ISABE-2005-1164

# Engine And Installation Configurations For A Silent Aircraft

***Cesare A. Hall*** [*] ***and Daniel Crichton*** [†]
*Cambridge University Engineering Department*
*Trumpington Street, Cambridge CB2 1PZ, UK*
cah1003@cam.ac.uk

## ABSTRACT

The Silent Aircraft Initiative is a research project funded by the Cambridge-MIT Institute aimed at reducing aircraft noise to the point where it is imperceptible in the urban environments around airports. The aircraft that fulfils this objective must also be economically competitive with conventional aircraft of the future and therefore fuel consumption is a key consideration for the design. This paper identifies some key features of a propulsion system that can achieve the Silent Aircraft noise target and explores the relationships between the factors that affect fuel consumption. It also considers the different demands made of an engine at different operating conditions in the flight envelope. These studies are used to propose viable engine and installation configurations that could meet the Silent Aircraft noise requirements. The findings point towards a multiple turbofan system with a variable geometry exhaust and a novel, embedded installation.

## NOMENCLATURE

**Symbols**

| | |
|---|---|
| $a$ | Speed of sound |
| $A$ | Area |
| $c_p$ | Specific heat capacity at constant pressure |
| $D$ | Diameter, Drag |
| $D_f$ | Fan tip diameter |
| $g$ | Acceleration due to gravity |
| $l$ | Length |
| $L$ | Lift |
| $\dot{m}$ | Mass flow rate |
| $n_{eng}$ | Number of engine units in the propulsion system |
| $p$ | Pressure |
| $P$ | Power |
| $Q_a$ | Fan flow capacity, $Q_a = \dot{m}\sqrt{c_p T_{02}} / A_f\, p_{02}$ |
| $Re$ | Reynolds number |
| $s$ | Distance, aircraft range |
| $T$ | Temperature |
| $V$ | Flow velocity (relative to moving aircraft) |
| $V_0$ | Flight speed of aircraft |
| $W$ | Weight |
| $X_N$ | Net thrust |
| $\eta_p, \eta_{th}$ | Engine propulsive, thermal efficiencies |
| $\rho$ | Density |

**Subscripts**

| | |
|---|---|
| $0$ | Total, stagnation value |
| $1$ | Conditions at engine inlet entry |
| $2$ | Conditions at the engine face |
| $eng$ | Engine parameter |
| $f$ | Fan parameter |
| $j$ | Conditions in the exhaust jet |
| $\infty$ | Far-field value |

**Abbreviations**

| | |
|---|---|
| *BPR* | Engine bypass ratio |
| *FPR* | Fan total pressure ratio |
| *HTR* | Hub-to-tip radius ratio for the fan rotor |
| *LCV* | Lower calorific value of fuel |
| *PR* | Pressure recovery |
| *sfc* | Thrust specific fuel consumption |

## INTRODUCTION

Since the dawn of the jet age the noise generated by civil aircraft has decreased by more than 20dB at a given thrust level. To the listener this is heard as a fourfold reduction in noise and it represents a fall of a factor of more than 100 in terms of the acoustic power generated [1]. The majority of this reduction has come from the introduction of high bypass ratio engines. Relative to earlier low bypass ratio engines these produce a slower jet that is much quieter as well as more efficient at generating thrust. Over the last twenty years, bypass ratios have continued to increase, but the resulting reductions in engine noise emission have been more incremental as internal noise sources have started to become dominant. There have also been many other technological improvements that have been made to further reduce noise, including advanced component design to minimise source noise and improved acoustic absorbers. However, the task of making significant further noise reductions for turbofans has become increasingly difficult.

* Research Associate, PhD.
† PhD Candidate.
Other Contributing Authors: T. Hynes, T. Law and M. Sargeant

For current configurations of aircraft and engines we have reached a point where design improvements for further noise reduction are often at the expense of fuel consumption. Increasing bypass ratio and thus fan diameter leads to greater drag on engine installations that is not necessarily offset by the simultaneous improvement in propulsive efficiency. A good example of this conflict between noise emission and fuel consumption is in the recent engine design for the Airbus A380 [1]. The fan diameter of this engine was increased so that the aircraft would incur fewer noise quota points when operating in and out of Heathrow airport [2]. This incurred a penalty in overall fuel burn.

The demand for aircraft to be both quieter and more fuel efficient is greater than ever. The increase in air traffic means the number of aircraft operations are continuously leading to both greater noise and greater emissions of pollutants. The ACARE 2020 vision, developed with industry, has the ambitious target of cutting both noise emission and fuel consumption of aircraft to one half of the levels from aircraft built in 2000 by the year 2020 [3]. This level of reduction is expected to require major technological breakthroughs in both engine and airframe design.

The Silent Aircraft Initiative is designing a concept aircraft with noise emission as the primary design variable. The aircraft is aimed at entry into service in about 20 years and the ambitious objective is to reduce the noise generated to the point where it would be imperceptible above background noise in a typical urban environment outside an airport. Such an aircraft could be deemed as 'silent' and this would represent a reduction in aircraft noise greater than that achieved over the last fifty years. Figure 1 illustrates the scale of this challenge.

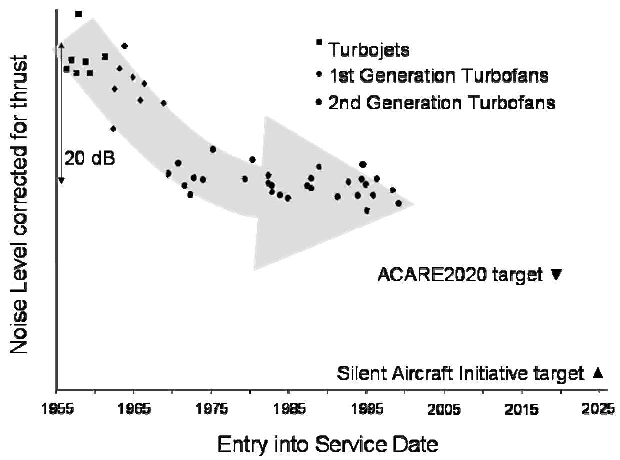



**Figure 1: Reduction in thrust corrected aircraft noise level over time**

In order to reach the Silent Aircraft noise target large reductions, relative to current technology, are required for all components of engine and airframe noise. In addition to this aggressive noise target, the new aircraft must be economic relative to other aircraft of the future. This will require a propulsion system that has competitive fuel burn as well as acceptable development, acquisition and maintenance costs.

There have been several studies of new engine configurations aimed at significant improvements in noise and fuel consumption. The NASA study of advanced engines for high efficiency [4] looks at several configurations, including geared fans and contra-fan designs, aimed at weight and fuel burn reductions. Another system study of engine concepts carried out by NASA [5] investigates the optimum engine parameters for low noise with acceptable operating costs. The work concludes that a low pressure ratio turbofan, in a conventional podded installation, can achieve a 10dB noise reduction without incurring unacceptable cost penalties. Reference [6] gives a good overview of the technology required to further reduce noise from conventional aircraft engines and proposes the use of geared turbofans to give a large improvement in noise emission. However, the noise reductions expected still fall far short of the Silent Aircraft target.

