Limited life engines for UAVs

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ABSTRACT

The ever expanding range of applications for unmanned air vehicles covers a wide variety of powerplant requirements. While many vehicles are high value assets and demand similar powerplant attributes to a conventional manned aircraft, there is an emerging requirement for powerplants which are designed to a limited life philosophy. This covers a range of applications: at the simplest level there are vehicles where the mission definition dictates that attrition rates will be high, for example low level reconnaissance, targeting or battle damage assessment, and the entire vehicle may only be expected to make a short number of missions. On the other hand there are applications where it may be more cost effective to remove the need for engine maintenance and to treat the powerplant as a disposable limited life unit.

In general, the industry trend is towards the reduction of life cycle costs, and a significant emphasis is placed upon continuing to increase aero-engine component lives though novel design and improved manufacturing techniques. A limited life application calls for a different approach, as it may be that the powerplant has a life requirement of anywhere between 50 and 250 hours. This allows scope to explore areas of design and manufacture which would not be suitable for a 'conventional' engine and can lead to large reductions in engine cost.

This paper seeks to identify the primary cost drivers for a small UAV powerplant in the 10kN thrust class, and to establish the relationships between cost, life and performance at both a whole engine and an individual component level. It also explores the feasibility of using new or unconventional designs and manufacturing methods, and presents a selection of examples.

1.0 INTRODUCTION

Over recent years we have seen the interest in unmanned air vehicles increase to such an extent that their introduction in all areas of aviation seems inevitable.

Notwithstanding their use as target drones and decoys, the first areas of application of UAVs have been for reconnaissance and surveillance aircraft such as the Global Hawk and the Predator. High profile programmes such as the X-45 and X-47 are also investigating the use of UAVs for combat roles such as the suppression of enemy air defences (SEAD). The vehicles in these programmes are predominantly high value assets where the demands on the powerplant will be at least equal to those of a manned application, and particularly in the area of engine control and health monitoring, may be even more demanding.

There is however, an emerging requirement for smaller, lower value vehicles which perform missions such as reconnaissance, targeting or battle damage assessment in a particularly hostile environment. For these vehicles, a certain degree of attrition (i.e. vehicle loss) will be inevitable and as a consequence, the emphasis for the vehicle and the powerplant is firmly on reducing the initial purchase cost. For vehicles such as this, the concept of a limited life engine design is particularly appropriate. In order to maximise the range of such concepts however, the drive for lower cost powerplants must not adversely affect the engine's performance, and herein lies the challenge.

In the UK, the Future Offensive Air System (FOAS) is indicative of the future direction of procurement, with the Tornado GR4 capability being replaced by a 'system of systems' which may include a mixture of manned aircraft, UAVs and cruise missiles.

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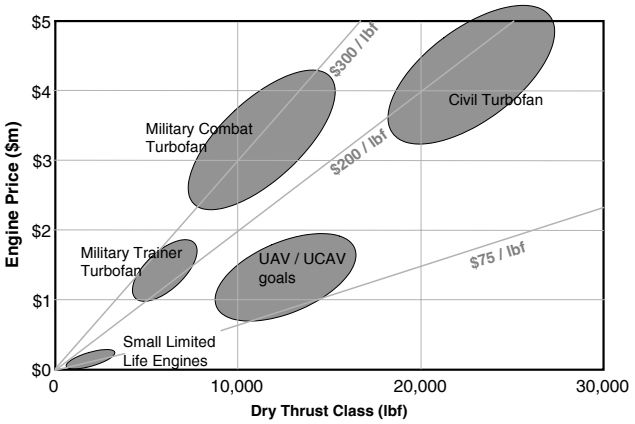


Figure 1. The relationship between thrust and cost.

Whilst the specific details of the type and number of the UAV options has yet to be decided, the potential implications are that the number of manned aircraft will reduce in the future, as the number of unmanned concepts (and cruise missiles) increases.

Having established that there is an emphasis on very low cost for an engine which has a limited life design, it is helpful to examine the relative costs of typical 'long-life' gas turbine engines and of existing expendable engines. This can be done by looking at the cost of the engine per unit thrust, or $ per lbf. Figure 1 shows the large difference in cost between the two design philosophies, with the limited life sector of the market being as low as $75/lbf, in contrast to a typical combat engine with reheat which may be in excess of $300/lbf[1].

This paper looks in more detail at the reasons behind the difference in cost between long life and limited life engine designs. In some part this is due to a difference in performance expectations, in addition to more obvious difference in life requirement.

