needs to be installed. This is done during maintenance and is carried out by the maintenance crew. The installation of the engine will take 1000 man hours, while installing the related systems will take 400 man hours. To carry out this modification, some additional equipment is required. This is shown in **Table 11**.

Unit	Unit amount	Unit costs [€/hr]	Total price [€]
Engine installation	1000 man hr	40,-	40.000,-
Related systems install.	400 man hr	40,-	16.000,-
Equipment & Tools	-	25.000,-	25.000,-
			Total 81.000,-

Table 11: Installation

C Crew training

The new engines comes with new specifications. This means the maintenance crew needs to gain additional information about the new engine in order to perform the maintenance **(Table 12)**. The engine needs to be maintained with a slightly different method. Also, the crew needs to learn how to handle the new test and maintenance equipment. Also, the pilots and instructors need to be trained in order to know has changed in flight performance since the modification.

Unit	Unit amount	Unit costs [€/hr]	Total price [€]
Instructors	600 man hr	200,-	120.000,-
Pilots	200 man hr	150,-	30.000,-
Technical staff	300 man hr	60,-	18.000,-
			Total 168.000,-

Table 12: Re-schooling

D Certification

Because the aircraft will have a structural change, the aircraft will have to be certified with this new configuration. This will require to hire specially trained test pilots which should be educated about the new installation prior to the certification flight. Also the EASA should check and inspect the new configuration. This is carried out by a special delegation. Also, to certify the engine, the current manuals need to be alternated which is costly **(Table 13)**.

Unit	Unit amount	Unit costs [€]	Total price [€]
Test pilot	100 man hr	200,-	20.000,-
EASA delegation	50 man hrs	100,-	5.000,-
Manual alteration	100 pages	460,-	46.000,-
			Total 71.000,-

Table 13: Documents and certification

E Total costs

All these costs can be summed up. These costs are the actual purchase, implementation and maintenance costs. These are shown in **Table 14**. The re-schooling costs are divided by twenty to spread the costs over the number of aircraft in service.

Aspect	Price [€]
Purchase	38.405.000,-
Installation	81.000,-
Re-schooling	8.400,-
Documents and certification	71.000,-
	Total 38.565.400,-

Table 14: Total costs

This concludes that the total modification costs per aircraft is € **38.565.400,-**

3.3.2 Benefits

Costs that are made by consuming fuel and a lot of maintenance hours before the modification are benefits after the modification. The new engine is a newer engine and brings fewer costs components will wear less. This new engine is also more fuel efficient and will burn less fuel, therefore less costs. The benefits that are produced by maintenance are shown **(A)**. The benefits that are produced by spilling less fuel are shown **(B)**. To show that the new engines have profit costs, made by fuel and maintenance, these are shown, respectively **(C)** and **(D)**. The total profit after the modification is shown **(E)**. All the calculations are relative and based on one year.

A Maintenance costs new engine

The new engine will have to undergo maintenance. These maintenance checks are very time consuming, which is very costly. By reducing the time necessary for maintenance money can be saved and the aircraft can be airborne sooner. There are two checks described as maintenance checks in **Table 15**. These are the A check and C check. The crew also needs the equipment and replacement parts to carry out the maintenance.

Aspect	Unit amount	Unit costs [€]	Total price [€]
A check	50hr	50,-	2.500,-
C check	150hr	50,-	7.500,-
Equipment	-	10.000,-	10.000,-
Overhaul maintenance	-	500.000,-	500.000,-
			Total 520.000,-

Table 15: PW-6122 maintenance costs per year.

B Flight cycle fuel consumption with new engines

By increasing the efficiency of the engines, the fuel consumption will decrease. This will result in a financial benefit concerning fuel consumption. **Table 16** describes the fuel necessary for the new engine, during a flight cycle.

Flight phase	Unit amount [kg·sec]	Unit costs [€/kg]	Total price [€]
Taxi	0,10kg ·900 sec	0,65,-	58,50,-
Take-off	6,20kg · 45 sec	0,65,-	181,35,-
Climb	3,07kg · 1200 sec	0,65,-	2.394,60,-
Cruise	1,54kg · 43200 sec	0,65,-	43.243,20,-
Decent	2,02kg · 1600 sec	0,65,-	2.100,80,-
Landing	0,66kg ·1600 sec	0,65,-	686,40,-
			Total 48.664,85,-

Table 16: PW-6122 example fuel costs per flight.

C Maintenance costs current engine

The maintenance costs on the current installed engines are somewhat higher that the new ones. This will result in a more inefficient maintenance schedule which is more time consuming. This will result in higher costs and will cause the aircraft to be on ground for an extended period of time. The current maintenance costs are described in **Table 17**.

Aspect	Unit amount	Unit costs [€]	Total price [€]
A check	100hr	50,-	5.000,-
C check	500hr	50,-	25.000,-
Equipment	-	20.000,-	20.000,-
Overhaul maintenance	-	700.000,-	700.000,-
			Total 750.000,-

Table 17: TF33 maintenance costs per year.

D Flight cycle fuel consumption with current engines

The fuel consumption of the current installed engines is drastically higher than with the new ones installed. The entire flight cycle fuel cost with the old engine is shown in **Table 18**.

Flight phase	Unit amount [kg·sec]	Unit costs [€/kg]	Total price [€]
Taxi	0,20kg ·900 sec	0,65,-	117,00,-
Take-off	13,80kg · 45 sec	0,65,-	279,45,-
Climb	6,15kg · 1200 sec	0,65,-	4.797,00,-
Cruise	3,40kg · 43200 sec	0,65,-	95.472,00,-
Decent	4,32kg · 1600 sec	0,65,-	4.492,80,-
Landing	1,57kg ·1600 sec	0,65,-	1.632,80,-
			Total 106.791,05,-

Table 18: TF33 example fuel costs per flight.

E Total profit

Since all aspects for the current engine and the new engine are compared to each other, a complete summary can be made. This includes a comparison for the maintenance costs and fuel consumption costs. This is shown in **Table 19**.

aspect	Price [€]
Maintenance PW-6122	520.000,-
Fuel PW-6122	20 · 48.664,-
	Total 1.493280,-
Maintenance TF33	750.000,-
Fuel	20 · 106.791,-
	Total 2.885.820,-
Total TF33 minus	2.885.820,-
Total PW-6122	1.493280,-
profit	**Total 1.392.540,-**

Table 19: Total benefits

This table shows that the total financial profit of the modification is **€ 1.392.540 per year.**

3.3.3 Recommendation

The group has investigated the current aircraft engine and the new aircraft engine. All aspects are reviewed, for build-up to implementation aspects and financial aspects. The cost-effectiveness of the modification should be investigated **(A)**. The financial costs and benefit aspects are crucial for the recommendation although these are all financial benefits. There are also non-financial benefits to be discussed **(B)**. Eventually, the group will give a final recommendation to the NATO delegation **(C)**.