A study of low-noise concepts and the technological barriers to a *functionally-silent aircraft* has been presented in [7]. This paper proposes some novel concepts, including distributed propulsion integrated with a blended-wing-body type aircraft.

The findings from the literature suggest that the aims of the Silent Aircraft Initiative can only be achieved with some radical change in the configuration of aircraft and propulsion system. The current paper aims to answer the question of what features of a propulsion system would be needed to achieve the Silent Aircraft noise target and what design philosophy could be adopted to make such an engine credible. The approach is as follows:

1. The basic requirements for the design of a viable, quiet propulsion system are developed (a large exhaust area at take-off, optimised operational procedures for aircraft departure and large surface areas for acoustic absorbers and noise shielding).

2. Installation design factors are investigated using some simple quantitative analyses and possible options are compared in terms of their impact on noise, fuel consumption and weight.

3. The need for a variable cycle engine is shown and the potential of an engine to be low noise at low altitude and fuel efficient at cruise is investigated.

4. Several candidate engine configurations are proposed and the relative merits of the different options are compared in preparation for future, more detailed, design studies.

## BASIC PRINCIPLES

The exhaust jet noise from a jet engine is highly dependent on the basic thermodynamic cycle of the engine and therefore we will consider this first. Lighthill's well known acoustic analogy [8] relates acoustic power to typical velocity and diameter here taken as absolute jet velocity and jet diameter:

$$P \propto \frac{\rho_j \left(V_j - V_0\right)^8 A_j}{a_0^5} \qquad (1)$$

Whilst progress has been made in reducing jet noise through nozzle shaping especially the use of lobes and/or chevrons ([9, 10] for example) the reductions achieved are modest when compared to that required for silence. The only sure way to obtain significant reductions in exhaust jet noise is to reduce the jet speed. However, it is the difference in velocity between the jet and the surrounding air that generates thrust:

$$X_N = \rho_j A_j V_j (V_j - V_0) \qquad (2)$$

To quieten the jet significantly whilst maintaining thrust therefore requires a very large exhaust area combined with a low jet velocity. Figure 2 shows the variation in required exhaust area with jet noise target for a 250 seat, 4000 nautical mile range aircraft.

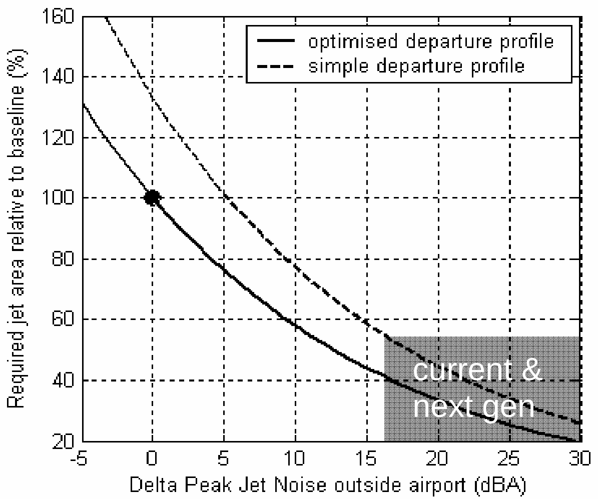



**Figure 2: Relationship between take-off exhaust area and jet noise outside airport for a 250-seat aircraft**

The simple departure profile is for a constant angle of climb after gear-up whilst the optimised profile is thrust-managed to maximize rate of climb whilst ensuring the noise limit is not exceeded. The baseline jet area is that required for 'silent' take-off when using an optimised departure profile. This jet area is 2 to 3 times as large as that of today's conventional jet engines, as indicated on the figure. The calculations use the Stone jet noise model [11] and further details on operational requirements and take-off conditions considered can be found in Ref [12].

Figure 3 shows four take-off profiles in which the jet noise outside of the airport boundary remains below the limit imposed for 'silence'. The baseline profile just meets all required operational and regulatory requirements and therefore can be considered optimum for a Silent Aircraft. The simple profile also meets all requirements but requires a 33% increase in jet area in order to meet the noise target. The remaining profiles are optimised but for areas 10% above and below baseline. For the smaller area, operational requirements cannot be met whilst simultaneously meeting the noise requirements. The larger area meets all requirements but will result in an unnecessarily large engine.

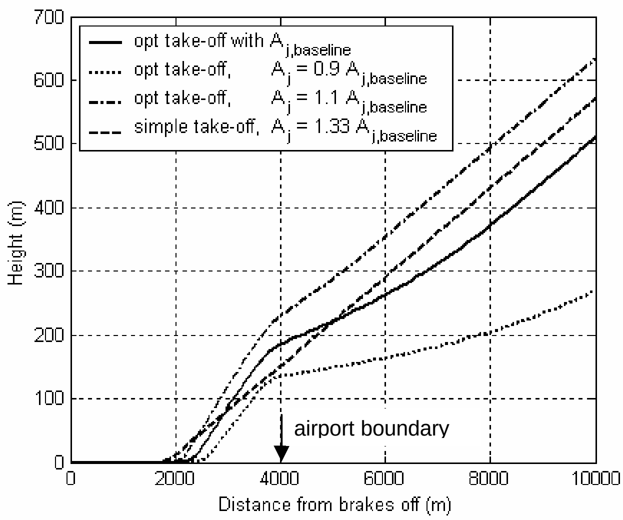



**Figure 3: Departure profiles for a 'silent' take-off.**

There are implications of a large exhaust area for the size, weight and performance of the engine. For a conventional turbofan, if the exhaust area increases the bypass ratio and the fan diameter must also increase. This increases the installation drag potentially leading to fuel burn penalties. The size increase implies an increase in engine weight because the size of the fan components and the engine ducting rises. These issues are discussed in the next section.

Once the thermodynamic cycle is set for low jet noise, the reduction of turbomachinery noise can be addressed. Source noise reduction is tackled initially through various simple design rules: blade speeds can be reduced to remove supersonic sources, numbers off for each blade row can be modified to prevent sources that are 'cut-on', and the gap/chord geometric ratios can be maximized to reduce interaction noise. Unfortunately, improving these parameters for noise will often compromise the aerodynamic performance and the noise reductions available will be limited. More advanced methods, such as 3-D design optimization, can enable additional reductions. However, source noise reductions alone will not be sufficient to reduce turbomachinery noise to the Silent Aircraft noise target, and for these components it will be necessary to develop shielding by the airframe to significantly reduce forward propagating fan noise and to maximize the potential of acoustic liners, particularly to attenuate rearward fan and turbine noise. The potential noise reductions available through shielding and acoustic liners are highly dependent on the propulsion system packaging with the airframe which is discussed below.

