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THE IMPACT OF ENGINE TECHNOLOGY ADVANCEMENTS ON THE RANGE v PERFORMANCE TRADE-OFF FOR A FUTURE COMBAT AIRCRAFT

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Abstract

The performance and military effectiveness of combat aircraft depend to a considerable extent on the capabilities of the propulsion system. For a new combat aircraft design, advanced engine technology can lead to a reduction in aircraft size and/or an improvement in performance, compared to an aircraft designed with current engine technology.

This paper investigates the cost effective balance between payload/range and manoeuvre performance for a future ground attack aircraft. The generalised study addresses these trade-offs in terms of aircraft Basic Mass Empty (BME) and engine technology level. Although there is no attempt to address cost issues directly, BME has been used as a discriminator since cost is still influenced by aircraft size.

List of symbols and abbreviations

b	wing span
BME	basic mass empty
BPR	bypass ratio
M_{dash}	dash Mach number
MVO	mutivariate optimisation
P_3	compressor delivery pressure
S	wing reference area
SEP	specific excess power
sfc	specific fuel consumption
SL	sea level
SLS	sea level static
SOT	turbine stator outlet temperature
STR	sustained turn rate
T_1	inlet total temperature
T_3	compressor delivery temperature
TOGR	take-off ground roll
W	aircraft total weight at a given combat condition

Introduction

The performance and military effectiveness of combat aircraft depend to a considerable extent on the capabilities of the propulsion system. For a new combat aircraft design, advanced engine technology can lead to a reduction in aircraft size and/or an improvement in performance, compared to an aircraft designed with current engine technology. Potential advances fall into two categories: aerothermodynamics and materials & structures. The former encompasses such issues as the aerodynamic design of the turbomachinery, aiming towards higher efficiencies and higher stage loadings, which can in turn increase the engine thrust and reduce fuel consumption. Materials research is geared mainly towards the development of improved high temperature metal alloys for combustors and turbines, and new lightweight materials such as metal and ceramic matrix composites and polymer composites. The main advantage of the latter materials is their much greater strength/weight ratio, thus opening up the potential for substantial reductions in engine weight.

How such advances in engine technology may benefit military aircraft design and performance has been an important field of study at the Defence Evaluation and Research Agency (DERA) over the past four years. An earlier phase of the work investigated the effects and trade-offs for an air-air combat aircraft, optimised for typical combat air patrol and intercept missions.[1] The present paper examines the impact on an aircraft designed for the quite different requirements of a ground attack mission with a significant proportion of high speed, low level penetration. This is the role currently fulfilled for the UK by the Tornado GR4.

The Tornado GR4 will be phased out around 2015 and what the replacement system should be is currently the subject of much study. It

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is unlikely that the replacement will simply be a modernised equivalent of the Tornado, and indeed a wide range of possible approaches are under consideration. However, a new-build aircraft naturally remains a major contender, in which case increased range, payload and survivability, at affordable cost, are likely to be important attributes. The paper presents results from a generic investigation into how engine cycle optimisation and advanced technologies can contribute towards these aims.

Demanding a degree of self-defence capability from what is primarily a ground attack aircraft requires a balance of design parameters. For example, for long range the aircraft demands low specific fuel consumption which would indicate the use of a high bypass ratio engine; however high manoeuvre capability demands high specific thrust, pointing towards a lower bypass ratio. Investigating the trade-offs between aircraft range and point performance requirements thus gives an indication of where a reasonable balance may be struck.

Scope of study

A number of study aircraft have been sized to sets of common performance requirements, using a family of generic engines representing both current and future technology in terms of engine cycle temperatures (turbine stator outlet temperature (SOT), compressor delivery temperature (T_3)), and component mass assumptions. Bypass ratios of 0.4. 0.8 and 1.2 have been considered. Since engine performance at high speed and low altitude can be affected by the maximum compressor delivery pressure (P_3), the implications of a constraint on this parameter was also investigated.

When the aircraft are sized to a common mission, the benefits of advanced engine technology are realised in a smaller, lighter aircraft. Alternatively, the aircraft may be sized to a common datum mass, the benefits resulting in an aircraft capable of greater performance. This second approach has been adopted here to provide performance trade-off characteristics between low-level penetration distance and selected design point performance requirements: sea level dash speed, take off ground roll (TOGR) and aircraft turn rate capability.

The benefit of increased dash speed is survivability. It results in reduced exposure time to ground-based defences, and also gives greater ability to outrun or evade a threat. This benefit is not without penalty however as increasing speed results in a rise in temperature in both airframe skin and engine exhaust, giving increased susceptibility to infra-red detection and tracking by heat-seeking missiles. A short TOGR capability results in basing flexibility, enabling operation from short or damaged runways or more payload to be carried from a runway where greater length is available. Increased turn rate capability enhances self-defence manoeuvrability.

Design Requirements

Weapons load

In order to maximise the performance of the aircraft, and to reduce its radar cross section, all weapons are assumed to be carried internally. This requirement is critical to the design of the airframe, as the size and position of weapons bays directly influence aircraft length and balance. A representative weapons load is chosen, comprising two 2000lb ground attack munitions housed in a large inner bay and two medium range air-air missiles carried singly in smaller outer bays.

Mission definition

The baseline mission chosen is a 50/50 high/low level mission with a total radius of action of 650nm, which may be regarded as a typical profile for the role. However both total range and proportions of high and low level operation are arbitrary, and have been defined for the purpose of this comparative study only; the mission does not represent any UK Staff target or requirement. The mission is illustrated in Fig 1, and a leg-by-leg breakdown is given in Table 1.

