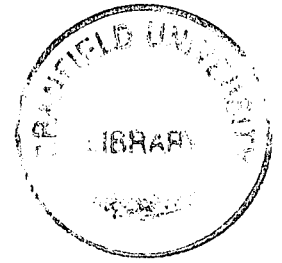


CRANFIELD UNIVERSITY



MARC LE DILOSQUER

**Influence of Subsonic Aero Engine Design
and Flight Routes on Atmospheric Pollution**

SCHOOL OF MECHANICAL ENGINEERING

PhD THESIS

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and Flight Routes on Atmospheric Pollution**

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This thesis is submitted in partial fulfilment of the requirements
for the Degree of Doctor of Philosophy.

Abstract

Gas turbine engine NO_x , CO_2 and H_2O exhaust emissions from civil subsonic fleets are potentially in sufficient amounts to affect atmospheric ozone and climate, particularly with the projected growth in air traffic. Because, it may be that the future envisaged low- NO_x combustor technologies may not keep up with the industry requirements for increased engine thermal efficiency, the potential benefits from optimising aero engine cycles and flight operations for low mission emissions deserve to be thoroughly investigated.

The SKY computer simulation system developed to examine such alternative routes integrates flight route performance, aero engine performance and the formation of pollutants within the combustor. Based on Turbomatch, Cranfield Gas Turbine Simulation System, SKY can be used to optimise mission/aircraft/engine/combustor combinations with respect to landing and take-off (LTO) as well as mission emissions. A model of the high capacity Boeing 747-400 powered by Turbomatch high bypass ratio turbofan models and simulated on long range routes such as London-Tokyo is selected for this work.

On the one hand, aero engine cycles can be designed at an optimum bypass ratio and deliver mission NO_x reductions of up to 10% over designs optimised for LTO NO_x , indicating that the current ICAO regulatory regime is an inadequate parameter to control mission NO_x . On the other hand, operational measures such as speed reductions could bring further reductions of the order of 10%, but some of the improvement would be made at the expense of fuel burn, CO_2 and H_2O emissions, payload-range capability and direct operating costs.

The benefits from such alternative routes are not negligible but smaller in comparison to the 30 to 80% potential cuts from future low- NO_x technology, as well as to the 30% reduction due to expected improvements in the next 20 years or so in airframe weight and aerodynamics and more efficient navigation practices.

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Notations

<i>Symbol</i>	<i>Definition</i>	<i>Unit</i>
a	Speed of sound	m.s^{-1}
A	Cross sectional area	m^2
AFR	Air to Fuel ratio	-
AR	Aspect ratio	-
b	Wing span	m
BPR	Bypass Ratio	-
CAS	Calibrated Air Speed	m.s^{-1}
C	Rate of climb	m.s^{-1}
C_D	Drag coefficient	-
C_L	Lift coefficient (aircraft)	-
C_p	Specific heat at constant pressure	$\text{J.kg}^{-1}.\text{K}^{-1}$
C_v	Specific heat at constant volume	$\text{J.kg}^{-1}.\text{K}^{-1}$
D	Drag (aircraft) ; diameter	N ; m
	Mean (fuel) droplet size	m
D_p	Mass of pollutants	kg
EAS	Equivalent Air Speed	m.s^{-1}
EI	Emission Index (in g of pollutant per kg of fuel burned)	g.kg^{-1}
f	Air fraction	-
F_{00}	Engine rated output at ISA SLS conditions (ICAO std)	N
FAR	Fuel to Air Ratio	-
FCV	Fuel Calorific Value	J.kg^{-1}
ff	Fuel flow	kg.s^{-1}
FPR	Fan Pressure Ratio	-
g	Gravitational acceleration (9.81)	m.s^{-2}
H	Enthalpy ; height	J ; m
h	Pressure height	m
IAS	Indicated Air Speed	m.s^{-1}
L	Lift (aircraft) ; length	N ; m
$\dot{m}$	Air mass flow	kg.s^{-1}
m	Aircraft mass	kg
Mn	Mach number	-
n	Number of moles	-
n_{eng}	Number of engines on wing	-
OPR	Overall Pressure Ratio	-
P	Pressure (stagnation)	Pa
p	Pressure (static)	Pa
q	Dynamic head $\frac{1}{2}\rho V^2$	Pa
Q	Heat rate	W
r	Range ; distance	m
R	Gas constant	$\text{J.kg}^{-1}.\text{K}^{-1}$

