COMMON SOLUTIONS TO COMMERCIAL AND MILITARY PROPULSION REQUIREMENTS

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Abstract

The propulsion requirements for commercial transports and military combat aircraft differ considerably, so much so that it is usual for gas turbine engines to be developed independently for each application with little or no commonality of parts. As military budgets tighten and with the need in the commercial world to remain competitive on price, there is increasing pressure to search for greater commonality as a means of reducing development costs.

This paper reports on studies to identify a future family of gas turbine engines designed to satisfy a wide range of applications with the maximum commonality.

The propulsion requirements are examined for a range of applications including the following:

- *commercial transports, e.g. regional jets*
- *military manned aircraft, e.g. fighters, primary and advanced trainers*
- *military unmanned aircraft, e.g. high altitude surveillance, strike and multi-role*

These requirements cover the following attributes:

- *performance, e.g. thrust, power off-take, inlet mass flow and fuel consumption*
- *mass*
- *environment, e.g. emissions, noise*
- *low observables, e.g. infrared radiation, radar cross section*
- *reliability and maintainability*
- *cost, e.g. development, unit, in-service*

This analysis enables the identification of those key requirements which drive the basic thermodynamic cycle and architecture of the engine and hence enables understanding of the possibilities for commonality between engines.

Examples of engine families with common architectural features are presented to illustrate a typical approach to increasing commonality. These examples highlight the following issues:

- *design compromises*
- *potential savings in development cost*
- *other benefits and issues*

Through increased commonality it is estimated that the development cost for a family of engines to meet three differing applications could be reduced by over 25%-30% relative to the development of three independent engines.

A future engine family will benefit from the introduction of new technologies, for example, in the fields of aerothermal and mechanical design, environment (emissions and noise), low-observables, materials, controls, monitoring systems and manufacturing. The paper examines technologies which support the concept of increased commonality.

1 Introduction

In the early days of gas turbine propulsion, engines such as the Rolls-Royce Avon were used in both high performance military fighters, e.g. the Hawker Hunter, and in commercial transports such as the Sud Aviation Caravelle, with only relatively minor changes between Mks. As time has progressed the differing requirements for commercial transports and combat aircraft have resulted in different engines for each of these classes of applications. The benefits in terms of performance and operating cost, which have come from optimizing the engine design to the application, have outweighed the extra cost associated with engine development. This is particularly the case when a large number of units is involved in a particular programme. For example, the Eurofighter engine programme was planned against an anticipated production of in excess of 1500 engines.

In the future, it is possible that military requirements will call for lower numbers of more specialized vehicles such as: stealthy subsonic strike Unmanned Combat Air Vehicles (UCAVs), High Altitude Long Endurance (HALE) surveillance Unmanned Air Vehicles (UAVs), and tactical reconnaissance UAVs. It is therefore likely to become increasingly more difficult to generate an acceptable business case for developing an all-new military engine with a large step change in technology level.

An alternative approach is to develop technologies and hardware that can be used in more than one engine type suitable for differing applications, e.g. a strike UCAV and a commercial regional transport. In this way the overall development cost for both engines is reduced, thereby making the business case more attractive.

This paper investigates the differing propulsion requirements for a number a commercial and military applications. Through this analysis it will be shown how the requirements drive towards differing propulsion system attributes and hence differing architectures. In addition, the analysis will indicate where there is scope for commonality and hence shared technologies and hardware. In particular, the paper will explore the concept of a common core approach to engine development and the technical difficulties this imposes.

Finally, the paper explores technologies which can be shared between types of engines and highlights those which support the common core philosophy.

2 Commonality

When discussing ‘common solutions’ it is helpful to define what is meant by commonality.

Fig 1 illustrates steps of increasing commonality starting with a minimum of a common ‘house style’ and leading to common part numbers. In the ‘Common Core’ approach, described in this paper, the aim is to have common part numbers within the core however in some cases a common architecture with common forgings may be a more likely outcome.

3 Propulsion System Requirements

In this paper the propulsion system is defined as the basic engine, exhaust and associated systems, e.g. controls, electrical power system.

Fig 2 illustrates the considerable differences between the basic engines in a commercial subsonic transport (low specific thrust) and a military supersonic fighter (high specific thrust). Although these engine have similar levels of Sea Level Static (SLS) they have very different architectures which result in different levels of Specific Fuel Consumption (SFC) and mass. These differences are driven by the differing requirements of the each of the applications as summarized in the following sections.

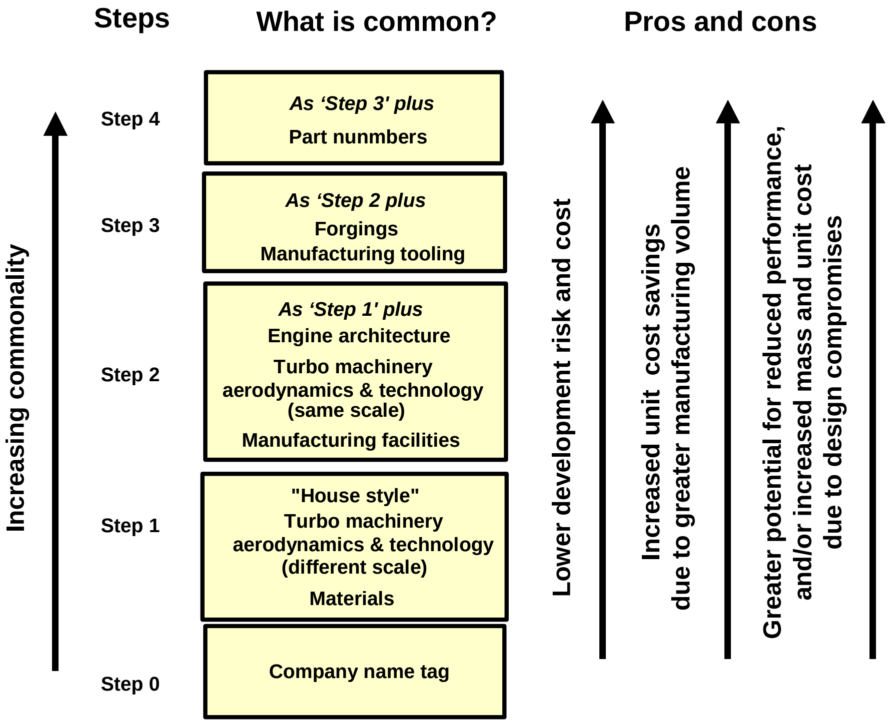
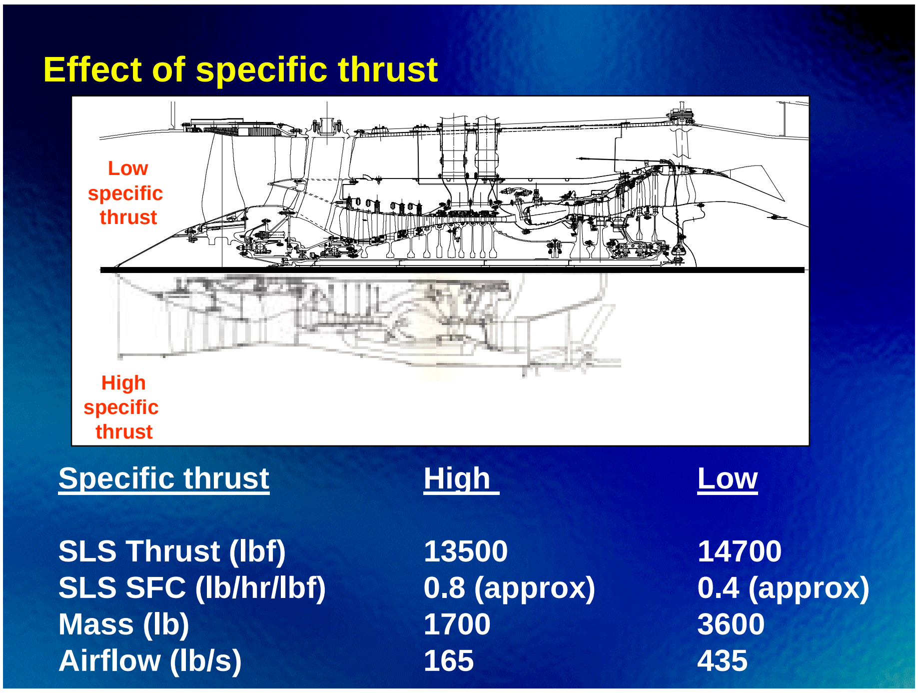


Fig 1 What is commonality?



Effect of specific thrust

Specific thrust	High	Low
SLS Thrust (lbf)	13500	14700
SLS SFC (lb/hr/lbf)	0.8 (approx)	0.4 (approx)
Mass (lb)	1700	3600
Airflow (lb/s)	165	435

Fig 2 Comparison of commercial transport engine (low specific thrust) and military fighter engine (high specific thrust)

3.1 Propulsion requirements vs aircraft requirements

Fig 3 identifies four types of commercial transport aircraft and six types of military aircraft which are typical of those which require gas turbine jet propulsion. In addition, a number of propulsion requirements are identified which are divided into the categories of: performance, environment, low observables, reliability and maintainability and cost.

The figure indicates which requirements are typically the strongest and weakest drivers for each of the applications through the use a High (H), Medium (M) and Low (L) symbol where H indicates the greatest influence, relatively speaking.

It is noted that the absolute level of thrust, although an important parameter when specifying propulsion systems for the various applications, is not included. The subject of thrust and its effect on engine scale is discussed separately in later sections of this paper.

It should be emphasized that this is a generalized subjective assessment used to illustrate the overall trends in propulsion requirements and, therefore, may vary where individual aircraft are concerned.

Notes:

“High T1 operation” refers to high air inlet total temperature generally encountered at supersonic flight speeds and/or high subsonic flight speeds at low altitude.

“High power off-take” refers to power required by the aircraft to drive systems such as passenger entertainment systems or radar and sensors.

