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SINGLE VS. TWO STAGE HIGH PRESSURE TURBINE DESIGN OF MODERN AERO ENGINES

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ABSTRACT

In this paper, the two-stage shrouded HPT engine configuration rated at 22000 lbs thrust is used as the baseline from which a single stage HPT unshrouded design is systematically derived to evaluate the potential weight and cost advantage. The baseline thermodynamic cycle at the rated thrust level was modified in order to optimize the turbine inlet temperature, overall pressure ratio, and core flow with a single stage HPT and deliver competitive performance. The comparative study, although preliminary in depth, has led to the advantages and disadvantages associated with an unshrouded single versus a two-stage shrouded HPT design. The results compare design configuration, secondary air system, weight, safety, life, specific fuel consumption (SFC), and future thrust growth capability. The main advantages of the single stage application are reductions in cost and complexity of design, lower turbine gas temperature, and ease of maintenance. The main disadvantages are in reduced turbine polytropic/isentropic efficiency for HPC pressure ratio greater than 9, increased SFC, higher rim speed, higher HPT exit Mach number, higher bypass ratio to achieve the desired thrust level, and possibly higher weight. A quantitative statement on the reduction of engine cost/weight is premature until a detailed design and the associated cost-benefit is performed. The paper concludes by recommending that the design philosophy of the modern unmixed turbofan engine (single or two-stage HPT) leads to a balance between the selected turbine gas temperature versus the by-pass ratio in order to minimize cost and maximize the thrust-to-weight ratio and the cycle efficiency. In either case, the expected high reliability and reduced engine cost/weight in the context of future thrust-growth capability need to be demonstrated by proven technology which seem to favor the two-stage HPT configuration.

NOMENCLATURE

A	area, m²
a	speed of sound, m/s
c	absolute velocity, m/s
c_0	inlet velocity, m/s
c_p	specific heat at constant pressure, J/kg-K
F	thrust, lbF
H	enthalpy, J/kg
H_u	fuel heating value, J/kg
m	mass flow, kg/s
N	rotational speed, RPM
P	pressure, N/m²
r	radius, m
s	entropy, J/kg-K
T	temperature, K
u	peripheral speed, m/s
w	relative velocity, m/s
η	efficiency
κ	ratio of specific heats
λ	bypass ratio
π	pressure ratio (P_{exit}/P_{inlet})
π'	pressure ratio (P_{inlet}/P_{exit})
ω	angular speed, Rad/s
Δ	downstream minus upstream

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ABBREVIATIONS

BPR	by-pass ratio
BRR/BR	BMW Rolls-Royce
FLA	future large aircraft
HPC	high pressure compressor
HPT	high pressure turbine
iso	isentropic
LPC	low pressure compressor
LPT	low pressure turbine
MD	McDonnell Douglas
NGV	nozzle guide vane
PR	pressure ratio (high-to-low)
PW	Pratt & Whitney
SOT	stator outlet temperature
SS	single stage
TS	two stage

INTRODUCTION

The BR715 unmixed turbofan aero engine rated at 22000 lbs thrust, which belongs to the BR700 engine family, is proposed for regional aircraft in the 100-130 seat class and for military transport aircraft. It has been selected to power the Boeing 717-200 (formerly MD 95) aircraft. The BR715 engines will be rear fuselage mounted with a fan diameter of 58 inches, or they will be mounted under the wings with a fan diameter of 56 inches.

In a gas turbine, the turbine work depends on the temperature drop between the turbine inlet and exit (Eq.1). The temperature drop depends directly on the pressure drop; hence, the turbine work is also proportional to the turbine pressure ratio.

$$\Delta H_T = c_p \Delta T$$

$$\Delta T = T_{exit} - T_{inlet} = T_{inlet}\left[\frac{T_{exit}}{T_{inlet}} - 1\right] \qquad (1)$$

$$\frac{T_{exit}}{T_{inlet}} = \left(\frac{P_{exit}}{P_{inlet}}\right)^{\frac{\kappa-1}{\kappa}} = \Pi_T^{\frac{\kappa-1}{\kappa}} \qquad \text{Isentropic relationship}$$

$$\Rightarrow \Delta H_T \propto \Pi_T$$

Moreover, the turbine has a maximum limit of power, which is proportional to the enthalpy difference. The turbine power as a parameter depends on the turbine aerodynamics; therefore, if more power is needed from a turbine to drive a compressor with a given compressor pressure ratio, the number of the turbine stages must be increased.

In a two spool aero engine, the high speed shaft connects the high pressure turbine (HPT) to the high pressure compressor (HPC). The number of the HPT stages depends on the pressure ratio across the HPC and at the same time, the thrust depends on the HPC pressure ratio; thus, the thrust depends directly on the HPT pressure ratio. The thrust depends also on the amount of the secondary air mass flow, which is taken from the total mass flow, and used to cool the hot engine parts without the turbine extracting work from it. Assuming that a two spool aero engine with a certain thrust level is to be designed, the engine components will be a fan, a low pressure compressor or booster (LPC), HPC, combustor, HPT and low pressure turbine (LPT). The LPT drives the fan and the LPC, and the HPT drives the HPC. The design constraint could be performance, weight, or cost.

The BR700 family has a common core (HPC, Combustor & HPT), and the HPT contains two stages (Fig. 1). The HPT configuration could contain only a single stage, similar to the PW6000 aero engine (Fig. 2, Moravecek, 1997), which has a similar thrust level to the BR715. The PW6000 propulsion system is designed for the regional 100 passenger aircraft market rated from 15000 - 24000 lbs of takeoff thrust, and according to the limited information provided by Moravecek (1997), this engine has a low manufacturing and maintenance cost. and reliability-maintainability and long life are ensured.