	Range	m
RLC	Coefficient akin to emissivity	-
ROC	Rate of Climb	m.s^{-1}
S	Surface (e.g. wing area)	m^2
SAR	Specific Air Range	m.kg^{-1}
SEP	Specific Excess Power	m.s^{-1}
s.f.c.	Specific fuel consumption	$\text{kg.N}^{-1}.\text{s}^{-1}$
SMD	Sauter Mean Diameter	m
t	Time	s
	Temperature (static)	K
T	Temperature (stagnation)	K
	Net thrust	N
T_{ISA}	ISA deviation	K
TAS	True Air Speed	m.s^{-1}
TET	Turbine Entry Temperature	K
U	Velocity	m
V	Velocity or aircraft speed	m.s^{-1}
	Volume	m^3
W	Weight	N
	Mass flow	kg.m^{-3}
x	Fuel carbon number	-
y	Fuel hydrogen number	-
Z	Surge margin	-
δ	Relative pressure p/p_0	-
ϕ	Equivalence ratio	-
γ	Ratio of specific heats	-
	Climb or descent angle	rad
η	Efficiency	-
λ	Evaporation constant	$\text{m}^2.\text{s}^{-1}$
π	Pressure ratio	-
θ	Fuselage inclination angle	rad
	Relative temperature T/T_0	-
ρ	Density	kg.m^{-3}
σ	Relative density ρ/ρ_0	-
	Surface tension	kg.s^{-2}

Subscript

<i>Symbol</i>	<i>Definition</i>
A	Air ; sound (for speed of sound V_A)
AC	Aircraft
ad	Adiabatic
bm	Blade metal
C	Combustor ; compressor

CAS	Calibrated air speed
D	Aircraft drag
E	Evaporation
e	Evaporation rate
EAS	Equivalent air speed
eff	Effective
eng	Engine
f	Formation (for enthalpy of formation)
g	Gas
I	Initial conditions
IAS	Indicated air speed
inje	Injector
isen	Isentropic
L	Aircraft lift ; combustor liner
max	Maximum
min	Minimum
nac	Nacelle
ov	Overall
p	Pollutant ; products
poly	Polytropic
prop	Propulsive
pz	Primary zone (combustor)
ref	Reference value
st	Stoichiometric
t	Total or stagnation
T	Turbine
TAS	True air speed
th	Thermal
W	Wing ; wind (for wind speed V_w)
θ	Reaction rate
0	Flight ; sea level ; ground ; standard or reference value
00	Sea level rated value (Cf. ICAO standards)
1	Intake inlet
2	Fan inlet
3	Combustor inlet station
4	Combustor outlet station
5	Last turbine stage outlet
6	Afterburner inlet
7	Core nozzle inlet
8	Nozzle throat (in the case of a convergent-divergent nozzle)
9	Core nozzle outlet

Abbreviations & Formulae

AAAF	Association Aéronautique et Astronautique de France
ADP	Aero Design Point (i.e. at top-of-climb conditions)
AGARD	Advisory Group for Aerospace Research and Development
AIAA	American Institute of Aeronautics and Astronautics
ANCAT	Abatement of Nuisances Caused by Air Transport
APPEM	Analysis and prediction of Pollutant Emissions (computer program)
ASTM	American Society for Testing and Materials (US)
ASK	Available Seat Kilometre
ASM	Available Seat Mile (1 ASM = 1.852 ASK)
ATA	Air Transport Association (USA)
ATC	Air Traffic Control
ATK	Available Tonne Kilometre
CAEE	Committee on Aircraft Engine Emissions (Committee set up by ICAO)
CAEP	Committee on Aircraft Environmental Protection (Committee set up by ICAO)
CAPE	Cycle Analysis of Performance and Emissions (optimisation computer program developed to drive Turbomatch iterations automatically)
CAS	Calibrated air speed
CCN	Cloud condensation nuclei
CFD	Computer Fluid Dynamics
CG	Centre of gravity
CH ₄	Methane
CN	Condensation nuclei
CO	Carbon monoxide
CO ₂	Carbon dioxide
DAC	Double Annular Combustor (concept featuring radial fuel staging)
DERD	The series designator for UK aviation fuel specifications - derived from the former Directorate of Engine Research and Development (UK) -, retained on grounds of simplicity and familiarity.
DGLR	Deutsche Gesellschaft für Luft- und Raumfahrt (German Society for Aeronautics and Astronautics, Germany)
DP	Design point
DRA	Defence Research Agency (UK)
DTI	Department of Trade and Industry (UK)
EAS	Equivalent air speed
ECAC	European Civil Aviation Conference
ECMWF	European Centre for Medium-range Weather Forecast
EEC	Electronic Engine Controller
EIS	Entry into service
EPA	Environmental Protection Agency (US)
EU	European Union
FAA	Federal Aviation Administration (US)