“High maneuver tolerance” refers to the ability to execute maneuvers such as high rate turns which result in high levels of ‘g’ loading and intake flow distortion, typical of a highly agile military fighter.

NOx = Nitrous oxides, a pollutant generated during combustion.

‘Cyclic usage’ refers to the number of major throttle changes required during a mission which has an impact on the rate that Low Cycle Fatigue (LCF) life of various engine components is used up.

RCS = Radar Cross Section

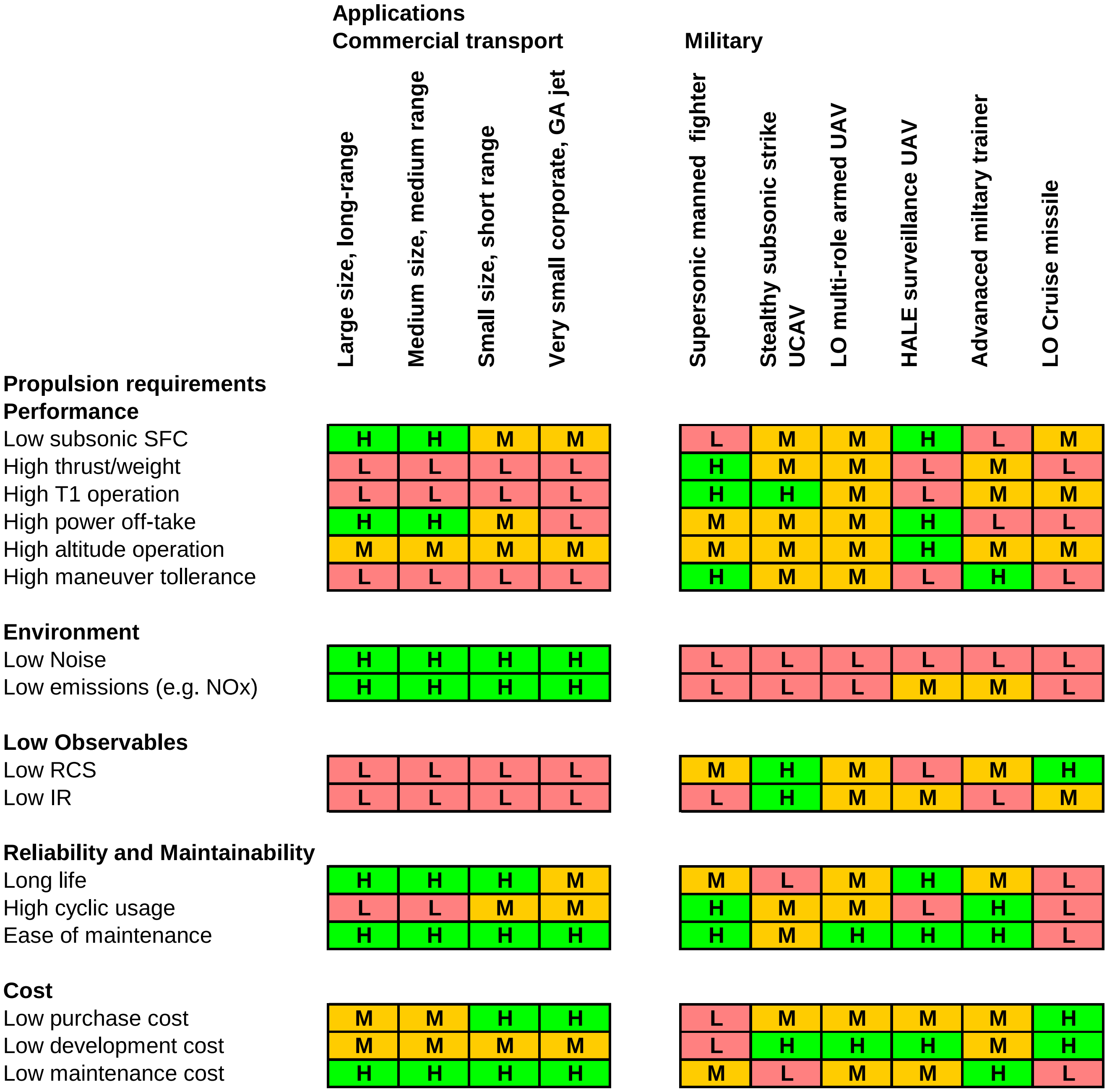
IR = Infrared Radiation

It can be seen that all the commercial applications are typically driven by low SFC, environmental requirements and low in-service costs, via long life and low maintenance costs . As the commercial applications tend towards smaller vehicles with shorter range then the emphasis for low SFC is generally replaced by greater emphasis on low purchase cost.

The military situation is generally more complicated. The majority of the military applications have little or no requirement to meet environmental standards. The relative emphasis on SFC and thrust/weight ratio varies between applications. For example, a manned supersonic fighter requires high maneuverability for air-to-air combat and therefore there is considerable emphasis on high thrust/weight. In contrast, a HALE UAV is required to have very long endurance and little maneuverability and therefore low SFC is the main driver.

Also of note is the influence of Low Observables requirements on a number of military applications, in particular future combat UAVs.

It stressed that the military UAV role is still evolving and as yet only the US military has outlined the requirements for a UCAV whilst other nations are developing technology demonstrators.



Applications

	Commercial transport				Military					
	Large size, long-range	Medium size, medium range	Small size, short range	Very small corporate, GA jet	Supersonic manned fighter	Stealthy subsonic strike UCAV	LO multi-role armed UAV	HALE surveillance UAV	Advanaced miltary trainer	LO Cruise missile
Propulsion requirements										
Performance										
Low subsonic SFC	H	H	M	M	L	M	M	H	L	M
High thrust/weight	L	L	L	L	H	M	M	L	M	L
High T1 operation	L	L	L	L	H	H	M	L	M	M
High power off-take	H	H	M	L	M	M	M	H	L	L
High altitude operation	M	M	M	M	M	M	M	H	M	M
High maneuver tollerance	L	L	L	L	H	M	M	L	H	L
Environment										
Low Noise	H	H	H	H	L	L	L	L	L	L
Low emissions (e.g. NOx)	H	H	H	H	L	L	L	M	M	L
Low Observables										
Low RCS	L	L	L	L	M	H	M	L	M	H
Low IR	L	L	L	L	L	H	M	M	L	M
Reliability and Maintainability										
Long life	H	H	H	M	M	L	M	H	M	L
High cyclic usage	L	L	M	M	H	M	M	L	H	L
Ease of maintenance	H	H	H	H	H	M	H	H	H	L
Cost										
Low purchase cost	M	M	H	H	L	M	M	M	M	H
Low development cost	M	M	M	M	L	H	H	H	M	H
Low maintenance cost	H	H	H	H	M	L	M	M	H	L

Fig 3 Propulsion requirements vs. aircraft requirements

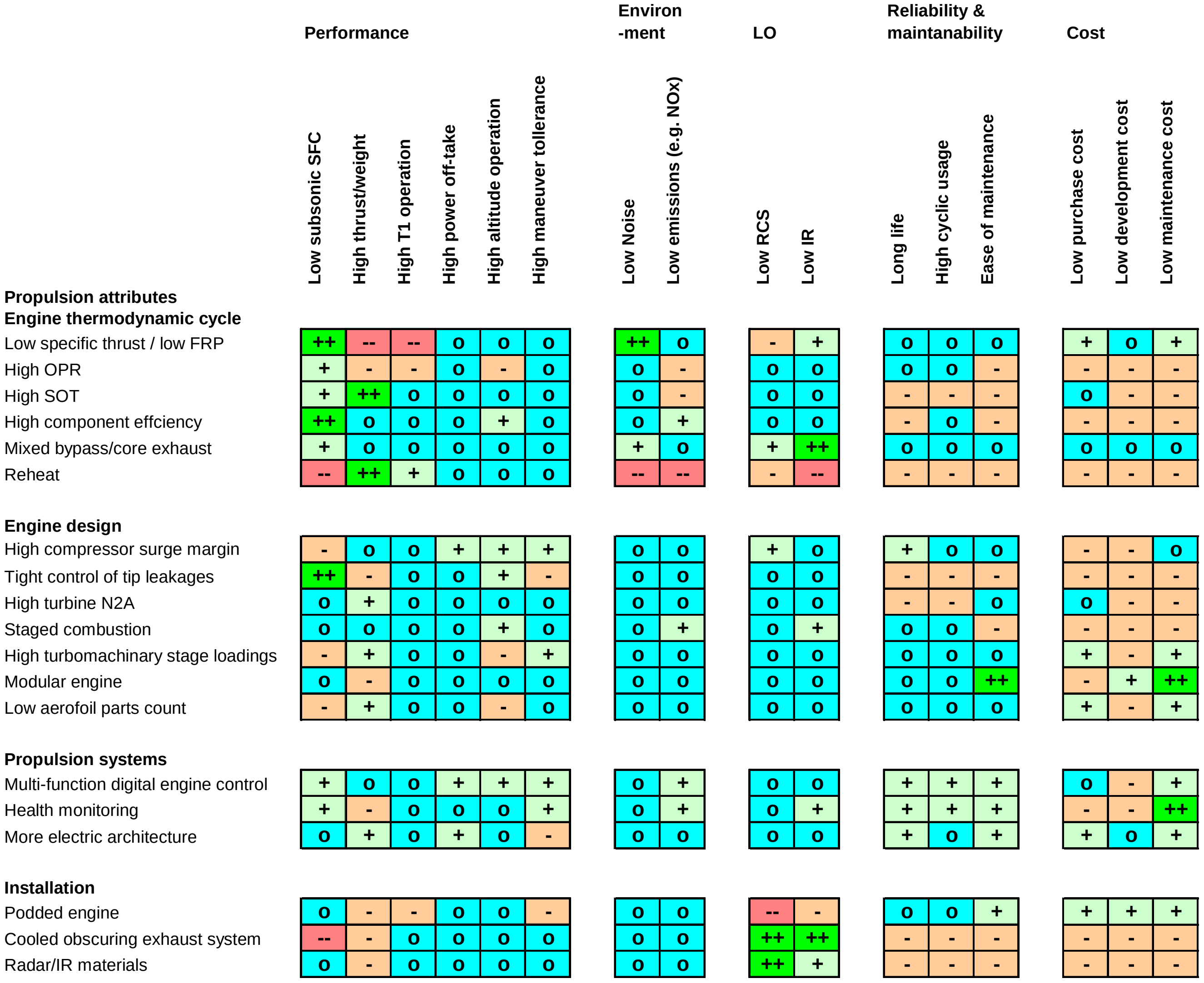
Two UCAV concepts have been created for the purposes of this study: “Stealthy subsonic strike UCAV” and an “LO multi-role armed UAV”. The Stealthy subsonic strike UCAV is envisioned as being capable of attacking difficult targets, e.g. mobile targets in high threat environments. Its primary method of survival is all-round stealth and therefore it is likely to have a tail-less flying wing configuration with highly swept wing leading-edges. It may carry its own sensors for locating targets or it may rely on off-board sensors.

