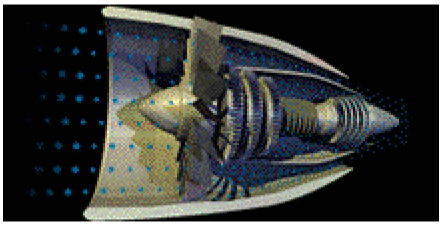
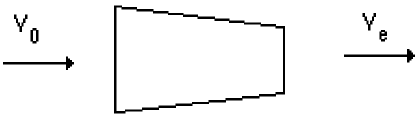
Propulsion Systems

Propulsion Systems: Basic Concepts



The operation of a propulsion system may be viewed simply as shown below. A fluid enters the system at speed V_0 with a mass flow of *dm/dt*. It exits at speed V_e, and mass is added to the outflow at a rate dm_f/dt. The force exerted by this system includes the rate of change of momentum through the system and a pressure term:



$$T = \dot{m}(V_e - V_0) + \dot{m}_f V_e + A_e(p_e - p_0)$$

This equation for thrust holds for systems ranging from chemical and electric rockets to ramjets, turbojets, and propeller-driven aircraft.

Engine Types

Rockets

The expression is simplest in the case of a rocket operating outside the atmosphere. In this case, the thrust is simply given by:

$$T = \dot{m}\ V_e$$

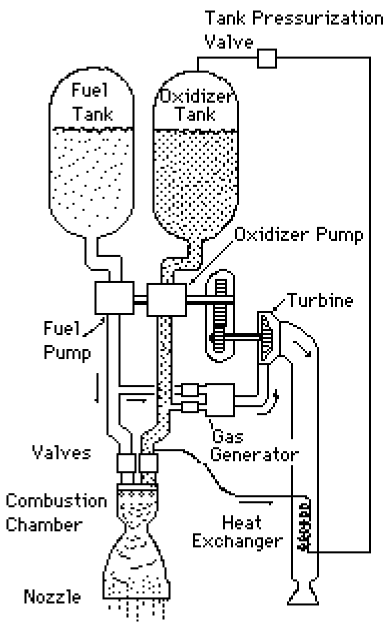
where V_e is the exit velocity of the exhaust flow. The exhaust gases may be the by-products of the rocket fuel combustion, or just unburned expanded gas, or any other mass. In the case of electric rocket propulsion, small droplets of Mercury or other heavy material are accelerated in an electric field to produce thrust. The fuel (or other mass) flow for a given thrust is minimized by achieving high exit velocities. Typical values of exit velocity are 3000 to 4000 m/s (10000-13000 ft/sec) for liquid propellant rockets.

There is a large advantage to be gained if one does not have to carry all of the mass used to generate thrust. This can be seen by examining the total energy required to produce the change in momentum.

The rate of change of energy is given by:

$$\frac{dE}{dt} = \frac{\dot{m}}{2}\left(V_e^2 - V_0^2\right) + \frac{\dot{m}_f}{2} V_e^2$$

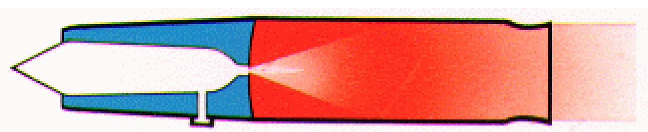
Thus, to produce the most thrust with the least energy consumption, it is best to do so with a large value of *dm/dt* and a small change in *U*. This is because the energy required varies with U^2 while the momentum change is linear in *U*. This basic principal applies to many systems. It is why helicopters have large diameter rotors, wings need large spans, and propellers are more efficient than jets at low speeds. This concept serves to distinguish the several types of propulsion systems, as discussed in the following sections.



Ramjets

Ambient air can be used, not only to provide oxidizer for burning fuel, but also as a source of mass. This is done most simply in the ramjet engine.

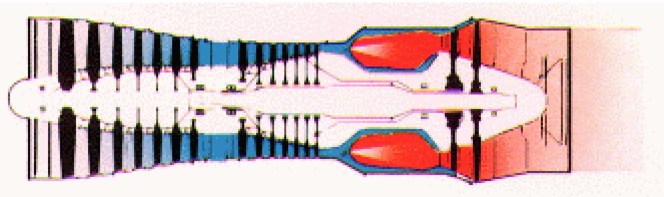
The ramjet has no moving parts. High speed air enters the inlet, is compressed as it is slowed down, is mixed with fuel and burned in the combustion chamber, and is finally expanded and ejected through the nozzle. For the combustion process to be efficient, the air most be compressed sufficiently. This is possible only when the freestream Mach number exceeds about 3, and so ramjets have been practical for only a few missile applications. A hybrid engine, part turbojet, part ramjet, was also used on the SR-71 high speed reconnaissance aircraft and is a topic of current research interest for several possible hypersonic applications.



Turbojets

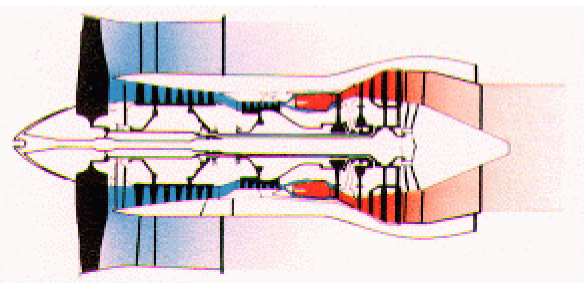
When additional compression is required of the intake air, a separate compressor may be added to the ramjet as shown in the figure below. A single-stage centrifugal compressor was used until about 1953. Such a compressor could produce an increase in total pressure of about 4. More modern axial compressors can produce overall pressure ratios (OPR) of about 8.5 with a single stage and by including several stages of compression, pressure ratios of 13 have been achieved on turbojet engines. For the turbofan designs discussed in the next section, the multi-stage compressors achieve pressure ratios of 25-30, enabling efficient operation at subsonic speeds.

In order to power the compressor, a windmill is placed in the engine exhaust-in principal that is what the turbine stage does. The turbine is located downstream of the combustor and is connected to the compressor blades with a shaft. It extracts power from the flow in the same way that a windmill extracts power.



Turbofans

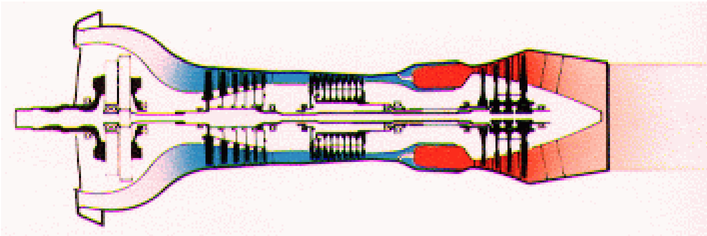
Increased efficiency at low speeds requires that the mass of air affected by the engine be increased. However, for a given rate of fuel burned, there is a corresponding mass of air that should be mixed with the fuel and one cannot simply force more air through the combustor. Instead, one may route some of the air around the combustor and turbine, and so bypass the engine core. Engines are characterized by their bypass ratio (BPR), the ratio of mass flux bypassing the combustor and turbine to the mass flux through the core. Engines with bypass ratios of 0 are called straight jets or sometimes turbojets. Engines with bypass ratios of 1 to 2 are generally termed low bypass ratio turbofans. High bypass turbofans found on most current transport aircraft have BPR's of 5-8. It is sometimes necessary to drive the first few stages of the compressor (fan) at a slower speed than the high pressure stages, so twin-spool engines or even triple spool engines (three separate shafts from turbine to compressor stages) are common. Gearing between the turbine and fan stages is also possible to provide more optimal fan performance. More detail is shown in the figures on the following pages.



The figure below shows a Pratt and Whitney 4084 engine used on the 777. The diameter of this 84,000 lb thrust engine with nacelle is only somewhat smaller than the diameter of a 717.

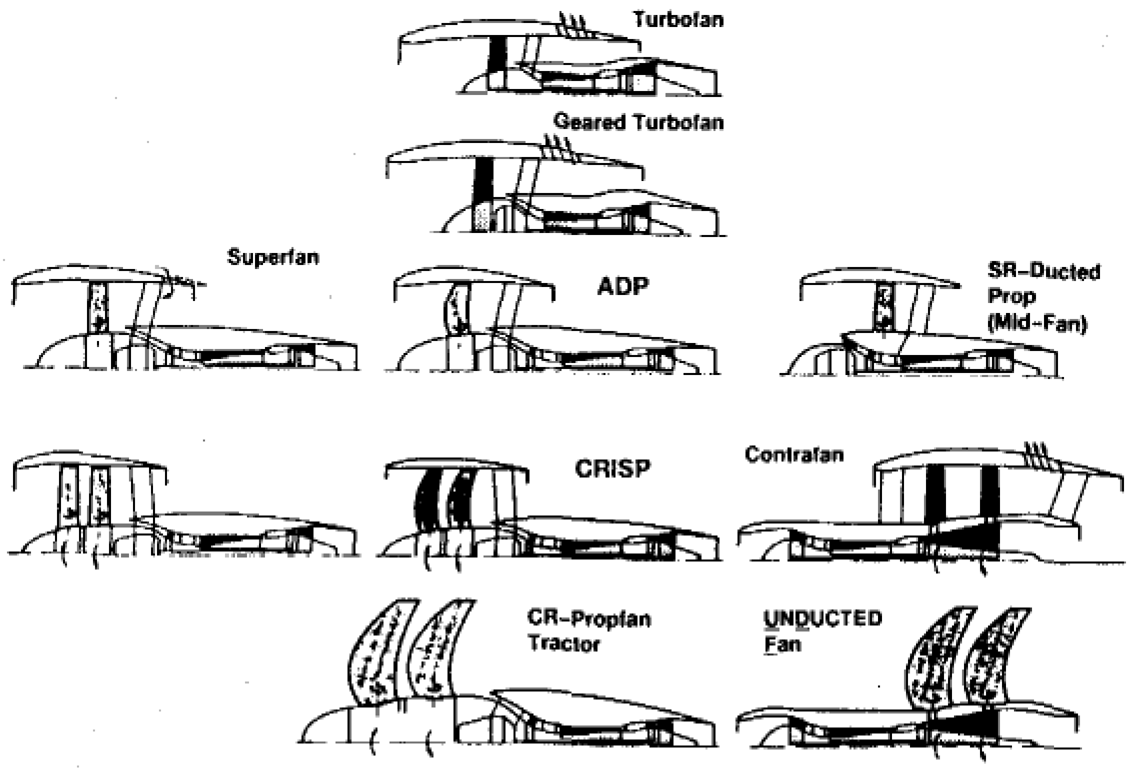
Turboprops

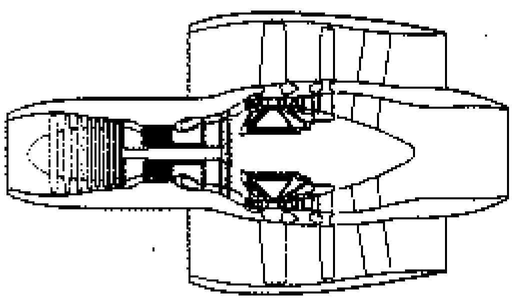
When the bypass ratio is increased to 10-20 for very efficient low speed performance, the weight and wetted area of the fan shroud (inlet) become large, and at some point it makes sense to eliminate it altogether. The fan then becomes a propeller and the engine is called a turboprop. Turboprop engines provide efficient power from low speeds up to as high as M=0.8 with bypass ratios of 50-100.



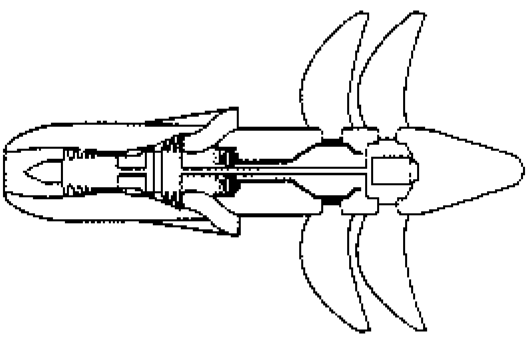
Advanced Turboprops and Ultra-high Bypass Ratio Turbofans

One can increase the efficiency of turbofans from their current values of 35% - 40% to values close to 45% by further increasing the bypass ratio. Advanced designs with bypass ratios of 12-25 are sometimes termed advanced ducted propellers or ADP's. Although the propulsive efficiency of such designs is very high, they are often less desirable than the engines with more moderate bypass ratios. This is due to the difficulties of installing these very large diameter engines, especially on low-wing configurations, and on the weight and drag penalties associated with the large duct.