The customer requirements in today's competitive commercial aircraft market indicate a preference for low overall cost in one case and high performance in another. For short-range aircraft serving as a shuttle between cities several times a day, low cost, high reliability, and ease of maintenance supersede high performance. To achieve a lower engine purchase price and maintenance cost by reducing engine parts-count leads to a configuration with a minimum number of stages and airfoils. These market requirements have led the BMW Rolls-Royce advanced technology team to perform a preliminary design study of a modern turbofan engine rated at 22000 lbs thrust with a single stage high pressure turbine (HPT) design and to compare its features with the baseline two-stage configuration. In his thesis, Ahmad (1998) investigated designing the two stage BR 715 HPT (abbreviated in this paper as TS) in a single stage (abbreviated as SS). Furthermore, a new disc design methodology was presented. The study (Ahmad, 1998) involved a preliminary investigation for HPT design and important aerothermodynamic parameters including weight, SFC, and cooling air consumption were compared between the TS and SS configuration.

This paper summarizes the merits of each HPT design configuration, in which section 2 describes the methodology for cycle analysis and cycle comparison, section 3 compares HPT rotor design features including turbine efficiency, power, blades/discs, and SFC, section 4 covers component life & reliability including impact on the LPT, and section 5 states the conclusions.

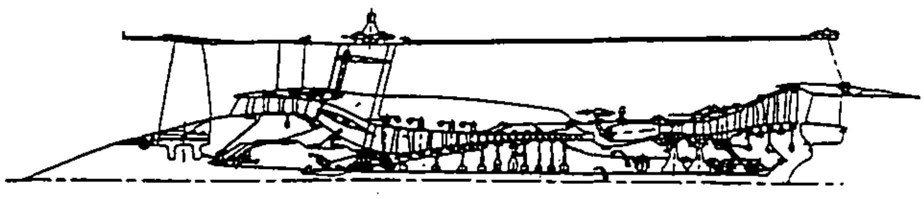

Fig. 1 TS HPT Engine Configuration (BR 715)

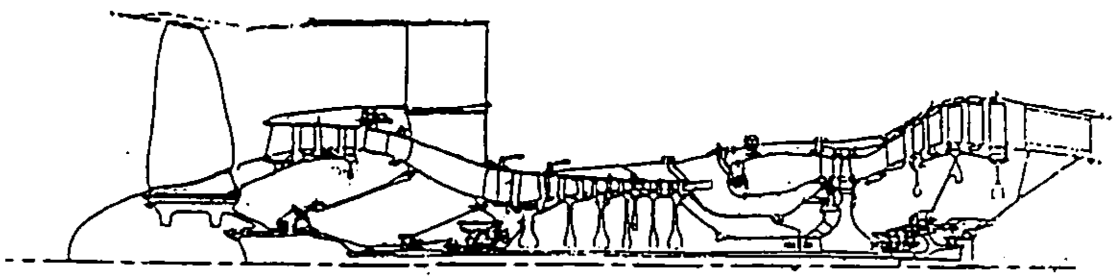

Fig. 2 SS HPT Engine Configuration (PW 6000)

2. CYCLE STUDIES

2.1 GASTURB 7.0 for Windows

GASTURB 7.0 for Windows is a FORTRAN computer program for calculating gas turbine performance (Kurzke, 1996). Several engine types can be chosen: a single spool turbojet or a two spool turboshaft with or without heat exchanger, mixed and unmixed flow turbofans with and without a booster. Afterburning and convergent/divergent nozzles are selectable with the turbojet, and the mixed flow turbofan, the single and the two spool turboshafts engines could also be configured as turboprops.

For a single cycle design point, the program can produce tables containing all the cycle details, preliminary information on blade velocity triangles as well as temperature-entropy diagrams. The output for parametric studies is shown graphically. An optimization routine can be used to find the best thermodynamic cycle. GASTURB is also able to create tables showing the effects of small changes made in the cycle input parameters.

2.2 Engine Cycles

The thermodynamic cycle of an engine is selected according to different performance parameters, such as thrust, SOT, mass flow, or pressure ratios at different locations of an engine. Given this information, the turbine designer establishes a design point at which the efficiency should be maximum (i.e., the SFC), or heat rate should be minimum (Dundas, 1985). The thermodynamic cycle of the two engines, TS and the SS were calculated for the maximum take off condition (MTO) where the circumferential speed and the blade metal temperature of the HPT have their maximum values.