The operating costs associated with the development, acquisition and maintenance of a quiet propulsion system are difficult to quantify. Fuel burn will be a major cost factor, but its precise impact will depend on future trends in aviation fuel prices and the regulation of aviation emissions. The basic effects of the propulsion system on fuel consumption can be explored using the Breguet range equation:

$$\frac{W_{fuel}}{sW_p} = \frac{1}{s}\left(1+\frac{W_e}{W_p}\right)\left(\exp(s/H)-1\right) \quad (3)$$

where, $$H = \frac{V_0\, L/D}{g.sfc} = \frac{LCV}{g}\eta_p\eta_{th}\frac{L}{D}$$

Equation 3 tells us that for an aircraft with a fixed range and payload, to minimise the fuel burn per passenger-kilometre we need to minimise the ratio of total aircraft empty weight to payload weight, $W_e/W_p$, minimise the specific fuel consumption of the engine, and maximise the lift-to-drag ratio of the aircraft. The engine cycle directly determines the specific fuel consumption, but the design of engine and installation will also affect the total weight and, for a highly integrated design, can significantly change the aircraft lift and drag.

## INSTALLATION DESIGN FACTORS

The Silent Aircraft airframe design is expected to be a configuration in which the wing and fuselage are merged together, as illustrated in figure 4. Several studies have shown that this shape of aircraft has a higher lift to drag ratio and significantly lower empty weight than a tube-and-wing aircraft carrying the same payload, [13] for example. These factors enable significant savings in fuel consumption (equation 3), but there are also advantages of the airframe for noise reduction. The large, continuous surface of the airframe maximises the potential to shield the forward propagating engine noise from the ground if the inlets are placed on or above the airframe. In addition, the aerodynamically smooth surfaces of an all-lifting body also reduce airframe noise sources significantly [7].

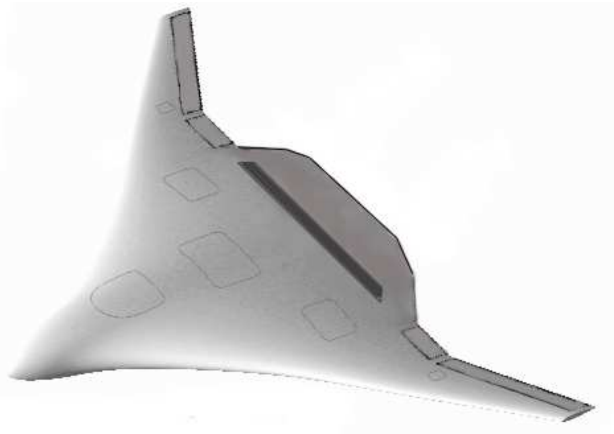
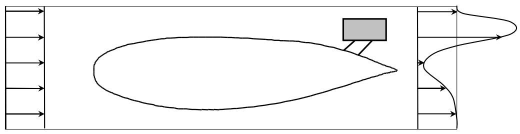
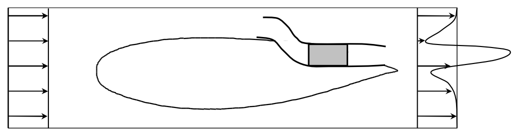


**Figure 4: An all-lifting body with embedded engines.**

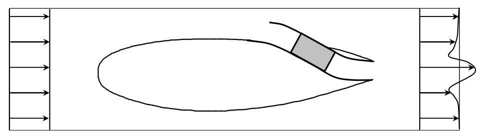
The propulsion system placement on this style of aircraft is limited by structural constraints, the locations of passenger bays, emergency exits, fuel tanks and the position of essential aircraft systems such as control surfaces and the undercarriage. The most feasible location is above (or within) the centre-body of the aircraft behind the passenger cabins. The flying wing has a greater volume to surface area ratio than a conventional aircraft and there is a lot of available space at the back of the airframe that can be used to accommodate embedded engines [13]. Figure 5 summarises the main options that are being considered for packaging the engines with the Silent Aircraft airframe.



**a) Podded propulsion system**



**b) Embedded system with boundary layer diversion**



**c) Embedded system with boundary layer ingestion**

**Figure 5: Options for powerplant integration.**

In order to determine a preferred integration option, the differences in fuel consumption and potential noise attenuation can be explored with the qualitative considerations and the simple quantitative analyses presented in the following sub-sections.

## The trade-off between propulsive efficiency and drag

For an aircraft in cruise, using the efficiency definitions in [14], the overall efficiency and rate of fuel consumption of the propulsion system can be expressed as follows:

$$\eta_o = \eta_{th}\eta_p = \frac{useful\_power}{thermal\_energy} = \frac{X_N V_o}{\dot{m}_{fuel}.LCV}$$

$$\Rightarrow \dot{m}_{fuel} = \frac{X_N V_o}{\eta_{th}\eta_p.LCV} \qquad (4)$$

If we consider increases in fan diameter, propulsive efficiency will improve because the exhaust jet velocity reduces. At the same time, however, the installation size and drag increase leading to a greater thrust requirement. This trade-off can be explored quantitatively by considering the engine design for a fixed aircraft at cruise. With net thrust equal to drag, the drag components can be expressed in terms of the jet area and velocity, using the thrust equation (2):

$$X_N = D_{airframe} + D_{eng} = \rho_j A_j V_j (V_j - V_0) \qquad (5)$$

If the thrust and drag parameters are known for a reference design point, equation 5 can be rewritten to show how the net thrust required varies with the drag contribution from the engine installations:

$$\frac{X_N}{X_{N,ref}} = \frac{D_{airframe} + D_{eng}}{D_{airframe} + D_{eng,ref}} \cong 1 + k\left(D_{eng}/D_{eng,ref} - 1\right) \qquad (6)$$

where $k = D_{eng,ref}/D_{airframe}$ and is assumed to be small.

Changes in the engine installation drag, $D_{eng}$, can be approximated to be proportional to changes in the installation wetted area. For the current study, the following simplistic relationships were assumed for relating the installation drag to the overall fan diameter:

For podded installations,

$$D_{eng} \propto \pi D_f l_{eng} n_{eng} = \pi\left(D_f\sqrt{n_{eng}}\right)^2 \left(l_{eng}/D_f\right)$$

For embedded installations,

$$D_{eng} \propto 2D_f l_{eng} = 2\left(D_f\sqrt{n_{eng}}\right)^2 \left(l_{eng}/D_f\right)/n_{eng}$$

The overall fan diameter, $D_f\sqrt{n_{eng}}$, is used because for a given aircraft thrust requirement, it is independent of the number of engines (see equation 14). If the expressions above are substituted into equations 5 and 6, the variation in jet velocity with overall fan diameter can be approximated. The Froude equation gives propulsive efficiency as a function of jet velocity:

$$\eta_p = \frac{2V_0}{V_j + V_0} \qquad (7)$$

Thus, the variation in overall fuel burn with fan diameter can be determined using equation 4. This approach was applied to produce figure 6, which shows how the cruise fuel burn is expected to vary for podded and embedded configurations with overall fan diameter and the number of engine units.