An unusual ADP with the fan located aft and attached directly to the turbine. Note the stator vanes in both turbine and fan sections to reduce swirl losses.



A counter-rotating prop-fan. At some value of bypass ratio, the advantages associated with the duct are overwhelmed by the weight and drag of the duct itself. Bypass ratio 50, ductless prop-fans such as the one shown here have been proposed for aircraft that fly up to Mach 0.8.

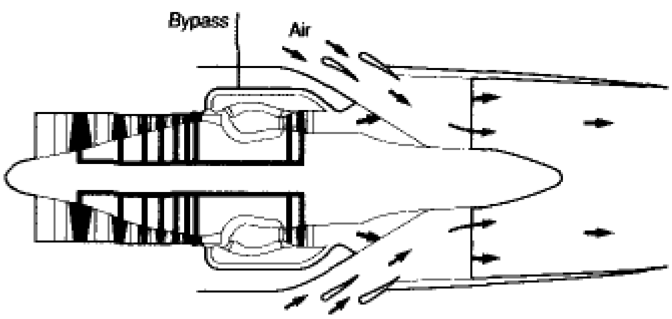
Propellers / Piston Engines

It is possible, of course, to power the propeller by any available means, from turbine to piston engine, electric motor to rotary engine, rubber bands to human muscle. In many of these cases, the bypass ratio is infinite. Very high efficiency especially at low speeds is possible, although as the propeller diameter is increased, installation issues become more severe.

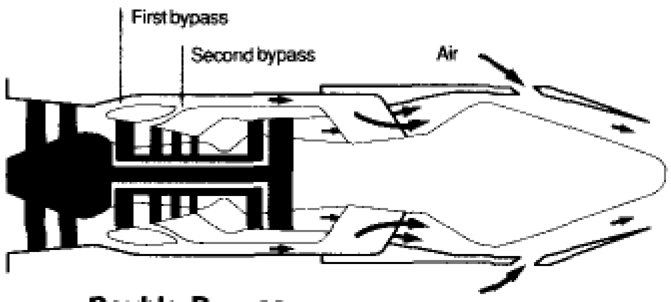
Engines for Supersonic Aircraft

The following discussion from Boeing describes the recent thrust of engine development work for the high speed civil transport (HSCT).

Considerable effort has been devoted to improvement of engine specific fuel consumption (SFC) at subsonic conditions over the past 20 years. The original U.S. SST had very poor subsonic SFC. High subsonic SFC penalizes the mission performance by reducing the efficiency during subsonic mission legs and by requiring larger amounts of reserve fuel. The key to good subsonic and supersonic SFC is a variable-cycle engine. The major objective for a future HSCT application is to provide some degree of engine cycle variability that will not significantly increase the cost, the maintenance requirements, or the overall complexity of the engine. The variable-cycle engine must have a good economic payoff for the airline while still providing more mission flexibility and reducing the reserve fuel requirements so that more payload can be carried. In the past, variable-cycle engines were designed with large variations in bypass ratio to provide jet noise reduction. However, these types were complicated and did not perform well. Today, the trend is toward turbojets or low-bypass engines that have the ability to improve off-design performance by adjustment of compressor bleed or by a relatively small variation in bypass ratio. The current engine offerings from Pratt & Whitney and General Electric fall into this category. Both of these engines will require an effective jet noise suppressor.
Rolls-Royce/SNECMA favors other approaches. One is a tandem fan that operates as a turbojet cycle for cruise but opens a bypass inlet and nozzle for higher flow at subsonic speeds. A second approach is to increase the bypass ratio by incorporating an additional fan and turbine stream into the flow path at subsonic speeds.



Turbine-Bypass Turbojet Engine



Some additional information on current supersonic engine development efforts from NASA Lewis follows:

> Following are five of the most promising engine concepts studied.
>
> (1) Turbine bypass engine (TBE) is a single spool turbojet engine that possesses turbofan-like subsonic performance, but produces the largest jet velocity of all the concepts. Hence, it needs a very advanced technology mixer-ejector exhaust nozzle with about 18 decibels (dB) suppression ability to attain FAR 36 Stage III noise requirements without over sizing the engine and reducing power during take off. This level of suppression could be reached if the ejector airflow equals 120 percent of the primary flow.
>
> (2) The Variable Cycle Engine (VCE) which alters its bypass ratio during flight to better match varying requirements. However, although its original version defined in the 1970's relied on an inverted velocity profile exhaust system to meet less stringent FAR 36 Stage II noise goals, the revised version needs a more powerful 15 dB suppression solution. A 60 percent mass flow augmented mixer-ejector nozzle together with modest engine oversizing would satisfy this requirement. It should not be inferred from the above that the TBE needs a 120 percent mass flow augmented mixer-ejector nozzle while the VCE only needs one that is 60 percent. There is uncertainty concerning the best combination of mass flow augmentation, acoustic lining, and engine oversizing for both engines.
>
> (3) A relative newcomer, the fan-on-blade ("Flade") engine is a variation of the VCE. It has an auxiliary third flow stream deployed during takeoff by opening a set of inlet guide vanes located in an external annular duct surrounding the VCE. The auxiliary annular duct is pressurized by extension to the fan blades and is scrolled into the lower half of the engine prior to exhausting to provide a fluid acoustic shield. It also requires a relatively modest mixer-ejector exhaust nozzle of approximately 30 percent flow augmentation.
>
> (4) The fourth concept is the mixed flow turbofan (MFTF) with a mixer-ejector nozzle.

(5) The final engine concept is a TBE with an Inlet Flow Valve (TBE/IFV). The IFV is activated during takeoff to permit auxiliary inlets to feed supplementary air to the rear compressor stages while the main inlet air is compressed by just the front compressor stages. While a single spool TBE/IFV still needs a mixer-ejector exhaust nozzle, it seems possible to avoid that complexity with a two-spool version because of greater flow handling ability in the takeoff mode.

Data on several specific engines is provided in the section on engine performance. Links to manufacturers' sites are provided in that section as well.

How Many Engines?

One of the questions to be answered early in the conceptual design stage is how many engines will be desirable. The recent trend is definitely toward fewer engines, with twin engine aircraft becoming the most popular design. This has become possible for larger aircraft as the thrust of engines has climbed to levels that were nearly unimaginable not long ago. 100,000+ lb sea level static thrust engines are now available.

The interest in large twin engine aircraft come from the greater economy afforded by using fewer engines. Current engine prices are such that it is less expensive to obtain a specified sea level static thrust level with two large engines than with three or four smaller ones.

However, when more engines are used, the system is more reliable. And it is not just the propulsion system that is more reliable. When additional electrical generators or hydraulic pumps are available, overall system reliability is improved. However, it is more likely that at least one engine will fail.

These considerations limited the use of twin engine aircraft for long flights. The U.S. operating rules limited two and three engine aircraft to routes over which the airplane could not be more than 60 minutes from an alternate airport after an engine had failed. In 1964, three-engine turbine-powered aircraft were exempted from this rule. More recently, the FAA approved extended range operations for twin engine aircraft requiring that the aircraft stay within 120 minutes (with engine failure) of an appropriate airport and 180 minute ETOPS are becoming more common.

Probability of Engine Failure

Failed Engines:	**1**	**2**	**3**	**4**
Total Engines:				
1	P	-	-	-
2	2P	P^2	-	-

3	3P	$3P^2$	P^3	-
4	4P	$6P^2$	$4P^3$	P^4

The probability, P, in this table depends on the particular engine and the flight duration, but for typical high bypass ratio turbines, the in-flight shutdown rate varies from .02 to .1 per 1000 hours, with the higher rates associated with engines in their introduction. A value of 0.05 is a typical average.

In addition to questions of reliability, several other considerations are important in the selection of the number of engines.

Twin Engine Aircraft: must meet climb requirements with one engine out. This means that the available thrust is reduced by more than 50% (more because of the extra drag associated with the failed engine and the need to trim with asymmetric thrust). Engine failure on a four-engine aircraft reduces the thrust by a bit more than 25%. This means that twins have engines that are often oversized for long range cruise. This adds weight, cost, and drag.

Four Engine Aircraft: must meet second segment climb requirements with 75% or so of installed power, usually leading to a better match with cruise performance, but the larger number of engines mean more parts, more maintenance, and more cost. The distribution of engine mass over the wing can reduce the bending loads on the wing, but may also result in greater penalties to prevent flutter.

Tri-jets: are a compromise losing favor. The third engine creates a problem with installation as discussed in the next section.

There are sometimes other considerations that are dominant in the selection of number of engines. General aviation aircraft are generally required to have a stall speed not greater than 61 knots if they have only one engine (although now this requirement may be waived). This is a major reason that most higher speed GA airplanes are twins. The BAE-146, a small four-engine feeder aircraft was designed to operate out of small airports without extensive maintenance facilities. It was desirable to be able to fly to a larger facility after one engine had failed. By using four engines, the aircraft is allowed to take-off with just three operating engines on a ferry mission (no passengers) to be repaired elsewhere.

The choice of number of engines is most strongly related to engine sizing. Typical ratios of aircraft sea-level static thrust to take-off weight are given below:

Typical T/W for Various Transport Aircraft

Aircraft Type:	**T/W**

Twin	.3
Tri-jet	.25
4-Engine	.2
Twin Exec. Jet	.4
SST	.4

Note: the data for commercial aircraft above come from Jane's All the World's Aircraft.
SST numbers include:
0.40 from a Japanese study (see References), 0.385 (Langley Study), .380 (Concorde w/ afterburners), .28 (Boeing Study w/ Turbine Bypass Engine concept of Pratt and Whitney), .24-.30 (Langley Study assuming 'advanced engines'), .36 (1970's U.S. SST), .398 (Douglas AST 1975 study), .32 (Douglas Mach 3.2 study airplane, 1989)

One starts with these rough estimates of thrust-to-weight ratio, selects an engine from the currently available list, and sometimes scales the basic engine as needed.

Propulsion Systems: Installation

This section deals with engine installation issues for preliminary design. The detailed integration of propulsion system and airframe is very complex, requiring some of the most sophisticated aerodynamic tools that are currently available, but some of the basic considerations are discussed in the following sections including:

Engine Placement
Nacelle Design and Engine Geometry
Supersonic Aircraft Engine Layout

Engine Placement

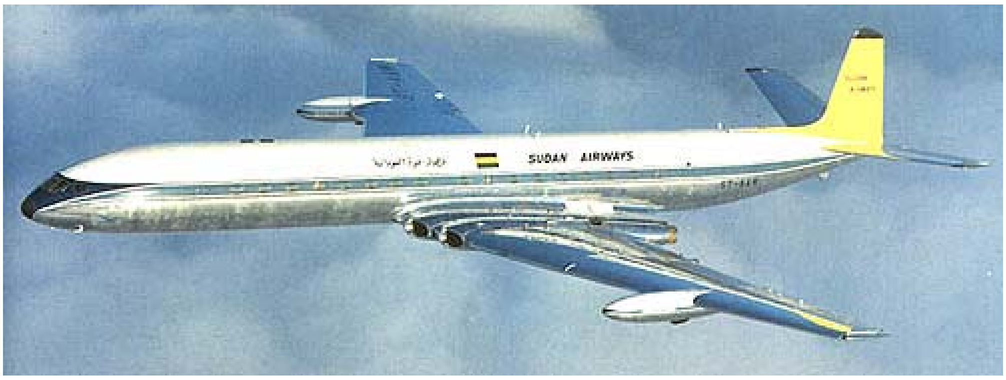
The arrangement of engines influences the aircraft in many important ways. Safety, structural weight, flutter, drag, control, maximum lift, propulsive efficiency, maintainability, and aircraft growth potential are all affected.

Engines may be placed in the wings, on the wings, above the wings, or suspended on pylons below the wings. They may be mounted on the aft fuselage, on top of the fuselage, or on the sides of the fuselage. Wherever the nacelles are placed, the detailed spacing with respect to wing, tail, fuselage, or other nacelles is crucial.