As an illustration of these differences in life, for a typical large turbofan for a civil airliner, the time between overhaul for the turbine is nominally 20,000 hours. For a military trainer engine however, the design target may be 4,000 hours life, and for a combat engine the time is around 1,600 hours. The difference is predominantly due to the harsher operating environment of the military applications, where the engines experience a much higher number of operating cycles per engine running hour. For a limited life engine on the other hand, the cyclic use may be relatively benign and the entire powerplant may only need to last for a total of between 50 and 250 hours.

Whilst it has to be acknowledged that production volumes play a significant part in determining the cost (and the selling price) of an engine, the intent of the following sections is to examine the cost and performance drivers at a design and manufacturing level. Potential solutions for reduced cost designs are then presented at a preliminary level of detail.

2.0 ENGINE COST COMPARISONS

Gas turbine engines are inherently complex and expensive devices. They consist of large numbers of components, often complex in design, manufactured to exacting tolerances and under tightly controlled and monitored processes. Often these processes are at the forefront of manufacturing technology development, for example: laser shot peening on turbine discs to enhance their service life, super plastically formed diffusion bonded hollow wide chord fan blades, linear friction bonded fan blisks to name but a few.

The materials often have to withstand very high temperatures and stresses, and again are often at the leading edge of technology — cast single crystal super-nickel alloy turbine blades, carbon fibre materials, metal matrix composites and so on. Couple this with comparatively low volumes with regards to many other large scale industries (e.g. automotive, electronics), from which it is difficult to leverage economies of scale in manufacture, and it becomes apparent why conventional gas turbines are expensive.



Figure 2. EJ200 inter-compressor case.

Figure 2 shows an example of a classic gas turbine engine component, namely the inter-compressor case from an EJ200. This is a single component, cast in titanium and then machined to its final shape, and is approximately 720mm in diameter. As one of the main structural load bearing components in the engine, the precision of its manufacture is critical. Given this degree of complexity, it is clear as to why this is one of the most expensive static components in the engine.

2.1 Whole engine unit cost

Pound (£) for pound (lb), a typical gas turbine costs considerably more than its own mass in sterling silver.

The unit production cost (UPC) of a typical gas turbine engine can simplistically be defined as the cost of all of the individual components, usually grouped together in production modules, and the cost of the time taken to assemble and test the engine prior to delivery to customer. Given the nature of the applications and corresponding design styles and philosophies of the various types of gas turbine, how this cost is spread within the whole engine can vary.

For example, one of the primary design drivers for an engine for a long range civil airliner is cruise fuel burn. This largely dictates the need for a high bypass ratio configuration with a large diameter fan required to meet the take-off and climb thrust requirements. As such, the fan is very large relative to the rest of the engine compared to that of a typical military turbofan, where engine maximum diameter is a key constraint. As a result, the civil engine's fan will account for a larger proportion of the cost of the whole engine.

The chart shown in Fig. 3 demonstrates how the cost of a selection of typical gas turbine engines in production is apportioned.

From this it is apparent that broadly the same categories of component account for the majority of the cost of each of the

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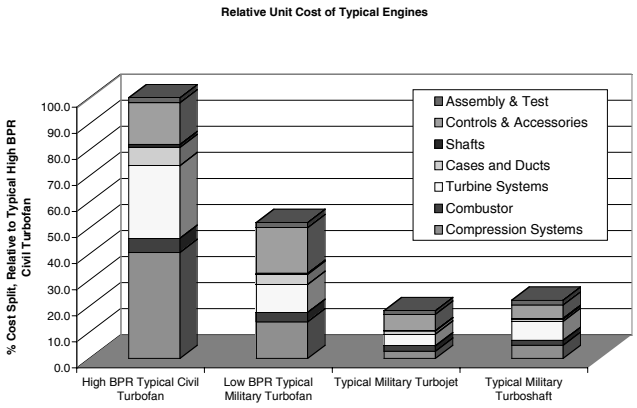


Figure 3. Whole engine UPC comparative breakdowns.