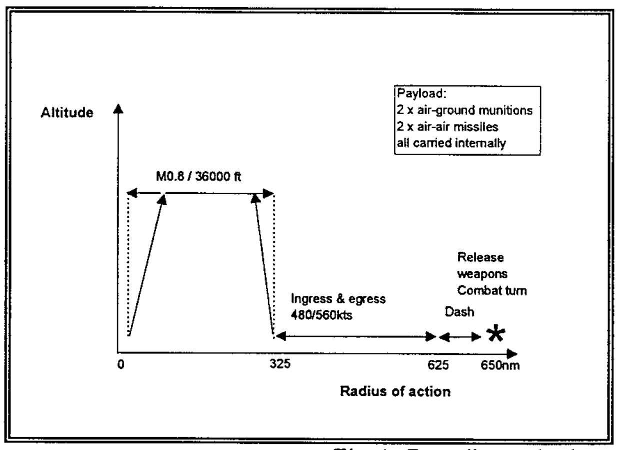

Fig 1: Baseline mission

Leg	Description
1	Engine start, taxi and take-off
2	Climb in max dry power to M0.8/36000ft
3	Outbound cruise at M0.8/36000ft to 325nm from base
4	Descend to sea level
5	Ingress at SL; 150nm at 480kts, 150nm at 560kts
6	Dash at M_{dash}/SL for 25nm. Drop air-ground weapons
7	360° turn at max load factor at M0.8/SL. Fire missiles
8	Return dash at M_{dash}/SL for 25nm
9	Egress at SL; 150nm at 560kts, 150nm at 480kts
10	Climb in max dry power to M0.8/36000ft
11	Return cruise at M0.8/36000ft to overhead base
12	Landing and reserves

Table 1: Baseline mission

Performance parameters

The point performance design requirements have been specified at low level to be representative of an aircraft in the ground attack role, and are in terms of sustained turn rate, attained turn rate and Mach number. See Table 2.

Parameter	Mach	Alt. (ft)	Power	Require-ment
Sustained turn rate (deg/s)	0.8	SL	reheat	14.3, **16.4**, 18.5 (7, **8**, 9g)
Attained turn rate (deg/s)	0.5	SL	reheat	22.9, **26.2**, 29.5 (7, **8**, 9g)
Specific excess power (m/s)	M_{dash}	SL	dry	2.5
Specific excess power (m/s)	M_{dash} +.05	SL	reheat	0
Mach number		36K	reheat	1.5
Take-off ground roll (m)				**600**, 700, 800
Approach speed (kts)				140

Table 2: Point and field performance requirements

A sustained turn is one which can be performed by the aircraft without any loss in energy. Good sustained turn capability is conferred by high engine thrust and low wing span loading (W/b). The attained turn rate is the maximum which the aircraft can achieve instantaneously whilst bleeding energy. Good attained turn capability is conferred by low wing loading (W/S) and high maximum lift coefficient. Specific excess power is essentially a measure of the aircraft acceleration capability at the given condition.

High turn rates enhance manoeuvrability, with resultant increased self-defence capability. High SEPs similarly improve manoeuvrability and for this purpose are usually specified with the engines in reheat power. However a dry power SEP requirement at the M_{dash}/ SL condition has been set here to ensure that the mission dash leg is performed in dry power, to avoid the enormous increase in infra-red emissions which would result from the use of reheat. The benefit of increased all-out speed is survivability as it gives reduced exposure to ground defences and greater ability to outrun or evade a threat.

Aircraft Synthesis

The Multivariate Optimisation Process

The study has been carried out using the DERA MultiVariate Optimisation (MVO) method.(2) This provides a means of developing consistent families of optimised aircraft to meet a given set of requirements, through the use of common design synthesis rules for each configuration. The approach enables parametric studies into the effects of technology advances, design variables, and changes in operational requirements to be undertaken. MVO has been used here to optimise the aircraft in terms of minimum basic mass empty (BME) in part because it is a convenient and clear parameter to work with, but also because aircraft size is generally seen as having a major influence on cost.

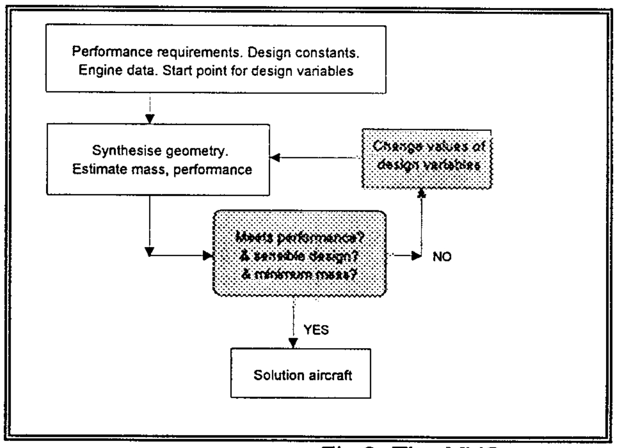

Fig 2: The MVO process

The operation of MVO is outlined in Fig 2. The program consists of aircraft design synthesis and performance estimation routines, linked to a general code for constrained, non-linear optimisation. The parts of the operation undertaken by the synthesis program are represented by white boxes, while those involving the optimiser are shown as shaded boxes. Input consists of performance requirements (mission, point performance), design constants i.e. values for parameters which remain unchanged during the optimisation (e.g. cockpit length, weapons bay size, structural design factors), engine performance data at a reference scale (thrust, fuel flow etc. throughout the flight envelope), and starting point values for those parameters which will change during the optimisation (e.g. engine size, wing area, fuselage length). The program then synthesises the aircraft geometry from the input data, estimates its mass and aerodynamic properties, and then, with the addition of the engine data, calculates its performance. Control now passes to the optimiser which considers whether the performance requirements are met, whether the design is sensible (e.g. centre of gravity within required range, fuselage volume sufficient to house the contents) and whether the synthesised aircraft is of minimum mass. If any of these considerations is not satisfied, the optimiser changes the value of one or more of the design variables, and a new aircraft geometry is synthesised. This process is iterated some several thousand times until all criteria are met and the details of the solution aircraft are then output.