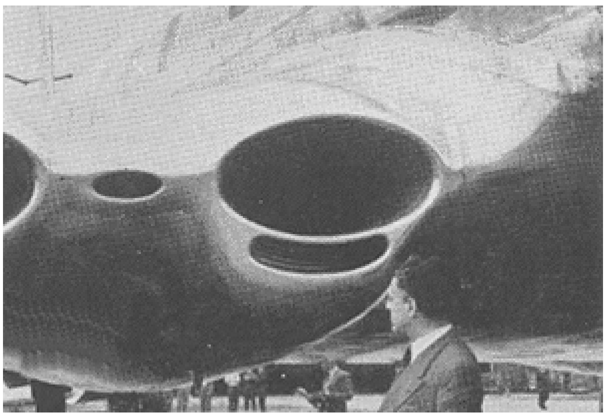
Wing-Mounted Engines

Engines buried in the wing root have minimum parasite drag and probably minimum weight. Their inboard location minimizes the yawing moment due to asymmetric thrust after engine failure. However, they pose a threat to the basic wing structure in the event of a blade or turbine disk failure, make it very difficult to maximize inlet efficiency, and make accessibility for maintenance more difficult. If a larger diameter engine is desired in a later version of the airplane, the entire wing may have to be redesigned. Such installations also eliminate the flap in the region of the engine exhaust, thereby reducing C_{Lmax}.

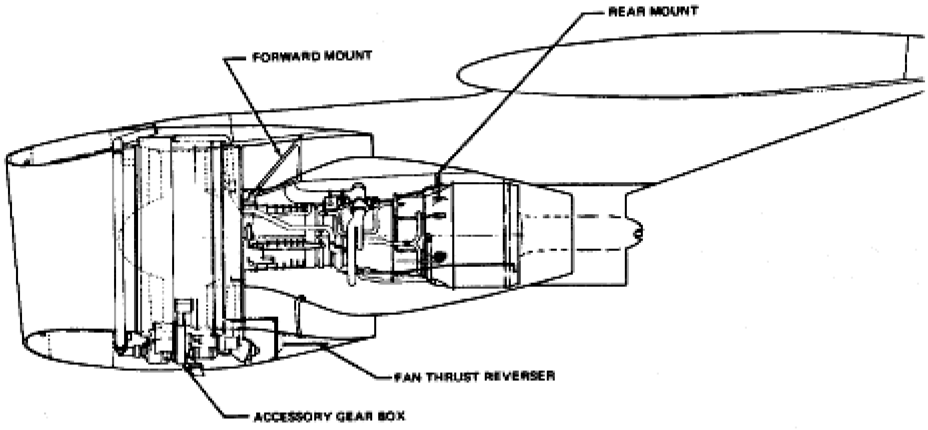
For all of these reasons, this approach is no longer used, although the first commercial jet, the deHavilland Comet, had wing-root mounted engines. The figure shows Comet 4C ST-AAW of Sudan Airways.



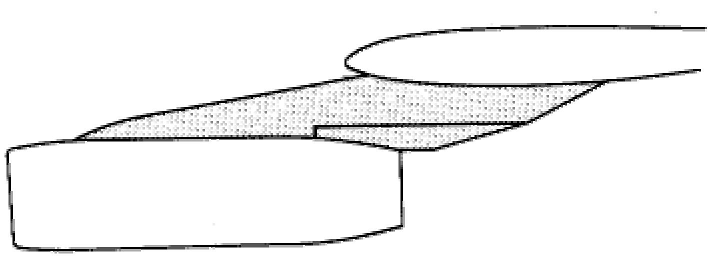
The following figure, from the May 1950 issue of Popular Science, shows the inlet of one of the Comet's engines. "Four turbine engines are placed so close of centerline to plane that even if two on one side cut out, pilot has little trouble maintaining straight, level flight."



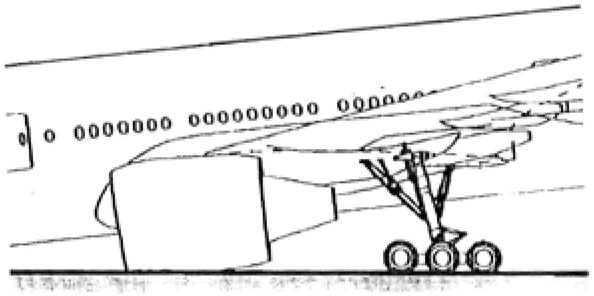
Wing-mounted nacelles can be placed so that the gas generator is forward of the front spar to minimize wing structural damage in the event of a disk or blade failure. Engine installations that do not permit this, such as the original 737 arrangement may require additional protection such as armoring of the nacelle, to prevent catastrophic results following turbine blade failure. This puts the inlet well ahead of the wing leading edge and away from the high upwash flow near the leading edge. It is relatively simple to obtain high ram recovery in the inlet since the angle of attack at the inlet is minimized and no wakes are ingested.



In the days of low bypass ratio turbofans, it was considered reasonable to leave a gap of about 1/2 the engine diameter between the wing and nacelle, as shown in the sketch of the DC-8 installation below.



As engine bypass ratios have increased to about 6 - 8, this large gap is not acceptable. Substantial work has been undertaken to minimize the required gap to permit large diameter engines without very long gear.



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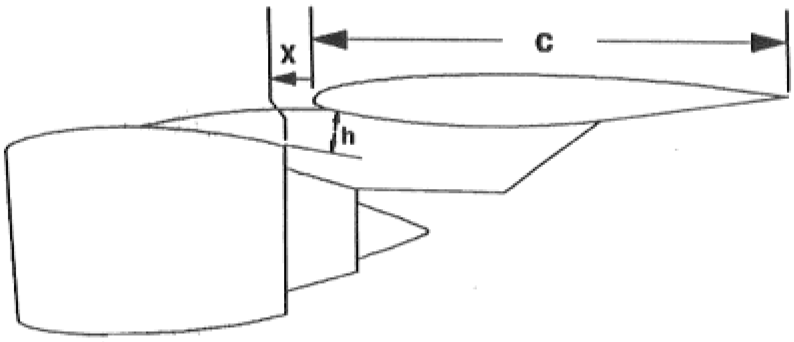
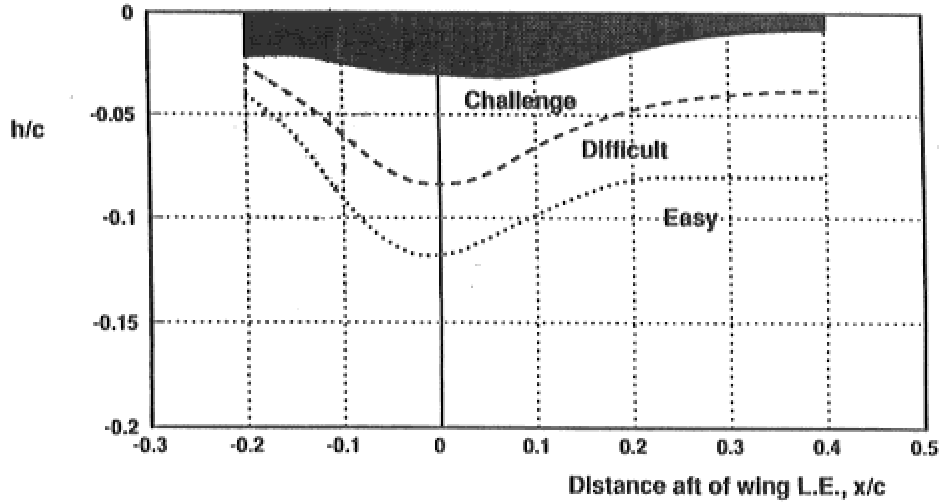
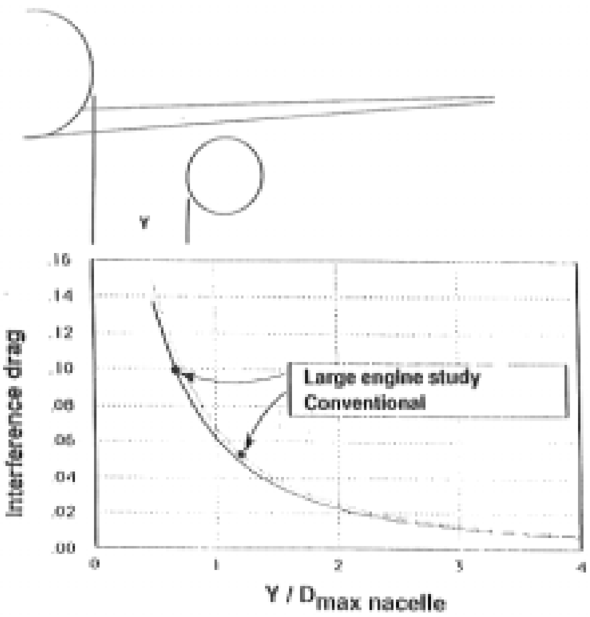
Current CFD-based design approaches have made it possible to install the engine very close to the wing as shown in the figure below. The 737 benefited especially from the closely mounted engines, permitting this older aircraft design to be fitted with high bypass ratio engines, despite its short gear.



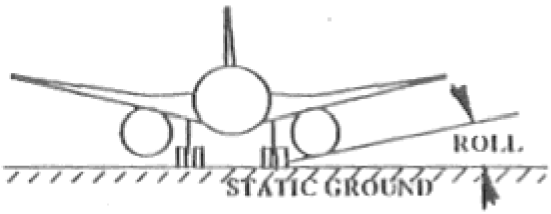


Laterally nacelles must be placed to avoid superposition of induced velocities from the fuselage and nacelle, or from adjoining nacelles. This problem is even greater with respect to wing-pylon-nacelle interference and requires nacelle locations to be sufficiently forward and low to avoid drag increases from high local velocities and especially premature occurrence of local supersonic velocities. The figure below from Boeing shows some of the difficulty in placing the engines too close to the fuselage.



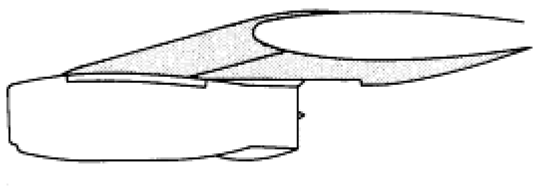
Influence of lateral nacelle position on interference drag

Structurally, outboard nacelle locations are desirable to reduce wing bending moments in flight but flutter requirements are complex and may show more inboard locations to be more favorable. The latter also favors directional control after engine failure. Finally, the lateral position of the engines affects ground clearance, an issue of special importance for large, four-engine aircraft.

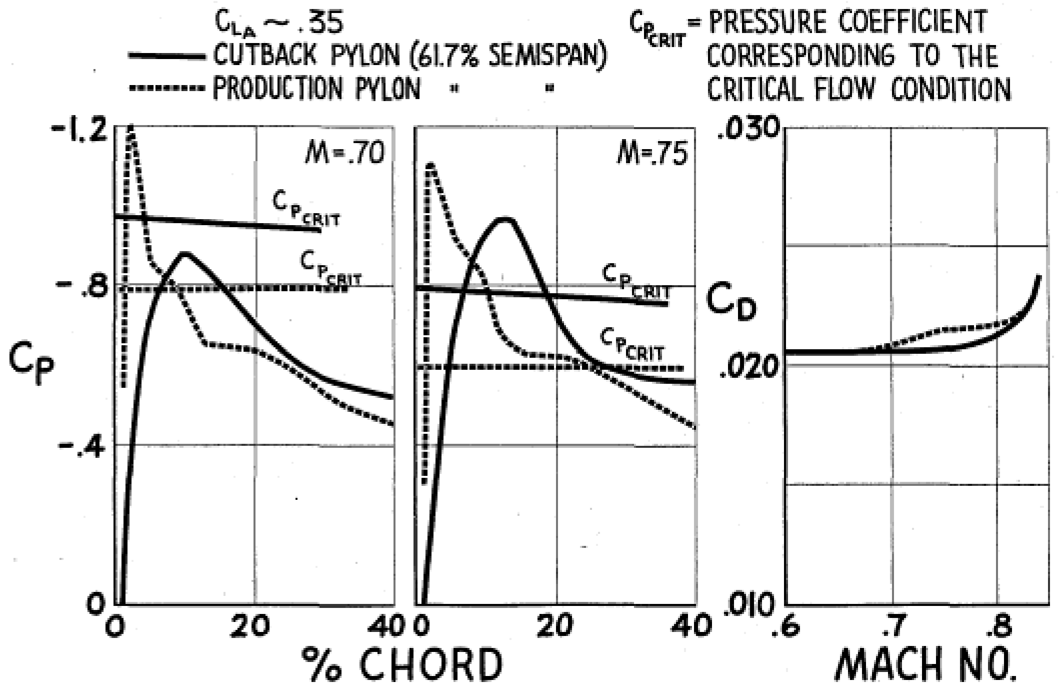


Another influence of wing-mounted nacelles is the effect on flaps. The high temperature, high 'q' exhaust impinging on the flap increases flap loads and weight, and may require titanium (more expensive) structure. The impingement also increases drag, a significant factor in take-off climb performance after engine failure. Eliminating the flap behind the engine reduces C_{Lmax}. A compromise on the DC-8 was to place the engines low enough so that the exhaust did not hit the flap at the take-off angle (25 deg. or less) and to design a flap 'gate' behind the inboard engine which remained at 25 deg. when the remainder of the flap extended to angles greater than 25 deg. The outboard engines were placed just outboard of the flap to avoid any impingement. On the 707, 747, and the DC-10, the flap behind the inboard engine is eliminated and this area is used for inboard all-speed ailerons. Such thrust gates have been all but eliminated on more recent designs such as the 757 and 777.