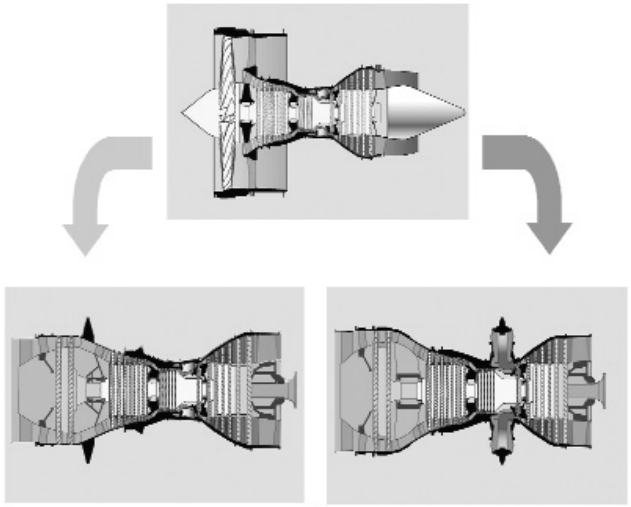


Figure 4. The Trent family of engines — multiple use technology.

different engine types. These categories are turbine system components, compression system components and control systems and accessories.

In many respects this is intuitive. The turbine and compressor components are the high technology parts of the engine, often experiencing high temperatures and stresses. The control systems and accessories category encapsulates a wide variety of components, from hydromechanical and electrical control system components, sensors and infrastructure to oil and fuel pumps, filters, heat exchangers and so on. Certainly the majority of these components are safety and reliability critical for the engine.

Another factor which could be seen to weigh very heavily on the cost of a gas turbine is the cost to develop a new product. This involves a long, complex and expensive design and development phase, including exacting qualification testing to provide sufficient evidence for the relevant airworthiness authority to certify the engine. Normally this would involve a significant 'up front' cost for manufacture and assembly tooling and infrastructure, which would be amortised into the UPC through volume production. For the purposes of this discussion, it is assumed that the UPC is applied across a nominal fixed volume and at a fixed point on the learner curve.

A common strategy to help overcome some of these issues is to look for commonality in design, even down to using the same part number across different engines in different applications. This

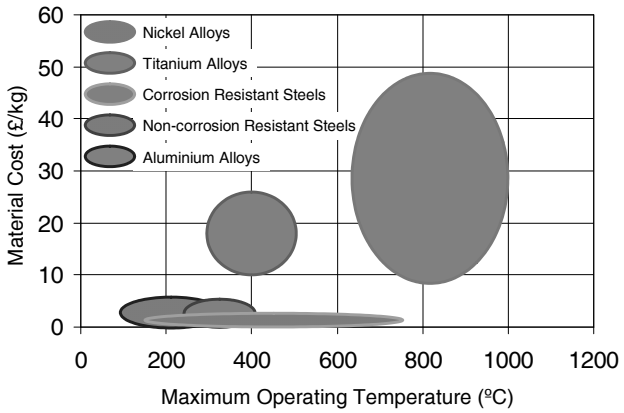


Figure 5. Raw material cost *vs* operating temperature capability.

'invent once, use many times' strategy has proven very successful for Rolls-Royce, and examples can be cited from all parts of the business: the Trent family of turbofans, including civil aerospace, marine and industrial applications (as demonstrated in Fig. 4), and the Adour military turbofan, in which technology insertion from other engines has enabled increases in life and thrust.

2.2 Individual component cost drivers

Of the cost of each individual component, there are essentially two significant sub-elements — the raw material (or purchase) cost and the labour (manufacturing or machining operations) cost. Again, this is a simplistic representation, as it takes no account of the commercial and administrative elements which further increase the cost.

A material will be selected for a typical gas turbine component that is the lowest cost, lowest mass material that fulfils the functional requirements of that component. A typical functional requirement would be operating temperature, and the chart below, Fig. 5, demonstrates the relationship between operating temperature and raw material cost for a selection of typical aerospace metals.

It is also true that there is a fairly good correlation between the capability of a material and its processing costs. This is influenced by two distinct factors. First, the material properties will dictate the capability of a material and as a general rule the stronger and harder a material, the more difficult and expensive it is to machine and form. Secondly, and perhaps more simply, high capability materials are at the forefront of technology and so their costs are influenced by the immaturity of their manufacturing and forming processes.

2.3 Implications for limited life engines

The previous discussion centred on the costs of 'conventional' longer life engines. A step change reduction in UPC is necessary in order for limited life engines to be commercially viable. This may be realised by the fact that it is possible to apply a different design approach for short life, low cost engines. Many of the time consuming and labour intensive processes which contribute to the cost of components may be relaxed in order to reduce their cost, in a trade for other capability factors. Examples of a number of these trades are discussed further in the following sections.

