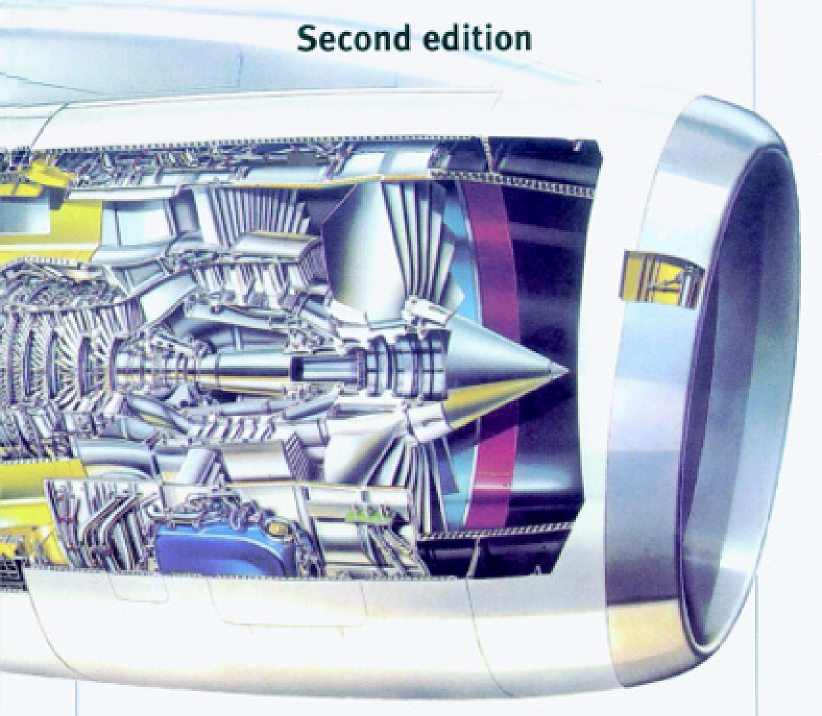
Jet Propulsion

A simple guide to the aerodynamic and thermodynamic design and performance of jet engines

Second edition



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JET PROPULSION

A Simple Guide to the Aerodynamic and Thermodynamic Design and Performance of Jet Engines

This is the second edition of Cumpsty's excellent self-contained introduction to the aerodynamic and thermodynamic design of modern civil and military jet engines. Through two engine design projects, first for a new large passenger aircraft, and second for a new fighter aircraft, the text introduces, illustrates and explains the important facets of modern engine design. Individual sections cover aircraft requirements and aerodynamics, principles of gas turbines and jet engines, elementary compressible fluid mechanics, bypass ratio selection, scaling and dimensional analysis, turbine and compressor design and characteristics, design optimisation, and off-design performance. The book emphasises principles and ideas, with simplification and approximation used where this helps understanding. This edition has been thoroughly updated and revised, and includes a new appendix on noise control and an expanded treatment of combustion emissions. It is suitable for student courses in aircraft propulsion, but also an invaluable reference for engineers in the engine and airframe industry.

JET PROPULSION

A Simple Guide to the Aerodynamic and Thermodynamic Design and Performance of Jet Engines

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PREFACE TO SECOND EDITION

The book has been well received and Cambridge University Press approached me with the invitation to bring out a second edition. This was attractive because of the big events in aerospace, most significantly the decision by Airbus Industrie at the end of 2000 to launch their new large aircraft, the A380. This meant that some changes in the first ten chapters were needed. Another major development is the decision to develop an American Joint Strike Fighter, the F-35.

Another more personal change took place when I left academia to become Chief Technologist of Rolls-Royce from the beginning of 2000. It should be noted, however, that the character and ideas of this second edition remain those of the university professor who wrote the first edition and do not reflect my change of role.

The aim and style of the book is unchanged. The primary goal of creating understanding and the emphasis remains on simplicity, so far as this is possible, with the extensive use of relevant numerical exercises. In a second edition I have taken the opportunity to update a number of sections and to include some explanatory background on noise; noise has become a far more pressing issue over the last four or five years. The book remains, however, very similar to the first edition and, in particular, numerical values have been kept the same and the exercises have not been changed. Fortunately I do not think that the changes are not large enough to mislead the reader.

In writing the first edition I was grateful for the help of many people. Mention should be made here of help from Professor Mike Owen of the University of Bath and from the students who took courses given at Rensselaer Polytechnic in Hartford Connecticut, leading to changes to the 2000 revision of the first edition. For the second edition I would like to acknowledge the additional help received in preparing the second edition from colleagues in Rolls-Royce, notably Nigel Birch, Andrew Bradley, Chris Courtney, Jason Darbyshire, Peter Hopkins, Andrew Kempton, Paul Madden, Steve Morgan, Mike Provost, Joe Walsh and Eddie Williams. From outside the Company the suggestions of George Aigret were gratefully received. Comments and corrections from readers will continue to be welcomed.

PREFACE TO FIRST EDITION

This book arose from an elementary course taught to undergraduates, which forms the first ten chapters concerned with the design of the engines for a new 600-seat long range airliner. Introductory undergraduate courses in thermodynamics and fluid mechanics would provide the reader with the required background, but the material is also presented in a way to be accessible to any graduate in engineering or physical sciences with a little background reading. The coverage is deliberately restricted almost entirely to the thermodynamic and aerodynamic aspects of jet propulsion, a large topic in itself. The still larger area associated with mechanical aspects of engines is not covered, except that empirical information for such quantities as maximum tip speed are used, based on experience. To cover the mechanical design of engines would have required a much bigger book than this and would have required a mass of knowledge which I do not possess.

In preparing the course it was necessary for me to learn new material and for this I obtained help from many friends and colleagues in industry, in particular in Rolls-Royce. This brought me to realise how specialised the knowledge has become, with relatively few people having a firm grasp outside their own speciality. Furthermore, a high proportion of those with the wide grasp are nearing retirement age and a body of knowledge and experience is being lost. The idea therefore took hold that there is scope for a book which will have wider appeal than a book for students – it is intended to appeal to people in the aircraft engine industry who would like to understand more about the overall design of engines than they might normally have had the opportunity to master. My ambition is that many people in the industry will find it useful to have this book for reference, even if not displayed on bookshelves.

The original course, Chapters 1–10, was closely focused on an elementary design of an engine for a possible (even likely) new large civil aircraft. Because the intention was to get the important ideas across with the least complication, a number of simplifications were adopted, such as taking equal and constant specific heat capacity for air and for the gas leaving the combustor as well as neglecting the effect of cooling air to the turbines.

Having decided that a book could be produced, the scope was widened to cover component performance in Chapter 11 and off-design matching of the civil engine in Chapter 12. Chapters 13 – 18 look at various aspects of military engines; this is modelled on the treatment in Chapters 1–10 of the civil engine, postulating the design requirement for a possible new fighter aircraft. In dealing with the military engine some of the simplifications deliberately adopted in the early chapters are removed; Chapter 19 therefore takes some of these improvements from Chapters 13 – 18 to look again at the civil engine.