Airframe Modelling in MVO

The generic aircraft synthesised in this study are all twin engined, single cockpit layouts. They are fairly conventional in terms of their aerodynamic configuration, consisting of a swept wing with a tailplane and twin canted tailfins. The aircraft have a large central weapons bay to house the two 2000lb ground attack munitions, and two smaller outer bays each carrying a single medium range air-air missile. A sketch of a typical aircraft from the study is given in Fig 3. The shaded parts of the wings indicate the extent of the wing fuel tanks. Fuel is also carried in the fuselage, but this is not shown for reasons of clarity.

The aircraft are stressed to a flight load limit of 8g in the baseline case and maximum design speeds are 725kts at sea level and Mach 1.6 at altitude. These figures are considered appropriate for a ground attack aircraft with a degree of self-defence and secondary fighter-type capability. Mass assumptions for aircraft structure reflect significant use of advanced materials and construction techniques and are kept constant throughout the study. Mass and volume assumptions for aircraft systems are consistent with modern combat aircraft. e.g. Eurofighter.

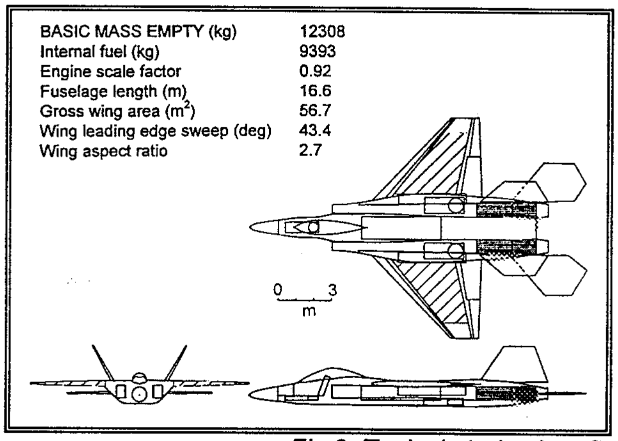

Fig 3: Typical study aircraft

Engine Modelling in MVO

Each engine is defined for a sea level static mass flow of 73.5 kg/s at the reference scale factor of unity. This size is similar to that of current/future UK engines such as RB199 and EJ200, and was considered to be a convenient starting point for the mission postulated here. The engine cycle parameters are fixed during the optimisation process, but the MVO program can scale the engine in terms of thrust, fuel consumption, mass and geometry, in order that the specified requirements are met with the minimum mass aircraft. Geometry assumptions are the same for all engines.

Engines

Range of engines

The set of generic engine models used in this work were created by DERA. All have the same sea level static (SLS) intake mass flow at unit scale factor and use the same temperature rating schedule. While turbine stator outlet temperature (SOT) and compressor delivery temperature (T_3 in conventional engine cycle nomenclature) define engine cycle constraints, the actual performance capability across the flight envelope depends on the flight conditions at which these limits are reached. These are defined here using the temperature rating schedule illustrated in Fig 4.

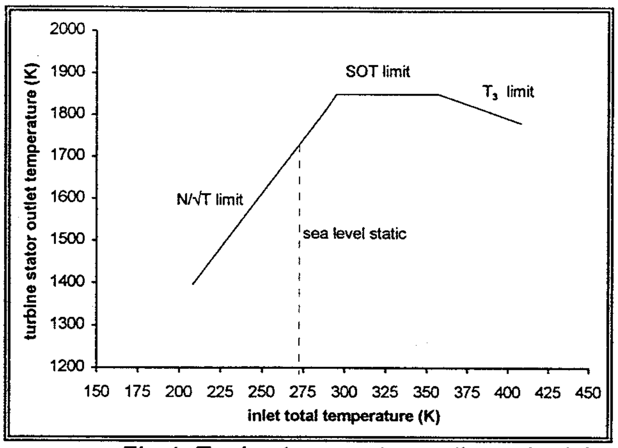

Fig 4: Engine temperature rating schedule

This schedule is typical of a modern combat engine but has not been optimised specifically for the requirements used in this study. At SLS and other low inlet temperature conditions, the engine is limited by non-dimensional compressor speed (N/√T). The SOT limit becomes critical as an inlet total temperature (T_1) of around 300K is reached, while at high inlet temperatures the engine is constrained by a T_3 limit. Polytropic efficiencies have been held constant, so variations in T_3 are equivalent to variations in compressor delivery pressure (P_3). The engine variations covered include changes in cycle temperatures (SOT & T_3) and bypass ratio, and consider the effects of a P_3 limitation.

Two 'current technology' baseline engines have been defined, having a maximum stator outlet temperature (SOT) of 1850K and a maximum compressor delivery temperature (T_3) of 875K. Bypass ratios of 0.4 and 0.8 are considered, and the engines are labelled AL and A respectively in Table 3. (L denotes low bypass ratio).

To investigate the effect of increased cycle temperatures, a number of engines with SOT increased to 2000K and T_3 increased to 950K have also been defined, with bypass ratios of 0.4, 0.8 and 1.2. These engines are labelled BL, B and BH respectively in Table 3. (H denotes high bypass ratio).