The LO multi-role armed UAV is envisioned as a less specialized lower cost vehicle which can be used for general surveillance missions as well as the possibility of being armed. Although it would have some LO characteristics it is likely to be configured with a traditional tail and relatively high aspect ratio wings for long endurance. As such the vehicle would be less survivable in high threat environments but would be better suited to patrolling a large medium-threat area persistently looking for targets. When a suitable target is found it may be able to deal with it using its own weapons or those of a nearby "buddy" aircraft thereby reducing the time from detection to 'shoot'.

3.2 Propulsion attributes vs. propulsion requirements

The gas turbine engine is a complex machine which can be described by a large number of attributes with many interactions. In the following section a selection of these attributes, relevant to commonality, are examined.

Fig 4 maps the relative influence of the previously defined propulsion requirements on various propulsion attributes separated into the following categories: Engine thermodynamic cycle, engine design, propulsion systems and installations.



	Performance						Environ -ment		LO		Reliability & maintanability			Cost		
	Low subsonic SFC	High thrust/weight	High T1 operation	High power off-take	High altitude operation	High maneuver tollerance	Low Noise	Low emissions (e.g. NOx)	Low RCS	Low IR	Long life	High cyclic usage	Ease of maintenance	Low purchase cost	Low development cost	Low maintenance cost
Propulsion attributes																
Engine thermodynamic cycle																
Low specific thrust / low FRP	++	--	--	o	o	o	++	o	-	+	o	o	o	+	o	+
High OPR	+	-	-	o	-	o	o	-	o	o	o	o	-	-	-	-
High SOT	+	++	o	o	o	o	o	-	o	o	-	-	-	o	-	-
High component effciency	++	o	o	o	+	o	o	+	o	o	-	o	-	-	-	-
Mixed bypass/core exhaust	+	o	o	o	o	o	+	o	+	++	o	o	o	o	o	o
Reheat	--	++	+	o	o	o	--	--	-	--	-	-	-	-	-	-
Engine design																
High compressor surge margin	-	o	o	+	+	+	o	o	+	o	+	o	o	-	-	o
Tight control of tip leakages	++	-	o	o	+	-	o	o	o	o	-	-	-	-	-	-
High turbine N2A	o	+	o	o	o	o	o	o	o	o	-	-	o	o	-	-
Staged combustion	o	o	o	o	+	o	o	+	o	+	o	o	-	-	-	-
High turbomachinary stage loadings	-	+	o	o	-	+	o	o	o	o	o	o	o	+	-	+
Modular engine	o	-	o	o	o	o	o	o	o	o	o	o	++	-	+	++
Low aerofoil parts count	-	+	o	o	-	o	o	o	o	o	o	o	o	+	-	+
Propulsion systems																
Multi-function digital engine control	+	o	o	+	+	+	o	+	o	o	+	+	+	o	-	+
Health monitoring	+	-	o	o	o	+	o	+	o	+	+	+	+	-	-	++
More electric architecture	o	+	o	+	o	-	o	o	o	o	+	o	+	+	o	+
Installation																
Podded engine	o	-	-	o	o	-	o	o	--	-	o	o	+	+	+	+
Cooled obscuring exhaust system	--	-	o	o	o	o	o	o	++	++	-	-	-	-	-	-
Radar/IR materials	o	-	o	o	o	o	o	o	++	+	-	-	-	-	-	-

Fig 4 Propulsion attributes vs. propulsion requirements

The symbols indicate the following:

"++" = the attribute is critical to achieving the identified requirement.

"+" = the attribute is important but not essential to achieving the identified requirement.

"-" = the opposite of this attribute is desirable when trying to achieve the identified requirement.

"--" = the opposite of this attribute is critical to achieving the identified requirement.

"o" = the attribute does not have a significant impact on the identified requirement or the impact can be either way depending on a combination of other attributes.

Notes:

Specific thrust is given by the thrust of the engine divided by the air mass flow into the engine. In a gas turbine jet engine, specific thrust is very closely associated with the FPR (fan pressure ratio) of the bypass fan flow. FPR is the ratio of total pressure at exit from the fan relative to entry. Alternatively, a low specific thrust can be achieved by using a propeller or an un-ducted fan.

OPR (overall pressure ratio) is the ratio of the peak total pressure in the engine, at exit from the high pressure compressor, relative to the total pressure at entry to the engine.

SOT (Stator outlet temperature) is the total temperature of the gas flow at entry to the first rotor of the high pressure turbine.

"High component efficiency" refers to the efficiency of the turbomachinary, e.g. compressors and turbines.

"Mixed bypass/core exhaust" refers to the mixing of the bypass and core streams downstream of the final turbine and ahead of a common final propelling nozzle.

"Tight control of tip leakage" refers to controlling the leakage of working fluid over the top of turbomachinary. In the case of a compressor this may be achieved by small clearances between the blade tip and the casing. In the case of a turbine, a sophisticated clearance control system maybe employed and/or shrouds incorporated onto the blade tips.

Turbine N^2A (turbine rpm^2 * turbine exit annulus area) is a measure of the stresses experienced by the turbine blade.

Staged combustion is a technique employed to control the formation of NOx and other pollutants in the combustor. There are a number of forms of staged combustion however they all require a degree of increase in combustor complexity.

"High turbomachinary stage loadings" refers to the enthalpy change ("work") / blade velocity^2 across and stage of compressor or turbine blades. It is a measure of the 'aerodynamic difficulty' for the blading. A high loading can reduce the number of stages required to achieve a required change of enthalpy however it increases the risk of lower efficiency.

A "modular" engine is one which is designed such that complete sections of the engine can be quickly removed in order to ease maintenance.

"Health monitoring" refers to a number of sensor and processing technologies to enable various parameters in the engine to be monitored and hence predict the health of the engine both in terms of diagnosing past failures and predicting likely future failures.

"More electric architecture" refers to technologies aimed at reducing or eliminating non-electric systems on the engines such as hydraulics and oil lubrication.

A “podded engine” is where the engine is housed in a self contained fairing with an intake and exhaust system which can be mounted externally to the aircraft.

A “cooled obscuring exhaust system” is one where the jet-pipe and final propelling nozzle are designed such that there is no visibility of the turbine and all visible surfaces are cooled.

“Radar/IR materials” refer to materials such as radar absorbing materials and controlled emissivity coatings which are required to reduce RCS and IR signatures.

Fig 4 illustrates that there is a very complex set of relationships between different propulsion attributes and requirements.

In some cases the engine attributes have opposite effects on certain requirements. For example, low specific thrust is important for low SFC, at subsonic speeds, and for low jet noise due to the inherent low jet exhaust velocity. However it is detrimental for high thrust / weight ratio and low RCS due to the large diameter of the fan.

Other attributes, e.g. “Radar and IR materials”, are only specified to address specific requirements, e.g. low RCS and low IR, but have a negative impact on other requirements such as cost. In contrast, other attributes such as “Multi-functional digital engine control” give benefits across a whole range of requirements.