A Cost effectiveness

To investigate the cost effectiveness, the 'remaining time in service' of the aircraft should be revised. The NATO plans to use the aircraft for another fifteen years to come. The financial benefits of the modification depends on this remaining time. From a financial perspective, the investment of the modification should be able to recoup in this fifteen years. **Table 20** shows a schematic overview which shows in what period of time the investment is recouped.

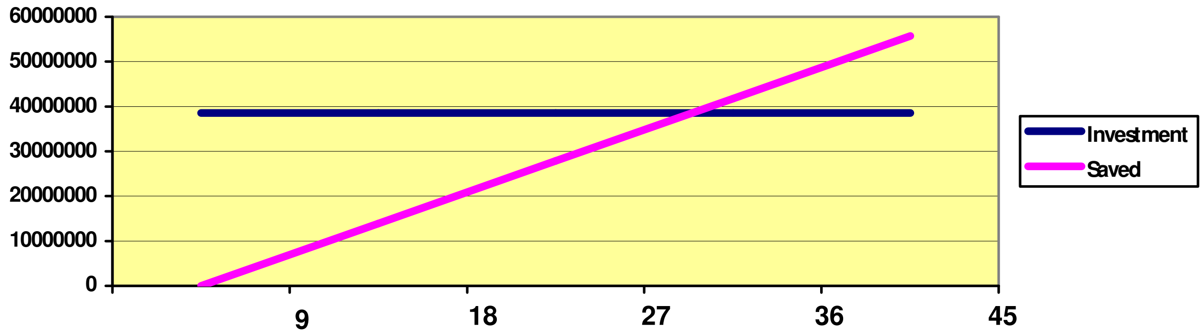


Table 20: Break-even Graphic

$$\frac{38.565.400}{1.392.540} = 27{,}7 \text{ years}$$

The investment will be recouped after 28 years. This is thirteen years more than the aircraft will remain in service. Now a conclusion can be made with help of the table. From a financial perspective, the modification is not profitable.

B Non-financial aspects

Although the modification is not financially profitable, it is not the actual conclusion. There are also non-financial benefits with this possible modification. These are almost equally important in deciding whether to perform the modification or not. The military airport of Geilenkirschen copes with governmental issues concerning environmental aspects. These are mostly noise nuisance related. By installing the new engines, this can be reduced drastically. The new engines are more efficient and produce relatively less noise. Eventually this is very profitable since Geilenkirschen airport can perform more flights a day. Also the emission is an issue. The new engine produces less emission which is harmful for the environment. This can also be useful for moral aspects. More important is the fact that the installed thrust reversers will decrease the landing distance required. This means that the aircraft will be able to land on more airports worldwide. Because the aircraft is more fuel efficient, this will not only be profitable in finances but also the aircraft can stay longer airborne.

C Final recommendation

Now since all aspects are reviewed a final recommendation can be made. This is our conclusion:

Although there is a improvement on yearly base, it will not make up for the investment within the fifteen years of remaining service. The benefits concerning environmental aspects are very positive but do not weigh up to the high investment costs. The aircraft are purchased for 70 million US dollars (1977), which is equal to 49,3 million euros. When comparing the modification costs to the actual purchase costs it is obvious a modification is not rational.

Project group 2A2K recommends: Not to perform the modification.

3.4 Conclusion Implementation

A jet engine has the purpose to power the NATO's AWACS, therefore a TF33 is used. Because of the inefficiencies and the produce of too much noise there is searched for a new engine. The TF33 gas turbine jet must be totally understand before this re-engine of the AWACS starts. There are physic laws that take place in a jet engine, the Brayton cycle is one of those laws. It is a thermodynamic cycle in a jet engine and knows four states: Intake, compression, expansion and exhaust.
The jet engine can be divided into different parts, the inlet, compressor, combustion chamber, turbine and the exhaust. These part are investigated to fully understand the working of the engine. Than the fuel system is described with all the subsystems, with all this knowledge there can be selected three possible engines for the re-engine project.
To know which engines can be selected the demands of the NATO must be clear, the demands are made for the fuel consumption and other thing like the produce of noise.
The three selected engines are the Pratt & Whitney PW 6122, the CFM 56 7B22 and the V2524 – A5. This selection is based on performance and the given demands. To get the best out of these three pre-selected engines there are calculations made, these are about the performance in different weather conditions. With this knowledge the advantages and disadvantages are summed to get a clear view about the performance of the engines. Then there is one engine chosen which has the best performance under every weather conditions, this chosen engine is the Pratt & Whitney PW 6122.
To place the new engine there must be looked at the used systems because it is possible that some of these system must be modified. Then the maintenance of the PW 6122 is investigated to know when and how this must be done. The costs of the modification are € 600.000.000,- total, with a break-even point in 27 years. Because all the AWACS will be replaced in 15 years it is not profitable, therefore the modification is not recommended.

List of sources

Bibliography

Books

Fundamentals of aircraft power plants
Department of the army
1990

Aircraft general knowledge - power plant
Oxford
2001

Rolls Royce - the jet engine
Rolls Royce
1996

Technology of the Jet Airplane
The Jet Age: Part II
1974

Websites

http://www.cfm56.com/

http://www.cfm56.com/index.php?level2=gallery&level3=gallery_viewer&gallery_id=1&gallery_image_index=2&gallery_start=1&affiliate_uid

http://www.hansonline.eu/wright100/techniek.htm#straalmotor

http://www.hansonline.eu/wright100/straalmotor.htm

http://www.aerospaceweb.org/question/propulsion/q0033.shtml

http://www.youtube.com/watch?v=p1TqwAKwMuM

http://www.pw.utc.com/vgn-ext-templating/v/index.jsp?vgnextoid=eb7ba372f544c010VgnVCM1000000881000aRCRD

http://travel.howstuffworks.com/framed.htm?parent=turbine.htm&url=http://www.ueet.nasa.gov/Engines101.html

http://books.google.nl/books?id=VpJEm7cFVE4C&pg=PA14&dq=gas+turbine+engines&sig=pfMusen1CJCGIuo2qCVf2Gy09UE#PPP11,M1

http://www.geae.com/engines/index.html

Abbreviation list

ADC	Air Data Computer
AWACS	Airborne Warning And Control System
APU	Auxiliary Power Unit
BPR	By-Pass Ratio
CS	Certification Specifications
EEC	Electrical Engine Control
EASA	European Aviation Safety Agency
EGT	Exhaust Gas Temperature
FCU	Flight Control Unit
FOD	Foreign Object Damage
FSN	Fuel Spray Nozzles
FADACS	Full Authority Digital Engine Control System
FQMC	Fuel Quantity Management Computer
GTF	Geared TurboFan
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IPC	Intermediate Pressure Compressor
ICAO	International Civil Aviation Organization
ISA	International Standard Atmosphere
LCD	Liquid Crystal Display
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
MSL	Mean Sea Level
MEL	Medium Equipment List
NATO	North Atlantic Threat organisation
OAT	Outside Air Temperature
RPM	Rounds per Minute
SFC	Specific Fuel Consumption
TALON	Technology for Advanced Low NOx
TSFC	Thrust Specific Fuel Consumption
TBO	Time Between Overhauls
TAS	True Air Speed
VSV	Variable Stator Vanes