2.2.1 SS Turbofan Derivation

The SS derivation from the TS-BR 715 engine was accomplished with two objectives in mind. The first was to assess the feasibility of an engine design which maintains the same components of the TS to the extent possible. This cycle will be referred to as the "adapted" SS. The other objective was to assess the SS cycle whose components are optimized to get the best efficiencies. This cycle will be referred to as the "optimized" SS cycle. To accomplish these objectives, an optimization procedure using the GASTURB program was carried out on the TS BR 715 turbofan engine of Fig. 1 consisting of a 56 inch fan, a two-stage booster, a 10 stage HPC, a two-stage HPT, and a three stage LPT. The new number of HPT stages was given to the program and then the cycle was calculated. However, several problems arose such as, the SOT increases, the turbine will have a high loading number, or the inlet/exit Mach number is very high, which will cause shock waves that produce losses. The HPT annulus area was therefore increased and then the parameters were optimized by changing the mid span radius taking into consideration the AN^2 parameter, because as this parameter increases, the blade stresses increase. To prevent the SOT from increasing, the SS can maintain the TS HPC by dropping the last stage (i.e. 9 stages) with the same PR of 1.32 per stage (adapted version), or the stages can be further reduced to six HPC stages (i.e. weight reduction) by incorporating advanced aerodynamic blading to get a pressure ratio of 1.51 per stage (optimized version). The overall PR is 24 (based on a fan PR of 1.5 and a two-stage booster yielding a PR of 1.32) which leads to an increase in core size and a decrease in BPR (4.6) to arrive at the same thrust level (adapted version). The alternative is to increase the overall PR to about 29 (optimized version) by increasing the booster PR per stage or by adding another stage to the existing two stage booster (i.e. LPC) which leads to reductions in engine core flow and the SOT, and an increase in BPR (5.6) to obtain the required thrust with competitive performance. Table 1 shows the resulting important aerothermodynamic input/output data at MTO condition for comparison.

2.3. Cycle Comparison

Table 1 contains the important cycle performance data for the different engines at MTO condition. The adapted SS engine was designed with the same HPC in mind, whereas the optimized SS cycle was designed for a near optimum overall PR and a lower SOT.

In comparing the optimized SS engine with the TS configuration, the TS has a higher overall PR, a lower by-pass ratio, higher total mass flow, and higher SOT. The SS has to deliver a certain amount of power to drive the HPC, and the power is proportional to the HPT torque and the rotational speed. Increasing the HPT torque affects directly the HP shaft and therefore, the shaft thickness and radius have to be changed. The optimized SS design philosophy is based on a higher rotational speed rather than increasing the HPT torque. Running at a faster rotational speed affects the disc design, the blade design, and the air system. For the disc design, it is preferred to rotate at a faster speed rather than to increase the annulus radius which would give more weight for the disc to carry. However, the total disc weight does increase to satisfy the burst speed and the life requirements.

The optimized SS uses a higher bypass ratio rather than increasing the SOT to produce the needed takeoff thrust and to reduce the SFC. During cruise condition, however, the higher bypass ratio is considered as a weight penalty (i.e. higher SFC compared to the TS) unless the core mass flow is reduced. Referring to Table-1, the optimized SS delivers a better fan efficiency due to a lower rotating speed, and in addition, the core mass flow is lower. A temperature increase on the other hand, requires more cooling mass flow and the application of temperature resisting materials. Hence, the optimized SS engine, at least on paper, is more suitable for low cost and optimum weight and performance.

The adapted SS has a high mid span radius to deliver the needed power; hence, the HPT turbine has a relatively high torque and nearly the same TS HP spool speed, which has to provide an HPC PR of 12. The advantage of such a design is the blade stresses, which are proportional to AN^2. Increasing the annulus area produces a linear addition to the blade stresses, whereas, the stresses are proportional to the rotational speed squared. The adapted SS cycle has a relatively high SOT temperature compared to the optimized SS design in order to produce the same thrust level. Due to the increase in the SOT, the HPT 1st NGV needs extra cooling air to sustain its required life, or, another NGV material with higher temperature resistance must be applied.

PARAMETER	*UNIT*	*TS*	*SS adapted*	*SS* optimized
Altitude	*m*	*0*	*0*	*0*
Mach	-	*0*	*0*	*0*
T Ambient	*K*	*ISA+15*	*ISA+15*	*ISA+15*
Compressor Configuration	-	*1-2-10*	*1-2-9*	*1-3-6*
Turbine Configuration	-	*2-3*	*1-3*	*1-3*
Fan Dia.	*m*	*1.42*	*1.42*	*1.42*
Net Thrust	*kN*	*98*	*98*	*98*
S.F.C	*g/(kN s)*	*10.7*	*12.1*	*10.4*
Bypass ratio	-	*4.8*	*4.6*	*5.6*
Core Size	*lb/s-$K^{0.5}$/psi*	*7.2*	*8.5*	*6.1*
Core Mass Flow	*kg/sec*	*51*	*46*	*41*
HPT shaft Torque	*Nm*	*16200*	*13400*	*9400*
NGV Cooling Air	*%*	*10*	*10*	*8*
HPT Disc/Blade Cooling Air #	*%*	*9.5*	*9.5 ##*	*8 ##*
LPT Disc/Blade Cooling Air	*%*	*3*	*4*	*3*
π_{HPC}	-	*16*	*12*	*12*
π'_{HPT}	-	*5.2*	*4.3*	*3.9*
π'_{LPT}	-	*3.7*	*3.7*	*4.0*
$\pi_{LPC\ Inner}$	-	*2.0*	*2.0*	*2.4*
$\pi_{overall}$	-	*32*	*24*	*29*
$(\Delta h/U^2)_{HPT}$	-	*1.6*	*1.8*	*1.8*
S.O.T	*K*	*1700*	*1690*	*1630*
105% N_H	*RPM*	*16200*	*16100*	*17950*
N_L	*RPM*	*6000*	*5900*	*5600*
$AN^2\ 10^6$	m^2RPM^2	*28*	*30.5*	*32.2*
$\eta_{HPC\ iso}$	-	*0.86*	*0.86*	*0.87*
$\eta_{HPT\ iso}$	-	*0.9*	*0.87*	*0.89*
$\eta_{LPT\ iso}$	-	*0.92*	*0.87*	*0.88*

\# The amount of cooling mass flow includes the rim sealing.

\## Cover plate blade cooling.