As shown in Fig. 3, the engine control system traditionally constitutes a significant proportion of the whole engine cost. The cost of the control system for a limited life engine may however vary enormously depending upon the requirements of the vehicle. In some instances, particularly if attrition rates are very high, a control system based upon low cost 'non-aerospace' components may be sufficient. Such a system may resemble that of a typical model

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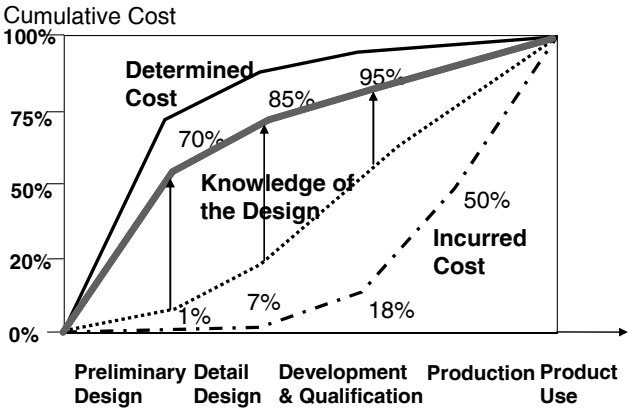


Figure 6. Product introduction cost profile.

aircraft gas turbine engine controller. If, on the other hand, the vehicle role demands that features such as engine health monitoring are required, however, the cost of the engine control system will be more in line with conventional engine experience. Because of the diverse nature of the control system requirements, a more detailed evaluation is deemed to fall outside the scope of this paper.

As a final point, conventional life engines are often designed for maintainability. Boundaries are built into the design to allow relatively easy assembly and strip of discrete modules. This would frequently call for features such as bolted flanges and joints between components. For a limited life or 'semi-disposable' engine, the requirement for maintenance would be limited, and hence the cost of these features could be avoided by designing them out.

3.0 THE KEY TO COST REDUCTION

3.1 Functional approach at a whole engine level

It is understood and accepted that some 70% of the cost of developing a new product is locked in at the preliminary design stage, where around only 1% of the total cost has been incurred, as Fig. 6 illustrates.

Preliminary design is therefore the area on which to focus in order to save money and to ensure the concept analysis, cycle performance data and engine architecture consider cost as a primary driver. It is not acceptable to wait until the product is defined and expect the cost to be reduced at a later stage through development.

Each component in an engine has cost associated with its design, development, verification, purchasing, traceability, storage and assembly. One fundamental feature of a limited life engine concept is that there is, by definition, no associated spares of support costs, hence all profit is made on engine sales alone. The key to successful cost reduction must therefore be to focus on a reduction in the engine parts count while still achieving the desired engine performance. In the UAV market this can be acomplished by taking advantage of the short life requirement and fully analysing the function of each element of not just the whole engine design, but also module and component.

For example the HP turbine module is one area of a modern gas turbine typically associated with high technology and cost — with the cost being locked in due to the pedigree of its design. The disc is traditionally forged in a nickel based alloy with directionally solidified or single crystal blades fixed to it using fir tree root attachments. These therefore require the need for axial blade retention, so front and rear seal plates together with sealing wires are introduced.

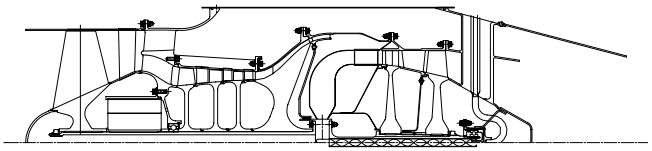


Figure 7. Baseline engine configuration.

In addition, the blades need to be cooled with multiple cooling passages and fanned film cooling holes, therefore a secondary air system needs to be provided to supply the cooling air, effecting the whole engine architecture.

A fundamentally new approach should be considered to re-think the engineering behind the design of low cost limited life engines. The question that needs to be asked is 'should the blades be cooled, what is driving the cooling requirement and does it improve the capability or functionality of the engine?'

If the blades are cooled then they will achieve a higher life at a constant turbine entry temperature, but cost is locked in and performance compromised as the cooling air is taken from the cycle. If the turbine blades are not cooled, then they can be integrated with the disc, by either casting or machining an integrally bladed disk, or blisk. This also removes the need for the fir tree root machining, seal plates, sealing wires and the supply of cooling air. The engine part count has now reduced and a significant engine cost reduction realised. This not only removes the design and development cost but also the tooling and logistics costs associated with each part and engine assembly time. The trade here is a reduction in turbine life to a level which is just able to meet the short life requirements. As a result there is a cost saving for the engine and for the whole production process, maximising profit to the business and offsetting the loss in after sales.