List of appendices

Appendix I Assignment definition

The assignment definition of this project is to give the students of the Amsterdamse School of Technology an explicit assignment to modify the engines of the Boeing 707-320 ‘E-3 Sentry’. This is an aircraft with an Airborne Warning And Control System [AWACS] used to monitor airspace for military purpose, while airborne. The engines of this aircraft, in service of the North Atlantic Treaty Organization [NATO], are out-dated and must be replaced. The possibility of replacement must be investigated and described in a report. These possibilities should be described. Seventeen of NATO E-3 Sentry’s are stationed at the airbase Geilenkirschen (BRD) in Germany. This airbase, close to the Dutch border, operates with inefficient aircraft. The out-dated engines are very noisy and contaminated. Because the pollution of air and noise nuisance are not a case of the NATO but the Dutch government, they must finance the cost of the modification. In case of a successful investigation the NATO shall cooperate.
Before the investigation starts, a clear plan of approach must be present. The purpose of the project is to investigate the possibility to replace the engines of the Boeing 707 E-3 Sentry in first instance. The investigation should include the possibilities if there are any similar engines, with the required performances and dimensions that can fit on this type of the Boeing 707. These engines can be chosen when the performance, dimensions, type and knowledge of the engine and related systems are investigated of the current engines. The current engines can operate during landing and take-off under the worst weather conditions on airfield, with an elevation of 6000ft. The current engine provides a thrust force of 98kN each. And the engines can have 10 hours of operational flying time without refuelling, with a True Airspeed [TAS] of 500kts. The new engines must have at least the same performance as the current engines. After all the main purpose is to find an engine that is less polluting as the current engine. With a model of a design investigation it is possible to find the best engine to fit on the E-3 Sentry. All additional matters such as costs, maintenance and modification plan must be described too.

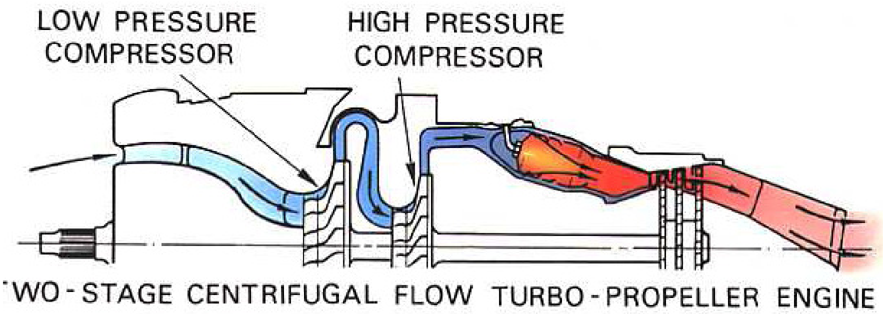
Appendix II Specifications AWACS

Wingspan	44,45 m
Length	46,48 m
Height	12,70 m
Radar dome diameter	9,1 m
Radar dome thickness	1,8 m
Power plant	4x TF-33 Pratt & Whitney 1C
Endurance	11 hour (without refuelling)
Flight crew	14 Persons

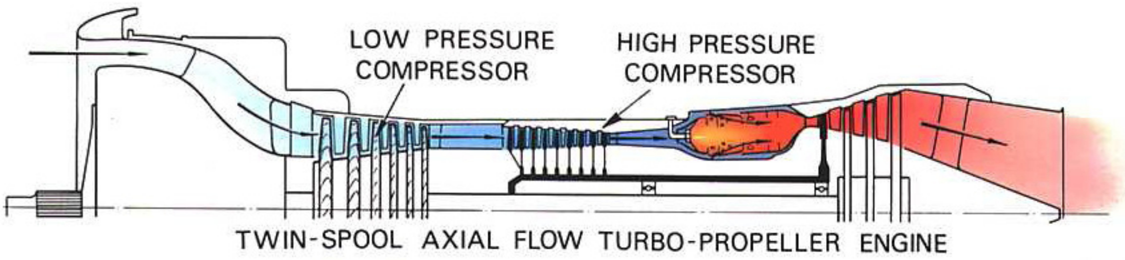
Appendix III Schematic overview engines

An schematic overview of the most common engines shows the way how the airflow is passing the core and by-pass section. Difference between temperatures of the airflow is representing with a colour. The red colour is representing a warm airflow and the blue colour is representing a cold airflow. The combustion is an orange chamber in the middle of each engine. By axial engines the black component is representing the high pressure compressor.