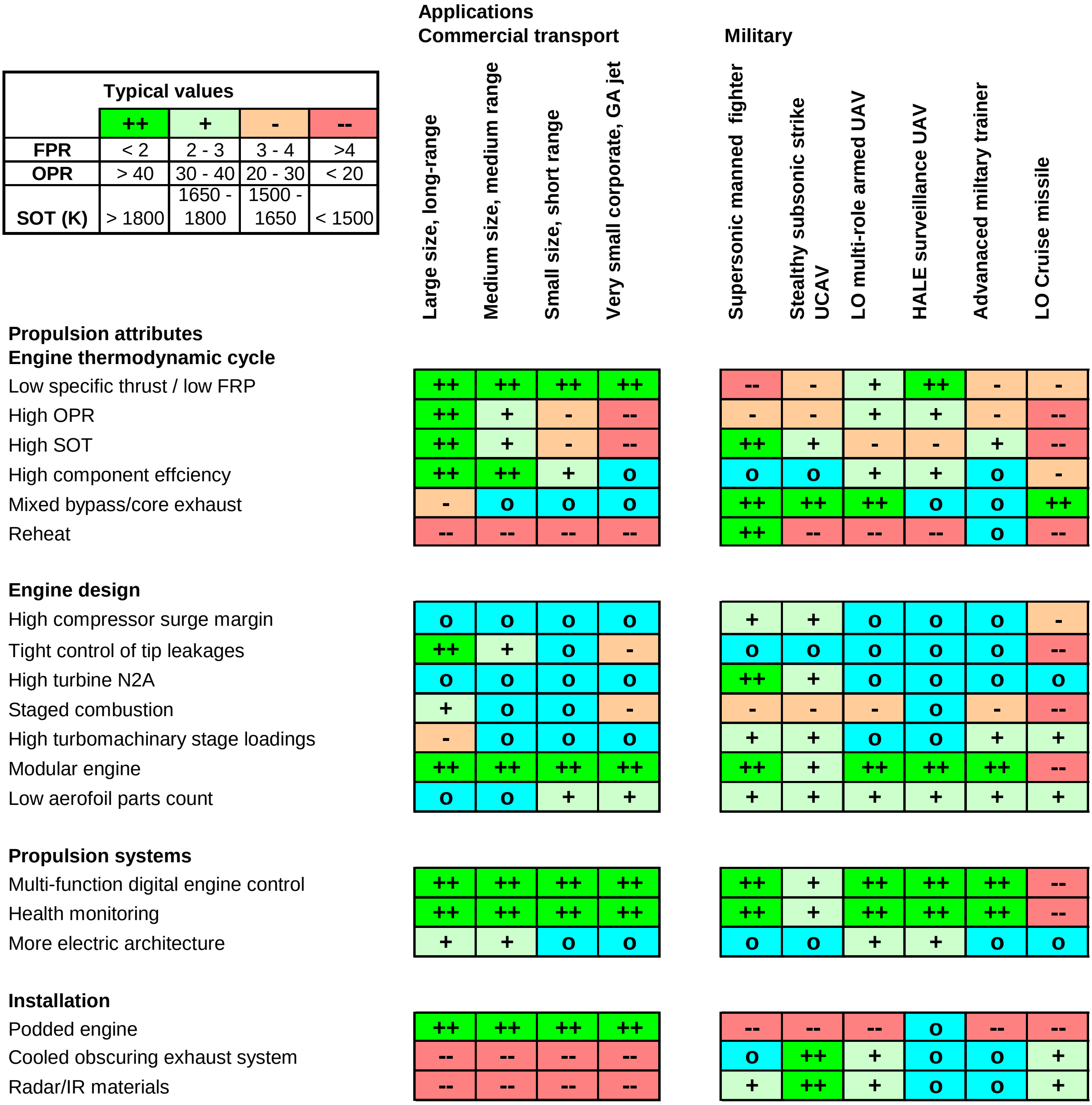
The majority of the engine attributes are judged to not have a critical effect on the engine requirements. This could be for a number of reasons.

Firstly, the attribute may have little or no impact on a requirement. For example, a modular engine construction which enables easy maintenance will have little or no impact on SFC as it only concerns how the engine is assembled.

Secondly, the effect of an attribute may be complicated by a number of factors which could result in either a positive or negative impact on a particular parameter. For example, higher SOT will result in a smaller engine core with less weight of material and hence lower cost. However, a higher SOT may also require more expensive types of materials and cooling systems to be used in the turbine and hence put up the cost of this component. Therefore, the net effect of SOT on purchase cost is dependent on the specific engine design. Similarly, a high SOT in combination with a high overall pressure ratio can reduce SFC due to higher cycle efficiency. However, at lower OPR these benefits may be eliminated by the extra cooling air required by the turbine blades to achieve the required life.

Thirdly, the effect of an attribute on a particular parameter may be only weak and could be compensated for by an improvement in another attribute. For example, the efficiency of a turbine may be improved by the inclusion of a shroud on the turbine blade, thereby improving the control of tip leakages particularly after time in-service. However, if the turbine was designed without a shroud, for example to reduce cost, then the reduction in efficiency may be compensated for by reducing stage loading (in combination with control of flow velocities).

In summary, a gas turbine engine is a very complex machine where there are a large number of combinations of differing attributes which can be used to achieve an overall set of requirements. However, there are some key attributes which must be adhered to achieve certain requirements. For example, to achieve low noise, with current technology, a low specific thrust engine cycle is not negotiable. It is these key engine attributes which are the focus of the following sections.



Typical values	++	+	-	--
FPR	< 2	2 - 3	3 - 4	>4
OPR	> 40	30 - 40	20 - 30	< 20
SOT (K)	> 1800	1650 - 1800	1500 - 1650	< 1500

Applications

	Commercial transport				Military					
	Large size, long-range	**Medium size, medium range**	**Small size, short range**	**Very small corporate, GA jet**	**Supersonic manned fighter**	**Stealthy subsonic strike UCAV**	**LO multi-role armed UAV**	**HALE surveillance UAV**	**Advanaced miltary trainer**	**LO Cruise missile**
Propulsion attributes										
Engine thermodynamic cycle										
Low specific thrust / low FRP	++	++	++	++	--	-	+	++	-	-
High OPR	++	+	-	--	-	-	+	+	-	--
High SOT	++	+	-	--	++	+	-	-	+	--
High component effciency	++	++	+	o	o	o	+	+	o	-
Mixed bypass/core exhaust	-	o	o	o	++	++	++	o	o	++
Reheat	--	--	--	--	++	--	--	--	o	--
Engine design										
High compressor surge margin	o	o	o	o	+	+	o	o	o	-
Tight control of tip leakages	++	+	o	-	o	o	o	o	o	--
High turbine N2A	o	o	o	o	++	+	o	o	o	o
Staged combustion	+	o	o	-	-	-	-	o	-	--
High turbomachinary stage loadings	-	o	o	o	+	+	o	o	+	+
Modular engine	++	++	++	++	++	+	++	++	++	--
Low aerofoil parts count	o	o	+	+	+	+	+	+	+	+
Propulsion systems										
Multi-function digital engine control	++	++	++	++	++	+	++	++	++	--
Health monitoring	++	++	++	++	++	+	++	++	++	--
More electric architecture	+	+	o	o	o	o	+	+	o	o
Installation										
Podded engine	++	++	++	++	--	--	--	o	--	--
Cooled obscuring exhaust system	--	--	--	--	o	++	+	o	o	+
Radar/IR materials	--	--	--	--	+	++	+	o	o	+

Fig 5 Propulsion attributes vs. aircraft applications

3.3 Propulsion attributes vs. propulsion requirements

The vehicle types, propulsion requirements and propulsion attributes have been analyzed in order to attempt to define the key propulsion attributes for each of the vehicle types. These are shown in Fig 5. The symbols indicate the following:

"++" = the attribute is key to the success of the engine in this application, e.g. low specific thrust.

"+" = the attribute is desirable but not essential to the success of the engine in this application. Therefore some compromise in the attribute is acceptable, e.g. low to medium specific thrust.

"-" = the opposite to this attribute is desirable but not essential to the success of the engine in this application. E.g. a medium to high specific thrust.

"--" = the opposite to this attribute is key to the success of the engine in this application., e.g. high specific thrust.

"o" = the attribute does not have a significant impact on the identified requirement or the impact is can be either way depending on a combination of other attributes.

Inspection of these data illustrates the following points.

Some propulsion attributes will be confined to some applications and not to others. For example, a reheat system or an LO exhaust system with radar and IR materials is unlikely to be required by commercial transport aircraft due to the impact on SFC, environment and cost. (This assumes that the protection of airlines against terrorist weapons, such as shoulder launched missiles, can be achieved through a combination of policing and, possibly, the use of countermeasures and not through LO measures.) Therefore, in the case of reheat and LO exhaust systems there is little or no scope for common hardware solutions and / or common technology between commercial and military applications.

In contrast, some propulsion attributes are universally attractive and therefore are likely to be adopted by most vehicles. For example, multi-function digital engine control and health monitoring offer advantages to both commercial transport and most military aircraft. The benefits in performance and maintenance costs outweigh the potential additional purchase and development costs in all vehicles with the exception of the cruise missile. Therefore, there is already a lot of scope for common solutions including possible common hardware.

The following sections examine separately the case for commonality in the Low Pressure (LP) System (fan and LP turbine) and the engine core (high pressure compressor (HPC), combustor and high pressure turbine (HPT)).

3.4 LP System commonality

When carrying out the analysis it is evident that in some vehicles there are conflicting requirements which demand opposing attributes.

For example, the "Stealthy subsonic strike UCAV" requires both low RCS and low IR. Low RCS favors a high specific thrust as this reduces the area of the intake, a major contributor to vehicle RCS, and reduces the diameter of the engine easing the task of integration into a low RCS vehicle. In addition, a high specific thrust reduces the installation penalties associated with the losses which might be expected in an LO intake and exhaust system. However, low specific thrust will result in lower exhaust temperature, and hence plume IR, and will generally provide a greater amount of bypass air which can be used to cool exhaust system surfaces and hence solid body IR. Therefore, a compromise is required and, in this example, a medium specific thrust is likely to be desirable and hence a medium FPR, e.g. 3 - 4.

In the case of commercial transports there is no ambiguity on this matter. A low specific thrust, and hence low FPR (less than 2), is required to achieve noise requirements regardless of any other requirements. In addition, for the larger aircraft the benefits for reducing subsonic SFC are also compelling.

For the manned supersonic fighter the case is also equally clear. To achieve supersonic flight requires a low frontal area (small engine diameter) and high T1 operation. Both of these lead to a high specific thrust and hence a FPR greater than 4. In addition, this enables high thrust-to-weight ratio and hence contributes to achieving vehicle acceleration, climb and sustained turn rates.

In summary, although it may be possible to use the same fan hardware for two different commercial transport engines, it will never be possible to use the same fan for a military fighter and a commercial transport. In other words, the days of the Rolls-Royce Avon being used in both a fighter and a subsonic commercial transport are well a truly passed.

The use of the same fan system for both a fighter and a UCAV is more difficult to predict. Whereas the analysis indicates that it would be advantageous for the UCAV to move to a lower specific thrust the pressure of reducing development costs may dictate the use of an off-the-shelf engine and hence accepting some compromise.

The design of the LP turbine is closely related to the fan design. Therefore, it is equally unlikely for there to be commonality in LP turbine hardware between commercial and military engines, other than the HALE.

3.5 Core commonality

Having established that there is only limited scope for commonality of hardware in the LP system this section now examines the engine core.

The main attributes of interest here are the following: OPR, SOT, relative component efficiencies, compressor surge margin, control of tip leakages, turbine N^2A, modular engine and aerofoil parts count.