Throughout the book the emphasis is on being as simple as possible, consistent with a realistic description of what is going on. This allows the treatment to move quickly, and the book to be brief. But more important it means that someone who has mastered the simple formulation can make reasonably accurate estimates for performance of an engine and can estimate changes in performance with alteration in operating condition or component behaviour. Earlier books become complicated because of the use of algebra; furthermore to make the algebra tractable frequently forces approximations which are unsatisfactory. The present book uses arithmetic much more – by taking advantage of the computer and the calculator the numerical operations are almost trivial. The book contains a substantial number of exercises which are directed towards the design of the civil engine in the early chapters and the military engine in the later chapters. The exercises form an integral part of the book and follow, as far as possible, logical steps in the design of first the civil engine and then later the military combat engine. Many of the insights are drawn from the exercises and a bound set of solutions to the exercises may be obtained from the author.

Because Chapters 1–10 were directed at undergraduates there are elementary treatments of some topics (most conspicuously, the thermodynamics of gas turbines, compressible fluid mechanics and turbomachinery) but only that amount needed for understanding the remainder of the treatment. I decided to leave this elementary material in, having in mind that some readers might be specialists in areas sufficiently far from aerodynamics and thermodynamics that a brief but relevant treatment would be helpful.

ACKNOWLEDGEMENTS

It is my pleasure to acknowledge the help I have had with this book from my friends and colleagues. The largest number are employed by Rolls-Royce (or were until their retirement) and include: Alec Collins, Derek Cook, Chris Freeman, Keith Garwood, Simon Gallimore, John Hawkins, Geoffery Hodges, Dave Hope, Tony Jackson, Brian Lowrie, Sandy Mitchell, James Place, Paul Simkin, Terry Thake and Darrell Williams. Amongst this group I would like to record my special gratitude to Tim Camp who worked through all the exercises and made many suggestions for improving the text. I would also like to acknowledge the late Mike Paramour of the Ministry of Defence. In the Whittle Laboratory I would like to record my particular debt to John Young and also to my students Peter Seitz and Rajesh Khan. I am also grateful for the help from other students in checking late drafts of the text. In North America I would like to mention Ed Greitzer and Jack Kerrebrock (of the Gas Turbine Laboratory of MIT), Bill Heiser (of the Air Force Academy), Phil Hill (of the University of British Columbia), Bill Steenken and Dave Wisler (of GE Aircraft Engines) and Robert Shaw. Above all I would like to express my gratitude to Ian Waitz of the Gas Turbine Laboratory of MIT who did a very thorough job of assessing and weighing the ideas and presentation – the book would have been very much the worse without him. In addition to all these people I must also acknowledge the help and stimulus from the students who took the course and the people who have added to my knowledge and interest in the field over many years.

THE EXERCISES

An important part of the book are exercises related to the engine design. To make these possible it is necessary to assume numerical values for many of the parameters, and appropriate values are therefore assumed to make the exercises realistic. These values are necessarily approximate, and in some cases so too is the model in which they are used. The answers to the exercises, however, are given to a higher level of precision than the approximations deserve. This is done to assist the reader in checking solutions to the exercises and to ensure some measure of consistency. The wise reader will keep in mind that the solutions are in reality less accurate than the number of significant figures seems to imply.

The usefulness of the book will be greatly increased if the exercises are undertaken. In some cases one exercise leads to another and a few simple calculations on a hand-held calculator suffice. In others it is desirable to carry out several calculations with altered parameters, and such cases call out of a computer and spread sheet.

SOLUTIONS TO THE EXERCISES

Solutions to all the exercises may be obtained from the publisher by e-mailing
solutions@cambridge.org

GLOSSARY

afterburner a device common in military engines where fuel is burned downstream of the turbine and upstream of the final propelling nozzle. Also known as an augmentor or as reheat.

aspect ratio the ratio of one length to another to define shape, usually the ratio of span to chord

blades the name normally given to the aerofoils in a turbomachine (compressor or turbine). Sometimes stationary blades are called stator vanes (or just vanes) and rotor blades are called buckets.

booster a name given to compressor stages on the LP shaft in two-shaft engines. The booster stages only affect the core flow.

bypass engine an engine in which some of the air (the bypass stream) passes around the core of the engine. The bypass stream is compressed by the fan and then accelerated in the bypass stream nozzle. These are sometimes called turbofan engines or fan engines.

bypass ratio the ratio of the mass flow rate in the bypass stream to the mass flow rate through the core of the engine.

chord the length of a wing or a turbomachine blade in the direction of flow.

combustor also known as a combustion chamber. The component where the fuel is mixed with the air and burned.

compressor the part of the engine which compresses the air, a turbomachine consisting of stages, each with a stator and rotor row.

core the compressor, combustion chamber and turbine at the centre of the engine. The core turbine drives only the core compressor. A given core can be put to many different applications, with only minor modifications, so it could form part of a high bypass ratio engine, a turbojet (with zero bypass ratio) or part of a land-based power generation system. The core is sometimes called the gas generator.

drag the force D created by the wings, fuselage etc. in the direction opposite to the direction of travel.

fan the compressor operating on the bypass stream; normally the pressure ratio of the fan is small, not more than about 1.8 for a modern high bypass civil engine (in one stage with no inlet guide vanes) and not more than about 4.5 in a military engine in two or more stages.

gross thrust the thrust F_G created by the exhaust stream without allowing for the drag created by the engine inlet flow; for a stationary engine the gross thrust is equal to the net thrust.

HP the **high-pressure** compressor or turbine are part of the engine core. They are mounted on either end of the **HP** shaft. In a two-shaft engine they form the core spool.

incidence sometimes called angle of attack, is the angle at which the wing is inclined to the direction of travel or the angle at which the inlet of a compressor or turbine blade is inclined to the inlet flow direction.

IP the **intermediate-pressure** compressor or turbine, mounted on the **IP** shaft. There is only an **IP** shaft in a three-shaft engine.

jetpipe the duct or pipe downstream of the LP turbine and upstream of the final propelling nozzle.

LCV the **lower calorific value** of the fuel; the energy released per unit mass of fuel in complete combustion when the products are cooled down to the inlet temperature but none of the water vapour is allowed to condense.

lift the force L created, mainly by the wings, perpendicular to the direction of travel.