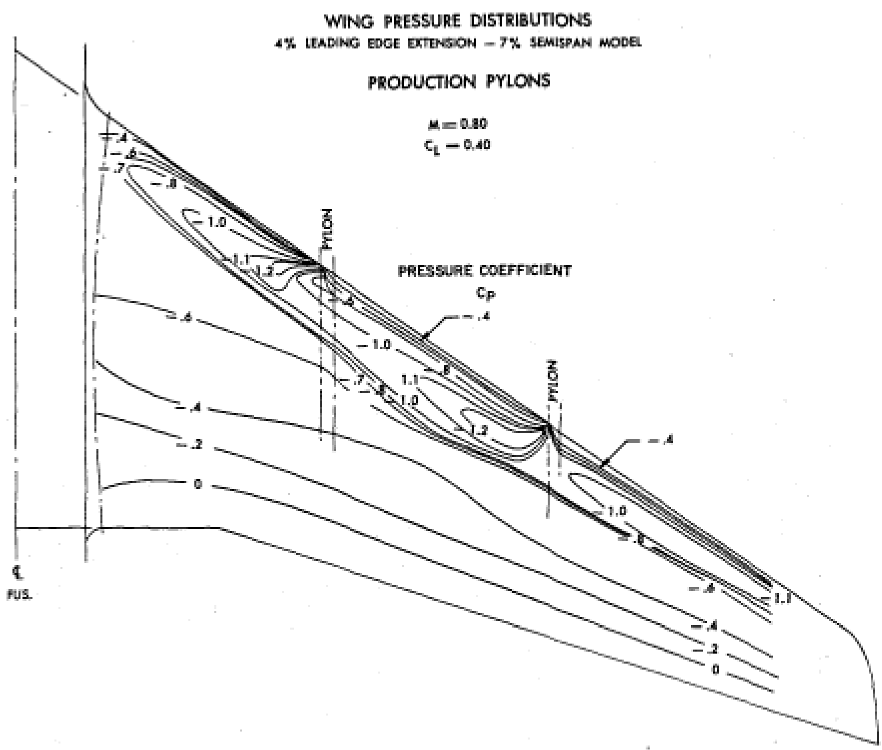
Pylon wing interference can and does cause serious adverse effects on local velocities near the wing leading edge. Drag increases and C_{Lmax} losses result. A pylon which goes over the top of the leading edge is much more harmful in this regard than a pylon whose leading edge intersects the wing lower surface at 5% chord or more from the leading edge.

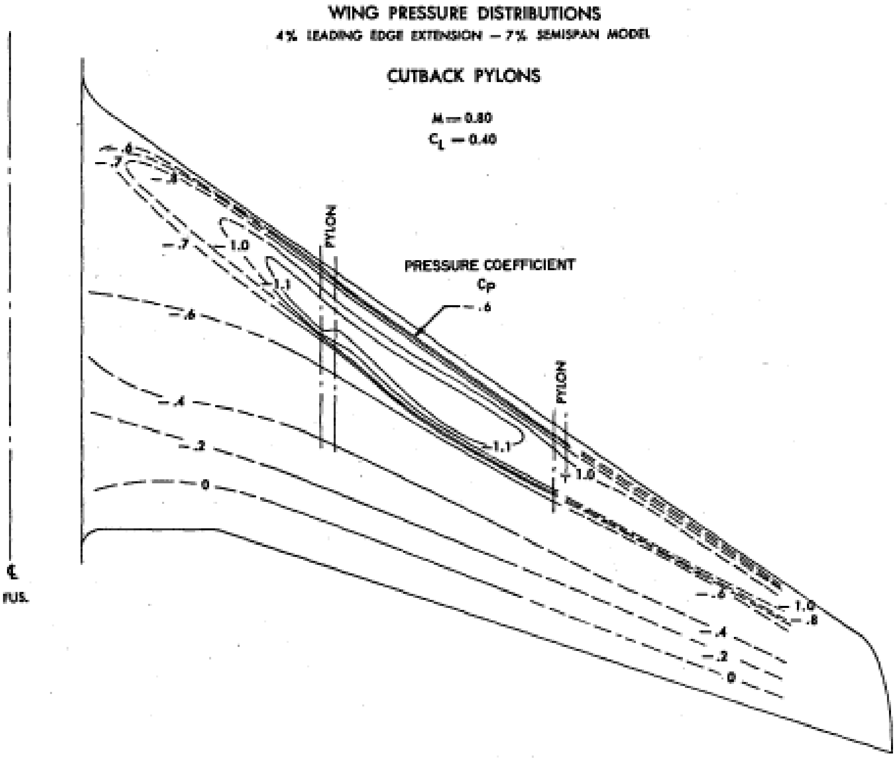


The original DC-8 pylon wrapped over the leading edge for structural reasons. Substantial improvements in C_{Lmax} and drag rise were achieved by the "cut-back pylon" shown in previous figures. The figures below show the effect of this small geometry change on wing pressures at high speeds.



Pressure Coefficient in vicinity of outboard pylons of DC-8.





In addition, wing pylons are sometimes cambered and oriented carefully to reduce interference. This was tested in the mid 1950's, although the gain was small and many aircraft use uncambered pylons today.

One disadvantage of pylon mounted nacelles on low wing aircraft is that the engines, mounted close to the ground, tend to suck dirt, pebbles, rocks, etc. into the inlet. Serious damage to the engine blades can result. It is known as foreign object damage. In about 1957 Harold Klein of Douglas Aircraft Co. conducted research into the physics of foreign object ingestion. He found that the existing vorticity in the air surrounding the engine inlet was concentrated as the air was drawn into the inlet. Sometimes a true vortex was formed and if this vortex, with one end in the inlet, touched the ground, it became stable and sucked up large objects on the ground. Klein developed a cure for this phenomenon. A small high pressure jet on the lower, forward portion of the cowl spreads a sheet of high velocity air on the ground and breaks up the end of the vortex in contact with the ground. The vortex, which has to be continuous or terminate in a surface, then breaks up completely. This device, called the blowaway jet, is used on the DC-8 and the DC-10. Even with the blowaway jet, an adequate nacelle-ground clearance is necessary.

The stiffness of the pylon for wing mounted engines is an important input into the flutter characteristics. Very often the design problem is to develop a sufficiently strong pylon which is relatively flexible so that its natural frequency is far from that of the wing.

Aft Fuselage Engine Placement

When aircraft become smaller, it is difficult to place engines under a wing and still maintain adequate wing nacelle and nacelle-ground clearances. This is one reason for the aft-engine arrangements. Other advantages are:

Greater C_{Lmax} due to elimination of wing-pylon and exhaust-flap interference, i.e., no flap cut-outs.
Less drag, particularly in the critical take-off climb phase, due to eliminating wing-pylon interference.
Less asymmetric yaw after engine failure with engines close to the fuselage.
Lower fuselage height permitting shorter landing gear and airstair lengths.
Last but not least - it may be the fashion.

Disadvantages are:

The center of gravity of the empty airplane is moved aft - well behind the center of gravity of the payload. Thus a greater center of gravity range is required. This leads to more difficult balance problems and generally a larger tail.

The wing weight advantage of wing mounted engines is lost.

The wheels kick up water on wet runways and special deflectors on the gear may be needed to avoid water ingestion into the engines.

At very high angles of attack, the nacelle wake blankets the T-tail, necessary with aft-fuselage mounted engines, and may cause a locked-in deep stall. This requires a large tail span that puts part of the horizontal tail well outboard of the nacelles.

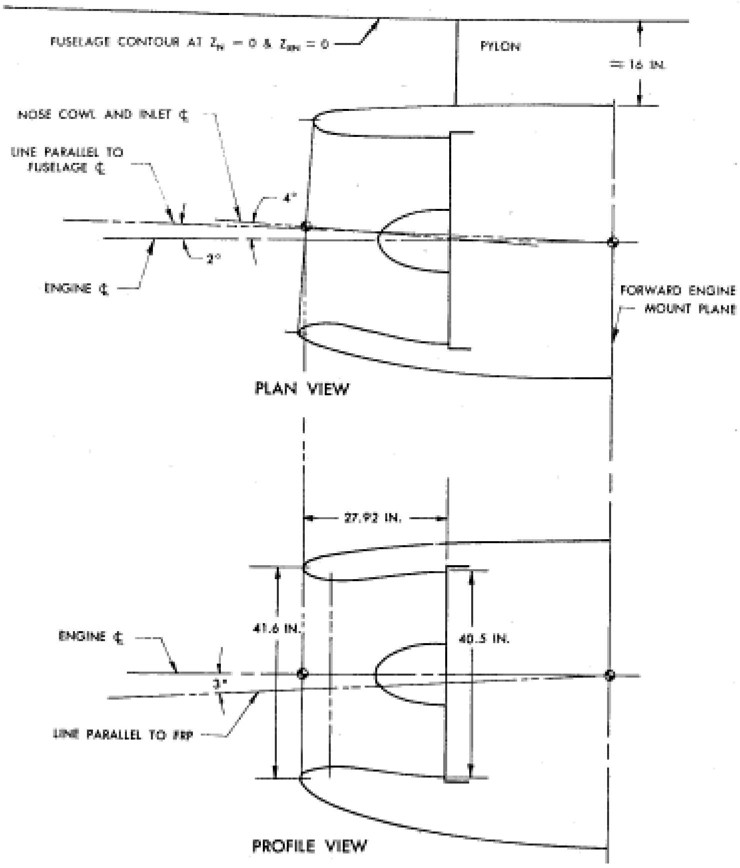
Vibration and noise isolation for fuselage mounted engines is a difficult problem.

Aft fuselage mounted engines reduce the rolling moment of inertia. This can be a disadvantage if there is significant rolling moment created by asymmetric stalling. The result can be an excessive roll rate at the stall.

Last but not least - it may not be the fashion.

It appears that in a DC-9 size aircraft, the aft engine arrangement is to be preferred. For larger aircraft, the difference is small.