At first it might appear that there is equally little common ground for there to be common solutions in the hardware of core components. However, a closer look indicates that it may be more encouraging for the following reasons.

A significant number of these attributes are not considered to be main drivers. For example, with the exception of the manned fighter, turbine N^2A is not considered to be a driving attribute and therefore not an impediment to commonality.

With other attributes there may be differences in the requirements however these could be addressed through relatively minor changes to the design when it is adopted for other applications. For example, a manned fighter and a stealthy UCAV are likely to require a large compressor surge margin due to the higher levels of pressure distortion it will encounter due to high aircraft maneuverability and/or an LO intake system. The surge margin requirements of a commercial engine, albeit sufficient to provide good operability throughout the life of the engine, are likely to be lower. However, the surge margin of the commercial compressor may be increased by effectively operating the same compressor with reduced aerodynamic performance. The penalty is a lower pressure rise and a possible fall in efficiency.

Similarly, a manned fighter may require slightly greater tip clearances to accommodate movement of the turbomachinary during high g maneuvers. This may require some detailed changes to the hardware however the overall architecture would remain the same.

The attributes where there is the greatest difference in the requirements are OPR and SOT. However, in both cases there are possible means for accommodating these differences when a common core is proposed. These are discussed in more details in the following sections.

In summary, it is believed that a common core between engines for differing applications is feasible. Based on the subjective analysis carried out the least difference between the attribute requirements and hence the greatest potential for a common core exists between engines for the following applications:

- Small size, short range commercial aircraft
- Stealthy subsonic strike UAV
- LO multi-role armed UAV
- HALE surveillance UAV
- Advanced military trainer

4 Design for a Common Core Engine

The greatest form of common solution in the core would be to use the same core hardware for a number of engine types for different aircraft applications, this is referred to as the 'Common Core' approach.

When considering the use of an engine core for more than one application there are three primary parameters to be considered:

- Core size
- HPC pressure ratio
- SOT limits

These parameters are considered in more detail in the following sections.

4.1 Influence of core size

The core size is given by the equation

$$\text{Core size} = W_{25}\, T_3^{\,0.5} / P_3$$

where:

W_{25} is the flow at entry to the HPC

T_3 is the gas total temperature at exit from the HPC

P_3 is the gas total pressure at exit from the HPC

The core size is closely related to the physical flow area at the back of the HP compressor and subsequently through the combustor and HP turbine. Therefore, for a given set of core hardware the core size will remain nearly constant.

Fig 6 and Fig 7 examine the relationship between core size and the thrust of a range of turbofan engines of low specific thrust ('Commercial') and medium to high specific thrust ('Military').

It can be seen that within a class of specific thrust there is a broad correlation between core size and thrust. However, within limits, a single core size can be used to cover a significant range of thrusts, typically + / - 20%.

Within a specific thrust class, greater thrust is achieved with a given core size by increasing the engine OPR and SOT. This gives benefits in T/W ratio and/or SFC, however, it is also likely to increase engine unit cost and/or development risk.

If all engines of the same specific thrust had the same OPR and SOT then the thrust would, to a first order, be directly proportional to core size. In reality, as core size increases then higher values of OPR and SOT are selected and hence the thrust for a given core size also increases. This is particularly true of the commercial engines where at the larger end there is a greater drive for lower SFC and hence higher OPR and SOT. In addition, the larger physical size of the core enables more complex turbine cooling systems and avoids aerodynamic problems associated with very small compressor blading at the rear of the HPC.

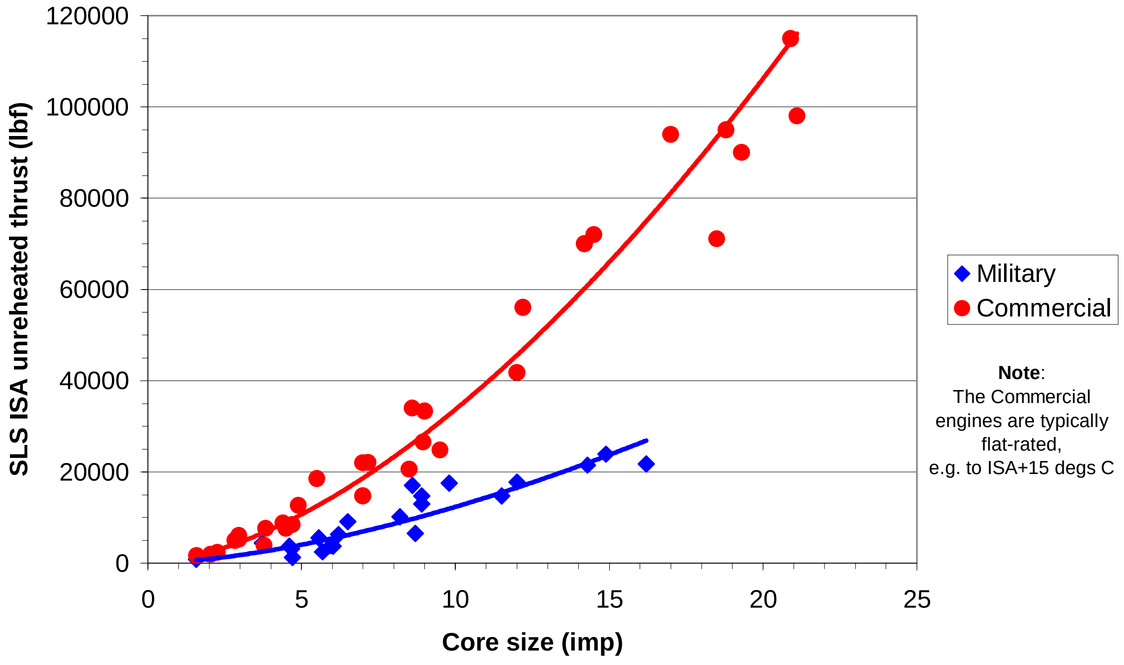


Fig 6 Thrust vs. core size

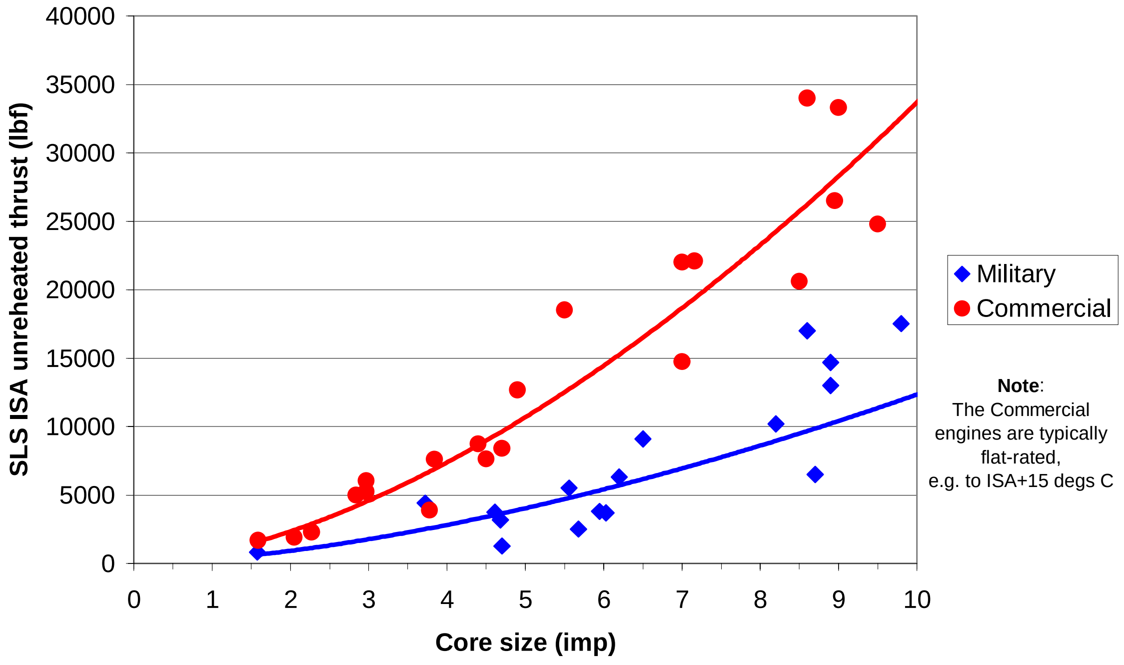


Fig 7 Thrust vs. core size (detail)

With high specific thrust military engines this effect is less pronounced as the benefits of high OPR are lower and the OPR may be constrained by high T1 operations.

The range of applications described in section 3.5 are all likely to require an engine thrust of approximately 5000 – 10000 lbf. Using Fig 7, it can be seen that selecting a core size of 5, for example, would be suitable for a low specific thrust (“commercial”) engine of approximately 10000 lbf and a high specific thrust (“military”) engine of approximately 5000 lbf, or greater. Therefore, there is scope to meet the two requirements with a single core size and, within limits, the thrust can be ‘tuned’ through changes in OPR and SOT.

4.2 Influence of HPC pressure ratio

In section 3 it was shown that the choice of OPR was important in achieving a number of propulsion requirements, e.g. SFC and high T1 operation. The OPR is given by the following equation

$$OPR = R_{fan} \cdot R_{LP\ boosters} \cdot R_{IPC} \cdot R_{HPC}$$

where:

R_{fan} is the pressure ratio across the portion of the fan that supplies flow to the core, including any losses in a downstream duct.

$R_{LP\ boosters}$ is the pressure ratio across boosters stages, if present. These are compressor stages which are mounted on the LP spool, behind the fan, and only work on the flow to the engine core.

R_{IPC} is the pressure ratio across an intermediate pressure compressor (IPC), if present, including any losses in a downstream duct. An IPC is achieved with a three spool engine configuration.

R_{HPC} is the pressure ratio across the high pressure compressor which forms part of the engine core.