An example of working this process was demonstrated during a five-day cost reduction workshop held at Rolls-Royce. A single spool engine configuration was defined using current engine technology and standard practices, based on experience of manned applications. The basic engine configuration is shown in Fig. 7. This was then reviewed with a view to reducing cost through minimising part count, complexity, reviewing the materials and manufacturing methods while still achieving the performance requirements.

The result of working through this process reduced the total engine cost by around 30% and flushed out a number of novel assembly and design methodologies. It also identified the technology levels required to design and develop limited life engines.

Table 1 below breaks down some of the reductions achieved.

The ultimate extension of this approach would result in a single spool impeller driven by a single stage turbine. However, in order to provide the performance required to enable longer range and higher thrust this is not practical. Each of these components would have to be designed beyond the limits of current technology for manned combat and civil engines, and this would be reflected in higher

Table 1
Potential whole engine cost reductions

	% Reduction from baseline
No of parts	36
No of assembly steps	49
Total assembly time	73
Tool fixture usage	46
Investment	21
Labour cost	73
Material cost	25
Total cost	27

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associated costs. This is not necessarily the ideal route to follow therefore in its purest form and an educated, balanced decision has to be taken. The deletion of a part increases the dependence on the other parts of the system. As a result, the relative cost per remaining component is increased in order to achieve the desired performance, through an increase in the level of technology required.

Performance shortfalls in an engine design ultimately result in a reduction in vehicle performance, be it in-flight performance or system range. To restore the performance therefore requires either more thrust (i.e. a larger engine) or more fuel (i.e. larger fuel tanks). In the design stage of a project, both of these scenarios ultimately result in a larger and more costly vehicle and serve to show how the performance of the engine influences the overall system.

3.2 Technology approach at a sub-systems level

Because it is not always practical to follow the functional approach to its ultimate conclusion, there are always drivers for the need for improved technology. To reduce specific fuel consumption (SFC) and improve thrust, engine overall pressure ratio and turbine stator outlet temperature (SOT) tend to be driven higher, making the requirements more demanding for each stage of the gas turbine cycle.

Here there are other ways of approaching the problem of meeting performance and efficiency requirements while maintaining a focus on cost. Traditionally the approach would be to go through a technology acquisition programme in order to develop the product, which can be expensive and time consuming (as mentioned in Section 2.1). Usually skills and methods have to be developed as well as materials and innovative techniques. These then have to be verified through test programmes and analysis introducing significant spend and time.

However, this is where the dissemination of technology can be employed. As methods and skills have been improved through years of developing high performance combat and civil engines, it is possible to leverage these and apply them to a low cost low life application without the need to develop new technology. It is possible to trade the features of a high life component designed for optimum efficiency and performance and scale it to suit the limited life UAV engine.

An example of this can be seen in the design of the fan. In a contemporary manned combat application the aerodynamic technology and methodology has been developed over years of experience, with the introduction of super plastically formed diffusion bonded wide chord blades for improved performance and damage tolerance. Superpolished finishes are applied to the blade surfaces to squeeze the last percentages of performance from the design, the blade root attachments are grit blasted to improve life and annulus lines are profiled for improved efficiency. These technologies are necessary to reduce operator costs in the traditional engine environment. They reduce maintenance and improve reliability, performance and life, but incur an associated increase in component cost.

In a limited life UAV application the need for these can be questioned, and for the most part, these operations can be deleted, resulting in a significant costs saving. However the skills and resources available can still be utilised to attain a high performance through good design. For example the aerodynamic computational fluid dynamics (CFD) techniques and lessons learnt from 3D aerofoil design can be applied to a UAV requirement in the same way as a military fighter, it is just the methods of producing those parts that change.

A pictorial representation of the above discussion is shown in Fig. 8, where it is the quest for the last percentages of performance, or the final hours of life which tend to drive the component cost.