LP the **low-pressure** compressor and turbine are mounted on either end of the **LP** shaft. Combined they form the **LP** spool.

nacelle the surfaces enclosing the engine, including the intake and the nozzle.

net thrust the thrust F_N created by the engine available to propel the aircraft after allowing for the drag created by the inlet flow to the engine. (Net thrust is equal to gross thrust minus the ram drag.)

ngv the **nozzle guide vane**, another name for the stator row in a turbine.

nozzle a contracting duct used to accelerate the stream to produce a jet. In some cases for high performance military engines a convergent-divergent nozzle may be used.

payload the part of the aircraft weight which is capable of earning revenue to the operator (can be freight or passengers).

pylon the strut which connects the engine to the wing.

ram drag the momentum of the relative flow entering an engine.

sfc **specific fuel consumption** (actually the *thrust* specific fuel consumption) equal to the mass flow rate of fuel divided by net thrust. The units should be in the form (kg/s)/kN, but are often given as lb/h/lb or kg/h/kg.

specific thrust the net thrust per unit mass flow through the engine, units m/s.

spool used to refer to the compressor and turbine mounted on a single shaft, so a two-spool engine is synonymous with a two-shaft engine

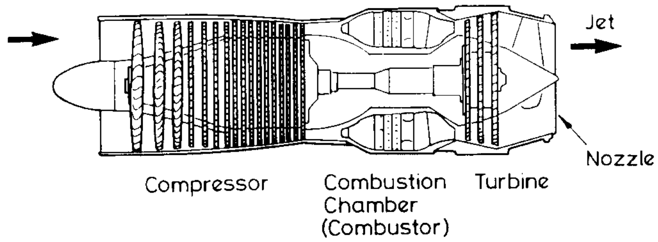
stagnation stagnation temperature is the temperature which a fluid would have if brought to rest adiabatically. The stagnation pressure is the pressure if the fluid were brought *isentropically* to rest. Stagnation quantities depend on the frame of reference and are discussed in Chapter 6.

static static temperature and pressure are the actual temperature and pressure of the fluid, in contrast to the stagnation quantities defined above.

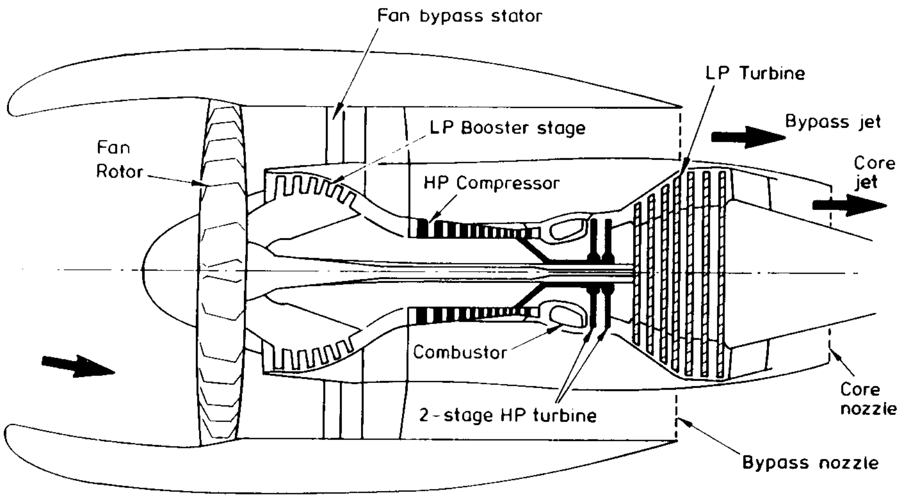
turbine a component which extracts work from a flow. It consists of rotating and stationary blades. The rotating blades are called rotor blades and the stationary blades are called stator blades or nozzle guide vanes.

turbofan a jet engine with a bypass stream.

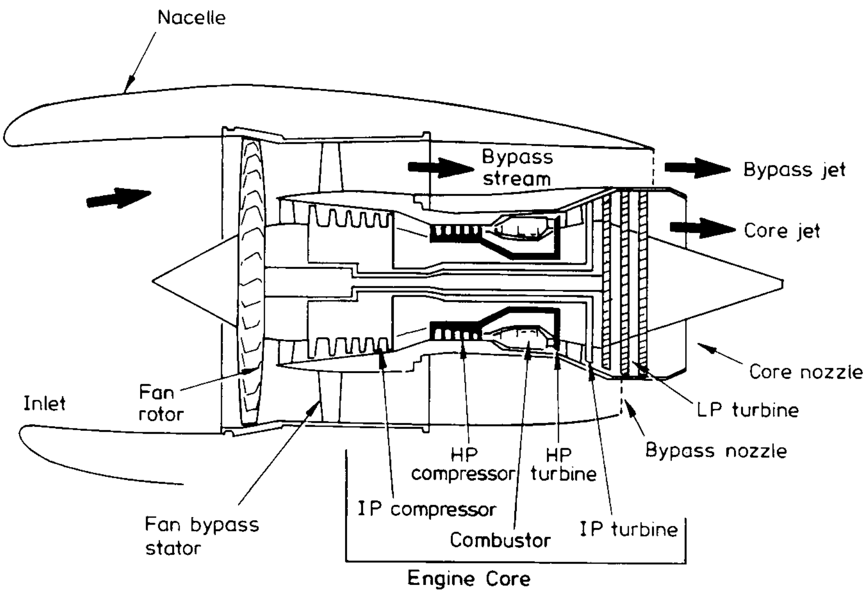
turbojet a jet engine with no bypass stream – these were the earliest type of jet engines and are still used for very high speed propulsion.



A single-shaft turbojet engine (no bypass)



A two-shaft high bypass engine



A three-shaft high bypass engine

NOMENCLATURE

a	speed of sound $\sqrt{\gamma RT}$
A	Area
bpr	bypass ratio
c	chord of wing or blade
c_p	specific heat at const. pressure
C_D	drag coefficient
C_L	lift coefficient
D	drag (force opposing motion)
D	diameter
E	energy state $m(gh + V^2/2)$
E_s	specific energy state $gh + V^2/2$
F_G	gross thrust
F_N	net thrust
g	acceleration due to gravity
h	static enthalpy
h_0	stagnation enthalpy
h,H	altitude
h	blade height (i.e. span)
i	incidence
L	lift (force perp. to direction of motion)
LCV	lower calorific value of fuel
m	mass
$\dot{m}$	mass flow rate
$\bar{m}$	non-dimensional mass flow rate, $\dot{m}\sqrt{c_p T_0}/Ap_0$
M	Mach number
n	load factor
N	shaft rotational speed
p	static pressure
p_0	stagnation pressure
q	dynamic pressure $1/2\rho V^2$
Q	heat transfer
$\dot{Q}$	heat transfer rate
r	radius (Chapters 9 and 18)
r	pressure ratio
R	gas constant
s	entropy
SEP	specific excess power
sfc	specific fuel consumption
T	static temperature
T_0	stagnation temperature
U	blade speed
V	velocity
V_j	jet velocity
V^{rel}	velocity relative to moving blade
w	weight
W	work
$\dot{W}$	work rate, power
α	flow direction (measured from axial)
α^{rel}	flow direction relative to moving blades
γ	ratio of specific heats c_p/c_v
δ	flow deviation (Chapters 9 and 18)
δ	p_0/p_{0ref}
θ	$\sqrt{T_0/T_{0ref}}$
ρ	density
ε	cooling effectiveness (Chapter 5)