Table 1 Engine Performance Data, at MTO Condition

The cooling flow is used to control the different component temperatures in the HPT. The main components to be cooled are the NGV's, blades, discs, and shrouds (if available). There is some work recovery of the cooling air supplied to the 1st stage HPT of the TS design. However, in a SS HPT design, the blade cooling air exits the turbine and its temperature changes without doing work on the turbine blades leading to a loss in the turbine efficiency. Therefore,the loss in the TS HPT blade cooling air system appears in the air which cools the second stage HPT blades. Due to the lower gas temperature, however, the blades do not need a big amount of cooling air.

The blade loading on a SS HPT is bigger than that on the TS HPT because it has to deliver the work of two stages. The stage loading is proportional to the turbine temperature drop and is inversely proportional to the peripheral speed (Eq. 2).

$$Blade\ Loading = \frac{\Delta H}{u^2} = \frac{c_p \Delta T}{r^2 \omega^2} \tag{2}$$

The single stage has a higher peripheral speed u, but the temperature drop along the single stage is bigger than the temperature drop along the 1[st] HPT in a multi stage HPT design. The EULER equation presents the relation between the turbine enthalpy and its velocities:

$$\Delta H_T = \left(\frac{c_1^2}{2} - \frac{c_2^2}{2}\right) - \left(\frac{w_1^2}{2} - \frac{w_2^2}{2}\right) + \left(\frac{u_1^2}{2} - \frac{u_2^2}{2}\right) \tag{3}$$

$$u_1 \approx u_2$$

$$\Rightarrow \frac{\Delta H_T}{u^2} = \frac{c_1^2 - c_2^2}{2u^2} - \frac{w_1^2 - w_2^2}{2u^2}$$

Blade reaction of 0.5 leads to $\Rightarrow c_1^2 = w_2^2, c_2^2 = w_1^2$

$$\Rightarrow \frac{\Delta H_T}{u^2} = \frac{c_1^2 - c_2^2}{u^2} = \frac{w_2^2 - w_1^2}{u^2}$$

In a single stage HPT design the blade flow becomes supersonic. As a result of the shocks at the front and trailing edges, the single stage HPT has about 4% lower efficiency compared to a multi-stage HPT. The supersonic shocks affect the blade vibrations which limit the blade life. To accommodate the vibration problem, the blade material must be cooled very well to increase its life.

3. DESIGN FEATURES COMPARISON

Considering only the HPT rotor, the total weight of the SS configuration is lower than that of the two stage configuration. The weight difference is mainly due to reductions in the total blade number, in the air system components between the two stages, in the connecting components between the two discs, and in the total disc weight. Table 2 presents the weight of the components for the single and the two stage turbine configuration. The list does not include those components which are common between the two types of turbine configuration.

Table 2 allows a comparison between the total mass of the different turbine configurations. The results demonstrate the mass reduction achieved by using a single stage design. It is also evident that to run the turbine at a higher angular speed as done on the optimized SS engine is better than increasing the mid span radius (adapted SS) which results in a heavier single stage turbine. The added weight in the two stage configuration is a result of the extra stage and the components between the two stages which are needed for stage connection and to control the air system.

Some of the other important design features which need to be compared between the single stage and the two stage turbine are ease of maintenance and simplicity of design. The components of the single stage turbine require lower maintenance cost, and assembly of the single stage turbine components are easier than that of the two stage configuration. The single stage design does not need the same axial and radial space as the two stage configuration. The distance between the HPT1 front cob face and HPT2 rear cob face is *168 mm*, and the HPT1 blade mid span radius is *270 mm*; whereas, the cob thickness of the single stage is only *100,5 mm*, and the blade mid span radius is *327,5 mm*. Such geometrical differences cause reductions in the HPT length and radius, which affect the engine components. For example the combustor must be inclined to get its exit duct in line with the HPT annulus.

Another component which is affected is the turbine casing and associated tip clearance control, which was investigated by Khatib (1998) and is a subject for another paper. The casing of the single stage has a bigger radius but it is shorter in axial length than the casing of the two stage HPT configuration. Due to the difference in the casing length, the casing build components are reduced in their number and the design complexity is reduced. However, its thickness will increase due to the requirement to contain lesser (i.e. heavier) blades with higher AN^2. Therefore the SS HPT casing may in fact increase in weight although the cost may be reduced.

PART	TS	SS adapted	SS optimized
	Mass [Kg]	Mass [Kg]	Mass [Kg]
HPT Disc 1	39,8	70	54,5
HPT Disc 2	40	-	-
NGV 2	13,5	-	-
HPT Inter Stage Seals	5,7	-	-
HPT1 Rear Cover Plate	1,3	-	-
HPT1 Front Cover Plate	-	13	13
Curvic Ring	8,5	-	-
HPT1 Blades	8,7	7,6	14,4
HPT2 Blades	8,5	-	-
Bolting HPT1 & HPT2	0,9	-	-
Total Mass	$\Sigma M = 126,9$	$\Sigma M = 90,6$	$\Sigma M = 81,9$

Table 2 Engine HPT Weight Comparison

3.1 Turbine Efficiency

The isentropic turbine efficiency depends on the turbine pressure ratio and on the turbine polytropic efficiency (Wilson, 1991),

$$\eta_{T,is} = \frac{1-\Pi'^{\frac{\kappa-1}{\kappa}\eta_{T,poly}}_{HPT}}{1-\Pi'^{\frac{\kappa-1}{\kappa}}_{HPT}} \tag{4}$$