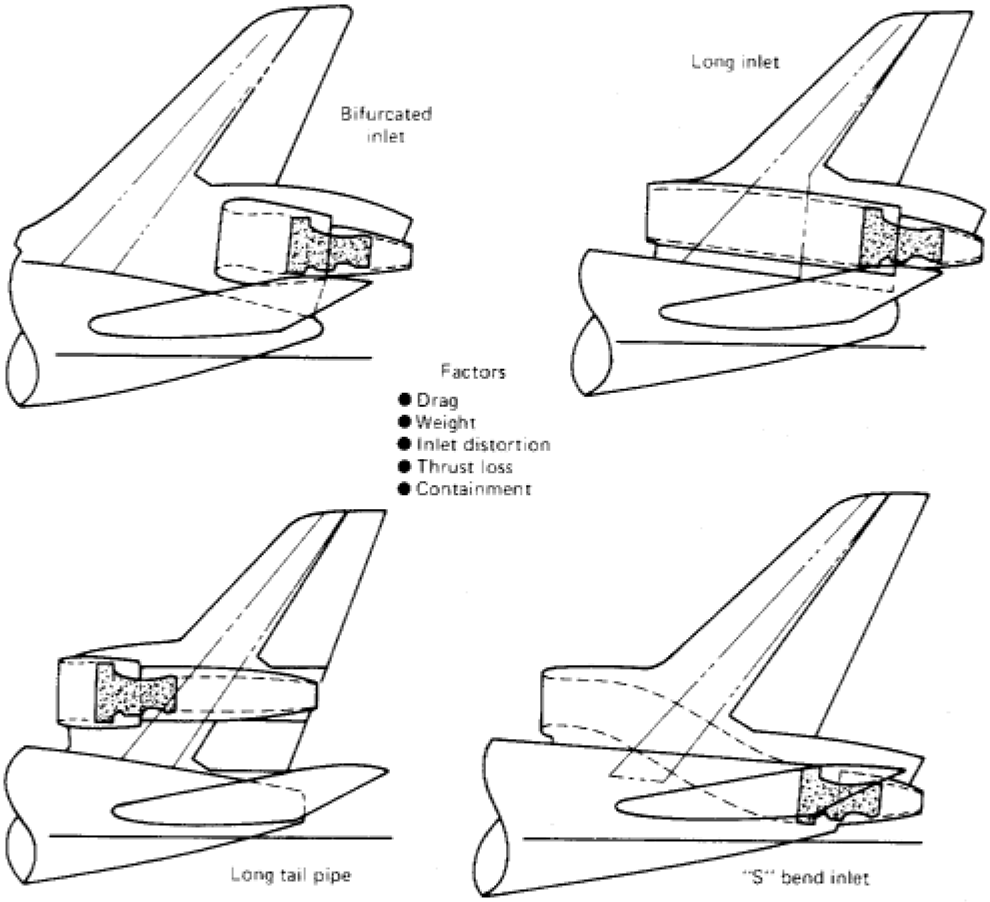
An aft fuselage mounted nacelle has many special problems. The pylons should be as short as possible to minimize drag but long enough to avoid aerodynamic interference between fuselage, pylon and nacelle. To minimize this interference without excessive pylon length, the nacelle cowl should be designed to minimize local velocities on the inboard size of the nacelle. On a DC-9 a wind tunnel study compared cambered and symmetrical, long and short cowls, and found the short cambered cowl to be best and lightest in weight. The nacelles are cambered in both the plan and elevation views to compensate for the angle of attack at the nacelle.



With an aft engine installations, the nacelles must be placed to be free of interference from wing wakes. The DC-9 was investigated thoroughly for wing and spoiler wakes and the effects of yaw angles, which might cause fuselage boundary layer to be ingested. Here efficiency is not the concern because little flight time is spent yawed, with spoilers deflected or at high angle of attack. However, the engine cannot tolerate excessive distortion.

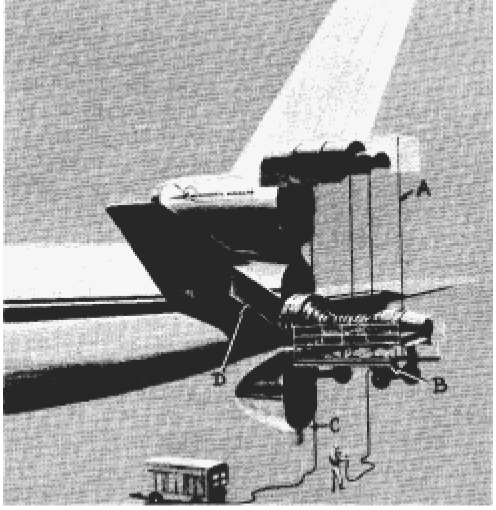
Three-Engine Designs

A center engine is always a difficult problem. Early DC-10 studies examined 2 engines on one wing and one on the other, and 2 engines on one side of the aft fuselage and one on the other, in an effort to avoid a center engine. Neither of these proved desirable. The center engine possibilities are shown below.



Each possibility entails compromises of weight, inlet loss, inlet distortion, drag, reverser effectiveness, and maintenance accessibility. The two usually used are the S-bend which has a lower engine location and uses the engine exhaust to replace part of the fuselage boattail (saves drag) but has more inlet loss, a distortion risk, a drag from fairing out the inlet, and cuts a huge hole in the upper fuselage structure, and the straight through inlet with the engine mounted on the fin which has an ideal aerodynamic inlet free of distortion, but does have a small inlet loss due to the length of the inlet and an increase in fin structural weight to support the engine.

Such engines are mounted very far aft so a ruptured turbine disc will not impact on the basic tail structure. Furthermore, reverser development is extensive to obtain high reverse thrust without interfering with control surface effectiveness. This is achieved by shaping and tilting the cascades used to reverse the flow.

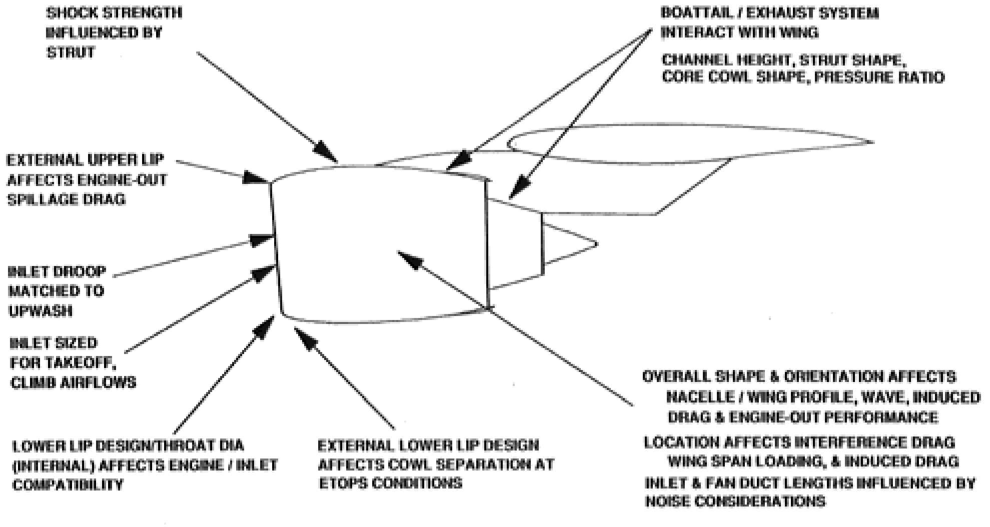


Solutions to the DC-10 tail engine maintenance problems include built-in work platforms and provisions for a bootstrap winch system utilizing beams that are attached to fittings built into the pylon structure. Although currently companies are developing virtual reality systems to evaluate accessibility and maintenance approaches, designers considered these issues before the advent of VRML. The figure below is an artist's concept of a DC-10 engine replacement from a 1969 paper entitled "Douglas Design for Powerplant Reliability and Maintainability".

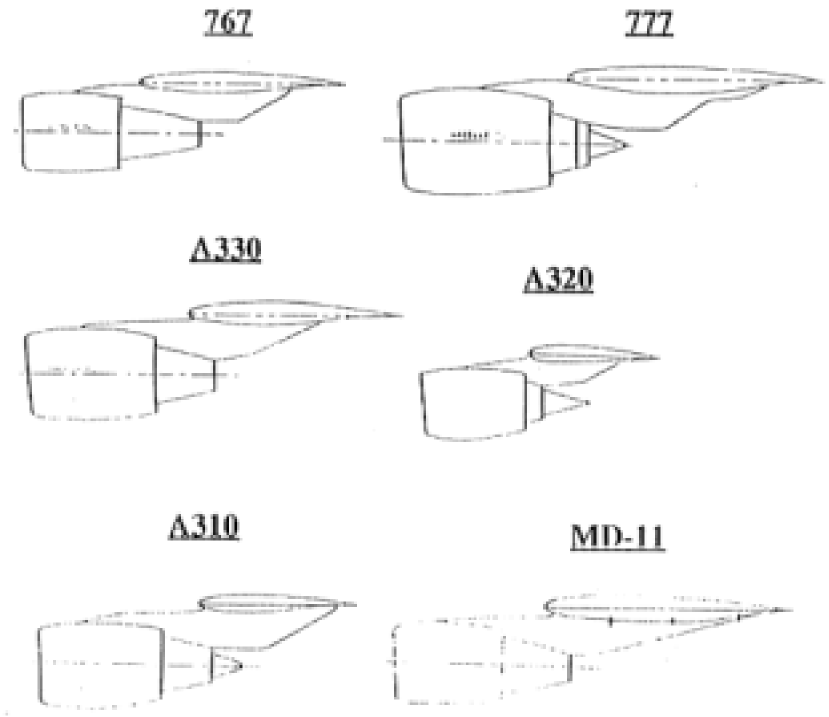
Nacelle Design and Sizing

The design of the nacelle involves both the external shape and the inlet internal geometry. The design of the engine inlet is generally the job of the airframe manufacturer, not the engine manufacturer and is of great importance to the overall efficiency.

The outer curvature of the cowl nose is as important as the inner contour shape. The cowl nose contour must be designed to avoid excessive local velocities in high sped flight. Here the design philosophy is somewhat similar to the fuselage and wing approach; supercritical velocities can be permitted far forward on the cowl provided the local velocities are subsonic well forward of the location of the maximum nacelle diameter. Many tests of cowling shapes have been made by NASA and various aircraft companies to determine desirable contours. Cowls are often cambered to compensate for the high angles of attack at which aircraft operate.



Some examples of nacelle designs and wing-mounted installations are shown below.