Subscripts

a	ambient
ab	afterburner
air	air
b	bypass
c	core
dry	no afterburner in use
e	combustion products (c_p and γ)
f	fuel
$isen$	isentropic (efficiency)
m	mean
p	polytropic (efficiency)
sl	sea level
$therm$	thermal (efficiency)

A NOTE ON NOMENCLATURE

The various stations or positions throughout an engine are given numbers and different companies have different conventions for the many positions along the flow path of a multi-spool engine. An internationally recommended numbering scheme applies to some of the major stations and of these the most important station numbers to remember are:

2 engine inlet face;
3 compressor exit and combustion chamber inlet;
4 combustion chamber exit and turbine inlet.

The above brief list shows the one superficial snag, the inlet face of the engine is station 2, whereas most teaching courses call it station 1. The reason for this discrepancy is that for some engine installations, particularly in high-speed aircraft, there can be a substantial reduction in stagnation pressure along the inlet; station 2 is after this loss has taken place. In this book the international standard will be used, where appropriate, with 2 at the inlet to the engine, and a simplified guide is shown in Fig. 7.1. For more detailed treatment of the engine the schemes in Fig. 12.7 or Fig. 15.1 should be consulted.

Subscript zero is used to denote stagnation conditions, for example stagnation pressure, p_0 and stagnation temperature, T_0. (See Chapter 6 for an explanation of the terms *stagnation pressure* and *stagnation temperature.* Some people use the word *total* in place of *stagnation*.) The stagnation pressure at engine inlet is therefore written p_{02} and temperature at turbine entry as T_{04}.

TERMINOLOGY

There are differences between British and American usage, but usually these are small - aeroplane and airplane, for example. It may be noted that in Britain it is normal to use the word *civil* when referring to aviation, aircraft and air transport, where in the USA the word *commercial* would normally be used. In the book the British usage *civil* is adopted. However, while it is still quite common in Britain to refer to *reheat*, the corresponding American term *afterburner* is used throughout the book.

Part 1

Design of Engines for a New 600-seat Aircraft

CHAPTER 1 THE NEW LARGE AIRCRAFT – REQUIREMENTS AND BACKGROUND

1.0 INTRODUCTION

This chapter looks at some of the commercial requirements and background to the proposals to build a new civil[1] airliner capable of carrying about 600 people. The costs and risks of such a project are huge, but the profits might be large too. In explaining the requirements some of the units of measurement used are discussed. Design calculations in a company are likely to assume that the aircraft flies in the International Standard Atmosphere (or something very similar) and this assumption will be adopted throughout this book. The standard atmosphere is introduced and discussed towards the end of the chapter. The chapter ends with brief reference to recent concerns about environmental issues.

1.1 SOME COMMERCIAL BACKGROUND

In December 2000 Airbus formally announced the plans to go ahead with a new large aircraft, dubbed the A380, intended in its initial version to carry a full payload (with 555 passengers) for a range of up to 8150 nautical miles. First flight is intended to be in 2004 and entry into service in 2006. There are already plans afoot for heavier versions, carrying more that 555 passengers and for all-freight versions with a larger payload. In December 2000 Airbus Industrie had received enough orders to justify the expected cost of over $10 billion, with an expected break-even point with a sale of 250 aircraft. They forecast delivery of the 250th aircraft in 2011.

The large capital expenditure and the long payback period highlight the risks, for cost over-run, project delay or slow sales could undermine all these estimates. Boeing, who have until now dominated the large end of the market with the Boeing 747, offered an updated version, the 747X to compete with the A380. The Boeing 747-400, currently the largest civil aircraft, was introduced into service in 1989 but it is a derivative of the 747-100 which entered service in 1970. The 747-400 incorporated some aerodynamic improvements, including improvements to existing engines, but more radical redesign would be needed to take full advantage of the developments in aerodynamics and materials since 1970. Adopting these technology developments for the A380, together with new engines, should result in a substantially more cost-efficient aircraft with about a 15% reduction in seat-mile costs, compared

[1] The word *civil* is used in Britain where *commercial* would be used in the USA.

with the Boeing 747-400. At the end of March 2001 Boeing had not received a single order for their 747X and the project was formally put on hold, Boeing stating that there was not an adequate market for a very large aircraft. While many expect that the 747X will ultimately be cancelled, Boeing firmly deny this. Boeing's intentions for new very large aircraft are not clear and it must be assumed that this is a topic of intense consideration within the company.

For several years Boeing and Airbus Industrie have separately and jointly discussed proposals for a much larger aircraft, with anywhere from about 600 to about 800 seats. All the proposals for very large aircraft have four engines hung from under the wing. However, at the same time as the announcement that the 747X was being postponed, Boeing announced a very different aircraft, unofficially dubbed the "sonic cruiser". This would cruise at a Mach number of at least 0.95 (whereas the 747X would have cruised at M=0.85) with a range of 9000 nautical miles but with only about 200 seats. The specification is still fluid at the time of writing. In any case this higher speed aircraft, which some in the industry believe will ultimately be unattractive on economic and environmental grounds, is *not* the subject of this book, though the topic of high- speed passenger carrying aircraft is returned to briefly in Chapter 19.

1.2 THE NEW LARGE AIRCRAFT

The first ten chapters of this book are concerned with a hypothetical New Large Aircraft (NLA) which bears a close resemblance to proposals put out by Airbus and by Boeing from around 1996. The final aircraft launched as the Airbus A380-100 in December 2000 differs in a number of ways from these and the A380-100 is compared with the hypothetical New Large Aircraft are compared in Table 1.1.

Table 1.1 Comparison of hypothetical NLA with Airbus A380-100

	New Large Aircraft NLA	Airbus A380-100*
No. of passengers	620	555
Range (nautical miles)	8000	8150
Payload at this range (tonne)	58.8	52.9
Max. take-off weight (tonne)	635.6	560.2
Empty weight (tonne)	298.7	274.9
Cruise Mach number	0.85	0.85
Initial cruise altitude (feet)	31000	35000
Cruise Lift/Drag	20	20
Wing area (metre^2)	790	845

* specifications as of 1 May 2001 1 tonne = 2205 lb mass

The main differences between the hypothetical New Large Aircraft and the A380-100 are the range, weight and smaller wing area of the hypothetical aircraft. The wing area assumed is close to one that Airbus first proposed before increasing it in a series of steps over the last five or so years. The larger wing area allows future growth in aircraft weight, but also allows take-off and landing at lower speeds, thereby reducing noise nuisance. The differences are sufficiently small that the aim of the book, which is the understanding of the aerodynamic and thermodynamic constraints and decisions for the propulsion of a new large civil aircraft, are not compromised by retaining the numerical values for the original hypothetical new large aircraft.