Engine P_3 increases as intake total pressure increases, and therefore reaches its highest value at low altitude and high flight Mach number. In the application considered here, it is the SL maximum Mach number requirement (M_{dash} + 0.05) which defines the maximum P_3 seen by the engine; Table 3 gives the values of P_3 at M1.0/SL, the effective maximum for the datum case. The values for the B-series engines can be seen to be very high, at levels which are considerably greater than the 3500kPa to 4000kPa typical of current military and civil turbofans. While there is no intrinsic technical limit in going to much higher levels, considerations of engine core weight and visible emissions will place practical constraints on this parameter. Consideration of the engines BL, B, BH provides an indication of the potential gain if there were to be no restrictions on engine operation. The effects of holding P_3 down to a more achievable level of 4250kPa are considered for the 0.8 bypass ratio case, with engine B(R).

Engine	AL	BL	A	B	B(R)	BH
Bypass ratio	0.4	0.4	0.8	0.8	0.8	1.2
SOT (K)	1850	2000	1850	2000	2000	2000
T_3 (K)	875	950	875	950	950	950
P_3 M1.0/SL (kPa)	3650	4840	3650	4840	4250	4840
Overall pressure ratio	28	38	29	39	39	39
Mass (kg)	1000	1000	920	920	920	880
Maxdry thrust SLS (kN)	58.5	63.5	49.5	54.9	54.9	47.8
Maxdry sfc SLS (g/(kN.s))	22.1	22.4	20.0	20.2	20.2	18.5
Maxreheat thrust SLS (kN)	85.3	90.9	80.8	85.8	85.8	78.4
Maxreheat sfc SLS (g/(kN.s))	45.8	43.4	48.6	46.0	46.0	49.3
Maxdry thrust* M1.0/SL (kN)	54.2	59.3	44.8	49.0	41.1	41.4
Maxreheat thrust* M1.0/SL (kN)	96.5	101.	90.4	94.5	80.8	89.0
SLS intake mass flow (kg/s)	73.5	73.5	73.5	73.5	73.5	73.5

* 'uninstalled net thrust'

Table 3: Engine characteristics

Since engine mass is mainly dependent on materials and engineering technologies, and is not directly affected by the thermodynamic parameters, it can conveniently be examined as an independent variable. The datum mass of the 0.4 BPR engine was taken to be 1000kg, fully installed. As the engines are designed to constant intake mass flow, the higher bypass ratio engines have a smaller core, and consequently a lower mass. The reference masses of the 0.8 and 1.2 BPR engines have been taken to be 920kg and 880kg respectively. The effects of a reduction in engine component mass were investigated by considering engines B and B(R) with engine mass reduced to 690kg, a reduction of 25%.

Effects of cycle temperature

Increasing SOT produces more thrust since more energy is being added to the core flow. However the resulting higher jet velocities mean that the propulsive efficiency falls, so sfc in dry power deteriorates.

Polytropic efficiencies have been held constant throughout the engine modelling, so variations in T_3 are equivalent to variations in core pressure ratio. For an increase in T_3, the increased thermal efficiency associated with burning fuel at high pressures means that sfc in dry power improves.

Hence increasing SOT and T_3 together, by the increments used here, gives an engine of greater thrust, but much the same dry power sfc. This can be seen from the comparison between AL and BL (BPR=0.4), and between A and B (BPR=0.8), in Fig 5. For either bypass ratio, beyond the maximum dry power point of the baseline engine, the engine with increased SOT and T_3 shows lower sfc. It has increased dry power thrust (due to increased SOT), and therefore for a given thrust is less far into reheat, with its vastly increased fuel burn, than its counterpart.

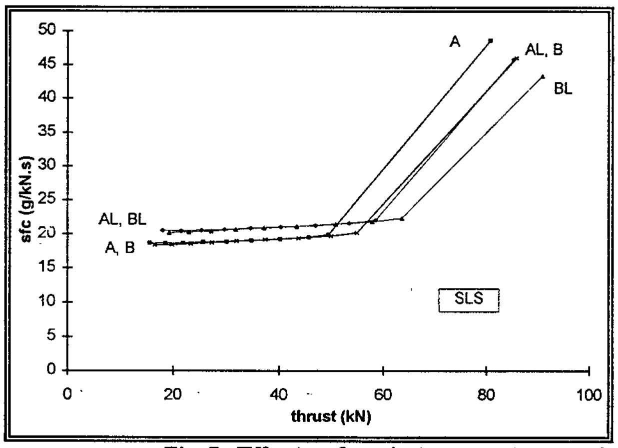

Fig 5: Effects of cycle temperature and bypass ratio

Where aircraft are sized for a given capability, the increased thrust of the higher cycle temperature engine means that a given requirement can be met with a reduced engine size. Thus the airframe housing the engine can be smaller, resulting in a lighter aircraft which demands less thrust to meet the requirement, and so the process continues, resulting in an optimised aircraft which may be significantly smaller and lighter and requires less fuel to achieve the mission. The quantitative aircraft results are discussed later.

Effects of bypass ratio

As already noted, the datum mass for the 0.4 bypass ratio engines is 1000kg. The reference mass of the 0.8 bypass ratio engines has been taken to be 920kg; that of the 1.2 BPR engine is 880kg.

As bypass ratio is increased at constant cycle temperature, the reduction in core flow, and hence core power, results in a lower specific thrust cycle. In general, increasing bypass ratio leads to a considerable improvement in dry power sfc in exchange for a loss of specific thrust.