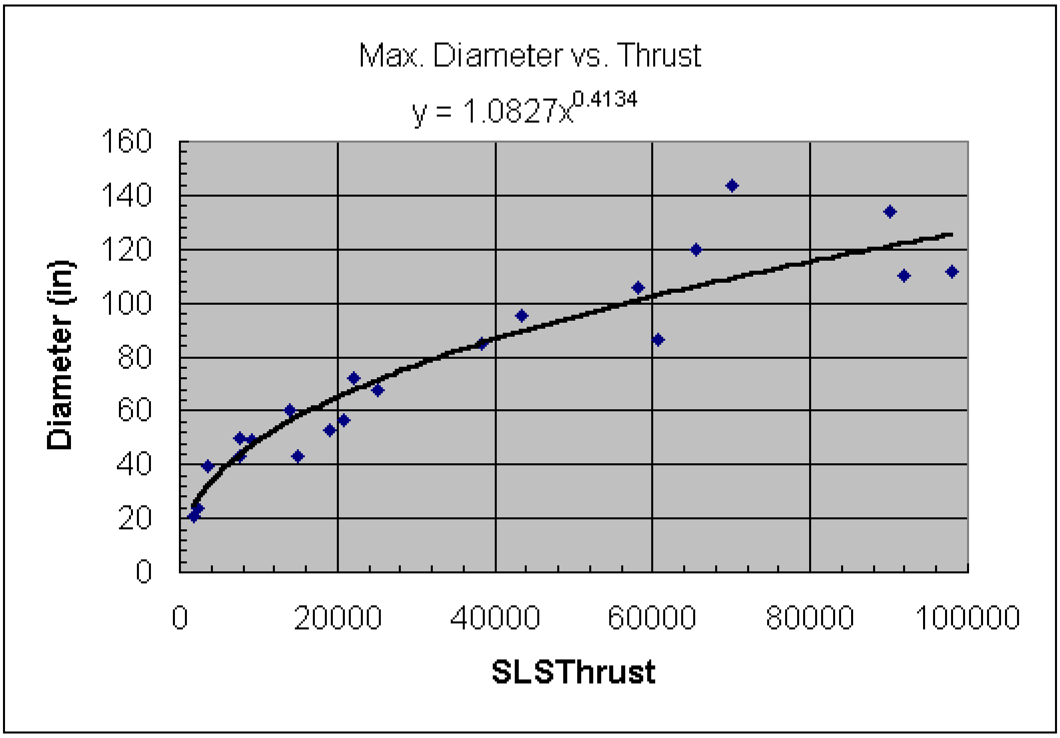


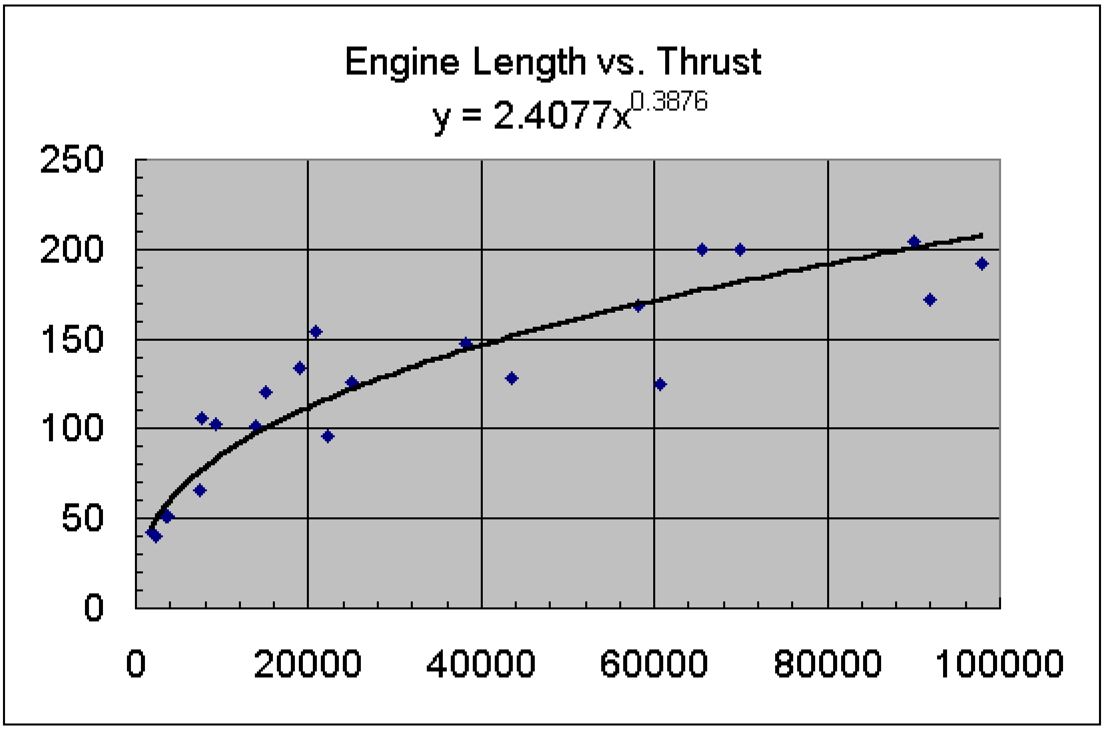
Commonality between engine installations, left and right, wing and tail, etc. is made as complete as possible. Airlines keep spare engines in a neutral configuration, i.e., with all parts installed that are common to all engine positions. Only the uncommon parts must be added to adapt the engine to a particular position. A neutral engine for the DC-10 consists of the basic engine with all accessories installed, generator electrical leads coiled, certain hydraulic and fuel lines not installed, nose cowl not installed, and engine control system not installed.

One of the most difficult design problems is fitting all the necessary equipment within the slender pylon. Fuel lines, pneumatic lines, engine and reverser controls, electrical cables, and numerous instrumentation leads must fit closely and yet permit maintenance access. The nacelle is made as small as possible but must provide space for all accessories plus ventilation for accessory and engine cooling.

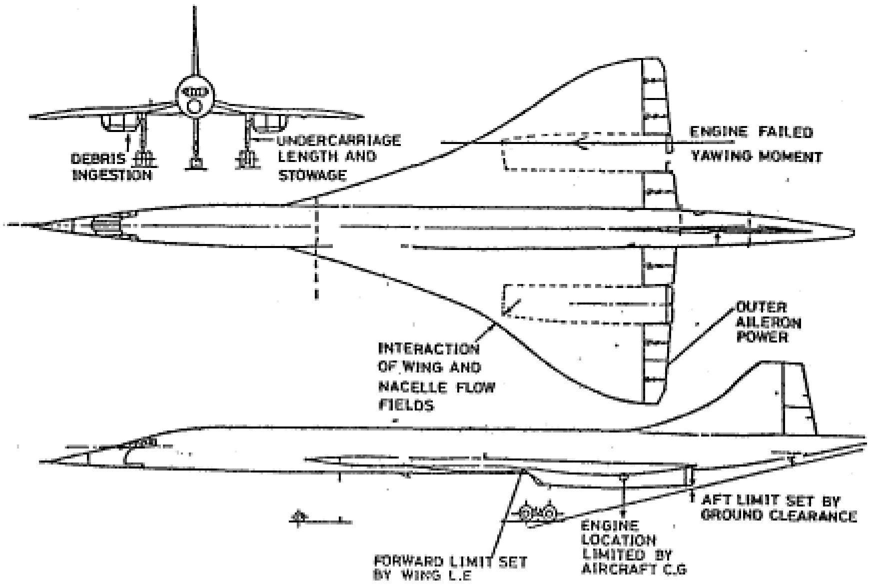
One can use some of the pictures in this section for initial nacelle sizing when the actual engine dimensions are known. The nacelle diameter tends to be roughly 10% greater than the bare engine to accommodate various engine systems. The inlet itself extends about 60% of the diameter in front of the fan face, and the actual inlet area is about 70% of the maximum area, although this varies depending on the engine type. For initial sizing, a representative engine may be selected and scaled (within reason) to the selected thrust level. One would expect the engine dimensions to vary with the square root of the thrust ratio (so that the area and mass flow are proportional to thrust). Statistically, the scaling is a bit less than the square root. The plots below show the variation in nacelle diameter and length as the thrust varies. The concept is sometimes called "rubberizing" an engine. Using the

85" diameter 38,250 lb PW2037 as a reference and scaling diameter by thrust to the 0.41 power yields reasonable diameters for engines over a very large thrust range. Somewhat more scatter is found in engine length but a 0.39 power thrust scaling is reasonable here as well. We note that the plots below show engine diameter and length, rather than nacelle dimensions. The nacelle must be scaled up as described above.



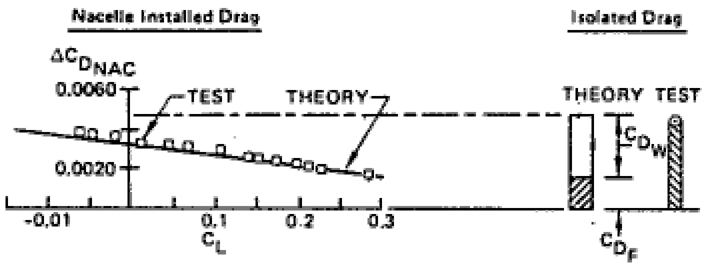


Engine Installation for Supersonic Aircraft



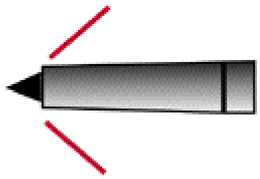
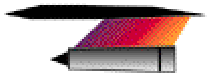
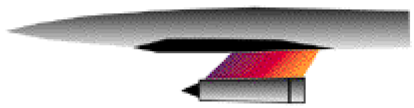
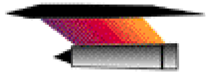
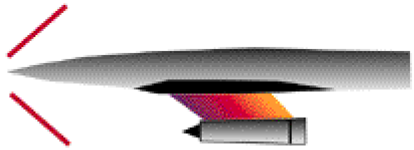
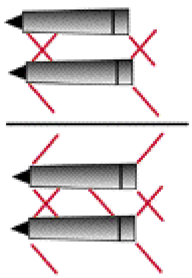
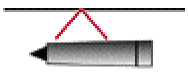
Factors affecting supersonic aircraft engine positioning.

The presence of volume-dependent wave drag means that the location of the engines may make a large difference to drag. In particular, interference of the nacelles with the fuselage, wing, and other nacelles is very sensitive to the relative position and orientation of the nacelles. The nacelle placement for supersonic aircraft can take advantage of favorable interference and detailed studies have shown that aft wing placement of engines can reduce the drag of the installation to little more than that associated with the skin friction drag of the nacelles.



Some of the interference effects are listed in the table below:

Effects of Nacelle on Lift and Drag	
Interference Drag	**Interference Lift**
Nacelle Pressure Drag	**Nacelle Interference Increases Wing Lift**

	
Nacelle-On-Wing/Body Interference 	**Wing Interference Decreases Nacelle Lift** 
Wing-On-Nacelle Interference 	
Mutual Nacelle Interference  Adjacent Nacelles  Self-Interference from Wing Reflection	

In addition to wave drag and lift considerations, nacelle placement is influenced by a variety of practical considerations such as:

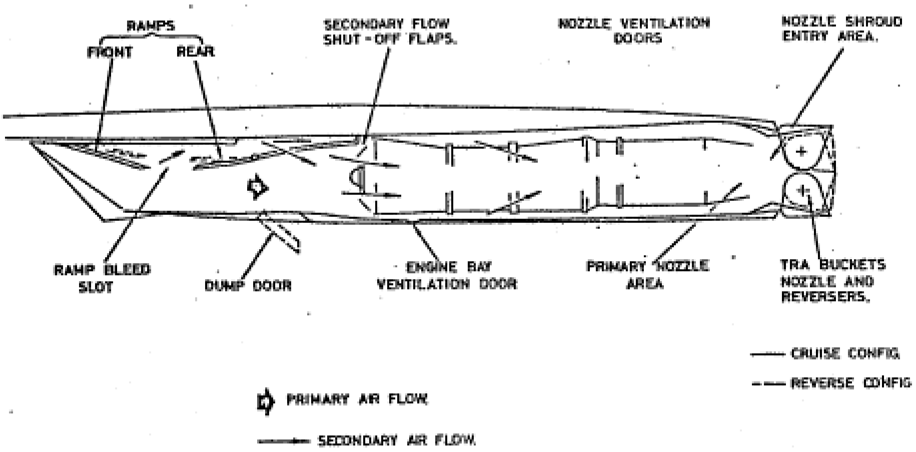
Inlets must be placed away from main gear to avoid excessive water ingestion.

Inlets must be located in an area ofd the wing with uniform flow, away from the leading edge shock to assure inlet stability. The inlets are often separated from each other laterally to improve the inlet stability as well.

The longitudinal position is constrained by structure, ground clearance, rotor burst, and flutter considerations. The spanwise position is governed by these same issues as well as engine-out yawing moment.

Nacelle Design

The nacelle size for SST engines follows different rules from those of subsonic engines. Nacelles tend to be much longer because of the length dependence of wave drag and because more substantial speed reduction must occur in the inlet. Typical inlet losses are still much higher than for subsonic inlets. Initial nacelle sizing can be based on many previous detailed studies and experience with the Concorde.



TBE Sample Engine Summary			
Design Mach Number:	**1.6**	**2.0**	**2.4**
Weights:			
Bare Engine + Accessories, lb	9,252	9,278	9,567
Inlet / Nacelle, lb	1,343	2,243	3,837
Nozzle, lb	4,OOO	4,000	4,000
Total, lb	14,596	15,521	17,424
Nacelle Dimensions:			
Length, ft	31.83	31.74	34.92
Maximum Diameter (at engine), ft	6.20	6.20	6.20
Reference Diameter (at exit), ft	4.47	4.96	5.92
Inlet Capture Diameter, ft	4.53	6.01	5.52
Maximum Area, ft^2	30.19	30.19	30.19
Reference Area, ft^2	15.69	19.32	23.93
Inlet Capture Area, ft^2	16.12	19.71	23.93

Performance (installed):			
Takeoff:			
Design Corrected Mass Flow, lb/sec	700	700	700
Installed Net Thrust, lb	70,610	69,035	65,482
Overall Pressure Ratio	29.07	29.18	18.93
Specific Fuel Consumption lb/hr/lb	0.8756	0.8728	0.9293
Cruise:			
Cruise Altitude, ft	45000	55000	65000
Installed Net Thrust, lb	29,628	21,911	18,955
Overall Pressure Ratio	27.50	21.30	12.04
Specific Fuel Consumption, lb/hr/lb	1.1177	1.1991	1.3098
Overall Efficiency, percent	34.51	40.21	44.18

Propulsion Systems: Performance

This section deals more specifically with engine performance. It is divided into the following subsections:

Thrust Variation with Speed and Altitude

SFC and Efficiency

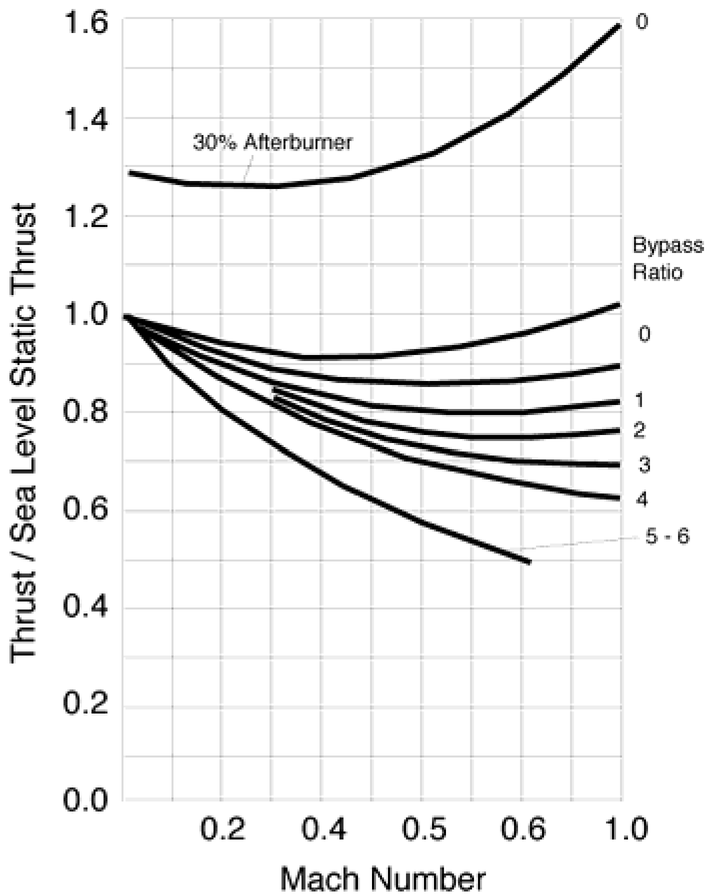
Specific Engine Data

- Large turbofans
- Small turbofans
- Engines for supersonic aircraft

Thrust Variation with Speed and Altitude

The following pages provide examples of the kind of information provided by engine manufacturers. Data on sfc and thrust as a function of Mach number, altitude, throttle setting and power extraction are generally provided in the form of plots and now as software based cycle decks.

Unlike propeller-powered aircraft for which the power output is approximately constant with changes in speed, turbojets produce a more constant thrust with speed. Modern turbofans are somewhat in-between constant thrust jets and constant power propeller systems. Significant reductions in net thrust are associated with increasing speed and altitude.



Typical trend of thrust vs. speed for turbojets and turbofans with varying bypass ratio at seal level.

A particular engine's thrust performance usually cannot be inferred well from generic cycle decks and it is common now to begin an aircraft design study with a number of computer decks from the different engine manufacturers. This is because many possible constraints on engine pressures, temperatures, and RPM's may be critical at different operating points. Many engines are flat-rated, meaning that they might actually be able to produce mush more thrust at low altitudes and speeds, but they are limited (often in software) to lower thrust levels to extend engine life and reduce maximum loads. Thus some supersonic engines show very little reduction in thrust from sea-level static conditions to Mach 1 at 30,000 ft.

Actual engine performance differs from the basic engine data in a number of ways. The air bled from the compressor for air conditioning, the power extracted for hydraulic pumps and alternators, and inlet and exhaust duct losses reduce engine thrust. The exact amount depends, of course, on the requirements of the accessories, the engine size, and the inlet and duct design, but reasonable estimates for conventional inlets are:

1) Thrust is reduced by 3.5% below engine specification levels
2) Specific fuel consumption is increased by 2.0%

During the take-off the air conditioning bleed is often shut-off automatically to avoid the thrust loss.

The remaining thrust loss is about 1%. If a long or curved (S-bend) inlet is involved as in center engine installations, an additional thrust loss of 3% and a specific fuel consumption increase of 1-1/2% may be assumed. This additional loss applies only to the affected engine.

Specific Fuel Consumption and Overall Efficiency

The engine performance may be described in several ways. One of the useful parameters is specific fuel consumption, or s.f.c. For turbojets and fans, the s.f.c. is usually expressed as the thrust specific fuel consumption or t.s.f.c.. It is defined as the weight of the fuel burned per unit time, per unit thrust. In English units, t.s.f.c. is usually quoted in lbs of fuel per hour per lb of thrust or just lb/hr/lb or 1/hr. (In SI units the t.s.f.c. is sometime expressed in kg/hr/kN.)

For turboprop or piston engines, the s.f.c. is often expressed as a power specific fuel consumption, i.e. weight of fuel per unit time per unit power delivered to the propeller. This quantity is often denoted b.s.f.c. (for brake-power s.f.c.) and has units of 1/length. It is expressed in the unwieldy, but familiar English units of lb / hr / h.p..

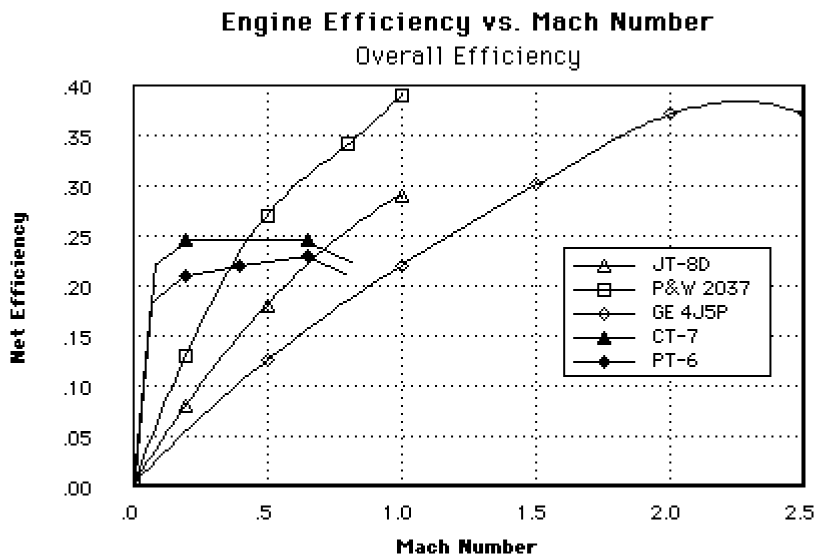
The overall efficiency of the propulsion system is given by:

= Power Available to Aircraft / Rate of Energy Consumption = T V / w h

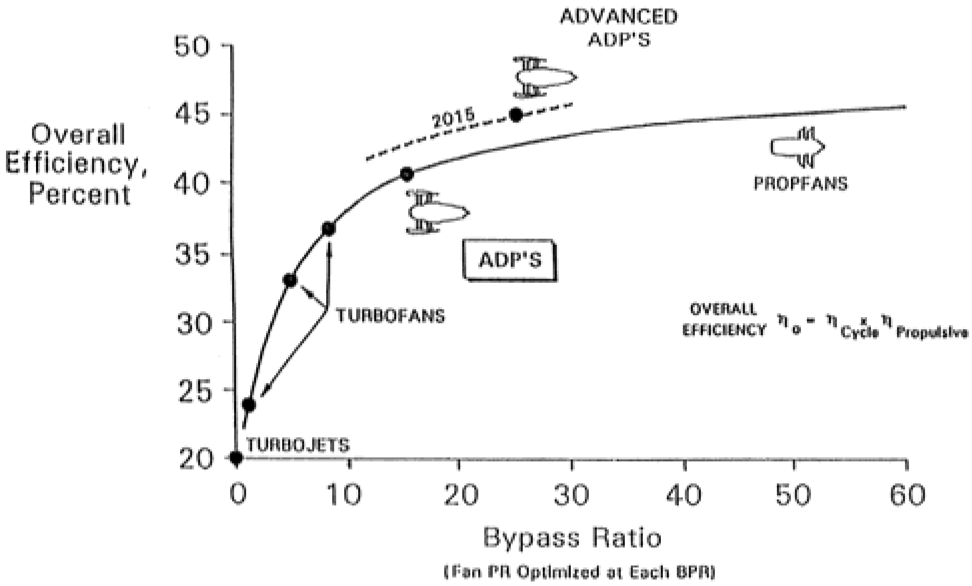
where T = thrust, V= aircraft speed, w = rate of fuel consumption (weight/unit time), and h = specific energy of the fuel (energy / unit weight).

In terms of the s.f.c.: = V / tsfc h.

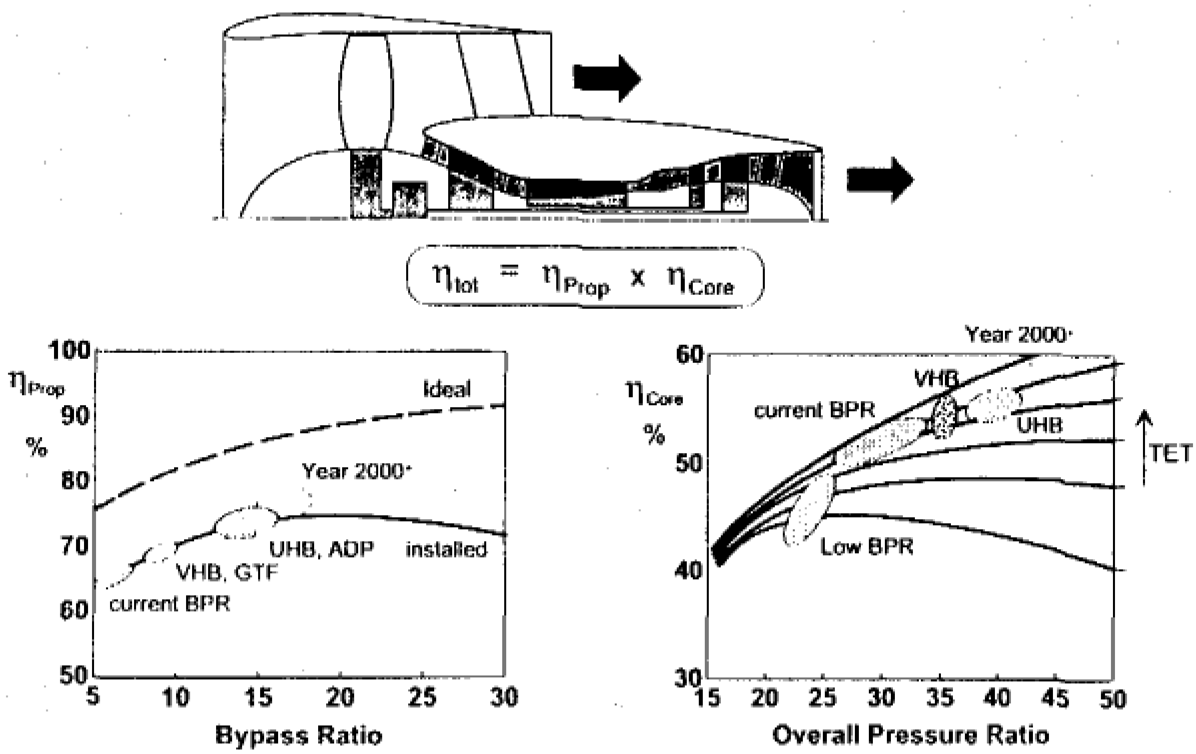
One must be careful to use consistent units in this expression.



Overall efficiency of several engines vs. Mach number.



Overall efficiency vs. bypass ratio for large commercial turbine engines. (From Dennis Berry, Boeing)



Trends in advanced engine efficiency.