Note that the reference drag parameters and fan size used to produce figure 6 were derived from data for a conventional 250-seat passenger aircraft with engines that entered service in the 1980s. Since this time fan diameters have already increased by up to 30% and on figure 6 a fan diameter appropriate to a current engine design is marked. Note that from figure 2 the overall fan diameter of a turbofan that would satisfy the Silent Aircraft noise target is expected to be 75% larger than a 1980s turbofan. The actual fan diameter required is examined in greater detail in the next section.

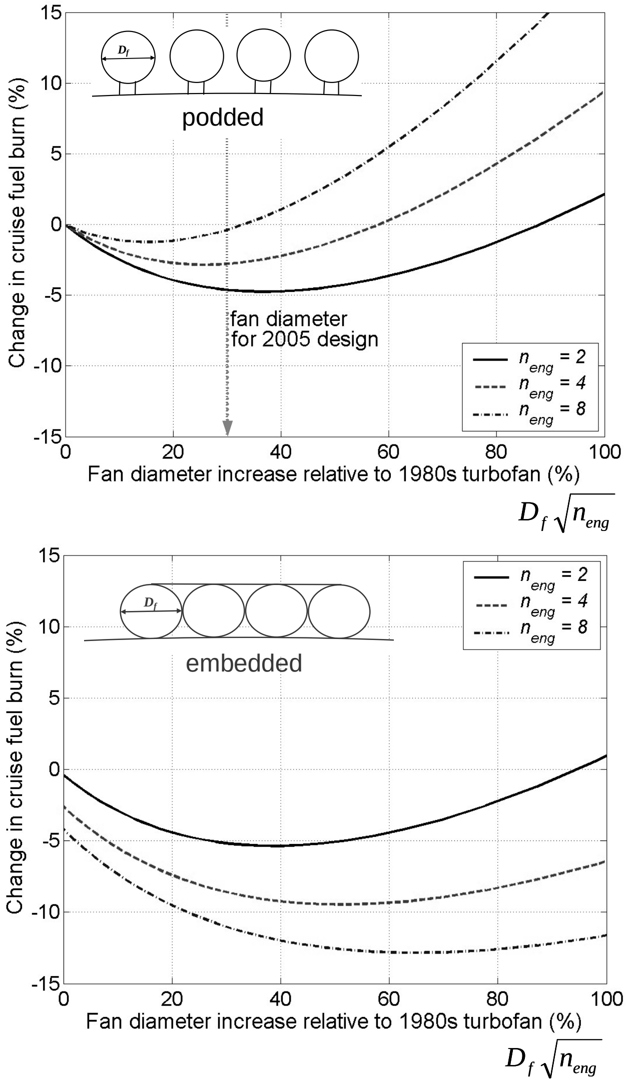



**Figure 6: Variation of fuel burn with fan diameter for a) podded and b) embedded systems.**

The above analysis is admittedly quite crude, but the results show some useful trends for selecting a propulsion system installation. Firstly, they show that with a podded propulsion system, current levels of fan diameter (for 2 or 4 engine systems) are close to the optimum level for minimum cruise fuel burn. With a podded system, the increase in installation drag with fan diameter is greater as the number of engines increases because the total wetted area is increased. For an embedded system, as the number of engines increases, the propulsion system can be better integrated into the airframe leading to a drag reduction. The plots suggest that an embedded propulsion system with a large number of engine units could enable a higher overall fan diameter to be achieved with significantly lower fuel consumption than a modern podded configuration. However, the analysis assumes that the thermal efficiency is unaffected by the choice of installation and it does not consider whether or not the airframe boundary layer is ingested by the embedded engines.

The impact of inlet loss on engine performance

With embedded engines the intakes can employ boundary layer ingestion (BLI) or boundary layer diversion (BLD). With boundary layer diversion, the non-uniform airframe boundary layer air upstream of the intake is prevented from entering the engine by some geometrical feature or device. With boundary layer ingestion, the airframe boundary layer is intentionally drawn into the intake in order to reduce the fuel consumption required. In both cases, embedding the engines leads to extra frictional losses approaching the engine because the shape of the inlet is more complex, typically an S-shaped duct (see figure 5).

The performance of an intake is quantified by its pressure recovery, which is the ratio of the total pressure at the fan-face to that at entry to the inlet, $p_{02}/p_{01}$. A value of 0.995 would be typical for a podded engine intake at cruise, whereas the value for an S-duct type inlet will be closer to 0.95, see [15]. A preliminary computational study of S-shaped inlets for the Silent Aircraft estimated that the pressure recovery would be about 0.96 with BLD and 0.94 if the effects of BLI were included.

The impact of the pressure recovery on the thermal efficiency of a fan can be determined by considering the work input with inlet pressure losses, relative to the work required for fully isentropic compression:

$$\eta_{th} = \frac{(FPR.PR)^{(\gamma-1)/\gamma} - 1}{FPR^{(\gamma-1)/\gamma} - 1}\eta_f \quad (8)$$

This shows that with a pressure recovery of unity, the thermal efficiency equals the fan isentropic efficiency, $\eta_f$. However, as the pressure recovery reduces the impact on efficiency is severe, and this impact increases as the fan pressure ratio is reduced. Also, as pressure recovery reduces, the thrust from an engine will decrease unless the fan pressure ratio rises or the fan diameter increases. To maintain net thrust at a fixed overall fan diameter, the design pressure ratio of the fan must be increased from the pressure ratio with zero inlet pressure loss according to the following equation:

$$FPR = (FPR)_{ideal} / PR \quad (9)$$

Figure 7 uses equations (8) and (9) to show the variation in thermal efficiency with inlet pressure recovery for three values of ideal fan pressure ratio. This analysis assumes that the effect of pressure recovery on the core and bypass flows will be similar.