Fig 8 illustrates the typical breakdown of pressure ratio across the various compressors in a range of production and study engines designed for the various aircraft applications. This is illustrated by plotting $Log_{10}\ R$ such that the following equation applies:

$$Log_{10}(OPR) = Log_{10}(R_{fan}) + Log_{10}(R_{LP\ boosters}) + Log_{10}(R_{IPC}) + Log_{10}(R_{HPC})$$

The following points are noted:

- The OPR is broadly similar within each aircraft application.
- There are a number of differing ways of achieving the desired OPR with two or three spool engine configurations.
- The HPC pressure ratio varies considerable between engine examples from approximately 2.5 to 20.

When it is proposed to use the same core for a number of applications then the HPC PR will remain broadly the same. (A number of techniques for changing the PR of the HPC, e.g. throttling and de-staging, are discussed in later sections, however, these result in some compromises to the engine design or the extent of commonality.) Therefore the choice of HPC PR will impact on the scope of commonality and the configuration of the engine family.

For example, it can be seen that a combat aircraft requires a low HPC PR of approximately 5 – 6. The use of this core in a small, medium or large commercial transport would require either an intermediate compressor or a large number of LP booster stages. Conversely, the core of a two spool commercial transport engine with a HPC PR of approximately 15 - 20 could not be used in the combat engine as it would result in too high an OPR and hence problems associated with very high HPC exit temperatures. As a result, this core would require considerable modification, e.g. removing stages and aerodynamic redesign, before it could form the basis of a common core

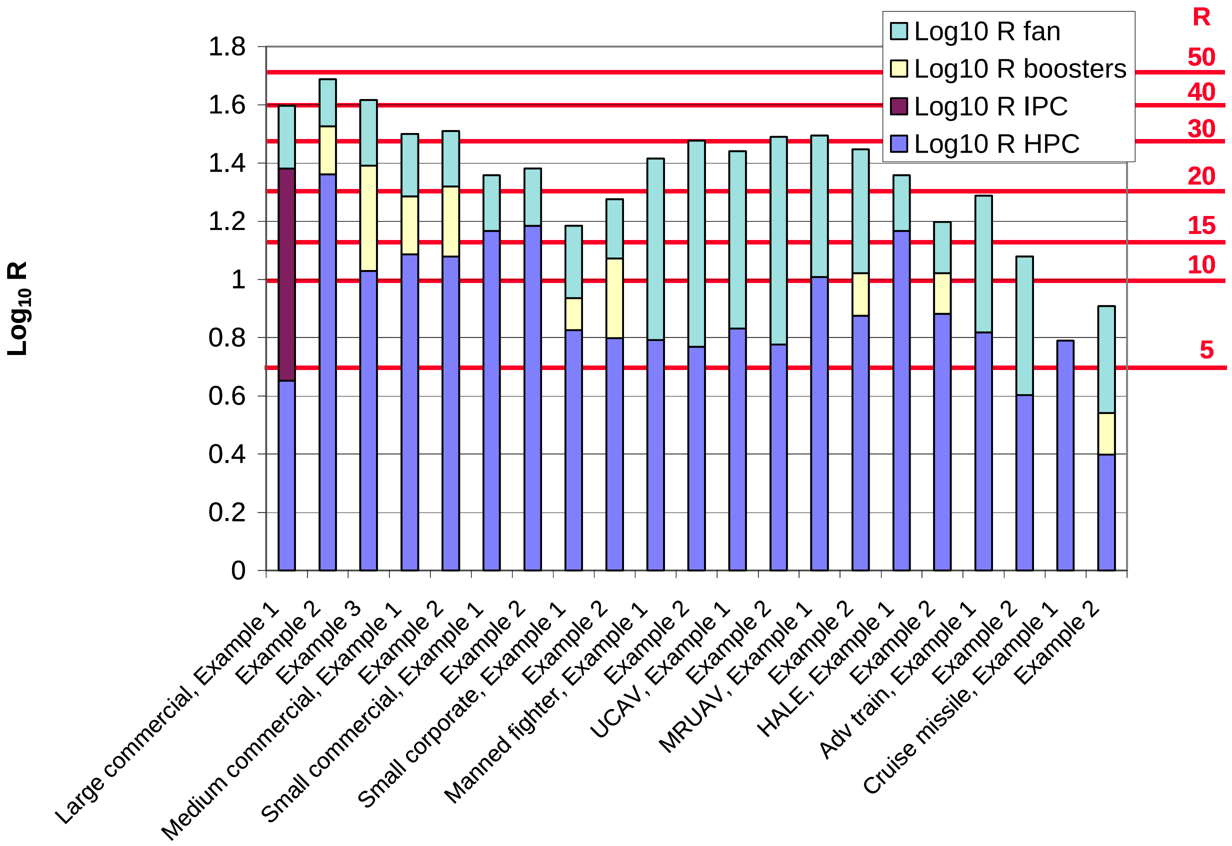


Fig 8 Compressor pressure ratio for differing applications

family which included high specific thrust turbofans.

Another consideration when trying to use the same HP compressor for differing engines are the compressor entry conditions. The most important parameter here is the non-dimensional speed Nh/√T, where Nh is the speed in rpm or rad/s and T is the compressor entry gas temperature. For the compressor to remain aerodynamically similar this parameter must be kept constant. When comparing a high specific thrust military engine with a low specific thrust commercial engines the entry temperature could vary significantly due to the differences in the fan pressure ratio and the temperature at entry to the engine. In order to maintain constant Nh/√T it is therefore necessary to increase the rotational speed, Nh, to match any increase in entry temperature. This will impose large increases in the mechanical loads in the compressor and turbine particularly in the discs, which hold the blades together. To accommodate this it would be necessary to provide larger discs, which naturally will weigh more.

Therefore, in order to maintain commonality it may be necessary for the engine with lower compressor entry temperature to carry around extra mass, which is not required in that particular engine type.

Ideally, to avoid this situation, it is advantageous to arrange for the temperature at entry to the HP compressor to be such that, at key stress cases, all of the engine types have similar mechanical speeds. This requires a complex evaluation of the engines at a range of conditions and an assessment of component overspeed capability and life. For applications operating at similar levels of peak T1 this means, to a first approximation similar level of OPR. In the case of the applications described in section 3.5 these all have an OPR of approximately 20 to 30.

4.3 Influence of SOT

It has been previously discussed that SOT will have an impact on a number of engine attributes.

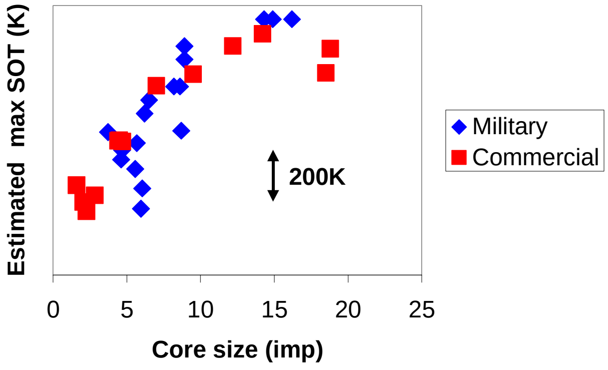


Fig 9 Estimated max SOT vs. core size

Fig 9 illustrates the estimated maximum SOT for a range of typical production and development engines for both military and commercial applications.

The following points are noted:

The SOT generally increases with core size. This is primarily due to two factors:

Firstly, the larger core size enables more complex cooling systems to be incorporated.

Secondly, in the case of the commercial applications, the larger engines have greater emphasis on SFC and hence are driven to higher OPR and SOT. Whereas, at the smaller size there is greater emphasis on low cost and hence lower OPR and SOT.

The maximum SOT of the military and commercial engines are broadly similar. The life of a civil engine can be an order of magnitude greater than a military combat engine. However, the time spent at the maximum SOT is usually considerably shorter, as a result of spending most of its life at a cruise condition.

In the case of military engines there is greater variation in SOT at a given core size. This due to the differing requirements resulting in a differing balance between high T/W, and hence high SOT, and low cost and/or long life, driving lower SOTs. For example, a manned fighter will require high T/W and hence high SOT. In contrast, Multi-role UAVs, HALEs and cruise missiles are likely to have lower SOT due to greater emphasis on reducing cost.

When a core is being investigated for a number of applications there will be an optimum combination of OPR and SOT which results in the correct thrust and the desirable T/W ratio and SFC characteristics. It is likely that this will result in a change in the design SOT between the different applications. This is not necessarily a problem provided that the engine combustor and turbine life can be achieved when the engine is operated at its new SOT levels for a given mission. Alternatively, some changes to the combustor and turbine, e.g. materials and/or cooling, may be necessary to allow increases in SOT while maintaining the same core architecture.

4.4 Selection of a common core

In the previous sections it has been shown that the greatest scope for a common core family occurs where the engine applications require similar levels of OPR and a core size which supports the required levels of thrust at the required specific thrust. Studies suggest the possibility of common core family of three engine for the following applications:

- Engine 1: Stealthy subsonic strike UCAV and advanced trainer (UCAV/Adv Trainer)
- Engine 2: L.O. multi-role armed UAV (MRUAV)
- Engine 3: Small size, short range commercial transport and HALE surveillance UAV (Small Civil/HALE)

The following section examines in more detail the issues encountered when looking at this particular scenario.

5 Example of common core engine families for differing applications

The common core engine families described in this paper all have a SLS thrust of approximately 5000 to 10000 lbf. Based on the discussion in the previous sections an OPR of approximately 25 (rising to 40 in some MRUAV examples) and a core size of approximately 5 (imperial) has been selected.

The paper does not try to draw any conclusions as to the best family approach. This is dependent on detailed analysis of the predicted market, the strategy of the company to address markets and the associated business cases. In addition, the use of the same core for turbo-prop and turbo-shaft engines, although feasible, is not discussed.