The turbine power is proportional to the turbine pressure ratio, and as was demonstrated, the compressor pressure ratio is proportional to the turbine power. Figure 3 shows the turbine efficiency as functions of the turbine and HPC pressure ratios for an uncooled engine. The inclusion of cooling shifts the graph down and to the right. As the HPC PR is increased, higher Mach numbers at the blade trailing edge lead to a drop in HPT efficiency. For an HPC PR of 15 and HPT PR of 3.2, the TS HPT is running about 2.25% more efficient than the SS. However, the graph also shows the advantage of applying the single stage HPT configuration to drive a compressor with a HPC PR less than 9 under the assumption of no cooling mass flow. In addition, the single stage is able to reach a higher isentropic efficiency as the compressor PR drops to 6. At this point, the difference in the isentropic efficiency between the two types of turbine configuration is about 1.5%. But as the compressor PR goes beyond the value of 9, the turbine efficiency drops for the single stage compared to the two stage configuration.

The component efficiency is important because the overall efficiency is proportional to the component efficiency. Assuming a constant polytropic efficiency, the compressor will give more isentropic efficiency as the PR drops, and the turbine shows the same effect; hence, the component efficiency increases for the turbine and for the compressor if the pressure ratio along the component drops. As a result, the overall efficiency of the single stage turbine design increases as the turbine is designed for the maximum efficiency by decreasing the HPC & HPT overall pressure ratios (see Fig. 3).

HPT Efficiency VS. HPT Pressure Ratio

The Intersection Occurs at a HPC Pressure Ratio of 9.

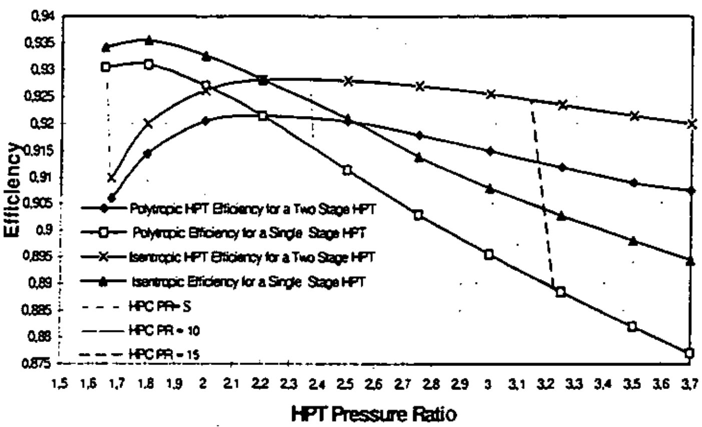

Fig. 3

3.2 Turbine Power

Figure 4 presents the turbine power as a function of the absolute exit Mach number and PR under the assumption of no cooling air to the turbine. The two curves, single and two stage HPT configuration, intersect at a point where the compressor pressure ratio is about 10. At a PR less than 10, the two stage HPT design has a higher power. As the PR exceeds 10, the single stage HPT curve shows a rapid increase in the HPT power and in the exit Mach number. The number of turbine stages affects the amount of gas flow through the turbine, and the aerodynamics and mechanical limitations in the turbine are considered to limit the maximum turbine gas flow, therefore; the inflection point of the single stage design occurs before the inflection point of the multi staged HPT design. The presented curves in Fig. 4 illustrate the high Mach numbers at the single stage exit, and also show the effectiveness of using a single stage instead of a two stage HPT configuration to drive a compressor with PR greater than 10. The HPT power depends on the rotational speed and on the turbine torque. The torque itself is a function of the lift force acting on the blades at a given radius; therefore, increasing the turbine power is possible by increasing the rotational speed or the lift force acting on the turbine blades, or by changing the blade mid span radius. If the rotational speed is increased, stress problems in the blade and in the disc are expected because the CF pull is proportional to the rotational speed squared. To increase the lift force , which acts on the blades, the aerodynamics of the turbine must be changed, and the turbine is converted to a sonic or supersonic turbine. Such turbines with high Mach number have lower efficiency due to the shock waves along the blade suction side. Nevertheless, the high exit Mach numbers reflect the energy content, which is not yet extracted out of the hot gas. This remaining energy can be extracted out of the hot gas through the LPT section.

HPT Exit Mach No. vs. HPT Power and HPC PR

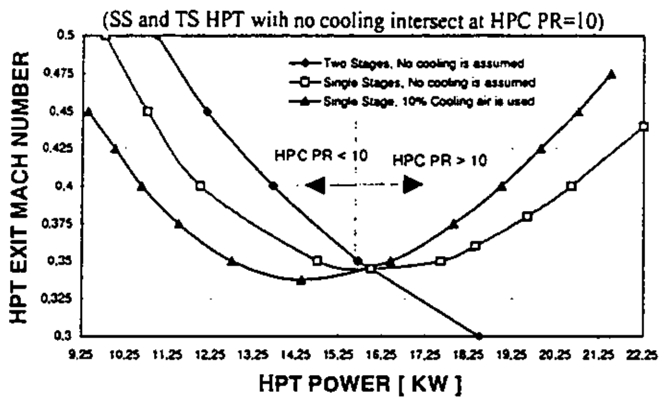

Fig. 4

3.3 Blade & Disc Requirements

The Blade is a rotating component which extracts the mechanical work out of the hot gas energy. The blade has deferent segments, namely the blade root, the platform, the airfoil and the shroud for a shrouded blade. The blade root has to transmit the forces from the blade to the disc. The platform separates the hot gas stream from the disc rim. The airfoil creates the lift force due to aerodynamic properties, and the shroud increases the turbine performance and in addition increases the blade natural frequency. The blade design is controlled by the aerodynamics, the blade stresses and the blade metal temperature. The aerodynamics is controlled by the airfoil shape including the twist, and the airfoil inlet and exit velocities. The blade stresses are controlled by the parameter AN^2. The blade metal temperature is governed by the amount and temperature of the cooling mass flow as well as the external hot gas conditions.