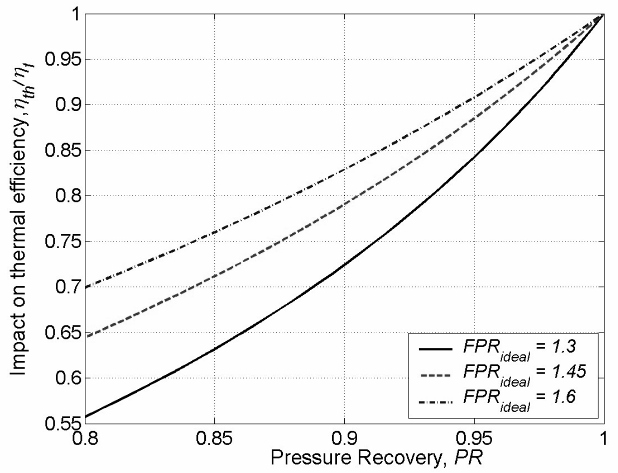



**Figure 7: Thermal efficiency effect of inlet pressure recovery for three fan pressure ratios.**

Figure 7 demonstrates the importance of carefully designing the engine inlets to maximise the pressure recovery. It also shows that for an embedded system with a pressure recovery of 0.95, the impact of inlet losses on a low pressure ratio fan will be a fuel burn penalty in excess of 10%. This could cancel out the fuel burn benefit gained from the drag reduction due to embedding the engines (figure 6). However, boundary layer ingestion offers an alternative opportunity for reducing fuel consumption. Several studies have examined the impact of BLI on engine performance, see [16] for example, but it is an area that requires further research and this is being undertaken as part of the Silent Aircraft Initiative. The following description is an overview of the effects of BLI on each of the terms in equation 4 that determine fuel consumption:

For a BLI system the overall thermal efficiency is even lower than a BLD system because the kinetic energy of the flow entering the engine intake is reduced. This effect can be considered as an additional inlet pressure recovery factor relative to the free stream conditions, $p_{01}/p_{0\infty}$, which can be estimated from the airframe boundary layer parameters at entry to the engine. The net thrust (equation 5) is reduced with BLI because some of the flow that goes through the engine and generates thrust would have otherwise contributed to airframe drag. The drag removed by the engines can be estimated as being proportional to the airframe surface area upstream of the engines [16]. The propulsive efficiency improves with BLI because the jet velocity relative to the flight speed is reduced, as indicated in figure 5c. The change can be estimated using equation 7, once the new thrust requirement has been determined.

Based on the reasoning described above, estimates of the fuel burn benefits of BLI are included in Table 1 on the following page.

Effect of the installation on core size

The core size of a quiet engine will be smaller than that of an equivalent current turbofan because the bypass ratio is higher. Thus the core components operate in lower Reynolds number regimes and the tip clearance gaps relative to the turbomachinery blade sizes are larger. The impact of this on component polytropic efficiencies can be approximated from the following formula based on information from [17] and [18]:

$$\eta_{poly} \propto \mathrm{Re}^{0.1} \propto \left( \frac{D_f \sqrt{n_{eng}}}{(1+BPR)\sqrt{n_{eng}}} \right)^{0.1} \qquad (10)$$

Equation 10 shows that, for a fixed thrust propulsion system, as the bypass ratio or the number of engines increases, the size of the core reduces leading to an efficiency penalty. This effect becomes significant for a quiet propulsion system with more than 4 engine units.

The benefits of a greater number of engines could be maintained without a reduction in core size, if a single core was used to drive multiple fans in separate ducts. This solution may also be more practical from an economic point of view in that there would still be few engine cores to maintain. This configuration is also proposed in [7].

Engine weight effects

As engine fan diameter increases the engine weight rises. The mass does not rise as the cube of fan diameter due to the hollowness of parts, and components, such as fan containment, which are more dependent on the fan tip speed rather than diameter. Equation (11) shows a very simple estimate for engine weight variation that fits reasonably well to available engine data, see also [19].

$$W_{eng} \propto n_{eng} D_f^{2.4} = n_{eng}^{-0.2} \left( D_f \sqrt{n_{eng}} \right)^{2.4} \qquad (11)$$

This suggests that for a fixed overall fan diameter, the overall weight will reduce as the number of engines is increased. The reduction expected is relatively small for ultra high bypass ratio engines and a larger change is expected to come from the reduced airframe structure needed to support an embedded engine. Embedded engines do not require a pylon and this can account for as much as 20% of the total propulsion system weight [19].

Noise considerations

The exhaust ducting of an embedded engine can be longer than that of an equivalent podded engine. However, the length of the airframe centre body available for the engine installations is limited by structural requirements and the need for the intakes to be positioned in flow of an acceptable Mach number. As a first estimate this length can be assumed to be constant for a given aircraft size. In this case the maximum length-to-diameter ratio of the exhaust ducts will rise as the square root of the number of engines. Simple ray theory would argue that the number of reflections, and thus the attenuation of the liners, should be proportional to the length-to-diameter ratio:

$$Attenuation \propto \frac{l_{duct}}{D_f} = \frac{l_{duct}}{D_f \sqrt{n_{eng}}} \sqrt{n_{eng}} \qquad (12)$$

In practice, liners are tuned to particular frequencies, so the attenuation will only apply to a portion of the total noise in a duct. Figure 9 compares acoustic predictions completed for an exhaust duct with varying length and a basic, single layer acoustic liner. Three lines are shown: the predicted attenuation increase for the complete fan noise spectrum, the predicted attenuation of the frequency that the liner was designed to attenuate and the attenuation expected using equation 12. The plot shows that while the effectiveness of the acoustic treatment will improve with the number of engines, the improvement does not keep increasing linearly with length-to-diameter ratio. However, it is expected that improved increases in attenuation will be possible with more advanced liner designs.

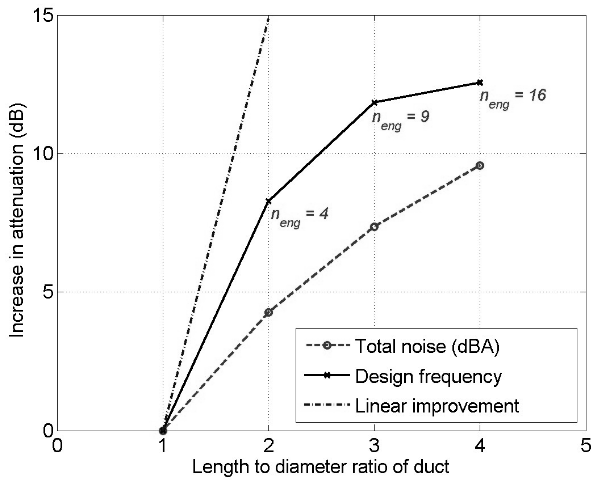



**Figure 8: Variation in attenuation of rearward fan noise with exhaust duct geometry.**

Increasing the number of engines will also increase the blade passing frequency. This is a result of the shaft speed increasing, which at a fixed thrust should also rise as the square root of the number of engines. A higher blade passing frequency will shift the entire spectrum of fan noise upwards in frequency. This will make the noise produced by the fan easier to attenuate by acoustic liners, increase the effectiveness of shielding by the airframe and increase the atmospheric attenuation.