Subsonic Engine Efficiencies:

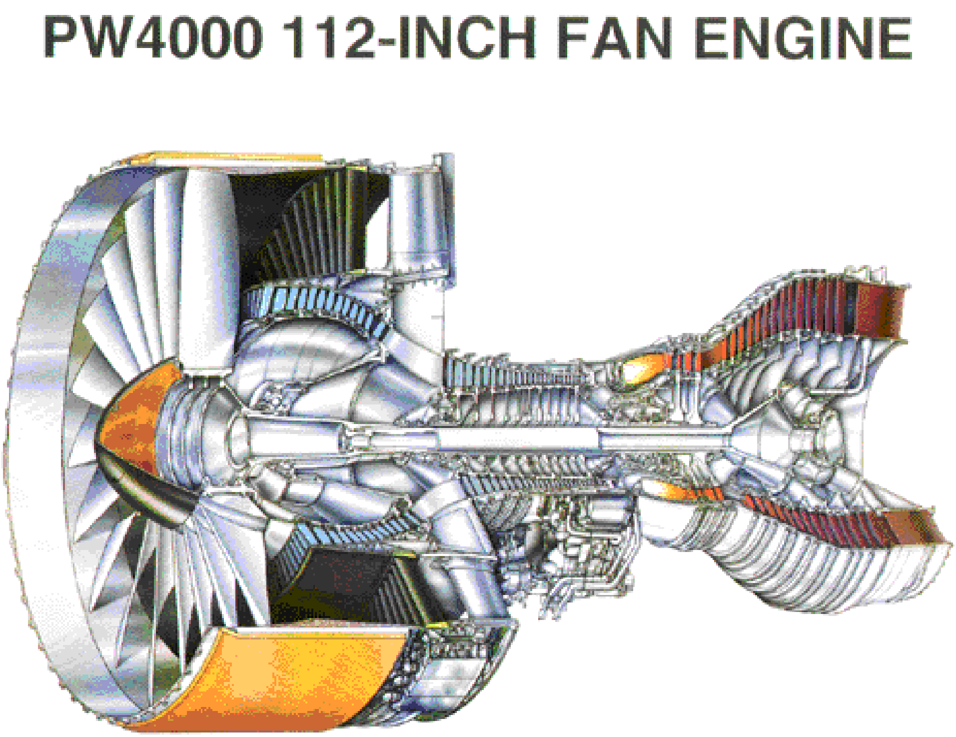
(At about min sfc throttle setting 80% at typical cruise conditions)

GE90	.361
PW4000	.348
PW2037	.351 (M.87 40K)
PW2037	.335 (M.80 35K)

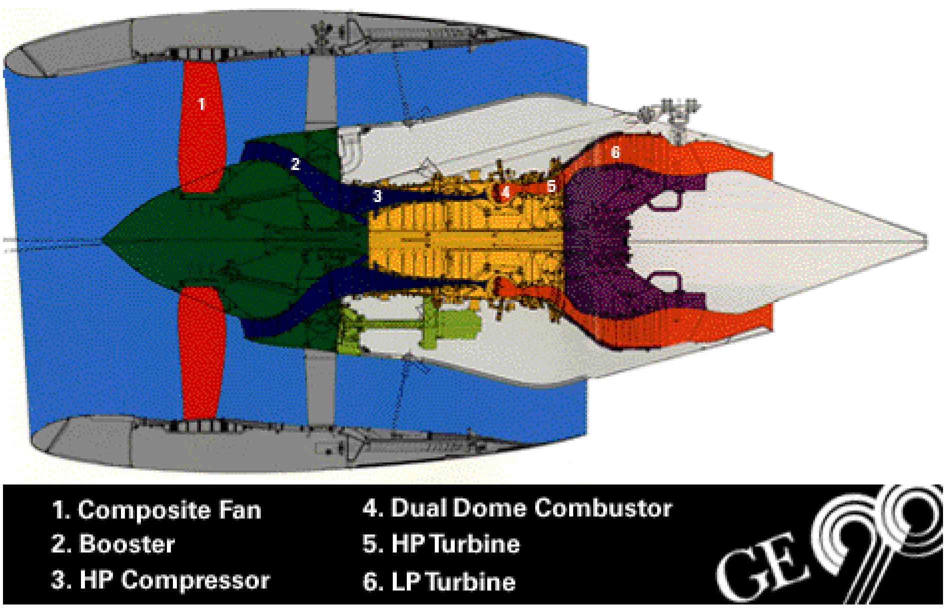
CFM56-2	.305
TFE731-2	.234

Data on Large Turbofan Engines

These pages conatin some basic data and pictures of larger turbofan engines.



Cut-away showing the PW4000-Series of Engine



Cross-Section of GE-90 Engine

Some Basic Data

Engine	SLS Thrust	SLS SFC	Max Diam	Length	Wt	BPR	Cruise sfc	Applications
ALF502R-6	7500	0.415	50	65.6	1375	-	-	Bae-146
TFE731-2	3500	0.493	39.4	51	725	2.67	0.87	Citation
TFE731-20	3650	0.441	39.4	51	885	-	-	Lear 45
BR710	20000	0.39	52.9	87	3520	-	-	G-V, Global Express
AE3007	7580	0.39	43.5	106.5	1581	-	-	Citation10, Embraer RJ145
CFM56-2-C1	22200	0.36	72	95.7	4635	6	0.64	A340
CF34-3B	9220	0.35	49	103	1670		-	Canadair Challenger, RJ
CF6-80C2B1F	58000	0.316	106	168	9499		0.605	B747-400
GE90-90B	90000		134	204	16644	9	.55 (est)	B777-200/300
V2500-A1	25000	0.36	67.5	126	5210	5.4	0.543	A319-321
RB211-524H	60600		86.3	125	9499	4.1	0.603	747-400 / 767-300
Tay 620	13850	0.43	60	102	3185	3.04	0.69	Fokker 70/100
Trent 800	92000	0.35	110	172	14400	6.5	0.56	777
JT8D-217	20850	0.53	56.3	154	4430	1.74	0.71	MD-80
PW2037	38250	0.33	84.8	146.8	7160	5.8	0.563	757, C-17
PW4098	98000		112	191.7	16165	5.8	.56 (est)	777
FJ44-1	1900	0.456	20.9	41.9	445			CitationJet
FJ44-2	2300		23.7	40.2	448	3.28		Raytheon Premier
JT3-D-7	19000	0.55	52.9	134.4	4300		0.79	
JT8D-11	15000	0.62	43	120	3310		0.82	
JT9D-3A	43500	0.346	95.6	128.2	8608		0.6	
ADP	65500		120	200	9500	12	0.53	Hypothetical 2015 Engine

ADP	70000		144	200	12500	20	0.49	
GE4	69000	0.9	90	296.04	13243		1.47	B2707 SST Design Mach 2
GE21J11B14	65000	0.8	74.16	282			1.35	SCAR study Mach 2.6
Olympus 593	38000	1.39	49	150	6780		1.195	Concorde
TBE-M1.6	70600	0.875			9252		1.12	NASA MACH 1.6 STUDY
TBE-M2.0	69000	0.873			9278		1.2	NASA MACH 2.0 STUDY
TBE-2.4	65500	0.929			9587		1.31	NASA MACH 2.4 STUDY
Rolls VCE	49460	0.55					1.1	HSCT Design Study
Rolls Tandem	49460	0.55					1.09	HSCT Design Study

Small Engines Summary

There are not many engines in the 2000lb to 4000lb thrust class appropriate for small turbofan aircraft. Here is the list of all viable turbofan engines (1K-10K lb thrust) currently in production or under development in the west (source: AW&ST, Janes, Web). Engines that have afterburners or have very low bypass ratio (SFC of 1.0 and up) are not listed here.

Engine	**Thrust** [lb]	**SFC**	**D**	**Length**	**Weight**,lb	**Application**
Allied Signal						//www.alliedsignal.com/
F109-GA-100	**1330**	0.39	31"	44"	439	Squalus, Phoenix FanJet
TFE731	**3500-5000**	0.51-.40	40"	50"	734-988	Cessna/Falcon/Lear/Astra
ATF3	**5400**	0.50	34"	103"	1120	Falcon, HU25
CFE 738	**6000**	0.37	48"	99"	1325	With GE. Falcon 2000

F124	**6300**	0.81	36"	70"	1100	Aero Vodochody L-139
ALF502/507	**6700-7800**	0.43-0.41	50"	65"	1350	Ch 600, Bae-146, AvroRJ
Allison						http://www.allison.com/
AE3007	**7200**	0.39	43"	106"	1580	Citation-X, Global-Hawk
General Electric						
CF700	**4500**	0.65	37"	54"	767	Falcon, Sabreliner
CF/TF-34	**9200**	0.35	49"	103"	1670	Challenger 601/RJ,A-10
IHI (Japan)						
F-3	**3700**	0.70	22"	79"	458	Kawasaki T-4
TF-40	**7300**	0.74	30"	114"	1690	Mitsubishi T-2, F-1
P&W/P&Wc/MTU						http://www.pwc.ca/
JT15D	**3000**	0.55	28"	61"	630	Citation 5, Beechjet 400
PW500/530/545	**3000-4500**	0.44	27"	70"	765	Citation Bravo, Excel
PW305/306	**4500-6500**	0.39	38"	81"	1040	Learjet 60
Williams/Rolls-Royce						//www.rolls-royce.com/
F107/F112	**700**	N/A	12"	40"	146	ALCM, Tomahawk
FJX-2	**700**	N/A	14"	41"	100	V-Jet 2
FJ44-1,2	**1900-2300**	0.456	21"	40"	445	Premier, Darkstar, SJ30

The FJX engine is currently being developed by Williams as part of a NASA program and has caused considerable excitement in the general aviation community. Here are some recent updates from NASA.

The GAP Turbine engine (FJX-2) is on its way to becoming reality. Hardware is being built, components are being tested and we expect to have the first complete engine ready for testing by August of this year. In addition to the FJX-2 turbofan, we are developing a the turboprop version of the engine (TSX-2) for ground testing in 1999. The FJX-2 will be flight demonstrated in the V-Jet II aircraft but the TSX-2 will not be flight tested as part of the GAP program, our main emphasis is on the fan version of the engine. This engine has many unique design features with a KISS (keep-it-simple-stupid) design philosophy to keep the costs down to the lowest possible level. This does not mean a low performance engine however, at less than 100 lbs. weight for 700 lbs. thrust and a fuel consumption rate per pound of thrust similar to larger modern turbofan engines this will be a world class engine. The FAA is participating in the program to ensure that the new and innovative design features of this engine will meet all certification requirements in a cost effective manner.

The first FJX-2 turbofan engine was fully assembled on December 18, 1998, by Williams International in Walled Lake, Michigan, marking a major milestone in the GAP program. On December 22, 1998, the first operational test of the new FJX-2 engine was conducted in the Williams static test facility. The engine was then disassembled for inspection and found to be in excellent condition. The engine is now being reassembled and will continue to be developed to a flight worthy status over the next 18 months.

The development of the FJX-2 engine commenced in December 1996 under a Cooperative Agreement between NASA/GRC and Williams International. The engine will be integrated into the V-Jet II concept aircraft and flight demonstrated at the EAA Oshkosh AirVenture in late July 2000.

Selected Data on Supersonic Engines

From NASA AIAA 92-1027 TBE

Design Mach	1.6	2	2.4
SLSThrust (klb)	70.6	69	65.5
Engine Weight	9252	9278	9587
Total Weight	14595	15521	17424
Cruise sfc	1.118	1.199	1.31

Some thrust and sfc lapse rates: (From 92-1027, Concorde brochure, Boeing CR, SAE901890, SAE1892)

M	h	T	sfc	eta	source
0	0	70610	0.8746	0	AIAA92-1027
1.6	45000	29528	1.118	0.346	
0	0	69035	0.8728	0	AIAA92-1027
2	55000	21911	1.1991	0.404	

0	0	65482	0.9293	0	AIAA92-1027
2.4	65000	18955	1.31	0.443	
0	0	38050			Concorde Brochure
2	60000	6791	--		
0	0	52730	--	0	Boeing CR
0.9	30000?	42q	0.98	0.22	
2.4	60000?	25q	1.28	0.454	
2	--	--	1.2	0.403	SAE 1890
0	0	49460	0.548	0	Rolls VCE
0.95	31000	7868	0.845	0.279	
1.3	35000	12930	0.902	0.351	
2	60000	8711	1.1	0.44	
0	0	------	1.39	0	Rolls Olympus Data
0.95	31000	-----	1.025	0.23	
1.3	35000	-----	1.415	0.224	
2	60000	----	1.195	0.405	
0	0	49460	0.551		Rolls Tandem Fan
0.95	31000	7868	0.816	0.288	
1.3	35000	12930	0.893	0.354	
2	60000	8711	1.094	0.437	

Overall engine efficiencies at cruise:

Mach	eta	eta_goal	source
1.0	.38	.38	Douglas CR pg47
2.0	.42	.45	"

3.2	.46	.56	"
5.0	.50	.58	"

Some rough additional rules from a Rolls-Royce SNECMA paper:
Nacelle isolated drag = 4.6% T (friction) + 4.4% T (wave)
SLSTH/Weng = 5.28
TOThrust = .37 GTOW (Concorde)