The cost breakdown for a conventional bladed turbine rotor disc is given below in Table 2, and is compared with a solution which removes the 'longer life' requirements in line with a limited life design philosophy. The use of cast blisks instead of forged, reducing

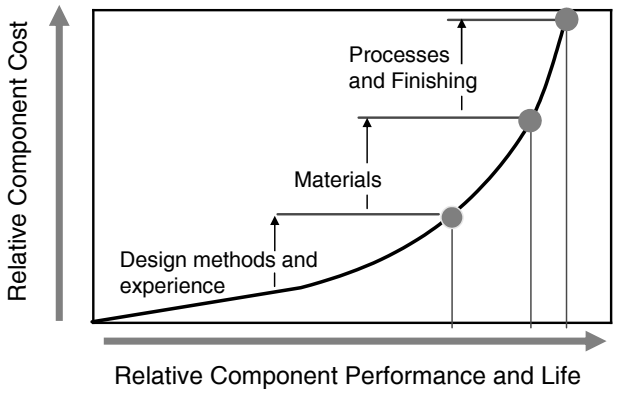


Figure 8. Cost *vs* performance and life.

the machining content, and increasing manufacturability of the parts can be seen to reduce the total rotor cost to less than 30% of the original, but the aerodynamic capability remains comparable.

It can therefore be seen that cost must be a primary driver during the preliminary design phase in order to have the best effect on the total product cost. It must also consider the holistic effects of each part within the engine and question their benefit on capability. A balanced approach must then be taken which considers the benefit of removing parts from the engine and loading the remaining components which would then need to have a higher level of technology. The ability to lever the skills from higher technology sources must also be used to maximise the performance of each element in the system at the lowest cost.

4.0 POSSIBLE ROUTES TO LOW COST SOLUTIONS

Examination of the engine cost breakdown in Section 2.1 shows that the compressor and turbine components are key target areas for cost reduction. The following sections examine the issues surrounding the design and manufacture of the rotors in more detail and also discuss the impact that the compressor design has upon the style and cost of the combustor.

By way of defining an engine scale, a suitable size for a small limited life engine is arguably around 10kN thrust, falling mid-way in thrust between existing expendable engines designed for missile applications, and current engines for military trainer aircraft. That is not to say that there are no existing engines in this thrust class. Those that exist however are predominantly medium bypass ratio

Table 2
Conventional *vs* limited life turbine costs

	% of conventional rotor cost	
	Conventional	**Limited life**
Materials	64	20
Machining	24·4	5
Polishing	1·8	–
Peening	3·6	–
Balancing	2·3	2·3
Swaging	1	–
Scrap	2·9	1
TOTAL	100	28·3

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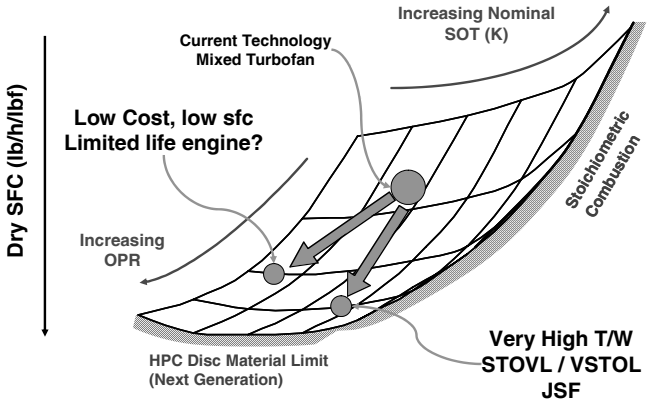


Figure 9. The engine cycle: performance *vs* affordability.

cycles designed for the small business jet and general aviation market and as currently designed can be considered as being too 'sophisticated' for the limited life market.

4.1 Rotors

When defining the engine cycle, the single most influential parameter in determining the specific fuel consumption of the concept, once the specific thrust has been chosen, is the engine overall pressure ratio. This is demonstrated by Figure 9 which shows the effect of variations of both pressure ratio and nominal turbine stator outlet temperature (SOT). Consequently the engine cycle will determine the materials chosen, whilst the cost targets will determine the method of manufacture

The engine rotative components, be they fan, compressor or turbine, have numerous potential methods of manufacture. Table 3 shows a selection of these methods, with those in red highlighted to show the 'conventional' method of manufacture, and those with potential for limited life applications shown in blue. It is assumed at this stage, for reasons highlighted in Section 3.1, that the design style will be that of integrally bladed discs (blisks) throughout as this removes the need for the blade/disc root attachment feature. The desire for optimum material properties also allows components to be designed for higher rotational speeds and lower weight.

4.1.1 Fan

As mentioned in Section 3.2, the current methods of producing fan blisks are to either machine from a forging or to linear friction weld the aerofoils to the disc. Both of these processes are very expensive and require significant machining and polishing. The result however is a component with forged material properties throughout. The challenge for a low cost application is to obtain the forged material properties without the need for machining and polishing.