In reheat the difference in thrust is less marked, since higher bypass ratio engines have more unburned air, so reheat produces a larger boost. More fuel is required for burning this additional air, so sfc increases. Thus reheat sfc increases with bypass ratio, the opposite trend from that seen in dry power.

These effects can be seen by comparing the sfc loops for engines A and AL (baseline temperatures), and for B and BL (advanced temperatures), in Fig 5.

In aircraft sized for the same performance, the results will be the optimised balance between the benefits of lower fuel consumption on the long-range mission and the benefits of increased thrust to meet the point performance requirements (STR, TOGR, SL M_{dash}). The corresponding aircraft results are again discussed later.

Effects of P_3 limitation

The imposition of a limit on P_3 would mean that, at a flight point where the restriction was active, the engine would be unable to achieve its full thrust potential. It would have to be throttled back, restricting the maximum dry thrust level, and consequently also the reheat thrust level. This is illustrated in Fig 6, for the SOT/T_3=2000K/950K BPR=0.8 engine at M1.0/SL. The area of the flight envelope where the P_3 limit has an effect is shown in Fig 7.

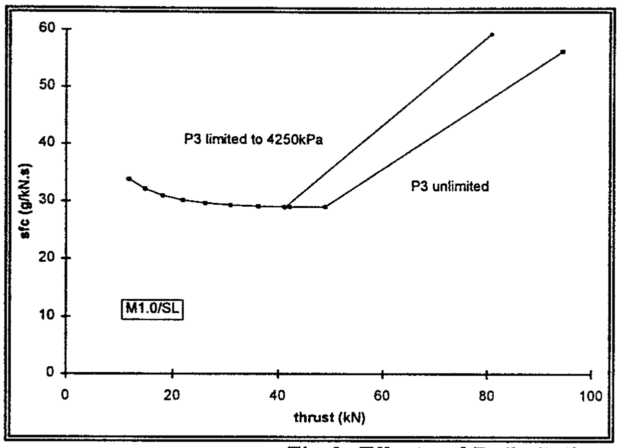

Fig 6: Effects of P_3 limitation

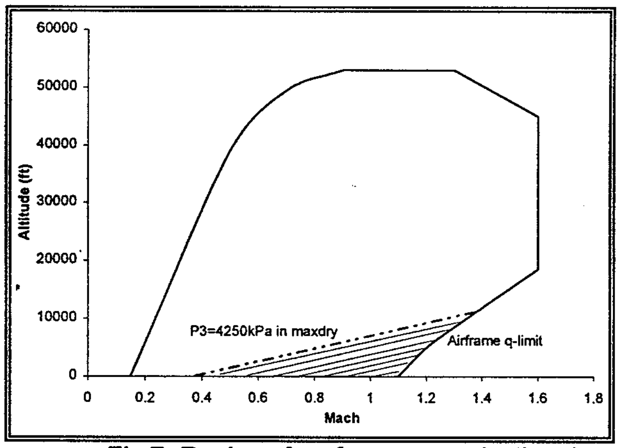

Fig 7: Region of performance reduction due to P_3 limit

This curtailment of thrust would mean that if the aircraft size were driven by a performance point in the penalised portion of the flight envelope, the engine would have to be scaled up to achieve the required thrust. This would result in a larger airframe, requiring further engine scaling, and the resulting aircraft would be larger and heavier.

Effects of component mass reduction

Engine mass is treated here as an independent variable, unaffected by the aerothermodynamic parameters. Therefore reducing the component mass for a given set of cycle parameters will give a lighter engine but maintain the same level of performance.

A lighter engine results in a lighter airframe. This in turn reduces the demand on wing area, which reduces airframe mass, and consequently the aircraft demands a smaller engine. This iterative process will result in a lighter airframe for a given set of requirements, the mass savings being greater than seen simply on engine mass, and will require less fuel to meet the given mission.

Study Results

Aircraft, optimised in terms of minimum basic mass empty (BME), have been synthesised around each engine for each given set of requirements. The parameters SL M_{dash}, take off ground roll distance and aircraft structural load limit (with its effect on turning capability) have been selected as specified design requirements to enable suitable trend lines of optimised aircraft BME to be developed.

Dash speed variation

Figs 8a - 8d illustrate trends of aircraft BME v SL M_{dash} requirement for selections of engines. In each case the SL M_{dash} requirement is varied between M0.85 and M1.0. The curves are all of the same general shape, showing a portion where BME is relatively insensitive to SL M_{dash} requirement, followed by a sharp rise in BME in the transonic region. On the 'flat' portion of each curve, the engine size is driven by the supersonic Mach number requirement at altitude, the specified M_{dash} being a less demanding requirement, which can be met with margin to spare. The small BME increase with speed is due to the increased fuel use in the dash legs. However, in the transonic regime, the dash speed requirement takes over as the driver on engine size, becoming more demanding than the specified altitude requirement. Here aircraft mass increases sharply because the engine has to be scaled up in order to compensate for the additional drag at the drag rise Mach number and above.