The price of a new aircraft is a complex issue, depending on the level of fittings inside the aircraft and on the various discounts offered. It may be assumed that the catalogue price of an A380 will be of the order of $200 million, with the engines costing around $12 million each. The market is variously estimated to be between 1100 and 1300 very large aircraft over the next 20 years, Boeing suggesting a much smaller number. Airbus want to be able to share in the profits from the market for large aircraft, hitherto dominated by Boeing (at present with the 747-400), with the potential this has given Boeing to cross-subsidise its smaller aircraft.

For new aircraft the manufacturers have to compete in terms of operating cost and potential revenue, as well as performance, most obviously range and payload. The proposal to increase the size of an aircraft is not without special additional constraints on size; currently the 'box' allowed at major airports is 80 m × 80 m and this limits both the length and the wingspan. In addition there are strong incentives to avoid making the fuselage higher from the ground because of the consequences for ground handling. The aspect ratio of a wing (the ratio of span to chord) has a large effect on its drag and Airbus have until now had a larger aspect ratio than Boeing, a feature which has contributed to the lower drag of Airbus aircraft. With the A380 the limit on wing span to fit in the airport 'box' has meant that its aspect ratio of 7.53 will be lower than that of the 747-400, which is 7.98. It is still reasonable to expect that the cruise lift/drag ratio for the A380 will be around 20, significantly higher than the much older 747-400.

It is essential to realise that both the new aircraft, and the engines which power it, will depend heavily on the experience gained in earlier products, particularly those of similar size and character. Most of the aircraft that Airbus have made to date have two engines (referred to as twins) and only their A340 has four engines. Airbus will be relying on their knowledge and experience gained with the earlier aircraft, but most significantly the A340-600, which had its first flight in April 2001. This is certainly a large aircraft, with a maximum take-off weight of 365 tonne, not far short of the 747-400 with a maximum take-off weight of 395 tonne. Airbus will also be looking to learn from the 747-400. In Table 1.2 below the proposed specifications for the hypothetical New Large Aircraft on which the first part of this book is based are set beside those achieved for the 747-400 as well as for the A340-500 and A340-600. For the new aircraft some of the quantities given are stipulations, such as the number of passengers and the range, whilst others, such as the lift/drag ratio (discussed below) are extrapolations of earlier experience. The proposed range of 8000 nautical miles makes possible non-stop flights between cities throughout North America and most of the major Pacific-Rim cities, even when strong head winds are liable to be encountered.

Table 1.2 Comparison of some salient aircraft parameters

	New Large Aircraft	Boeing	Airbus A340	
	NLA	747-400	-500	-600
No of passengers	620	400	313	380
Range (nautical miles)	8000	7300	8550	7500
Payload at this range (a) (tonne)	58.8	38.5	29.7	36.1
Max. take-off weight (d) (tonne)	635.6	395.0	365	365
Empty weight* (b) (tonne)	298.7	185.7	170	177
Max. weight of fuel (c) (tonne)	275.4	174.4	171	157
Cruise Mach number	0.85	0.85	0.83	0.83
Initial cruise altitude (feet)	31000	31000	31000	31000
Cruise Lift/Drag	20	17.5	19.5	19.5
Wing area (m^2)	790	511	439	439

(Note that $d \approx a + b + c$)

* no fuel, no payload 1 tonne = 2205 lb mass

In calculating payload one passenger is taken to be 95 kg, a similar value in pounds is specified by Boeing. In looking at the specifications for the new aircraft it is worth noting that the maximum payload is only 58.8 tonne, compared to the total weight of the new aircraft at take off, 635.6 tonne. More seriously, the payload (the total weight of passengers and freight) is not much more than one third of the fuel load. It follows from this that small proportional changes in the weight of the engine (which is 5 - 6% of the maximum take-off weight) or in the fuel consumption can have disproportionately large effects on the payload. Of the fuel carried not all could be used in a normal flight; typically about 15% ($\approx$38.6 tonne) would need to be kept as reserve in case landing at the selected destination airport is impossible. Based on past experience it may be assumed that about 4% (around 11 tonne) of fuel would be used in take off and climb to the initial cruising altitude, with the bulk of the fuel consumption being involved in the cruise portion of a long flight.

1.3 PROPULSION FOR THE NEW LARGE AIRCRAFT

It takes several years to design, develop, and certificate (i.e. test so that the aircraft is approved as safe to enter service) a new aircraft, though the length of time is becoming shorter. It seems to take even longer to develop the engines, but until the specifications of the aircraft are settled it is not clear what engine is needed. There are three major engine manufacturers (Rolls-Royce in

Britain, Pratt & Whitney and General Electric in the USA) and it is their aim to have an engine ready for whatever new large aircraft it is decided to build. The costs of developing a wholly new engine are so high that it is always the objective of a manufacturer to use whenever possible an existing engine, perhaps with some uprating. On a recent new large aircraft, the Boeing 777, all three major manufacturers offered an engine and the competition was fierce. Pratt & Whitney and Rolls-Royce offered developments of existing large engines; General Electric developed a wholly new engine, the GE90. The *Economist* of 18 September 1999 reported that the GE90 had cost General Electric \$1 million per day for $4^1/_2$ years, in total about \$1.6 billion; it is not clear how much extra was spent by risk sharing partner companies. This huge sum can be made more understandable if an average wage for an employee, with the appropriate overheads, is taken to be \$150,000 per annum - the \$1.6 billion cost then translates into over 10,000 man-years of work. To reduce the financial exposure Pratt & Whitney and General Electric have formed an alliance to produce a wholly new engine for the A380, the GP7200, in competition with Rolls-Royce, who have offered the Trent 900, a derivative of their earlier engines.

Whilst discussions are going on between aircraft manufacturers and airlines they are also going on between aircraft manufacturers and the engine manufacturers. As specifications for the 'paper' aircrafts alter, the 'paper' engines designed to power them will also change; many potential engines will be tried to meet a large number of proposals for the new aircraft before any company finally commits itself. The first ten chapters of the book will attempt, in a very superficial way, to take a specification for an aircraft and design the engines to propel it – this is analogous, in a simplified way, to what would happen inside an engine company.

Because engines are large and heavy there are good aerodynamic and structural reasons for mounting engines under the wing. For example, a Rolls-Royce Trent 800, which is the lightest engine to power the Boeing 777, weighs about 8.2 tonne when installed on the aircraft. Most of the lift is generated by the wings, so hanging the comparatively massive engines where they can most easily be carried makes good structural sense. This reduces the wing root bending moment and makes possible a reduction in the strength and weight of the whole aircraft. It is the trend for new engines to be bigger and heavier for the same thrust than the ones they replace, originally to reduce fuel consumption, but now mainly to reduce noise. This will be discussed later in Chapter 7 and in the Appendix.