One method of manufacture which appears to offer the potential for cost reduction in the future is the use of net shape hot isostatic pressing (net shape HIPping, or NSH). This process removes porosity during solidification which results in improved mechanical properties which are comparable to those of forgings and gives an improved surface finish without polishing. NSH does however require a furnace to encapsulate all the tooling and for this reason it is more suited to smaller applications.

Composites also offer a potential solution, although there are two factors which require investigation to facilitate their use. These are cost reduction and temperature capability. The latter is a function of the shift in operations towards the need for operation in hot climates, where it may be that the mission dictates that the gas temperature at fan exit is in excess of current material capabilities.

4.1.2 HP compressors

Net shape HIPping could also be applied to any axial stages of the high pressure compressor, as the current methods of manufacture are the same as those of the fan. The favoured material for HP compressors is generally titanium, however as the engine overall pressure ratio increases, the gas temperature at the compressor exit starts to exceed the material capabilities of titanium and it is customary for a nickel based alloy to be used for the latter stages of compression.

For a relatively small engine, such as a 10kN thrust cycle, it is likely that the HP compressor will employ a centrifugal compressor in the interest of reducing cost (through reduced parts count) and also maintaining efficiency. By way of an explanation, as the physical size of engines reduce, the overall dimensions of the axial blades at the rear of the compressor decrease to such an extent that a number of problems begin to arise. These problems stem from a range of issues, including the increased relative effect of end-wall aerodynamic losses (due to boundary layer growth and pressure field interactions) and the reduction in Reynolds number. The result is a loss in efficiency, leading to the choice of centrifugal devices at small engine scales.

Currently the preferred manufacturing techniques are to machine the

Table 3
Manufacturing methods for rotors

Method of manufacture	Fan	Compressor		Turbine		
		Axial	Centrifugal	Uncooled	Cooled	
Mill from wrought forging	**A&T**	**T**	**N**	N	N	
Investment casting	A&T	T	**N**	*N*	*N*	KEY:
Net shape hipping	*T*	*T*	N	N	N	A = aluminium
Composite	C/F	n/a	n/a	n/a	n/a	T = titanium
Monolithic ceramics	n/a	n/a	n/a	SiN	n/a	N = nickel
Intermetallics	TA	TA	TA	NA	NA	C/F = carbon fibre
Additive manufacturing (SMD)	T	T	*N*	N	N	TA = titanium aluminide
Metal injection moulding (MIM)	T	T	N	N	N	NA = nickel aluminide
Injection moulding	PEEK	n/a	n/a	n/a	n/a	SiN = silicon nitride
Bladed/disc	T	T	N	**N**	**N**	PEEK = polyetheretherketone

KEY: **BOLD** = Conventional methods *ITALICS* = Potential for limited life

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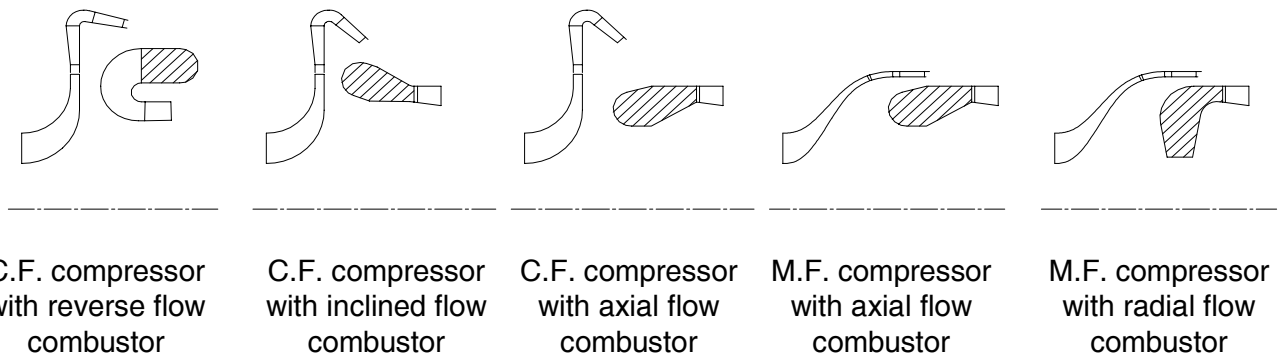


Figure 10. Compressor effects upon combustor design.

component from solid, or to use investment casting — both of which are expensive. A possible alternative with the potential to reduce cost is the use of additive manufacturing, where the disc could be turned from bar and the blades then built up from the disc surface.