Comparison of installation options

Using the simple qualitative analyses above, several options for the Silent Aircraft propulsion system installation were compared in terms of their expected impact on fuel burn, weight and rearward turbomachinery noise. The results are summarised in table 1, which shows changes relative to an advanced next generation turbofan (2005 design). No allowances are made for any improvements in engine component technology over time.

| Type | $n_{eng}$ | $PR$ | $\Delta sfc$ | $\Delta X_n$ | $\Delta \dot{m}_{fuel}$ | $\Delta W_{eng}$ | $\Delta Noise$ |
|---|---|---|---|---|---|---|---|
| **POD** | 2 | 1 | -6% | +9% | +3% | +12% | - |
| **BLD** | 2 | 0.96 | +3% | +8% | +11% | -7% | -4 dB |
| **BLD** | 4 | 0.96 | +7% | +2% | +9% | -19% | -8 dB |
| **BLD** | 16 | 0.96 | +11% | -6% | +4% | -35% | -13 dB |
| **BLI** | 4 | 0.94 | +7% | -9% | -2% | -19% | -8 dB |
| **BLI** | 16 | 0.94 | +10% | -20% | -11% | -35% | -13 dB |

**Table 1: The effect of engine installation on cruise fuel burn, engine weight and rearward noise.**

The results in the table are very approximate, but they demonstrate some of the trade-offs that are important in the choice of engine integration configuration. The podded system is significantly larger than a current turbofan, which leads to a fuel burn penalty and greater weight. Embedding only two engines with boundary layer diversion gives a large thermal efficiency penalty due to the inlet pressure losses and minimal improvement in the drag contribution. As the number of embedded engines increases, the installation drag reduces, but there is also a decrease in the core component polytropic efficiencies leading to fuel consumption levels that are still higher than current turbofans. With boundary layer ingestion, the potential for significant thrust reductions are increased leading to overall benefits in fuel consumption.

Table 1 indicates that the preferred installation for the Silent Aircraft should be embedded with boundary layer ingestion and multiple engine ducts. Unfortunately, this configuration also carries the highest design risk, and it is expected to have high development and maintenance costs. The greatest risk to embedded engines is the impact of non-uniformity of the flow at the engine face. The distortion coefficient, DC60, is the standard measure of total pressure non-uniformity for engine intakes and typical DC60 values measured for an embedded S-duct are in the range 0.10 to 0.30 [15]. This is a significant amount of flow distortion, especially for a low pressure ratio turbofan, and it will apply at all points in the flight envelope. The distortion impacts the engine performance, stability, reliability and noise.

BLI introduces additional total pressure distortion to the flow entering the inlet. This distortion is non-uniform, in both the radial and circumferential directions. It is in addition to that generated by the inlet duct and it is present at all flight conditions. Thus, the design risk posed by inlet distortion will be greatest for a boundary layer ingesting system. The challenge is to realise the fuel burn benefits of BLI without them being outweighed by the negative effects of the inlet distortion.

## VARIABLE CYCLE REQUIREMENT

The propulsion system for an aircraft has very different requirements at different points in the flight mission. Cruise is the most thermodynamically demanding condition, because this is where most fuel is consumed and there is the greatest need for high efficiencies. Top-of-climb is the most aerodynamically demanding condition. At this point, the engine has to maintain sufficient thrust to keep the aircraft climbing at an altitude where the air is very thin. Take-off is the most mechanically demanding condition: The temperatures within the engine are highest and the risk of damaging the engine is greatest because the fan is closer to instability and there are transient effects from cross-winds and maneuvers that can initiate vibration. Current turbofan designs manage to satisfy all these requirements with a fixed cycle and fixed geometry configuration.

For the Silent Aircraft engines, take-off is also the most acoustically challenging condition, because sufficient thrust must be provided without exceeding the noise target. The current section shows that this additional requirement means that the propulsion system needs an additional degree of freedom in its operation, which can be provided by a variable cycle.

The top-of-climb point is the key aerodynamic design condition because it determines the overall size of the engine. Consider the design of a turbofan for fixed thrust requirements and ambient flow conditions. From conservation of energy the fan pressure ratio (neglecting inlet and exhaust losses) determines the jet velocity:

$$V_j = \sqrt{2c_p T_{02}\left(FPR^{\gamma-1/\gamma} - 1\right) + V_0^2} \qquad (13)$$

This jet velocity sets the fan-face area required through continuity, and this can be geometrically related to the overall diameter:

$$n_{eng} A_f = \frac{X_N}{V_j - V_0} \frac{\sqrt{c_p T_{02}}}{Q_a p_{02}}$$

thus,

$$D_f \sqrt{n_{eng}} = \left( \frac{4X_N}{\pi\left(1-HTR^2\right)} \frac{1}{V_j - V_0} \frac{\sqrt{c_p T_{02}}}{Q_a p_{02}} \right)^{1/2} \quad (14)$$

In equation 14, once the top-of-climb fan pressure ratio has been chosen, all of the terms on the right hand side are fixed by the aircraft mission requirements, except the fan capacity at top-of-climb, *Qa*, and the design hub-to-tip radius ratio, *HTR*.

The fan flow capacity, *Qa*, is highest at top-of-climb, because the flow through the engine must be maximised to achieve the thrust requirement. The choice of this is crucial to the design: a high flow fan will reduce fan diameter and lower the flow diffusion in the intake, however, reducing the fan flow will reduce the fan speed and tend to improve fan efficiency and stability. It is expected that a future quiet engine will have a similar maximum fan capacity to today's turbofan designs.

The hub-to-tip radius ratio is minimised subject to stress level limits in the fan root and disc system. A future quiet engine is expected to have a *HTR* slightly lower than current turbofans.

With the total fan size fixed by the top-of-climb condition, now consider the engine at take-off. The thrust equation (2) can be rearranged to show how the jet velocity at take-off depends on the flight speed, ambient conditions, thrust requirement and engine flow capacity:

$$\frac{V_j}{\sqrt{c_p T_{02}}} = \frac{V_0}{\sqrt{c_p T_{02}}} + \frac{X_N}{n_{eng} A_f\, p_{02}} \frac{1}{Q_{a,T/O}} \quad (15)$$

In this equation, the capacity, $Q_{,a,T/O}$, is based on the total mass flow through the engine exhaust during take-off. For a fixed take-off condition, all the other terms on the right hand side of the equation are already determined. Equation 1 shows how jet noise depends mainly on the jet velocity. Thus, to design a turbofan for minimum jet noise, equation 15 shows that we need a configuration that produces the maximum engine flow capacity at take-off with the fan sized at top-of-climb.

For a fixed geometry, fixed cycle turbofan, the engine flow capacity at take-off is determined by the exhaust nozzle area. However, by using some form of variable exhaust geometry, the engine capacity at take-off can be increased significantly. This idea is demonstrated by figure 9 which shows the working lines for a fan with a design pressure ratio of 1.45. This indicates the wide separation between the top-of climb and take-off working lines for a fixed geometry system. This arises because the nozzle is choked at high altitude and flight Mach number, but un-chokes at low speed and passes less flow.