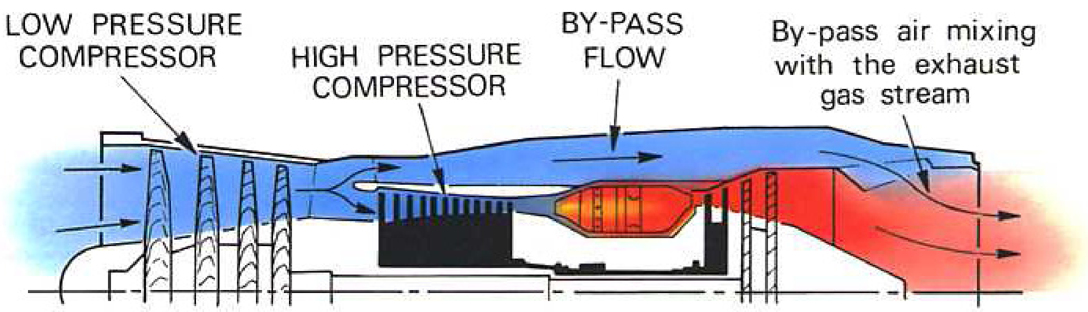
A Two stage centrifugal flow engine



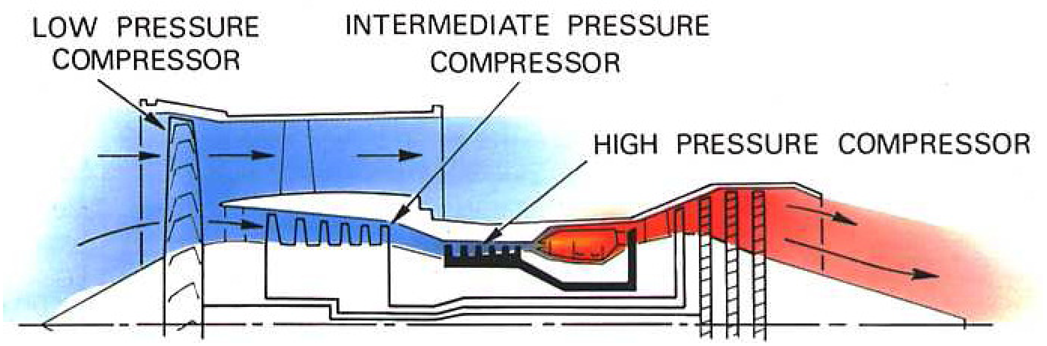
B Twin spool axial flow engine



C Twin spool axial flow low by-pass engine

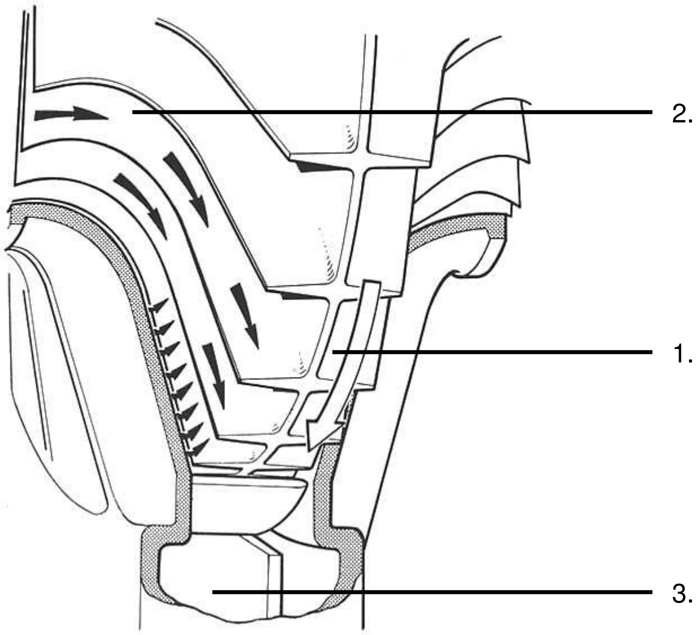


D Triple spool axial flow high by-pass engine



Appendix IV Centrifugal Flow Compressor

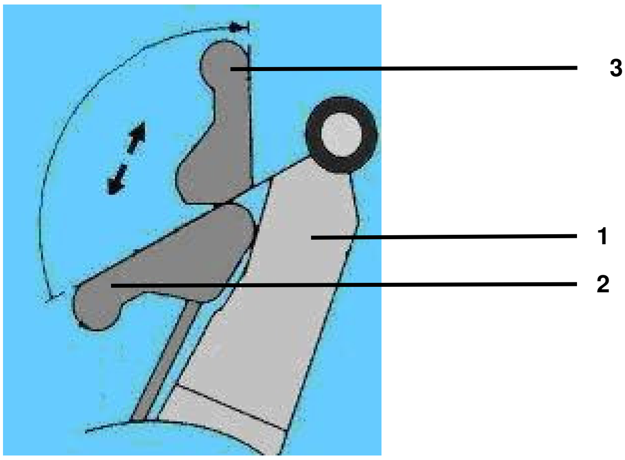
The rotating centrifugal flow compressor impellors **(1)** causes an centrifugal action on the air. The air moves from the centre to the rim of the impeller **(2)**. The high air velocity and pressure is captured at this edge by an diffuser **(3)**. The diffuser leads the compressed air to the next impeller.



1. rotating impellor
2. Centre of impellor
3. Diffuser

Appendix V Throttle

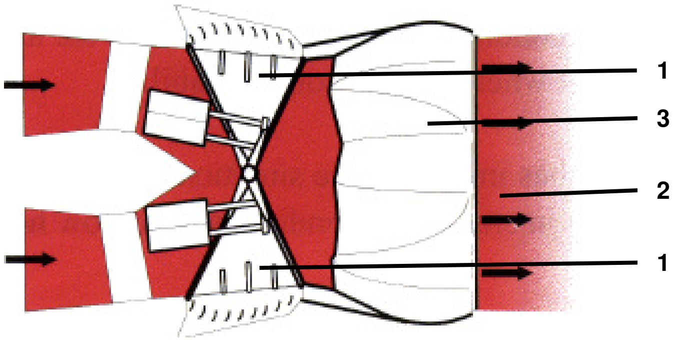
When the throttle is in the idle position **(1)** and the thrust reverse handle is in the down position **(2)**, the thrust reverser is stowed. When the handle is in the up position **(3)** the thrust reverser deployed and reverse thrust is applied.



3. Throttle
4. Thrust reverse handle down
5. Thrust reverse handle up

Appendix VI Clamshell doors stowed

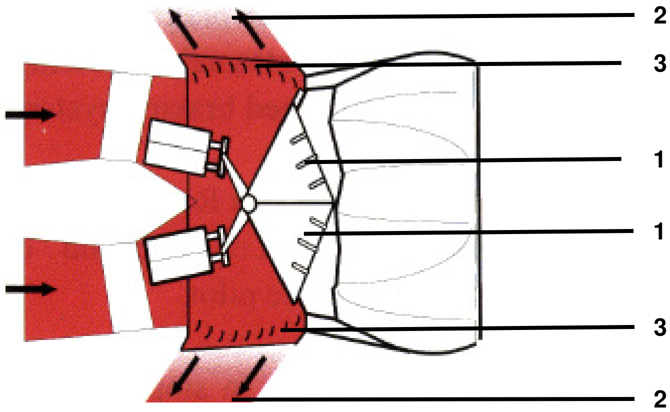
When the clamshell doors **(1)** are stowed the exhaust gas **(2)** leaves the engine through the nozzle **(3)**.



1. Clamshell door
2. Exhaust gas
3. Nozzle

Appendix VII Clamshell doors deployed

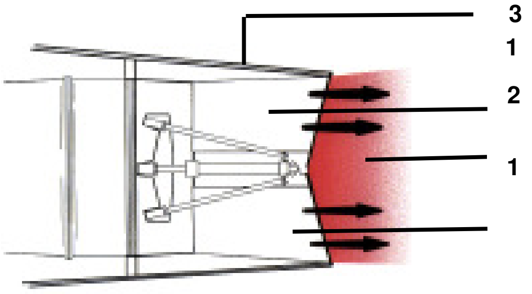
When the clamshell doors are deployed **(1)** the exhaust gas exit is closed, so all the exhaust **(2)** gas leaves the engine through cascade vanes **(3)**.



1. Clamshell door
2. Exhaust gas
3. Cascade vanes

Appendix VIII Bucket doors stowed

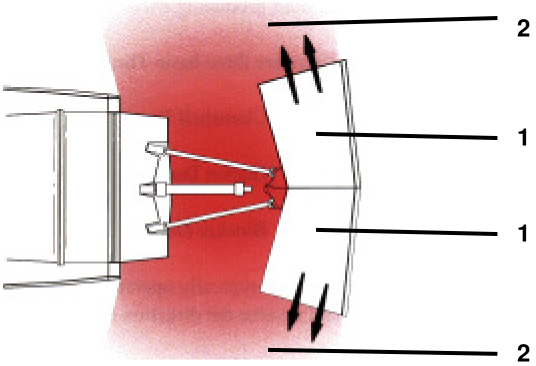
When the bucket doors **(1)** are stowed the exhaust gas **(2)** leaves the engine through the rear part of the nozzle **(3)**.