The A380 is to have four engines, two slung under each wing and the same arrangement is adopted here for the New Large Aircraft. Not very long ago it would have been unthinkable to have a trans-oceanic aircraft with only two engines because the reliability of the engines was inadequate. Now two-engine aircraft are very common, being the dominant type now crossing the Atlantic, but four engines offer advantages for the New Large Aircraft for two reasons. First, every aircraft must be able to climb from take off with one engine totally disabled. For a two-engine aircraft this means that there must be twice as much thrust available at take off as that just necessary to get the aircraft safely into the air. The engines must therefore be oversized for take off, implying too much available thrust at cruise (and therefore excess weight) with the engines 'throttled back'. For a four-engine aircraft the same rule requires that there is only 4/3 times as much thrust available at take off, and for aircraft designed for very long flights it is desirable to carry as little surplus weight as possible. The success of the Boeing 777 as a very long range aircraft has undermined this argument in recent years; as is discussed in later chapters the apparent disadvantage with two engines can be mitigated by cruising at higher altitude and the benefits in reduced first cost and maintenance cost compensates for a small increase in fuel consumption.

The second reason for having four engines is that it is not considered practical to make the wing much higher off the ground than current aircraft like the 747-400, since to do so would raise the cabin and if the cabin were raised higher the existing passenger handling facilities at airports would be unusable; it would also make the undercarriage much bigger and heavier. If the New Large Aircraft, or the Airbus A380, were to have only two engines these would be too large to fit under the wings at their current height from the ground.

It should be added in parenthesis, however, that because engines are expensive to buy and to maintain it is likely that smaller aircraft than the New Large Aircraft we are considering here will have only two engines, even when they are to be operated over large distances. Recent examples are the Airbus 330 and the Boeing 777; both of these large twins are used for flights that are sufficiently long that until recently a four-engine aircraft would have been needed.

1.4 THE UNITS USED

In Table 1.1 a number of the quantities are in non-SI units. This is common because the industry is dominated by the United States which has been rather slow to see the advantages of SI units. It is helpful to remember that

1 lb mass	=	0.4536 kg,	1000 kg = 1 tonne
1 lb force	=	4.448 N	
1 foot	=	0.3048 m	(altitude in feet used for air traffic control)
1 nautical mile	=	1.829 km	(nautical mile abbreviated to nm)
1 knot	=	1 nm/hour =	0.508 m/s

The nautical mile (abbreviated to nm) is *not* arbitrary in the way other units are, but is the distance around the surface of the earth corresponding to 1 minute of latitude (North–South). Treating the earth as a sphere this is equivalent to 1 minute of longitude (East–West) around the equator. (The circumference of the earth around the equator, or any other great circle, is therefore 360×60 nautical miles.)

The data in Table 1.1 also give the cruising speed as a Mach number, defined as V/a the ratio of the flight speed V to the local speed of sound a. Wherever possible aerodynamicists use non-dimensional numbers and Mach number is one of the most important in determining the performance of the aircraft. The speed of sound is given by

$$a = \sqrt{\gamma R T}$$

where T is the local atmospheric temperature (i.e. the **static** temperature) γ is the ratio of the specific heats c_p / c_v (which is taken here to be 1.40 for air) and R is the gas constant (0.287 kJ/kg K for air). Since $c_p = \gamma R/(\gamma - 1)$ this leads to $c_p = 1.005$ kJ/kg. These values will be used for the atmosphere and in Part 1 (Chapters 1–10) for the gas in the engine. These values would *not* be accurate enough for use in a real design, particularly for the products of combustion, but also for pure air at elevated temperatures. Although this simplification suffices for the treatment in Part 1 of the book it will be relaxed in later parts.

Exercise

1.1 The shortest distance between two places on the surface of the earth is the *Great Circle Distance*, which, for a perfectly spherical earth, would be equal to the radius R_e of the earth times the angle A subtended between vectors from the centre of the earth to the points on the surface.

Express the positions of points 1 and 2 on the surface of the earth in terms of Cartesian vectors about the centre of the earth, using θ_1 and ϕ_1 to denote the latitude and longitude respectively for point 1 and likewise θ_2 and ϕ_2 for point 2. Then take the dot product of the vectors to show that the cosine of the angle A is given by $\cos A = \cos\theta_1 \cos\theta_2 \cos(\phi_1 - \phi_2) + \sin\theta_1 \sin\theta_2$.

Find the shortest distance in nautical miles between London (latitude 51.5° N, longitude 0) and Sydney in Australia (latitude 33.9° South, longitude 151.3° East). (**Ans**: 9168 nm)

1.5 THE STANDARD ATMOSPHERE

The atmosphere through which the aircraft flies depends on the altitude, with the pressure, temperature and density falling as altitude increases. The temperature profile with height is determined primarily by the absorption of solar radiation by water vapour and subsequent radiation back into space. At high altitude the variation with season, location and time of day is much less than at ground level and it is normal to use a standard atmosphere in considering aircraft and engine performance. Temperature, density and pressure are plotted in Fig.1.1 according to the *International Standard Atmosphere* (ISA). Standard sea-level atmospheric conditions are defined as $T_{sl} = 288.15$ K, $p_{sl} = 101.3$ kPa, $\rho_{sl} = 1.225$ kg/m^3. In the standard atmosphere temperature is assumed to decrease linearly with altitude at 6.5 K per 1000 m below the *tropopause* (which in the standard atmosphere is assumed to be at 11000 m, that is 36089 feet), but to remain constant above this altitude at 216.65 K. (The discontinuity in temperature gradient must give a discontinuity in the pressure and density gradients too, but this is small and the curve fitting programme has smoothed it out.)

As noted above, non-SI units are common in aviation, and air traffic control assigns aircraft to corridors at altitudes defined in feet. Cruise very often begins at 31000 ft, and the corridors are separated by 2000 ft. Although this book will be based on SI units, altitudes for the civil aircraft will be given in feet. Table 1.3 may be helpful.

Table 1.3 Useful values of the International Standard Atmosphere*

Altitude feet	km	Temperature K	Pressure 10^5 Pa	Density kg/m^3
0	0	288.15	1.013	1.225
31000	9.45	226.73	0.287	0.442
33000	10.05	222.82	0.260	0.336
35000	10.67	218.80	0.238	0.380
37000	11.28	216.65	0.214	0.344
39000	11.88	216.65	0.197	0.316
41000	12.50	216.65	0.179	0.287
51000	15.54	216.65	0.110	0.179

*Also known as the ICAO Standard Atmosphere.