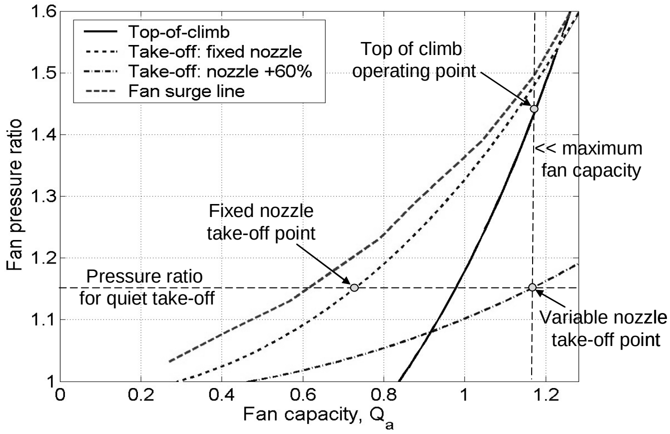



**Figure 9: Fan working lines showing operating points with and without variable exhaust.**

The fan pressure ratio required to meet the Silent Aircraft jet noise target at take-off is below 1.2. Thus, with a fixed exhaust, the take-off operating point is close to the surge line with low flow capacity. A variable exhaust nozzle allows this operating point to be moved away from instability and the fan capacity can be increased to the value at top-of-climb.

Using equations 13-15 it is straightforward to consider the operating points at top-of-climb and take-off for a series of engine designs each with different design fan pressure ratios. Figure 10 plots the resulting variation of jet noise, as calculated with the Stone Jet noise model [11], against the overall fan diameter for a fixed aircraft mission and varying design fan pressure ratio. The plot shows that a variable exhaust gives a significant jet noise reduction at a given fan diameter (~10dBA), or for the fixed noise target of the Silent Aircraft, it enables a reduction in fan diameter of about 20%. Similar reductions in engine size can be obtained with a 2:1 area ratio ejector deployed at take-off. This configuration is discussed further under candidate engine configurations.

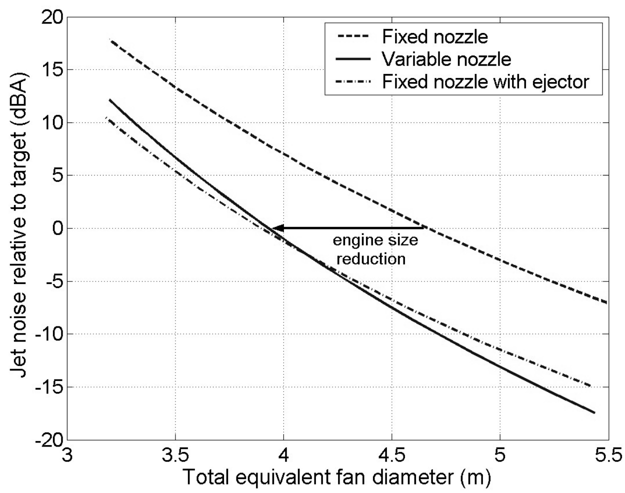



**Figure 10: Variation of jet noise with fan diameter using different exhaust systems for a 250-seat aircraft**

This lower overall fan diameter reduces the drag of the nacelle during cruise (figure 6) and implies a higher fan pressure ratio, which will also reduce the impact of inlet pressure losses on the overall efficiency (figure 7). In addition, a variable exhaust can be adjusted to enable the fan to operate at peak efficiency for a given cruise thrust requirement. Overall this is expected to lead to significant fuel consumption savings. The fan system will be more stable, because the exhaust area can be adjusted to avoid fan conditions prone to aeromechanical vibration.

All of the benefits of a variable exhaust system can be applied equally to any of the installation options considered in table 1, however, variable geometry will be easier to accommodate within an embedded configuration. For an embedded system with multiple engine units, the engines could have a common, two-dimensional variable geometry exhaust system, which may offer additional benefits in terms of lower weight and reduced complexity.

## CANDIDATE ENGINE CONFIGURATIONS

The datum candidate engine for the Silent Aircraft is a conventional turbofan engine with the fan driven via a reduction gearbox and a large variable exhaust nozzle (figure 11). The gearbox allows a low-speed, quiet fan to be driven by a high-speed, low-weight and low-noise turbine. The variable geometry nozzle is opened up during take-off and approach and closed down at cruise, giving improved operating points, as shown in figure 9.

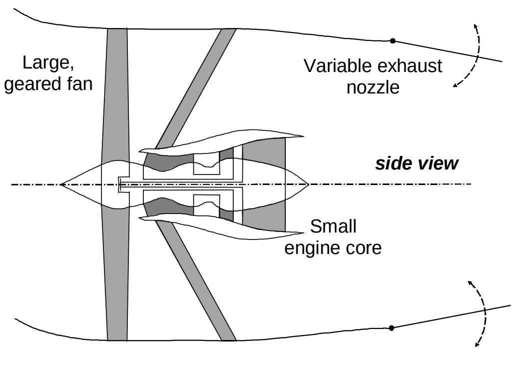



**Figure 11: Ducted high diameter engine with geared fan and variable exhaust nozzle**

A second option, shown in figure 12, is to have a conventional jet engine that uses devices called “ejectors” for take-off and landing. Ejectors are ducts outside of the engine exhaust that entrain additional air into the exhaust flow, thus increasing the mass flow and reducing the mean jet velocity. The ejectors can be stowed at cruise to remove their drag effect and they do not have to be circular, which makes them more amenable to an embedded system. Figure 10 includes a plot of the variation in jet noise with fan diameter for an ejection system that doubles the effective exhaust area at take-off. As the ejector area ratio increases, the exhaust flow capacity in equation 15 increases, although their potential is limited by the mixing efficiency that they can achieve. Ejectors can also be used in combination with a variable nozzle to enhance their effect. The two-stage aft contra-rotating fan arrangement shown in figure 12 has been examined in several studies, which have shown that it could provide weight and cost benefits. However, the ejector could also be used with the conventional engine architecture shown in figure 11.

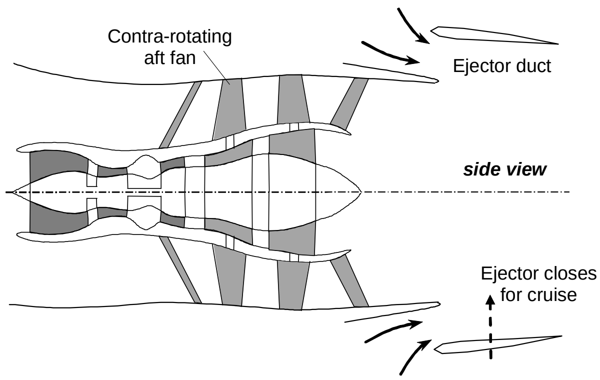



**Figure 12: Embedded aft contra-fan engine with exhaust ejector ducts**

A large, low-speed jet area can also be produced by having extra fans that are only operating at take-off (figure 13). These fans can be driven by the main engine but only exposed at low altitude. Thus, their design can be optimised solely to minimize take-off and approach noise whilst the main engine could be designed to have the best possible cruise performance.