1.	Bucket door
2.	Exhaust gas
3.	Rear nozzle

Appendix IX Bucket doors deployed

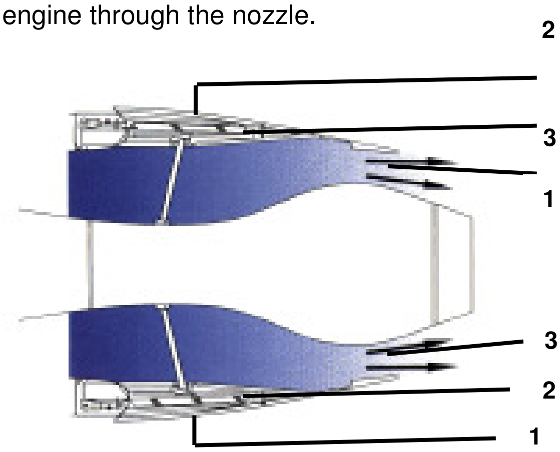
When the bucket doors are deployed **(1)** the exhaust gas exit is closed, so all the exhaust gas **(2)** leaves the engine.



1. Bucket door
2. Exhaust gas

Appendix X Blocker doors stowed

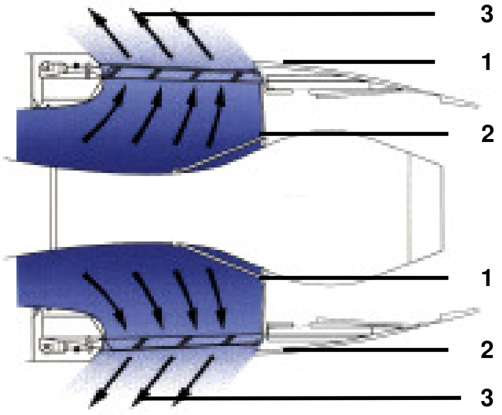
When the translating cowls **(1)** are stowed and the blocker doors **(2)** are open, the by-pass air **(3)** leaves the engine through the nozzle.



1. Translating cowl
2. Blocker door open
3. By-pass air

Appendix XI Blocker doors deployed

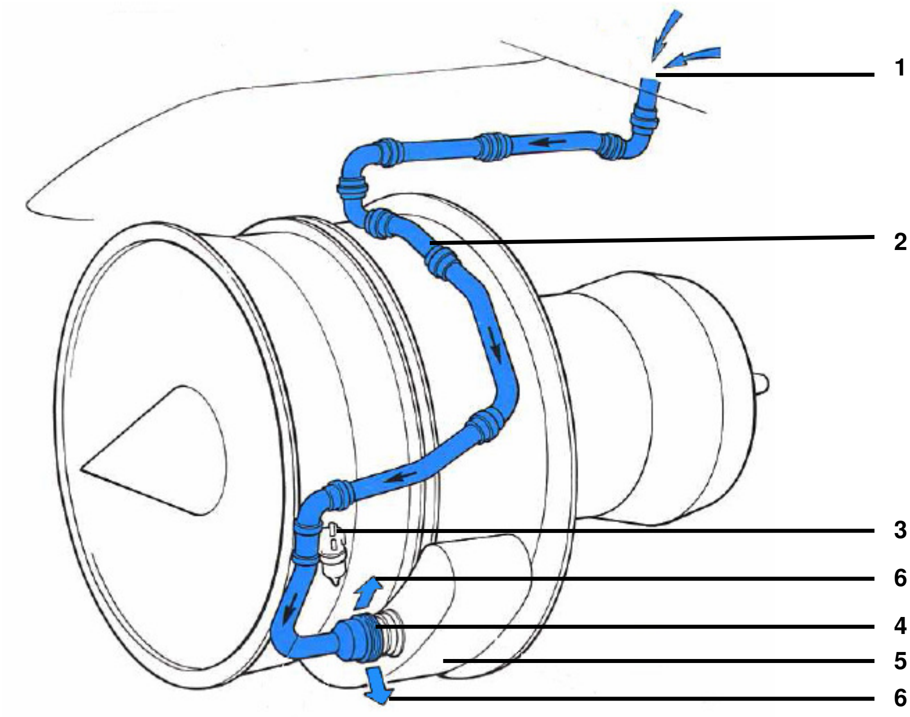
When the translating cowl slides backwards **(1)** the by-pass is closed by blocker doors **(2)**, so the by-pass air **(3)** leaves the engine.



1. Clamshell door
2. Blocker door closed
3. By-pass air

Appendix XII Inlet starter motor

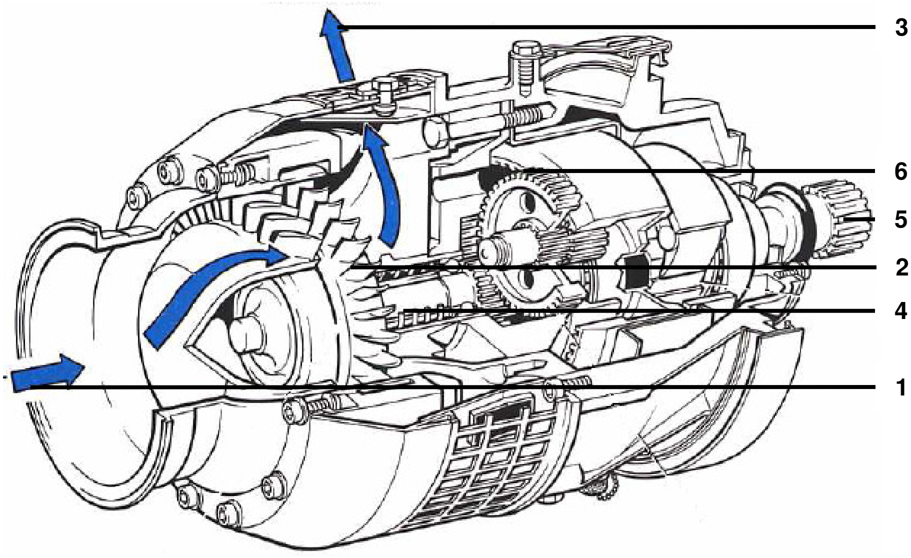
The air for the inlet of the starter motor is obtained from the APU or a ground power unit **(1)**. The air is travelled by a pipe **(2)** through an air control valve **(3)**. From now the air enters the air starter motor **(4)**, which is connected to the gearbox **(5)**. The exhaust air **(6)** is escaped sideways from the starter motor.