Assuming that the turbine has to drive a compressor with a given PR, a certain amount of power is needed to drive the compressor. The single stage turbine could have a higher rotational speed, or the mid span radius must be increased in order to compensate for the reduction in the lift force due to the drop of one stage. Hence, the single stage turbine has a higher AN^2 compared to the two stage turbine. The AN^2 controls the airfoil root stresses, and the stress margin in the airfoil root limits any extra loads on the airfoil, such as a shroud. Consequently, a single stage turbine is usually designed without a shroud and the single stage turbine performance is not as good as the two stage turbine.

To control the blade metal temperature, cooling mass flow is needed. The amount of the cooling mass flow affects many turbine parameters, such as the turbine power turbine isentropic efficiency, the specific fuel consumption and the specific thrust. Figure 4 presented the dependence of the turbine power on the cooling mass flow. The turbine power decreases as the cooling mass increases. In a single stage turbine, the air used to cool the blade does not do any work because the turbine airfoils do not extract the cooling air energy. On the other hand, the cooling air which is used in the two stage turbine configuration to cool the second stage blades does not do any work. According to the gas relative temperature (dependence on the peripheral speed), it is known that due to the higher turbine peripheral speed the single stage turbine has a lower relative temperature. Therefore, the single stage configuration needs less cooling mass flow to control the blade metal temperature compared to the two stage.

Figure 5 presents the relation between the first rotor blade metal temperature and the HPT PR at various amounts of cooling mass flow for the single stage and two stage HPT. As the cooling mass flow increases, the blade metal temperature drops, and the difference in the blade metal temperature between the different turbine configurations is clear. The single stage turbine has always a lower first rotor blade temperature if the same amount of cooling mass flow is used.

air consumption or other sources. The efficiency is related to the losses as follows (Wilson, 1991):

$$\eta_{T,is} = \frac{1-\Pi'^{\frac{\kappa-1}{\kappa}\eta_{poly}}_{HPT} - \sum losses}{1-\Pi'^{\frac{\kappa-1}{\kappa}}_{HPT}} \qquad (5)$$

As the cooling mass flow increases, the efficiency curve shifts down and its value reduces. Hence, the losses due to the cooling air consumption in a single stage turbine are lower than the losses in a two stage turbine, and the reduction in the turbine efficiency will be lower for a single stage turbine.

Disc rotation creates a radially outward flow motion by the action of viscous and centrifugal forces. The inherent disc pumping action will necessarily produce a low pressure region near the disc center which requires a replenishing flow to make up for the mass deficit. Hence, the annulus hot gas is encouraged to get into the disc cavity. If the annulus gas were allowed to enter the disc cavity, thermal stresses appear due to the increase in the disc temperature, and reduction in the material life occurs. The hot gas ingestion could be reduced by increasing the coolant mass flow rate. The amount of the needed flow to seal ingestion at the disc rim depends also on the number of such locations. The number of disc rim sealing is twice the number of stages. Consequently, as the number of turbine stages decreases, the needed amount to seal the rim decreases. A SS turbine needs lesser mass flow to seal only two ingestion locations, however, the increase in rim sealing radius may offset the reduction in rim sealing air. Furthermore, the transfer system for blade cooling air will most likely be a self-carried cover-plate requiring additional cooling air, because the higher stresses in the rim of a SS will lead to even higher stresses with blade cooling via feed holes.

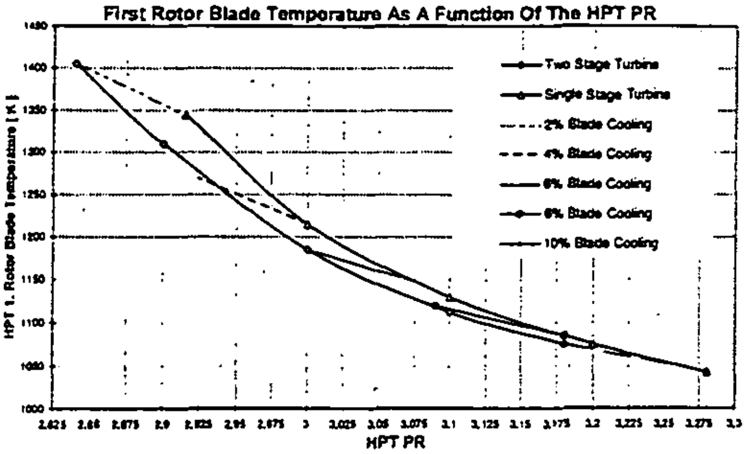

Fig. 5

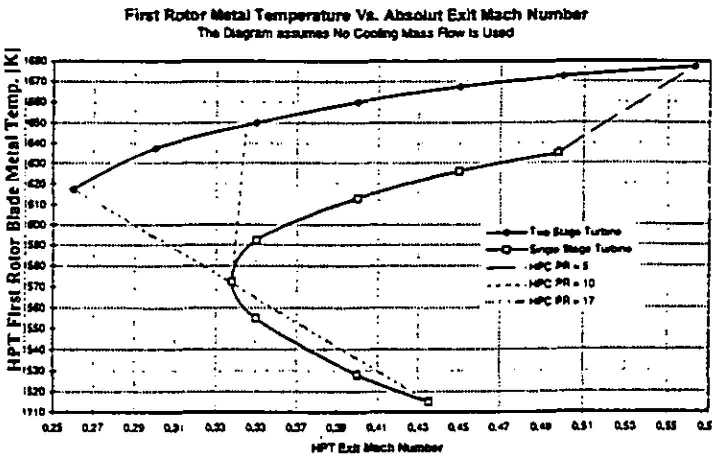

Fig. 6

Figure 6 shows the first rotor blade temperature as a function of the exit Mach number, assuming no cooling mass flow is applied to cool the blade. From the relationship between the blade metal temperature and the exit Mach number at any PR, the single stage turbine has a blade metal temperature which is less than that of a two stage turbine. Such a property allows less cooling air consumption for the single stage turbine.