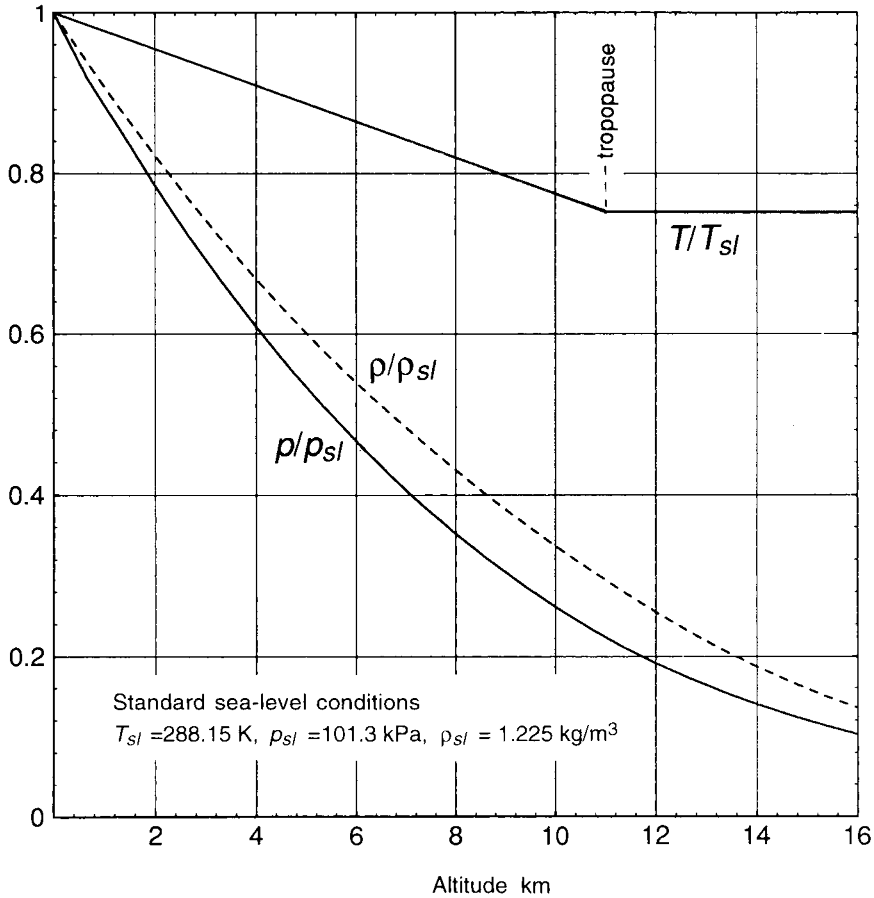


Figure 1.1 The International Standard Atmosphere

For the purpose of this book the conditions of the standard atmosphere will be assumed to apply exactly – this makes for consistency in the numbers and facilitates checking the exercises. It will be clear, however, that the standard atmosphere is at best an approximation to conditions averaged over location and season. The temperature varies more than the pressure and this variation is greatest close to the ground. It is not uncommon, for example, for the temperature at an airport in continental North America to be as low as –40 °C in winter and as high as +40 °C in summer. It is normal to refer to conditions relative to the standard atmosphere, so that if at 31000 feet altitude the temperature were 236.7 K it could, by reference to Table 1.3, be described as ISA+10°C. The corrections from standard conditions are often large for high altitude airports. Johannesburg airport, for example, is 5557 feet above sea level and the ISA temperature for this altitude is 4.0°C: suppose on a hot day that the temperature at Johannesburg airport were 35°C – in this case the conditions would be described as ISA+31°C.

Exercises

1.2 Express the maximum take off weight (mtow) for the New Large Aircraft in pounds (the units that much of the airline industry uses). Make a rough estimate of the flight time for a range of 8000 nm if cruise were at the initial altitude and Mach number for the whole flight.

(**Ans**: range = 14632 km; altitude = 9448 m; mtow = $1.4.10^6$ lb; time of flight ≈ 15.8 hours)

1.3* Find the cruising speed in m/s and km/h corresponding to the specified cruise Mach number and the initial cruise altitude. If the altitude at the end of the flight is 41000 ft, (p_a = 17.9 kPa, T_a = 216.7 K) what is the flight speed then for the same Mach number. (Note air traffic control usually allots aircraft cruising altitudes in 2000 ft steps: 31000, 35000 and 39000 going from East to West, and 33000, 37000 and 41000 going from West to East.)

(**Ans**: Initial speed at 31000 ft, 256.5 m/s, 923 km/h; at 41000 feet, speed 250.8 m/s, 903 km/h.)

1.4 The pressure change with altitude h due to hydrostatic effects is given by $dp = -\rho g\, dh$.

a) For an idealised atmosphere the temperature falls with altitude at a constant rate so that $\partial T/\partial h = -k$, where k is a constant with units K/m. Show that the pressure p at altitude H can be written

$$p = p_{sl}\{1-kH/T_{sl}\}^{g/Rk} = p_{sl}\,(T/T_{sl})^{g/Rk}$$

where p_{sl} and T_{sl} are the static pressure and temperature at sea level, 101.3 kPa and 288.15 K.

For the International Standard Atmosphere the rate of change in temperature with altitude is taken to be 6.5 K per 1000 m up to the tropopause at 11 km. Show that when g =9.81 m/s^2 and R =287 J/kgK , the pressure at altitude H, in metres, is given by

$$p = p_{sl}\,(T/T_{sl})^{5.26} = p_{sl}\{1-2.26\times10^{-5}H\}^{5.26}$$

up to the tropopause, above which the pressure is given by

$$p = p_T\exp\{-1.58\times10^{-4}(H-11.10^3)\}$$

where p_T is the pressure at the tropopause.

b) If the relationship between pressure and density were that for isentropic changes (i.e. reversible and adiabatic) p/ρ^γ = constant, show that the pressure at altitude H can then be written as

$$p = p_{sl}\left[1 - \frac{\gamma-1}{\gamma}\frac{gH}{RT_{sl}}\right]^{\gamma/(\gamma-1)}.$$

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* Exercises with an asterix produce solutions which should, for convenience, be entered on the Design Sheet at the back of the book.
Note that to maintain consistency and to make checking of solutions easier, answers are given to a precision which is much greater than the accuracy of the assumptions warrants.

Plot a few values of pressure, density and temperature on Fig.1.1, the International Standard Atmosphere.

Notes: Atmospheric air is not dry. For saturated air the rate of temperature drop is given as 4.9 K per km, compared with 6.5 K per km in the International Standard Atmosphere. The isentropic calculation assumed dry air.

Different 'standard' atmospheres are sometimes used to model situations more closely: for example over Bombay in the monsoon season the atmosphere is very different from over Saudi Arabia in summer or northern Russia or America in winter.