1. Air inlet
2. Pipe
3. Air control valve
4. Air starter motor
5. Gearbox
6. Exhaust air

Appendix XIII The air starter motor

The air from the inlet **(1)** drives the turbine **(2)**. Air after the turbine is drained through the air outlet **(3)**. The power from the turbine shaft **(4)** is given to the engine drive shaft **(5)** through a reduction gear **(6)**



1. Air inlet
2. Turbine
3. Air outlet
4. Turbine shaft
5. Engine drive shaft
6. Reduction gear

Appendix XIV Type substantiation section E

SECTION E – TURBINE ENGINES; TYPE SUBSTANTIATION
CS-E 600 Tests - General
CS-E 620 Performance Corrections
CS-E 640 Pressure Loads
CS-E 650 Vibration Surveys
CS-E 660 Fuel Pressure and Temperature
CS-E 670 Contaminated Fuel
CS-E 680 Inclination and Gyroscopic Load Effects
CS-E 690 Engine Bleed
CS-E 700 Excess Operating Conditions
CS-E 710 Rotor Locking Tests
CS-E 720 Continuous Ignition
CS-E 730 Engine Calibration Tests
CS-E 740 Endurance Tests
CS-E 745 Engine Acceleration
CS-E 750 Starting Tests
CS-E 770 Low Temperature Starting Tests
CS-E 780 Tests in Ice Forming Conditions
CS-E 790 Ingestion of Rain and Hail
CS-E 800 Bird Strike and Ingestion
CS-E 810 Compressor and Turbine Blade Failure
CS-E 820 Over-Torque Test
CS-E 830 Maximum Engine Over-speed
CS-E 840 Rotor Integrity
CS-E 850 Compressor/Fan and Turbine Shafts
CS-E 860 Turbine Rotor Over-Temperature
CS-E 870 Exhaust Gas Over-Temperature Test
CS-E 880 Tests with Refrigerant Injection for Take -Off and/or 2½ -Minute
OEI Power Certification Specifications for Engines – Issue 1
EASA CS-E book 1 Rev-book 7 21 March 2003
CS-E 890 Thrust Reverser Tests
CS-E 900 Propeller Parking Brake
CS-E 910 Relighting in Flight
CS-E 920 Over-temperature Test

Appendix XV TF-33 Specifications

Manufacturer	Model	Thrust [lbf]	SFC [lb/lbf hr]	Airflow (static) [lb/s]	BPR (static)	Cruise Speed [M]	Cruise Altitude [ft]	Fan Stages	LPC Stages	HPC Stages	HPT Stages	LPT Stages	Fan Diameter [inches]	Length [inches]	Diameter [inches]	Dry Weight [lb]
Pratt Whitney	TF33-PW-100A	21000	0,56	450	1,25	0,8	33000	2	7	7	2	2	51,2	136,3	56	4145
Pratt Whitney	PW6122	22000	0,36	650	5	0,8	34000	1	4	5	1	3	56,5	92	60	4115
CFM	CFM56-7B22	22700	0,36	726	5,4	0,8	35000	1	3	9	1	4	61	98,87	65	5216
International Aero Engines	V2524-A5	23500	0,36	772	4,9	0,7	35000	1	4	10	2	5	63,5	126,0	67,5	5139

Appendix XVI Excel Calculations

Legenda	
T stand = Standard temperature	η fan = fan efficiency
T am = Ambient temperature	η jf = jet fan efficiency
P stand = Standard pressure	η lpc = low pressure compr. efficiency
P am = Ambient pressure	η hpc = high pressure compr. efficiency
π ldc = low pressure ratio	η lpt = low pressure turbine efficiency
π tot = total pressure ratio	η hpt = high pressure turbine efficiency
EGT = Exhaust gas temperature	η mech = mechanical efficiency
FPR = Fan pressure ratio	η jet = η pn = propelling nozzle efficiency
BPR = By pass ratio	
m total = total mass of air per second	ρ = air density according to the standard atmosphere
m fuel = Fuel mass per second	ρ 0 = ambient air dencity
m hot = Mass of air through core engine	ρ 1.8 = air density after fan
m cold = mass of bypass air	ρ 8 = gas density after exhaust
Ygas = gas Poisson exponent	
Yair = air Poisson exponent	
T 01 = Total Air temperature	P 01 = Inlet total air pressure
T 012 = True total air temprature after fan	P 012 = Air total pressure after fan
T 012' = Isentropic total air temperature after fan	P 012c = Total pressure after low pressure compressor
T 01.8 = Inlet temperature jet fan	P 03 = Total pressure after high pressure compressor
T 1.8 = true temperature after jet fan	P 04 = Gas total pressure after combustion chamber
T 1.8' = Calculated temperature after jet fan	P 04.9 = Gas total pressure after high pressure turbine
T 02c = True total air temperature begin High pressure compressor	P 05 = Gas total pressure after low pressure turbine
T 02c' = Isentropic begin total temperature High pressure compressor	P 8 = Exhaust gas pressure
T 03 = True total temperature after high pressure compressor	P cr = Critical gas pressure
T 03' = Isentropic total temperature after High pressure compressor	
T 04= True total temperature after combustion chamber	Cax = Speed of air in the inlet
T 04.9 = True Total temperature after high pressure turbine	C 2.8 = Air speed after fan
T 04.9' = Isentropic total temperature after high pressure turbine	C 8 = Gas speed after exhaust
T 05 = True total temperature after low pressure turbine	
T 05' = Isentropic total temperature after low pressure turbine	D fan = Diameter fan
T 08 = True total exhaust gas temperature	D cone = Diameter cone
T 08' = Isentropic total exhaust gas temperature	Rs = Specific gas constant
	A 1.8 = Fan nozzle area
TSFC = Thrust Specific Fuel Consumption	A 8 = Core exhaust nozzle area
	a sound = local sound speed

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Appendix XVII Formulas for calculations