Fig 10 illustrates a family of engines based around a relatively low HPC PR core (approximately 7:1) with no modification to this core. The UCAV/Adv Trainer (Option A1) and the MRUAV engines (Option A2) both have advanced conventional military fans with high pressure ratio per stage. To increase commonality, the MRUAV fan is a direct scale-up of the SUCAV engine. The Small civil / HALE engine (Option A3) has a conventional civil fan with a gearbox and booster stages.

The booster stages are required to achieve the necessary OPR. However, a relatively large number of booster stages are usually required to raise the pressure by only a modest amount (e.g. typically 2.2:1 pressure ratio (PR) in 4 stages). This is because the booster stages have the same rotational speed as the fan which is determined by the fan tip speed. Therefore, due to the lower radius of the booster stages, their tip speed is correspondingly lower. Low tip speed limits the pressure ratio achievable per stage before the stage loading exceeds a limit at which the flow over the blades breaks down. In other words, booster stages that rotate at the same speed as the fan will have a poor PR per stage. The penalty of this is a greater number of stages and hence greater mass and cost.

In the example of engine Option A3 the number of booster stages has been reduced through the use a gearbox mounted between the fan and the booster stages. This allows the speed of the LP spool, behind the gearbox, to be increased thereby allowing greater pressure rise per stage without increasing stage loadings. In addition, the higher LP spool speed will reduce the number and/or diameter of LP turbine stages giving additional weight and cost reduction. The disadvantage of this arrangement is the weight, cost and reliability of the gearbox, which is required to transmit high levels of power and torque.

Alternatively, the booster stages could be mounted on a separate intermediate spool, which is allowed to rotate independently from the fan spool. In this way the tip speed of the booster blading can be increased thereby allowing greater pressure rise per stage for a given stage loading. In this situation there are penalties associated with the additional shaft and bearings. In general, this approach is best suited to larger engines with an OPR greater than 25.

The "A" family represents the maximum commonality between the cores of the various engines however it requires the additional design and development of the gearbox and booster stages. This family gives the most optimized solution for high specific thrust UCAV/Adv Trainer engine and the least with the Small Civil/HALE engine.

Fig 11 illustrates a family of engines based around a medium PR HPC (approximately 10.5:1). For the SUCAV engine (Option B1) the HPC has been de-staged to reduce the pressure ratio to approximately 7:1. As with the previous engine family an advanced military style fan is used on both the UCAV (Option B1) and MRUAV (Option B2). The Small Civil/HALE engine (Option B3) is similar in arrangement to the previous family except a gearbox has not been specified. This is because the greater HPC PR means less boosting is required which can be achieved with an acceptable number of stages without the penalties associated with a gearbox. This family utilizes an HPC that is a compromise between the two extremes of the UCAV and the Small Civil/HALE engines. This results in some compromise in the later engine due to the use of booster stages.

Fig 12 illustrates a family of engines based around a relatively high HPC pressure ratio (approximately 15:1). In this case the Small Civil/HALE engine (Option C3) has a conventional fan with no boosters. It is noted that to drive the higher PR HPC a two-stage HP turbine has been specified. However, due to the lower power required by the fan only a two stage LP turbine is required.

Two MRUAV engine options have been investigated. Firstly, the same HPC has been used except the maximum non-dimensional speed has been limited ('throttled') in-order to restrict the PR to 13.5:1 (Option C2.1). In this option the two stage HPT has been retained. Secondly, the HPC has been de-staged to produce a pressure ratio of approximately 9 (Option C2.2). To power this compressor a single stage HPT has been specified to reduce cost.

For the UCAV/Adv Trainer engine (Option C1) the de-staged HPC has been used except the maximum non-dimensional speed has been limited in-order to restrict the PR to 7:1. The same single stage turbine has been retained.

This family gives the most optimized solution for the Small Civil/HALE engine whilst the UCAV/Adv Trainer engine has the greatest compromise. In addition, this family has the least commonality in the core due to the changes required to both the HPC and the HPT.

An analysis has been carried out to estimate the cost of developing each member of the engine family as separate engines compared to developing them as part of a common core family. The results indicate that the total development cost can be reduced by approximately 25%–30%. Alternatively, if there is a requirement to develop an engine for a new requirement and it is possible to use the core from an existing engine then the development cost could be up to 50% less than developing an all-new engine.

The three sets of common-core families illustrate only some of the configurations available to produce a common core engine. However, it illustrates the issues and compromises that the engine designer needs to consider when looking for ways to reduce the non-recurring costs associated with the development of engines for a set of diverse requirements.