Even below the tropopause the standard atmosphere assumes a slower reduction in temperature with altitude than that which would follow from an isentropic relation between pressure and temperature; the standard atmosphere is therefore stable. To understand this, imagine the atmosphere perturbed so that a packet of air is made to rise slowly. As the packet rises its pressure will fall to be equal to the pressure of the air that surrounds it and, as a reasonable approximation, the temperature and pressure for the packet of air will be related by the isentropic relation $p/T^{\gamma/(\gamma-1)}$ = constant. If the ascending air, which has an isentropic relation between temperature and pressure, were slightly warmer than its surroundings it would be less dense than the surrounding air and would continue to rise; such an atmosphere would be unstable. If, on the other hand, the ascending packet of air has a temperature lower than that of its immediate surroundings, as occurs in the standard atmosphere, it would be denser than the surrounding air and would fall back; such an atmosphere would be stable. In the first few hundred metres above the ground the convection frequently tends to make the atmosphere locally unstable, which is useful because it helps disperse pollutants. Stable atmospheres can occur near ground level, and frequently do at night under windless conditions when radiation leads to the ground cooling more rapidly than the air above it. Under stable conditions near the ground the natural mixing of the atmosphere is suppressed and the conditions for fog and pollution build-up are liable to occur.

1.5 ENVIRONMENTAL ISSUES

When jet propelled passenger transport was initiated, little or no thought was given to the environment, either near the airports or in the upper atmosphere. By the late 1960s the situation near airports was becoming intolerable, mainly because of the noise, but also because of pollution. The pollution involved unburned hydrocarbons, smoke (i.e. small particles of soot, which is unburned carbon) and oxides of nitrogen. Gradually steps have been taken to rein in these nuisances by international agreement with regulations both for combustion product emissions near airports and for noise during take off and landing.

The international agreements are reached so that the interests of various parts of the industry (from manufacturers of engines through to the airlines which operate rather old aircraft) are addressed. The net result is that the international agreements have lagged behind public pressure for amelioration and as a result local regulations at important airports around the world have tended to be more challenging for the makers of new engines to meet. The international limits on noise are so far above the noise produced by new aircraft with modern engines that the international limit serves merely as the benchmark from which the margin of lower noise is set. For noise the airport which tends to determine the level which new large aircraft have to achieve is London Heathrow. For products of combustion an airport which sets the level is Zurich, where charges are varied depending on the amount of pollution released in a standard landing and take-off operation. The issues and rules for emissions of pollutants are addressed briefly in Section 11.5. Noise is considered in an appendix at the end of the book.

The effect of regulations for combustion emissions has not, so far, had very much effect on the overall layout of the engine. General Electric have used a staged combustor (like two connected annular combustion chambers, one used all the time and the other only for high power) on their GE90 and it is available on the CFM-56, but so far other manufacturers have managed to avoid even this change by attention to detail in a more conventional single combustor. The 1999 report by the Intergovernmental Panel on Climate Change (IPCC)[2] may lead to greater pressure for control of oxides of nitrogen, amongst other things, during the cruise. The effect of noise regulation, however, has recently lead to very significant alterations to the engine, with consequent reduction in aircraft performance and a slightly larger fuel burn. Principally this is because at take off the largest noise source is still produced by the jet, and no method of jet-noise reduction is more certain than reducing the jet velocity. This requires bigger engines for the same thrust, engines which are bigger than those which would be chosen for optimum aircraft range, a topic taken further in Chapter 7.

SUMMARY CHAPTER 1

New engines are extremely expensive to develop and the risk of designing an engine for an aircraft which does not get built is a serious concern. Unfortunately the time to design and develop the engines has in the past been greater than for the airframe. The hypothetical New Large Aircraft which forms the basis of the first 10 chapters of this book bears some resemblance to the Airbus A380 currently under design. For such a large aircraft, intended for very long range operation, there will be four engines slung under the wings.

There is an International Standard Atmosphere used for calculating aircraft performance, which gives temperature, pressure and density as a function of altitude. Temperature is assumed to fall linearly with altitude (at 6.5 K per km) until 11 km, beyond which it is constant to 20 km.

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[2]See bibliography

Subsonic civil air transport does not normally fly above 41000 ft (12.5 km), though business jets fly at up to 51000 ft (15.5 km). The atmospheric temperature normally falls more slowly with altitude than is implied by an isentropic variation between temperature and pressure.

Whenever possible non-dimensional variables are used, such as Mach number. When non-dimensional variables cannot be used SI units will be used throughout the book unless there is a clear reason otherwise (e.g. feet for altitude and nautical miles for range).

Environmental issues are becoming more important, with the emphasis in regulations currently being around the airport. The potentially more serious effects of emissions in the upper atmosphere will probably be the subject of future regulation. Limiting noise during take off and landing has already lead to the engine layout being modified so that it is no longer optimum for range or fuel consumption.

Chapter 1 sets out to define the needs, the operating environment and the broad specification of the aircraft. Chapter 2 moves to the next stage, which is to consider the aircraft itself.

Chapter 2 THE AERODYNAMICS OF THE AIRCRAFT

2.0 INTRODUCTION

The engine requirements for an aircraft depend upon the size, range and speed selected, but they also depend on the aerodynamic behaviour of the aircraft and the way in which it is operated. In this chapter some very elementary aspects of civil aircraft aerodynamic performance are described; if further explanation is needed the reader is referred to Anderson(1989). These lead to a brief description of the conditions which are most critical for the engine: take off, climb and cruise. It is possible to see why cruising fast and high is desirable, and to calculate the range. Knowing the ratio of lift to drag it is possible to estimate the total thrust requirement.

2.1 SIZING THE WING

The aircraft has to be a compromise between a machine which can travel fast for cruise and relatively slowly for take off and landing. Some modification in the wing shape and area does take place for take off and landing by deploying slats and flaps, but there is a practical limit to how much can be done. As mentioned before it is normal to work with non-dimensional variables whenever possible. Lift Coefficient is defined by

$$C_L = \frac{L}{\frac{1}{2}\rho A V^2} \tag{2.1}$$

where L is the lift force, which is the force acting in the direction perpendicular to the direction of travel. In steady level flight the lift is equal to the aircraft weight. Also used in the definition of C_L are ρ the air density, A the wing area and V the flight speed.

Fig. 2.1 shows how the lift coefficient of the aircraft varies with angle of attack (i.e. incidence) at low speeds, such as at take off. It can be seen that C_L rises almost in proportion to the incidence until around the peak, beyond which it falls rapidly. This rapid fall in lift is referred to as stall and in simple terms occurs when the boundary layers separate from the upper surface of the wing. If an aircraft were to stall near the ground it would be in a desperately serious condition and it is important to make sure that this does not occur. To make sure that stalling is avoided it is essential that the flight speed is high enough for lift to be equal to aircraft weight at a value of lift coefficient which is well away from the stalling value.