Variables	**Formulas**
P 01 = Inlet total air pressure [Bar]	$P01 = P_{am} \cdot (\frac{T01}{T_{am}})^{\frac{\gamma}{\gamma-1}}$
T 01 = Total Air temperature [K]	$T01 = T_{am} + (\frac{C_{vl}{}^2}{2 \cdot C_{pl}})$
m total = total mass of air per second [kg/s]	
m fuel = Fuel mass per second [kg/s]	$\Phi_{fuel} = \frac{\Phi_{BP} \cdot T04 \cdot C_{pg} - T03 \cdot C_{pl}}{H0 \cdot \eta_{burner} - C_{pg} \cdot T04}$
a sound = local sound speed [m/s]	$a = \sqrt{\gamma_{air} \cdot R_s \cdot T_{am}}$
P 01.2 = Air total pressure after fan [Bar]	$FPR \cdot P01$
T 01.2' = Isentropic total air temperature after fan [K]	$T01.2' = T01 \cdot (\frac{P01.2}{P01})^{\frac{\gamma}{\gamma-1}}$
T 01.2 = True total air temperature after fan [K]	$T01.2 = T01 + \frac{T02' - T01}{\eta_f}$
Pcr = Critical gas pressure [Bar]	$P_{cr} = P01.2 \cdot (1 - \frac{(\gamma - 1)}{\eta_{if} \cdot (\gamma + 1)})^{\frac{\gamma}{\gamma-1}}$
T 1.8' = Calculated temperature after jet fan [K]	$T01.8' = T01.2 \cdot (\frac{2}{2 \cdot \gamma})$
T 1.8 = true temperature after jet fan [K]	$T_{cr} = T01.2 \cdot (\frac{2}{\gamma + 1})$
C 1.8 = Air speed after fan [m/s]	$C1.8 = \sqrt{\gamma_{air} \cdot R_s \cdot T1.8}$
F thrcold = Thrust by-pass [kN]	
ρ 1.8 = air density after fan [kg/m³]	$\rho 1.8 = \frac{P_{cr} \cdot 10^5}{R_s \cdot T1.8}$
A 1.8 = Fan nozzle area [m²]	$A1.8 = \frac{\Phi_{air} \cdot (\frac{BPR}{BPR + 1})}{C1.8 \cdot \rho 1.8 \cdot \tau}$
P 02c = Total pressure after LPC [Bar]	$P02c = \pi_{LPC} \cdot P01$
P 03 = Total pressure after HPC [Bar]	$P03 = \pi_{tot} \cdot P01$
T 02c' = Isentropic begin total temperature HPC [K]	$T02c' = T01 \cdot (\frac{P02c}{P01})^{\frac{\gamma}{\gamma-1}}$
T 02c = True total air temperature begin HPC [K]	$T02c = T01 + \frac{T02c' - T01}{\eta_{LPC}}$
T 03' = Isentropic total temperature after HPC [K]	$T03' = T02c \cdot (\frac{P_{am}}{P03c})^{\frac{\gamma}{\gamma-1}}$
T 03 = True total temperature after HPC [K]	$T03 = T02c + \frac{T03' - T02c}{\eta_{HPC}}$
T 04= True total temperature after combustion chamber - T 04.9 = True Total temperature after high pressure turbine [K]	$T04 - T04.9 = \frac{C_{pl} \cdot (T03 - T02c)}{cpgas \cdot \eta_{mech}}$

T 04.9 = True Total temperature after high pressure turbine - T 05 = True total temperature after low pressure turbine [K]	$T04.9-T05=\frac{\Phi_{BP}\cdot C_{pl}\cdot(T02-T01)+m_{ce}\cdot C_{pl}\cdot(T02c-T01)}{m_{ce}\cdot cpgas\cdot\eta_{mech}}$
T 04.9' = Isentropic total temperature after high pressure turbine [K]	$T04.9'=T04-\frac{T04-T04.9}{\eta_{HPT}}$
T 04.9 = True Total temperature after high pressure turbine [K]	$T04.9=T04-(T04-T04.9)$
T 04= True total temperature after combustion chamber =TIT [K]	$T04=EGT+(T04-T04.9)$
T 05 = True total temperature after low pressure turbine [K]	$T05=T04.9-(T04.9-T05)$
T 05' = Isentropic total temperature after low pressure turbine [K]	$T05'=T04.9-\frac{T04.9-T05}{\eta_{LPT}}$
C 8 = Gas speed after exhaust [m/s]	$C8=\sqrt{\gamma_{gas}\cdot R_s\cdot T8}$ of $C8=\sqrt{2\cdot C_{pl}\cdot(T05-T08)}$
P 04 = Gas total pressure after comb. cham. [Bar]	$P04=P03-\Delta P$
P 04.9 = Gas total pressure after high pressure turbine [Bar]	$P04.9=P04\cdot(\frac{T04.9'}{T04})^{\frac{\gamma}{\gamma-1}}$
P 05 = Gas total pressure after low pressure turbine [Bar]	$P05=P04\cdot(\frac{T05'}{T04})^{\frac{\gamma}{\gamma-1}}$
Pcr = Critical gas pressure [Bar]	$P_{cr}=P05\cdot(1-\frac{(\gamma-1)}{\eta_{jf}\cdot(\gamma+1)})^{\frac{\gamma}{\gamma-1}}$
Tcr = true temperature critical [K]	$T_{cr}=T05\cdot(\frac{2}{\gamma+1})$
T 08 = True total exhaust gas temperature = EGT [K]	$T08=T05-\eta_{pn}\cdot(T05-T08')$
T 08' = Isentropic total exhaust gas temperature [K]	$T08'=T05\cdot(\frac{P08}{P05})^{\frac{\gamma}{\gamma-1}}$
F thrhot =Thrust engine core [kN]	$F_{ce}=\Phi_{gas}\cdot(C08-C_{vl})+A08\cdot(Pcr-Pam)\cdot 10^5$
Tce=Temperature core engine [K]	$T_{ce}=\Phi_f\cdot(C08-C_{vl})$
F thrust total = F thrhot + F thrcold [kN]	$F_{ce}=\Phi_{gas}\cdot(C08-C_{vl})+A08\cdot(Pcr-Pam)\cdot 10^5$ +
A 8 = Core exhaust nozzle area [m²]	$A1.8=\frac{\Phi_{gas}\cdot R_s\cdot T08}{Pcr\cdot C8}$
TSFC = Thrust Specific Fuel Consumption [kh/N.h]	$TSFC=\frac{m_{fuel}\cdot 3600}{F_{tot.thrust}\cdot 1000}$
F_{fan} = Thrust fan when chocked [N]	$\Phi_{Bp}\cdot(C1.8-C_{vl})$
F_{fan} = Thrust fan when un-chocked [N]	$\Phi_{Bp}\cdot(C1.8-C_{vl})+A1.8\cdot(P_{cr}-P01)\cdot 10^5$
m_{bp} = Air trough the bypass per second [kg/s]	$\Phi_{Bp}=\Phi_{air}\cdot(\frac{BPR}{BPR+1})$
M_{ce} = Air trough the core engine per second [kg/s]	$\Phi_{ce}=\Phi_{air}\cdot(\frac{1}{BPR+1})$

η thd = Efficiency thd	$\eta_{thd} = \dfrac{\tau_h \cdot (1 - \frac{1}{\tau_\lambda}) \cdot \eta_{HPT} - (T_c - 1)\frac{1}{\eta_{HPC}}}{\tau_\lambda - (\frac{\tau_c - 1}{\eta_{HPC}} + 1)}$
Endurance [hr]	$End. = \dfrac{\max fuel - resfuel - taxifuel}{\Phi_{fuel} \cdot 3600}$
Range [nm]	$Rng. = End. \cdot \dfrac{TAS \cdot 3{,}6}{1{,}852}$
η thd = Efficiency prop	$\eta_{prop} = \dfrac{2 \cdot BPR \cdot (C1.8 - TAS) \cdot TAS + (C08 - TAS)}{BPR \cdot (C1.8^2 - TAS^2) + (C08^2 - TAS}$