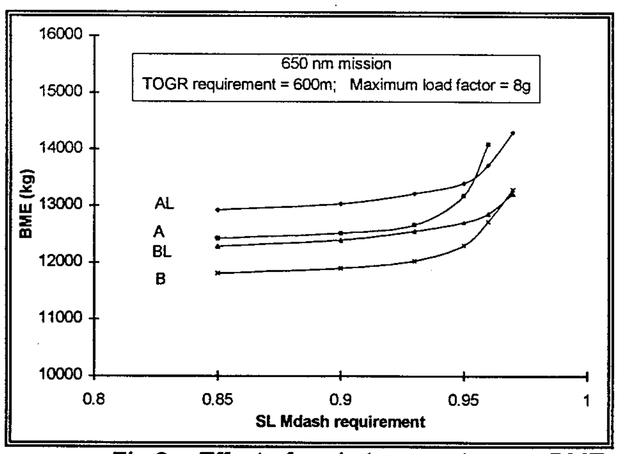

Fig 8a: Effect of cycle temperature on BME

Fig 8a also shows that aircraft with higher cycle temperature engines and unrestricted P_3 (engines BL and B) show a mass benefit over those with current temperature engines (AL and A). This is independent of bypass ratio, and is about 6% at a SL M_{dash} of 0.95.

Fig 8b illustrates the effects of bypass ratio. At low values of SL M_{dash} requirement, where this parameter does not drive the design, the aircraft mass decreases with increasing bypass ratio. Here it is the lower specific fuel consumption (sfc) of the higher BPR engine which brings the benefit. However as the SL M_{dash} requirement is increased the position reverses, the benefits of the higher thrust of the lower BPR engine now outweighing the sfc penalties. At a SL M_{dash} of M0.95 the 0.8 bypass ratio engine is optimum, showing a 2% benefit over the 1.2 engine, and a 3% benefit over the 0.4 engine. The steep rise in aircraft BME for values of SL M_{dash} higher than about 0.93 show the increasing unsuitability of the 1.2 bypass ratio engine for such high levels of speed. In fact, even when the design is not driven by the SL M_{dash} requirement, the high bypass ratio engine offers very little advantage, suggesting that 0.8 bypass ratio is close to the optimum for the type of mission considered here.

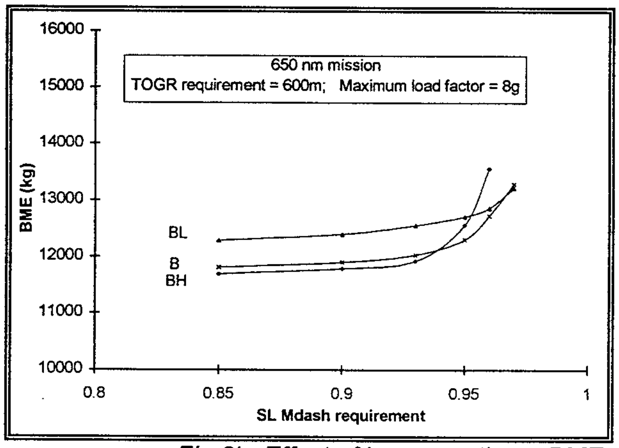

Fig 8b: Effect of bypass ratio on BME

Fig 8c illustrates the effect on BME of P_3 limitation, showing that the curve for the B(R)-engined aircraft diverges from that for the B-engined aircraft. As SL M_{dash} requirement increases, so curtailment of potential thrust capability at this driving condition increases, forcing the engine to be scaled up more and resulting in a progressively heavier aircraft.

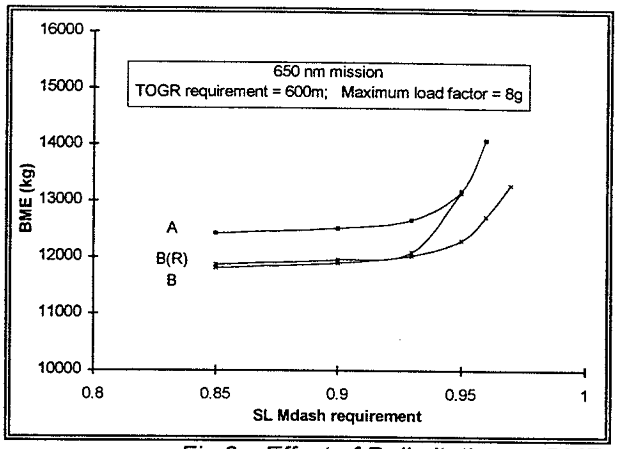

Fig 8c: Effect of P_3 limitation on BME

The benefits of decreased engine component mass are illustrated in Fig 8d. It can be seen that the trends are exactly the same as for the heavier engines, except that the synthesised aircraft are some 7% lighter.

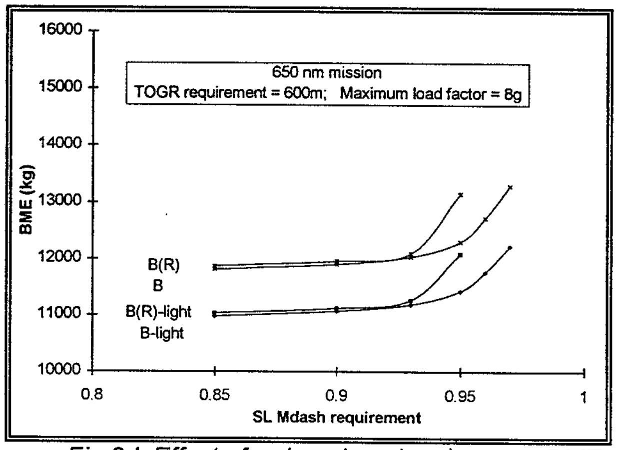

Fig 8d: Effect of reduced engine mass on BME

<u>Low level penetration distance v SL M_{dash} trade-off</u>

As shown in Figs 8a and 8b, increased cycle temperatures and optimised bypass ratio result in aircraft of lower BME when the aircraft are designed to a common mission. An alternative approach is to design to a constant BME, the benefits being realised in terms of an aircraft of equal mass able to complete a longer mission.