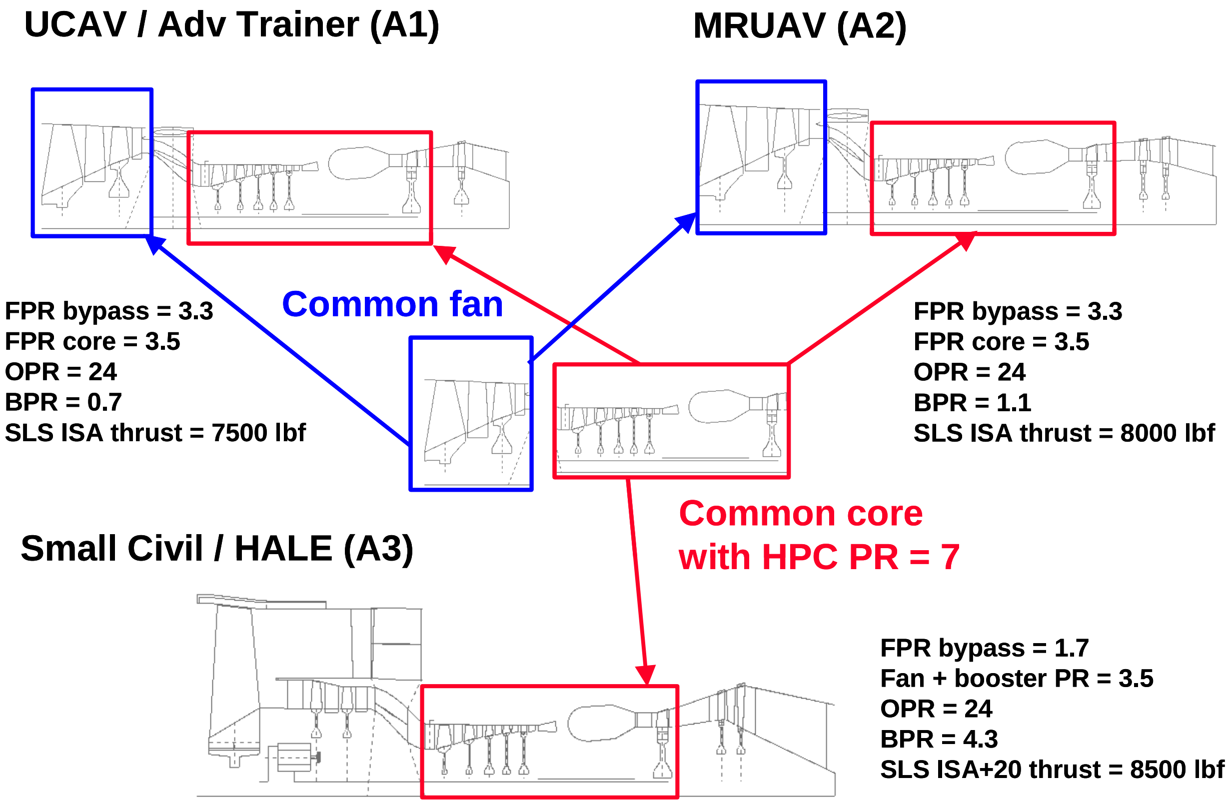


Fig 10 Common core family – A

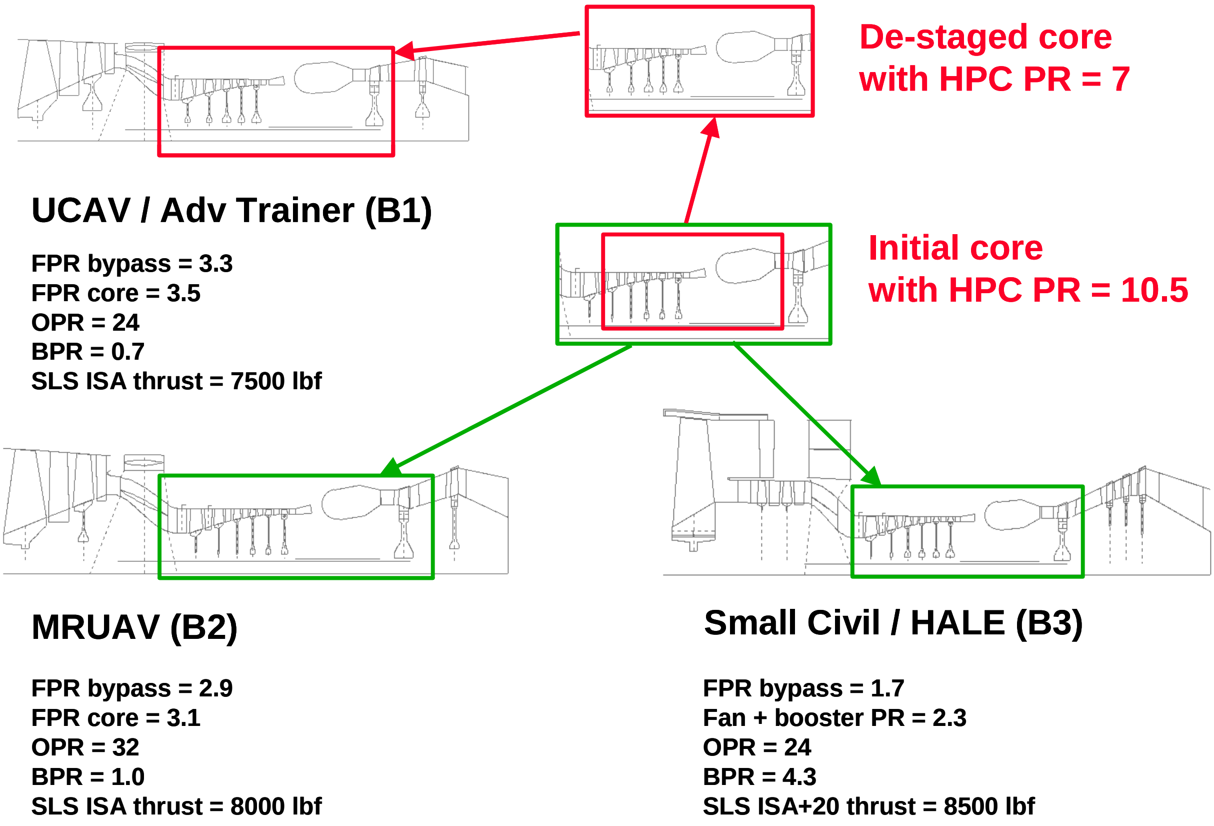


Fig 11 Common core family – B

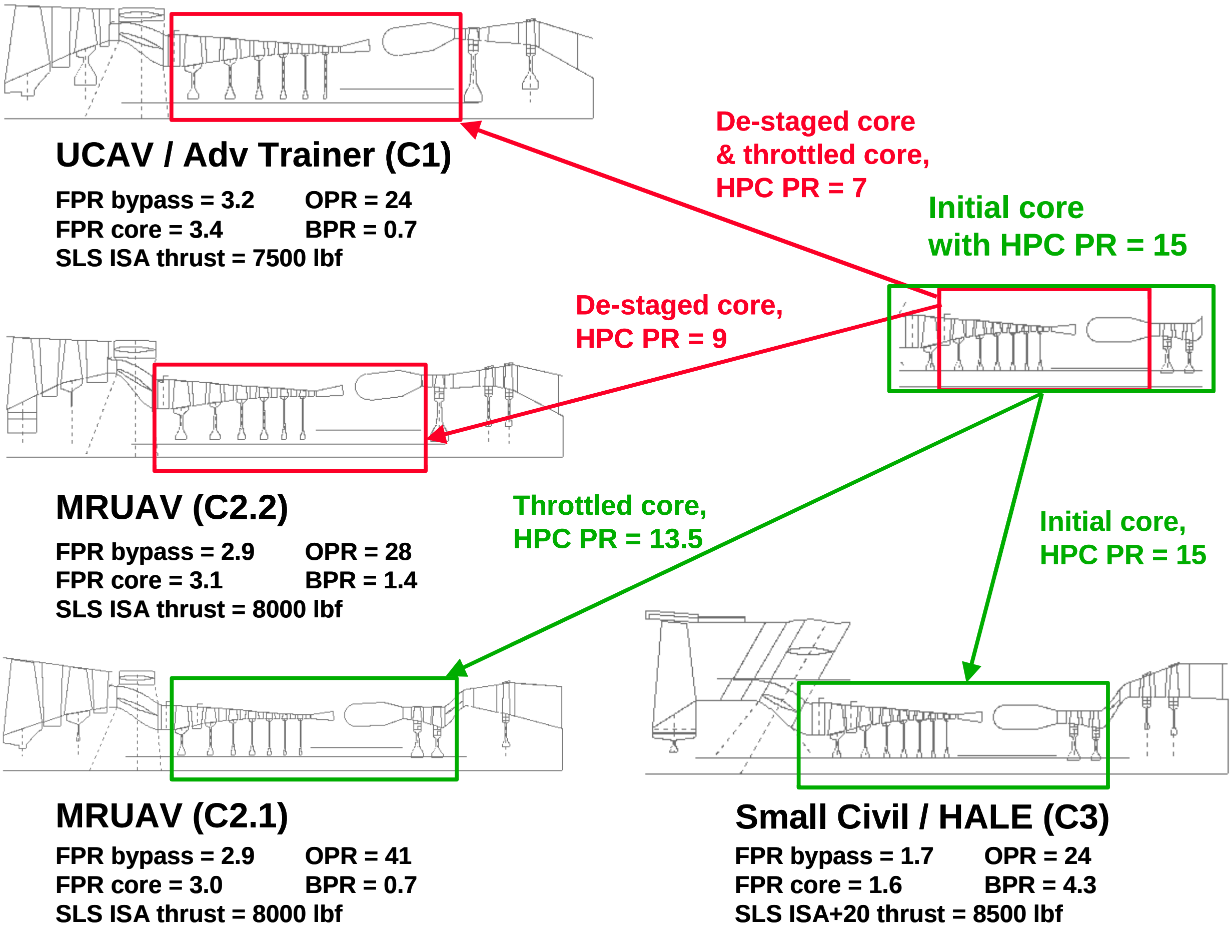


Fig 12 Common core family – C

6 Common core technologies

Depending on the approach taken to achieve commonality in the core, as described in section 5, then various technologies could be beneficial. These are described below against the various modules in the engine:

6.1 Fan

As previously described the requirements of the commercial fan and the military fan differ considerably and therefore common hardware is unlikely. However, there is scope for common technologies. For example, hollow fan blades are well established on large commercial engines, but more recently this technology is being applied to manned fighter engines. More generally, there is scope for the development of generic aerothermal and mechanical methods.

In a number of the engine families presented (A and B) fan booster stages are used to achieve the required OPR. However, fan booster stages require a large number of stages to achieve a modest pressure ratio. In order to reduce this penalty it would be advantageous to be able to significantly increase the pressure ratio of the fan root without adding stages. This may be possible through the use of aspiration. In this technology air is sucked into the blade surface in order to control the development of the boundary layer. In this way it is aimed to achieve greater flow turning and hence pressure rise without the flow breaking down.

This technology is at an early stage of development and a number of issues still require validating such as aerodynamic and system efficiency, mechanical complexity and cost.

In the C family of engines it has been necessary to reduce the pressure ratio of the HPC by throttling and/or de-staging with the subsequent loss of commonality. This has been necessary in order to limit the OPR with the high FPR military fan. The high FPR is required in the air stream which passes down the bypass duct in order to achieve the required specific thrust. The FPR of the inner core stream does not effect this. It would therefore be advantageous to have a fan which has considerably greater pressure ratio in the outer stream relative to the inner stream. Fig 13 illustrates how this arrangement might appear with a drive arm from the tip of the first stage fan driving a second stage, which only works on the outer bypass stream.

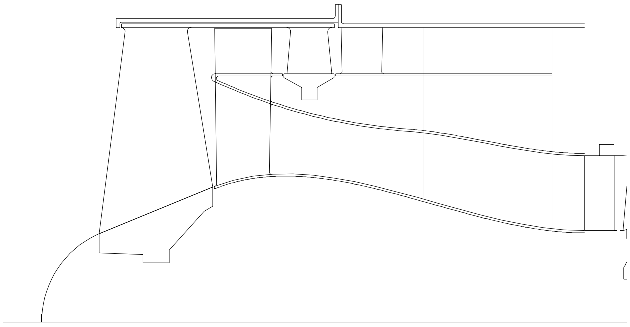


Fig 13 Fan bypass stream booster

6.2 HPC

In a common core engine there could be advantages in an HPC which from the outset is designed to be de-staged with the minimum penalty. For example, the distribution of work between stages could be selected to give the required pressure ratio after de-staging. In addition, the mechanical drive arm could be arranged so that it is not effected by the removal of a stage. More generally, the ability to change compressor surge margin and/or tip clearances with minimum penalties could be advantageous.

6.3 Combustor

The design of the combustor is often a compromise between two conflicting requirements: the control of emissions (Smoke, NOx etc) and the requirement for low weight and cost. The former has become a mandatory requirement for commercial transport aircraft and could become a requirement for HALEs, particularly those carrying out civil operations. Although many military aircraft already have requirements to control smoke emissions the need to maximize performance, e.g. Thrust-to-weight, has in the past been a higher priority than control of NOx. To increase the commonality between engines in a family designed to meet a wide range of applications it would be advantageous to develop combustion technologies which enable dual use with the minimum penalty.

6.4 HP/LP turbine

In the example of common core engine families presented, the HP turbine may be required to cope with a range of power requirements within the same annulus. This could result in the turbine operating outside of normal design limits. Therefore it could be advantageous to acquire the technology to design an aerodynamically efficient turbine over a wide range of inlet and outlet mach numbers.

6.5 Others

A number of other technologies will provide benefits to a wide range of future engines regardless of whether they are part of a common core engine family. Some of these are listed below:

- Low cost controls
- Improved diagnostics and prognostics
- More / all electric technologies
- Integrated power plant and power solutions
- Advanced materials
- Improved durability (turbomachinary high cycle fatigue tolerance)

7 Conclusions

A subjective analysis has been carried out of the attributes of gas turbine engines against the requirements of various commercial and military vehicles. This indicates that in certain areas such as the engine installation and the LP system there is little scope for common hardware to be used in both commercial applications and military combat applications. However, there is the possibility for the use of common core architectures and hardware particularly between the following applications:

- Small size, short range commercial aircraft
- Stealthy subsonic strike UAV
- LO multi-role armed UAV
- HALE surveillance UAV
- Advanced military trainer

The desire to use a common core for a range of turbofan engines of vastly differing specific thrust presents a number of technical difficulties described in the paper. In particular, varying specific thrust implies a significant variation in the fan pressure ratio. Therefore with a constant HPC pressure ratio this will give a significant range of OPR and hence HPC exit temperature. The extent to which this can be tolerated is limited by mechanical constraints. A number of techniques are discussed to overcome this problem through a set of example families of engines. Depending on the technique adopted, there is likely to be some compromise in the design of one or more of the engines in the family and/or a reduction in the level of commonality. The attractiveness of this approach will be dependent on the balance between the investment required to develop the engines and the potential benefits to be gained by the operators.

An analysis of development costs indicates a potential saving in the overall development cost of a three engine common core family of approximately 25%-30% compared to developing the engines separately.

Finally, a number of technologies are described which would help the use of a common core for a range of engines designed to meet differing UAV requirements.

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