Appendix XVIII Maintenance schedule

ITEM	NOT EXCEED LIMIT	REQUIREMENT
Engine oil tank	Flight termination	Check oil level. Replenish as necessary. Record amount taken
Cowls	Transit	Check the pod cowls for damage and external evidence of fuel and oil leaks
Caps and access panels	Transit	Check secure
Engine intake	Transit	Check clear. Free from damage and loose objects
Turbine and exhaust collector	Transit	Visually inspect for signs of damage and metal deposits
Engine intake	25 hours	Visually inspect front of engine through air intake for signs of damage paying particular attention to intake guide vanes and leading stage rotor blades
Turbine and exhaust collector	25 hours	Visually inspect L.P.2 turbine blades, nozzle guide vanes and mixer unit for cracking and damage by viewing from rear using a strong spot light
Fuel filter	125 hours	Drain sample and check for water contamination
Magnetic chip detector	200 hours	Remove and inspect
Igniter plugs	200 hours	Audibly check operation
Oil pressure filter	600 hours	Check and clean/renew filter element
Fuel filter	800 hours	Remove filter element, check and renew

Appendix XIX Group process

Anthony Hovenburg

This project was a very interesting project which I've learned from a lot. Now I really have the feeling like I master all the aspects on an aircraft. I also got very interested in the subpart jet engines . I found it a very educating project. The project assignment was also very good. Since the beginning of this study I've been looking forward to this assignment. Too bad I did not perform as well as I could, due to certain private circumstances and therefore did not meet every deadline. I'm glad I managed to do every task which was assigned to me eventually, with success. Also there were some minor problems with the minutes, of which I'm happy it was solved. The project group was a nice group which was fun to work with, and with nice people which where I could laugh a lot. It was the first time I was in a project group where the schedule which was made up prior to the project, was followed all the way through the project. Also the minutes were followed very good although sometimes the deadlines were sometimes nearly pros poned, also because of me. This is probably the most educating part of the project for me. I've learned a lot from being in a group which functions properly. I'm quite happy about this.

Robert de Haas

Just like the first project we had to complete this project in seven weeks. We started with a preliminary document to become familiar with the project assignment and found general information about an engine. We also made a tight planning with acceptable deadlines, but just like the previous projects things went good and wrong. We had to deal with private circumstances in the third week followed by a displacement of the deadlines more forward. As a result of the displacement we had to work harder in the last couple of weeks. Now coming to the end of the project everybody worked hard and we delivered a nice report.

Arthur van Schalkwijk

This project was very interesting and educational. I have learned a lot about the gas turbine and its subsystems. We made a good planning and the deadlines were determined, but not always the given deadlines were acquired. One and a half week I was absent, because I was hit by a pneumonia. This delayed the progress of the report. There was at most of the time a good mood between the group members, which is also important. I think that we worked well on this project report.
This period was also a very hard period for me, because I had a lot of important subjects, like mathematics and mechanics, which must be re-examinated.

Thomas Schijf

Seven weeks for such a comprehensive project is to short. If I read the report, I shall discover the description of the most important engine explanation. The report is too basic in comparison to the level it has to be. My opinion is we had to little information sources and it was difficult to find them. The process during the weeks was bad, this due to a slow start-up of the project. We spent two weeks for making a simple start document, from that point we got behind.

Erwin Steen

The main problems that most students faced during the last project were that pieces of the project were not finished in time, that students did not show up or came late at meetings and that the students did not follow the lay-out agreements.
The first problem we faced was that some students always showed up late during or simply did not show up when a meeting was planned. Sometimes this was not such a problem, but on the other hand it created delay in the progress of the project because those students were not aware of the status of the project or what their tasks were. Another negative side of this problem was that they either did not know what had to be corrected in their previously made parts.
The second problem was that some group members would not hand in their work on time. This all eventually resulted in a higher work load for the group in the last weeks, because we had to transform the bits and pieces into one report with proper lay-out and had to correct the mistakes in the pieces.
The special assignment needed a lot of time to and was done by three students. This was taking into account when making the planning, so it was fine.
A positive thing about this project was the planning, which had an evenly spread work load over the whole period and made it possible for the group to hand in the report on time.

Daan Touw

The assignment to re-engine the AWACS was a very interesting project, there are a lot of new thing I have learned. The project group consists out of seven people, only one of them has worked with me in an earlier project. At the start everybody was motivated and really want to do thing for the project but when the first deadline came there where parts that were not done. This can happen once but that continues to happen. That was a problem in this period, after we talked together there was a little difference in the work attitude. After all it was an interesting project and the project group was nice but sometimes there must be some harder work.

Dion Zumbrink

The time working in project group 2AK was over all a good experience. Everybody started this project very motivated although some problems occurred during the time of the project. A sickness of a team member and some private problems of another member caused some delays and not all the deadlines where made by everybody. At the end all the delays where made up by a great team effort in the last week.
The cooperation in the project group was good because the communication was good and the problems where cleared out. If anybody needed help there were always other members who helped them out.
The ‘buddy system’ that was inserted at the start of the project did not worked well for everybody in the group, I however did used it and it helped me well in some cases.
After all I am glad with the result and group A2K.

Appendix XX Task list

	Robert	Anthony	Arthur	Thomas	Erwin	Daan	Dion
<u>Chapter1. General purpose (TF-33)</u>							
1.1 Several engines and engine E-3A Sentry		X					
1.1.1 Purpose		X					
1.1.2 Gas turbine engines			X				
1.1.3 The E-3A Sentry						X	
1.2 Description engine E-3A Sentry							
1.2.1 Inlet				X			
1.2.2 Compressor				X			
1.2.3 Combustion chamber						X	
1.2.4 Turbine					X		
1.2.5 Exhaust					X		
1.2.6 Fuel	X						
1.2.7 Related systems	X						
1.3 Forces and Vibrations on an engine							
1.3.1 Forces during different phases of flight							X
1.3.2 Vibrations							X
1.4 Statutory demands			X				X
1.5 Summary TF-33				X			
<u>Chapter2. Engine selection</u>							
2.1 NATO demands		X					
2.2 Engine possibilities							
2.2.1 Engine possibilities						X	
2.2.2 Engine specifications			X				
2.2.3 Engine calculations	X				X		
2.2.4 Advantages and disadvantages							X
2.3 Conclusion Engine selection							X
<u>Chapter3. Modification aspects</u>							
3.1 Technical modification aspects							
3.1.1 Replacement of the chosen engine					X		
3.1.2 Replacement or maintain subsystems			X				
3.2 Maintenance							X
3.3 Costs, benefits and recommendation							
3.3.1Costs and benefits				X			
3.3.2 Recommendation		X					
3.4 Conclusion implementation						X	
Cover				X			
Summary							X
Introduction	X						
Table of contens	X					X	
Abbreviation list				X			
List of appendices						X	
Verslag ordenen				X		X	
Bijlage ordenen						X	