This latter approach will now be considered, with the range variations made to the low-level ingress leg. The datum mass chosen was 12.3 tonnes, equal to that of the aircraft synthesised around engine B for a SL M_{dash} requirement of M0.95 and the datum range mission. The 0.8 bypass ratio engines have been chosen to illustrate the trends, as this BPR is arguably the best suited, based on the evidence presented here.

Fig 9 shows that the low level penetration distance of the B(R)-engined aircraft falls increasingly short of that achieved by the B-engined aircraft as the SL M_{dash} requirement is made more demanding and the available thrust of the B(R) engine is more severely curtailed due to the P_3 limit. For a SL M_{dash} requirement of M0.95 and above, the imposition of the P_3 limit has more than outweighed the benefit of increased cycle temperatures.

The engines with reduced component mass can be seen to exhibit exactly the same trends as their nominal mass counterparts, but with low-level penetration distance increased by some 17%.

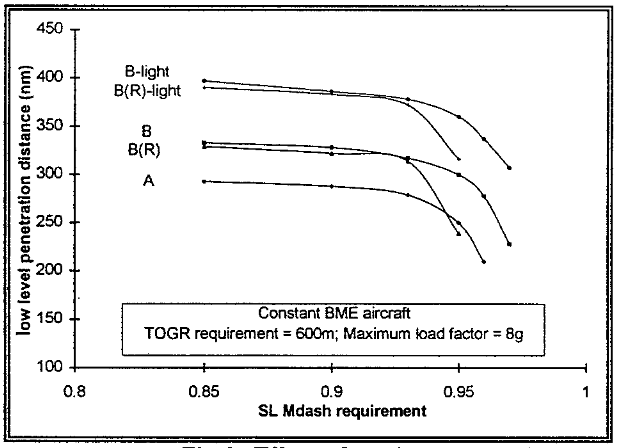

Fig 9: Effect of engine parameters on penetration distance

<u>Take-off ground roll and maximum load factor variation</u>

For the SL M_{dash} requirement set at M0.95 and the baseline mission, the MVO program was used to find optimised solutions for a matrix of cases with TOGR taking values between 600m and 800m, and the maximum load factor taking the values 7g, 8g and 9g. The engines considered were the 0.8 bypass ratio engines A and B, with current technology mass assumptions. In addition the TOGR variation was carried out for engine B(R), for a maximum load factor of 8g only, this being considered sufficient to demonstrate the effect of the P_3 limit.

The results for engines A and B are presented separately in Figs 10a and 10b. For the 7g cases, as the TOGR requirement becomes more demanding, the engine size and wing area are increased, resulting in a heavier aircraft. In the 9g cases, the engine and wing are sized to meet the demanding turn rate requirements, and the synthesised aircraft is more than capable of meeting a TOGR requirement of 600m. There is therefore no change in mass with TOGR in this range. The 8g cases show the hybrid effect; the sizing of the engine and wing to meet the turn rate requirements enables TOGR distances of 700m and greater to be met. More demanding TOGR requirements require an increase in wing area and engine size, and hence the aircraft mass increases.

The results for engine B(R), at a maximum load factor of 8g, are overplotted on Fig 10b, and can be seen to have the characteristics of the 9g case with a slightly heavier aircraft. The curtailment of thrust at high speed and low level by the imposition of the P_3 limit means that the B(R) engine has had to be scaled up to meet the thrust requirement for the sustained turn at M0.8/SL, with the consequent escalation of mass in the aircraft. This scaling to meet the thrust requirement at the driving condition gives additional thrust at flight points where the thrust is not curtailed. Therefore at SLS the TOGR requirement can be met without additional mass, throughout the range considered.

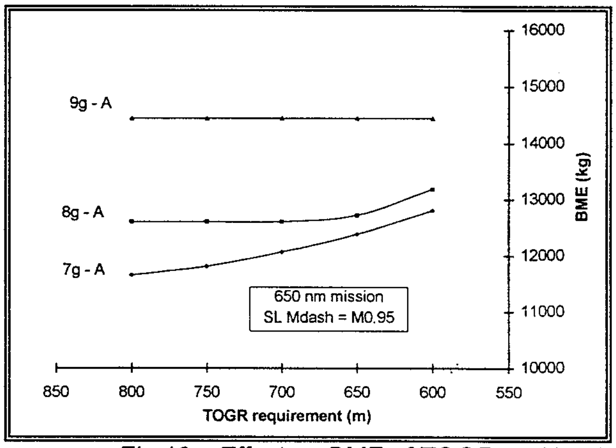

Fig 10a: Effect on BME of TOGR and load factor requirements - A engines

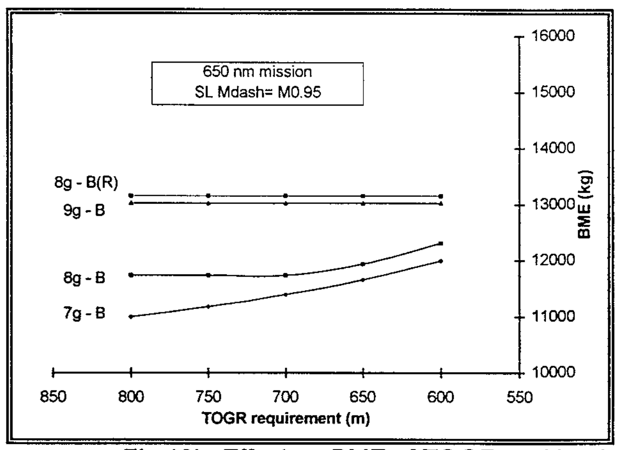

Fig 10b: Effect on BME of TOGR and load factor requirements - B engines

Low level penetration distance v TOGR trade-off

For requirements SL M_{dash} = M0.95, maximum structural load factor = 8g and a range of TOGR requirements between 600m and 800m, the mission low level penetration radius has been increased or decreased as appropriate to synthesise aircraft to a constant BME. The value of BME chosen is again 12.3 tonnes, equal to that for the B-engine aircraft for a TOGR of 600m. The resulting performance trade-off curves for all the 0.8 bypass ratio engines are given in Fig 11.