The turbine isentropic efficiency was described in Equation 4 as a function of the HPT PR without considering the losses due to cooling

3.4. Specific Fuel Consumption (SFC)

The SFC which is a function of fuel mass flow and the engine net thrust is defined as follows:

$$SFC = \frac{Fuel\ Mass\ Flow}{Net\ Engine\ Thrust} \quad [g/s/kN] \qquad (6)$$

The thrust itself is a function of the total mass flow and the difference between the gas inlet and exit velocity. The specific thrust is then the thrust divided by the total mass flow.

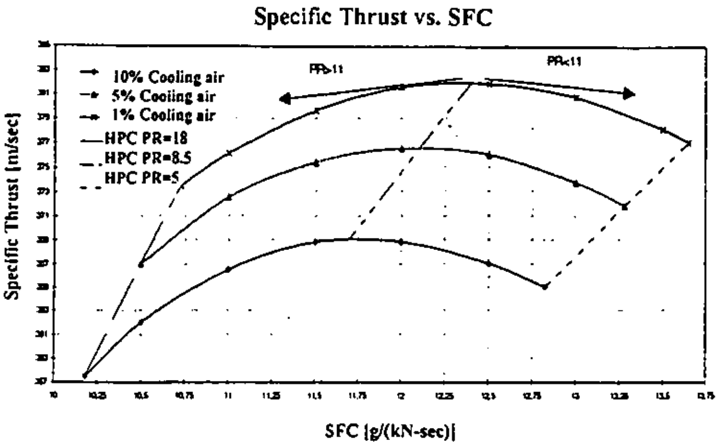

Fig. 7

Figure 7 presents the relation between the SFC and the specific thrust for different compressor pressure ratios and for different consumption of cooling air. To reduce the SFC, the compressor pressure ratio must be increased. Another method to reduce the SFC is by increasing the amount of the cooling mass flow, but such an increase causes a reduction in the specific thrust. High SFC is undesirable because the SFC affects the first rotor blade temperature. The following equation (Hourmouziades, 1995) shows the relationship between SFC and the heat input to the combustor.

$$\frac{H_u}{a_0}\frac{\dot{m}_{fuel}}{F} = \frac{\dfrac{1}{1+\lambda}\dfrac{\alpha H_u}{a_0^2}}{\dfrac{1}{a_0}\dfrac{F}{\dot{m}}} \qquad (7)$$

$$\alpha = \frac{\dot{m}_{fuel}}{\dot{m}}$$

where, a_0 is sonic velocity

The heat input depends on the fuel mass flow. To increase the SFC without reducing the thrust, the fuel mass flow must be increased. The higher the heat input, the higher is the SOT unless the combustion product gas is cooled-down with air prior to leaving the combustor. Figure 8 presents the effect of the SFC on the first rotor blade temperature for the different turbine configurations. The single stage turbine has a lower first stage rotor blade metal temperature. On the other hand, the two stage turbine configuration has a lower SFC.

4. IMPACTS ON ENGINE COMPONENTS

4.1. Component life & Reliability

The HPT configuration affects the total engine components, namely the HPC, LPT, LPC and the bypass duct. A single stage HPT system is not able to deliver the same power as the two stage. Therefore, to compensate for the reduction in power, the bypass ratio has to be increased, and the components of the HP system (HPT & HPC) become highly loaded. Highly loaded components have low life, unless they are efficiently cooled or robustly designed (i.e. extra weight).

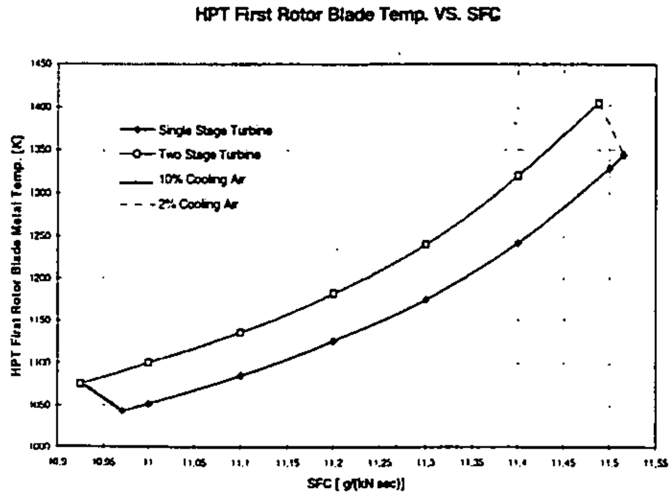

Fig. 8

Reducing the number of the HPT stages leads to a reduction in the HPT PR in order to have a high component efficiency (see Fig. 3). The HPT has to deliver a required torque to the HPC which has to compress the core mass flow to the needed pressure. The delivered torque is produced by converting the extracted annulus stream energy from heat to rotational energy. The energy conversion occurs during the hot stream flow through the rotating airfoils. Hence, if one of the HPT blades fails, the produced turbine torque drops. As a result of the torque drop, the HPC PR goes down which affects different engine parameters such as thrust, SFC and component efficiency. In a TS HPT which is usually shrouded, a blade failure leads to a total torque reduction as shown in Table 3. On the other hand, a blade failure by a SS HPT configuration which is usually unshrouded leads to a 1.8% torque reduction due to a lower blade count.