4.1.3 Turbine

The range of current limited life engines tend to use uncooled turbine designs, which allows the turbine rotor to be produced as a one piece integrally bladed disc relatively easily, typically by casting.

Although increasing the SOT of the turbine alone does not give an appreciable improvement in engine specific fuel consumption, it does have the effect of reducing the physical size of the engine core and this leads to a reduction in engine size and weight. It may well be the case therefore that the next generation of limited life engines will demand an increase in turbine SOT which excludes the use of conventional uncooled blades.

One solution is to use blade cooling, as is used on the majority of current generation gas turbine engines. The manufacturing process traditionally involves casting hollow blades using the lost wax investment casting process with ceramic cores, and does not allow for the production of the rotor as a single piece blisk.

Ceramic turbine blisks are considered by many to be the answer to problem of increasing the turbine temperature without incurring the need for cooling. The issue of cost however remains to be resolved since the manufacturing costs are still in excess of metallic components, as does the issue of mechanical integrity.

If the cost drivers dictate that a metallic blisk solution must be used, then the method of creating the blade cooling system is critical. One alternative which would not affect the casting yield rates may be to produce a solid nickel alloy cast blisk and create simple blade cooling air passages using electrical discharge machining (EDM).

4.2 Compressor effects on combustor design

The design architecture of the engine is influenced by a variety of factors, though predominantly by the basic thermodynamic cycle in terms of overall pressure ratio, engine inlet mass flow, thrust requirements and technology levels. At a more detailed level however, the compressor configuration has a fundamental effect upon the design of the combustor.

As mentioned in Section 4.1.2, for a small engine the latter stages of compression are generally performed by a centrifugal device in favour of several axial stages.

With a centrifugal compressor it is often convenient to adopt a reverse flow style of combustor which reduces the engine length and contributes to a saving in weight, together with alleviating some of the problems associated with shaft whirling. It is still possible however to combine an all axial combustor with a centrifugal compressor and there are many examples of this style of design. For applications where engine diameter is a critical parameter, the use of a mixed flow compressor may be an attractive solution.

Rather than the radial exit flow path of the centrifugal compressor, a mixed flow impeller retains an axial component of velocity, giving a 'diagonal' exit flow direction, which can be turned back to the axial in a smaller radius than the centrifugal design. This gives the scope for a smaller diameter engine, albeit with a slight increase in length. The mixed flow compressor therefore tends to move the combustor design away from the reverse flow style towards an axial solution.

A further alternative is a slinger style of combustor, widely used by low cost engine manufacturers in the USA, which flings fuel radially from the engine shaft and offers the potential for reduced engine length, weight and cost.

Figure 10 shows the effects that the compressor has upon the design of the combustor. The final choice ultimately will be determined by the relevant importance of the design drivers: engine diameter, engine length, weight and cost. For example the centrifugal compressor with the reverse flow combustor has the largest diameter and the shortest length. The mixed flow compressor with the axial combustor has the smallest diameter but the longest length, whereas the radial flow slinger combustor offers the lowest weight solution.

Once the design of the combustor has been determined, the performance requirements need to be assessed. The requirements for reduced life engines are similar to conventional engine, but the significantly lower manufacturing cost targets have a major influence on the final combustor design, with compromises being made. This makes the design an order of magnitude more challenging. A brief comparison of the requirements is given in Table 4.

Table 4
Combustor characteristics

Requirements	Conventional life	Limited life
Exit temperature profile	Good profile essential	Good profile desirable
Starting	Sea level to high altitude	Sea level to high altitude
Efficiency	High efficiency essential	High efficiency desirable
Operability	Idle to max thrust	Cruise to max thrust?
Cost	Low cost desirable	Low cost essential

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5.0 CONCLUSIONS

It is evident that powerplants for UAVs will become a key sector of the market for propulsion system providers over the coming years. Some applications will demand the latest engine technologies in order to provide the required levels of thrust, specific fuel consumption and engine life. Other applications will be suited to low cost engines where engine life is traded for a large reduction in cost. These vehicles will typically be either expendable or have limited life features to some extent due to their operation in high threat scenarios.

In this latter section of the market, the key to success will lie in the application and leverage of knowledge and experience gained in more traditional markets. This will allow high performance products to be brought to market with reduced development costs, coupled with novel design and manufacturing techniques to realise low production costs.

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