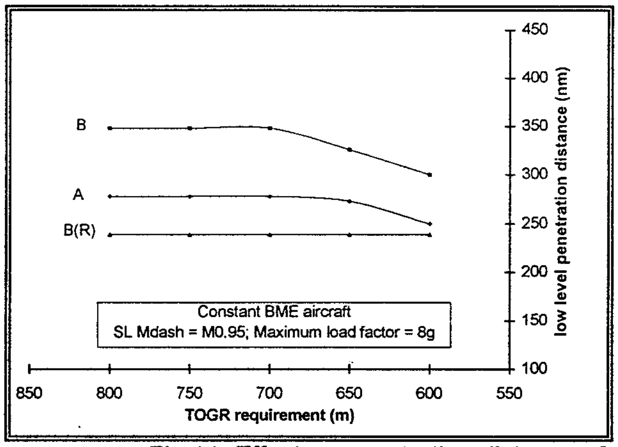

Fig 11: Effect on penetration distance of TOGR requirement

The trends are flat where the TOGR requirement is not active in driving the design. As the TOGR requirement becomes more demanding (shorter), the curves for A and B show a decrease in low level penetration distance; that for B(R) remains flat. Because of the P_3 limit restricting thrust at M0.8/SL, the engine is scaled significantly to meet the STR at this flight point, with the subsequent loss in penetration distance. Due to the engine scaling, at the take-off condition there is more than enough thrust to meet a TOGR requirement of 600m.

Low level penetration distance v maximum load factor trade-off

In the same way, for requirements SL M_{dash} = M0.95, TOGR requirement = 600m and maximum structural load factors of 7, 8 and 9g, the mission low level penetration radius has been increased or decreased as appropriate to synthesise aircraft to the same constant BME. For the 0.8 bypass ratio engines the performance trade-off between penetration radius and aircraft maximum load is given in Fig 12.

Although increased cycle temperatures appear to offer significant increases in aircraft penetration distance (around 35% at 9g), the inclusion of a practical limit for P_3 more than removes the advantage. With this engine the 9g aircraft shows a decrease in penetration radius of around 30% compared with the lower cycle temperature engine.

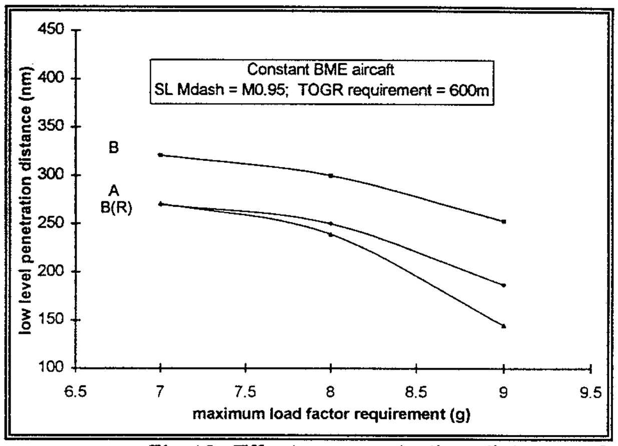

Fig 12: Effect on penetration distance of load factor requirement

Conclusions

- For an aircraft sized to fly this 50/50 high/low mission with a degree of manoeuvre performance, the optimum engine bypass ratio choice is affected by the required dash speed. As this is increased the benefits of the increased thrust from a low BPR engine outweigh the advantage of the low dry power sfc of a higher bypass ratio engine. Of the BPRs considered, 1.2 is marginally the best choice for dash speeds below M0.93, but in practical terms shows little real advantage over 0.8 bypass ratio. The latter cycle appears to be a good choice until low level dash speeds above M0.96 are called for, in which case 0.4 bypass ratio is to be preferred.

- It is shown that increased cycle temperatures offer significant benefits, but only if high values of P_3 can also be achieved. If no limit is imposed on this parameter, the choice of an engine of higher cycle temperatures results in an aircraft some 6% lighter. This is independent of bypass ratio.

- If considerations of core weight and visible emissions force some restriction on engine P_3, then this parameter becomes a very important driver in cases where requirements demand high capability at low-level, reducing the potential performance of the aircraft considerably. Where the requirements are made very demanding, a restriction on P_3 can more than outweigh the benefits of increased cycle temperature.

- A reduction in engine component mass of 25% results in synthesised aircraft some 7% lighter than the datum.

- Combining the benefits of increased cycle temperatures with the benefits of reduced component mass would increase the nominal (bare engine) thrust/weight ratio from today's technology, ≅10, to advanced technology ≅15. The benefit shown is 13% reduction in aircraft BME for unrestricted P_3, 8% if a realistic P_3 limit is imposed.

- The choice of values for point and field performance requirements can have a strong effect on the overall design, and should therefore be chosen with care. In particular a SL M_{dash} requirement in the transonic/supersonic regime is shown to be a very strong driver. Any demand for transonic/ supersonic capability at low level will have strong penalties in terms of aircraft mass, or, alternatively, aircraft penetration.

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