	HPT-1	HPT-2	Total
TS	0.75	0.55/0.8*	1.3/1.55*
SS	1.8*	----	1.8

(* denotes unshrouded blades)

Table 3 Torque Reduction (%) due to one Blade Failure

4.2 Impacts to the Low Pressure Turbine

In a single stage HPT, the peripheral speed has a high value and the turbine exit flow will be supersonic and hotter. Consequently, strong shocks develop at the front and trailing edges of the turbine blades. Since the LPT inlet conditions depend directly on the HPT exit parameters, the LPT is affected as the turbine configuration changes to a SS.

The temperature drop across a single stage turbine is bigger than the temperature drop across the first stage of a multi stage turbine. But the total temperature drop along the multi stage turbine is higher. This phenomenon of the single stage turbine has an advantage for the HPT and a disadvantage for the LPT. The advantage is that the bigger temperature drop along the first HPT stage reduces the needed amount of the cooling mass flow. But as a disadvantage, the LPT inlet temperature for a single stage turbine is greater than that of the TS turbine configuration. Moreover, due to the higher bypass ratio, the LPT must deliver more power to the fan/LPC to generate the required PR. This leads to a higher LPT stage loading for the SS compared to a TS. Table-1 reflects the effect of an increased stage loading of the LPT by the 4-5% reduced LPT efficiency compared to the TS.

It is not desirable to have big values of the LPT inlet Mach number which could be the same as the HPT exit Mach number. One way to reduce the LPT inlet Mach number is to diffuse the HPT exit. The diffusion could be achieved by increasing the flow exit area which allows the static temperature and pressure at LPT inlet to increase. The total gas temperature is expected to drop mainly due to heat loss in the extended annulus. Figure 9 presents the effect of the HPT exit mach number on the LPT inlet temperature. For a compressor PR < 11, the LPT inlet temperature of a single stage HPT is higher than the one for the two stage configuration. At a compressor PR = 11, the LPT inlet temperature does not realize any difference between the turbine stage configuration. In addition, Fig. 9 displays how the HPT exit Mach number affects the LPT inlet turbine for a compressor PR > 11. The two stage turbine continues to reduce its exit Mach number to reduce the LPT inlet temperature; whereas in the single stage configuration, beyond a critical PR=11, an increase in exit Mach number leads to a reduction in the LPT inlet temperature. In the optimized SS-56, a goose-neck shaped duct connects the HPT exit with the LPT inlet. Such a design allows a reduction in the LPT inlet Mach number and inlet gas total temperature. The LPT NGV is no longer necessary and the LPT can rotate within a counter rotational direction, if desirable. Still, the LPT first stage rotor blades must be designed with an alloy which resists the higher LPT temperature. Alternatively, the LPT can run with a higher rotational speed which is not the same as the fan rotational speed, to reduce its relative temperature.

5. CONCLUSIONS

The paper has presented an objective preliminary comparison between the two types of HPT configuration. Based on the main market drivers of cost, growth potential, performance, weight, and reliability, the following conclusions are made with caution.

Each type of HPT configuration has its own advantages and disadvantages. The SS HPT on paper has presented an ease in maintenance, ease of air system, lower HPT rotor weight, lower HPT relative temperature, and lower engine first cost. While the TS configuration shows an achievable performance level, high HPT efficiency, lower LPT inlet temperature, lower maintenance cost, and lower rim speed. A shroud on the blade tip increases the turbine efficiency by reducing the losses, and the disc weight reduces by about 2%. The two stage configuration accommodates a shroud with relative ease compared to the single stage.

The advantage of an overall engine weight reduction for the single stage compared to the two stage requires careful review. Although, the HPT rotor of the SS configuration leads to a weight reduction, the additional weight of the LPT, of the higher by-pass ratio fan, and any extra weight required to increase component reliability should be considered in an engine to engine weight comparison. It was also demonstrated that the SS HPT (at least on paper) can be optimized to deliver a comparable SFC to that of the TS (BR 715 SFC has already been demonstrated in flight) at MTO condition.

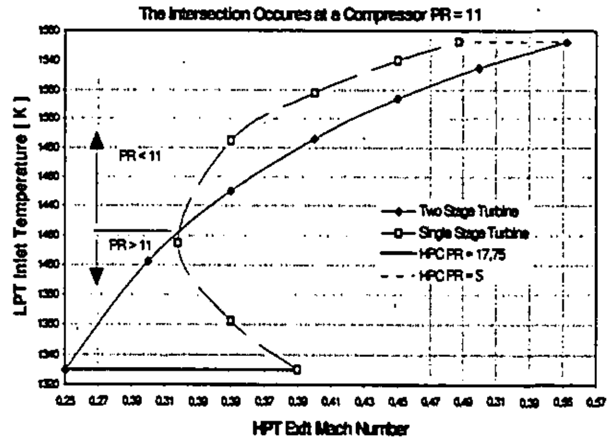

Fig. 9 LPT Inlet Temp. vs. HPT Exit Mach No. with Lines of Constant HPC PR

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