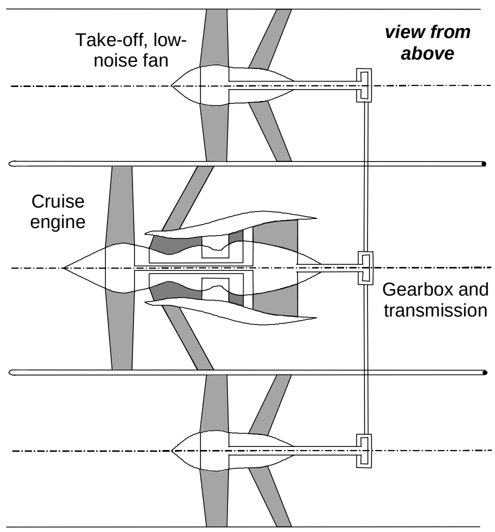



**Figure 13: Optimised cruise engine with auxiliary fans for take-off and approach**

## CONCLUSIONS AND FURTHER WORK

The main findings of the studies in this paper can be summarised with the following points:

1. For low noise, a large exhaust jet area at take-off is required. The area needed for the Silent Aircraft engines can be reduced significantly by using power managed departure procedures, but it will still be 2-3 times larger than that of existing turbofans.
2. Embedding the engines into an all lifting body aircraft can reduce the installation drag, increase noise attenuation and enable boundary layer ingestion. However, total pressure losses upstream of the engine have a significant detrimental impact on performance and there is a large, uncertain risk to the design from the effects of inlet flow distortion.
3. A greater number of embedded engines are expected to give lower weight, reduced drag contribution and more effective noise attenuation. However, smaller engine cores will have lower thermal efficiency.
4. A variable geometry exhaust system allows a smaller, low-weight engine that can be quiet at low altitude and efficient at cruise. These benefits have been demonstrated with a variable area exhaust nozzle, and other configurations have been proposed.

Work is underway to develop propulsion system designs for the Silent Aircraft based on the engine and installation configurations proposed in this paper. The different designs will be assessed in detail to determine their noise emission, weight and performance. The datum design is an embedded 4-engine system with a variable exhaust nozzle and boundary layer diversion. This will be followed by designs with boundary layer ingestion, a greater number of engine ducts and alternative variable exhaust systems.

The studies in this paper have identified several key challenges to reaching the technical objectives of the Silent Aircraft propulsion system. These are being addressed in the following research activities that are already underway as part of the Silent Aircraft Initiative:

1. The design of embedded intakes that deliver flow to a fan with minimum losses and minimum non-uniformity throughout the flight envelope.
2. The development of robust, low-weight engine architectures that generate low turbomachinery source noise.
3. The design of extended exhaust ducts that minimise rearward propagating noise using advanced acoustic liner technology.
4. The development of efficient, low-noise, fan systems that are tolerant of inlet distortion and compatible with a variable exhaust.
5. The study of the impact of boundary layer ingestion on propulsion performance, noise and reliability. This is needed in order to show that the fuel burn benefits of boundary layer ingestion can be realised despite the inherent practical problems.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the Cambridge-MIT Institute for the financial support of this research through the Silent Aircraft Initiative project. They would also like to thank Rolls-Royce plc for access to their preliminary design methods and for technical advice given during the course of this research. Several other members of the Silent Aircraft team have also contributed to the work that has made this paper possible. Particular thanks to Anurag Agawal, Mark Drela, Chris Freeman, Patrick Freuler, Ed Greitzer, Geoff Hodges, Tom Hynes, Tom Law, Vahid Madani, Matthew Sargeant, Zoltan Spakovszky and Liping Xu.

## REFERENCES

[1] "Air Travel - Greener by Design: The Technology Challenge," Greener by Design, 2001.

[2] "Review of the quota count (QC) system," Department for Transport, UK Government, 2003.

[3] ACARE, "European Aeronautics: A vision for 2020," Advisory Council for Aeronautics Research in Europe, 2000.

[4] D. L. Daggett, S. T. Brown, and R. T. Kawai, "Ultra-Efficient Engine Diameter Study," NASA CR-2003-212309, 2003.

[5] P. R. Gliebe and B. A. Janardan, "Ultra-High Bypass Engine Aeroacoustic Study," NASA-2003-212525 Oct 2003, 2003.

[6] D. E. Crow, "A comprehensive approach to engine noise reduction technology," presented at ISABE-2001, Bangalore, India, 2001.

[7] A. Manneville, D. Pilczer, and Z. S. Spakovszky, "Noise reduction assessments and preliminary design implications for a functionally-silent aircraft.," presented at 10th AIAA/CEAS Aeroacoustics Conference, Manchester, UK, 2004.

[8] M. J. Lighthill, "On sound generated aerodynamically (Part 1: General theory)," *Proceedings of the Royal Society of London. Series A: Mathmatical and Physical Sciences*, vol. 211, pp. 564-587, 1952.

[9] C. K. W. Tam and K. B. M. Q. Zaman, "Subsonic Jet Noise from Nonaxisymetric and Tabbed Nozzles," *AIAA*, vol. 38, pp. 592-599, 2000.

[10] N. H. Saiyed, K. L. Mikkelsen, and J. E. Bridges, "Acoustics and Thrust of Separate-Flow Exhaust Nozzles With Mixing Devices for High-Bypass-Ratio Engines," presented at the 6th Aeroacoustics Conference, Lahaina, Hawaii, 2000.

[11] J. R. Stone and F. J. Montegani, "An Improved Prediction Method for the Noise Generated in Flight by Circular Jets.," NASA TM-81470, 1980.

[12] D. Crichton, D. Tan, and C. Hall, "Required Jet Area for a silent aircraft at take-off," presented at the 8th ASC-CEAS Workshop, Budapest University of Technology and Economics, Hungary, 2004.

[13] R. Liebeck, "Design of the Blended Wing Body Subsonic Transport," *Journal of Aircraft*, vol. 41, pp. 10-25, 2004.

[14] N. A. Cumpsty, *Jet Propulsion: A simple guide to the aerodynamic and thermodynamic design and performance of jet engines*. Cambridge, UK: CUP, 2003.

[15] A. J. Anabtawi, R. F. Blackwelder, P. B. S. Lissaman, and R. H. Liebeck, "An Experimental Study of Vortex Generators in Boundary Layer Ingesting Diffusers with a Centerline Offset," University of Southern California, Los Angeles, CA, USA, 2001.

[16] D. L. Rodriguez, "A Multidisciplinary Optimization Method for Designing Boundary Layer Ingesting Inlets," Stanford University, Stanford, CA, USA, 2001.

[17] C. Freeman, "Personal communication on engine design podded versus embedded," 2004.

[18] J. Kurzke, *GasTurb 10*, 2004.

[19] J. Protz, "Engine Models," Massachusetts Institute of Technology, Cambridge, MA, USA, 2004.