FANS	Future Air Navigation Systems
FAR	Federal Aviation Regulation (USA)
FAST	Flight Analysis of Subsonic Transport (computer program)
FCCC	Framework Convention on Climate Change
FCV	Fuel Calorific Value
FSII	Fuel System Icing Inhibitor (NATO)
GDP	Gross Domestic Product
GE	General Electric
GG	Gas Generator
GPS	Global Positioning System
H ₂ O	Water
H ₂ SO ₄	Sulphuric acid
HC	Hydrocarbons
HNO ₃	Nitric acid
HPC	High Pressure Compressor
HPT	High Pressure Turbine
HSCT	High Speed Civil Transport
IAS	Indicated air speed
IATA	International Air Transport Association
ICA	Initial cruise altitude
ICAC	Initial cruise altitude capability
ICAO	International Civil Aviation Organisation
IEA	International Energy Association
IFR	Instrumental Flight Rules
IGW	Increased Gross Weight
IPC	Intermediate Pressure Compressor
IPT	Intermediate Pressure Turbine
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
JP	Jet Propellant (US)
JSD	Joint Services Designation (UK)
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
LPP	Lean Premixed Prevapourised (combustor)
LTO	Landing and Take-Off (Cycle)
MCL	Maximum climb rating
MCT	Maximum continuous rating
MTO	Maximum take-off rating
MFC	Maximum fuel capacity
MIL	The series designator for military specifications (US)
MLW	Maximum landing weight
MRW	Maximum ramp weight
Mt	Mega tonne (= 10 ⁶ tonnes)
MTOW	Maximum take-off weight
MZFW	Maximum zero-fuel weight
NASA	National Aeronautics and Space Administration

NATO	North Atlantic Treaty Organisation
NGV	Nozzle guide vane
NMHC	Non Methane Hydrocarbon
NO	Nitrogen monoxide
NO ₂	Nitrogen dioxide
NO _x	Oxydes of Nitrogen, the chemical family incorporating NO and NO ₂
NO _y	The chemical family incorporating NO, NO ₂ , HNO ₃ , HNO ₂ , N ₂ O and N ₂ O ₅
OEW	Operational Empty Weight
O ₃	Ozone
OD	Off design
OECD	Organisation for Economic Cooperation and Development
OH	Hydroxyl radical
OTDF	Overall Temperature Distribution Factor
PKP	Passengers Kilometres Performed (same as RPK)
ppbv	Parts per billion (10 ⁻⁹) by volume
ppmv	Parts per million (10 ⁻⁶) by volume
pptv	Parts per trillion (10 ⁻¹²) by volume
PSC	Polar Stratospheric Cloud
PW	Pratt & Whitney
RAeS	Royal Aeronautical Society
RPK	Revenue Passenger Kilometre
RPM	Revenue Passenger Mile (1 RPM = 1.852 PKP)
RQL	Rich-burn Quick-quench Lean-burn (combustor)
RR	Rolls-Royce
RTDF	Radial Temperature Distribution Factor
SAC	Single Annular Combustor
SAR	Specific Air Range (i.e. fuel mileage)
SLS	Sea Level Static
SN	Smoke Number
SNECMA	Société Nationale d'Etude et de Construction de Moteurs d'Aviation
SO ₂	Sulphur dioxide
SST	Supersonic Transport
TAS	True air speed
TKM	Tonne kilometre performed
TNM	Tonne nautical mile (1 TNM = 1.852 TKM)
TOFL	Take-Off Field Length
TOMCAT	Toulouse Off-line Model of Chemistry and Transport
UHC	Unburned hydrocarbon
UNEP	United Nations Environment Programme
UV	Ultra-Violet
VFR	Visual Flight Rules
WMO	World Meteorological Organisation

Introduction

1

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1.1 BACKGROUND

Atmospheric pollution can be defined as the presence of substances in the ambient atmosphere resulting from the activity of man or from natural processes, causing adverse effects to man and the environment. The substances emitted by aircraft gas turbine engines burning hydrocarbon fuels such as kerosene include water vapour (H_2O), carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (UHC), sulphur oxides (mainly SO_2), and other minor trace gases.

Public awareness of air traffic as a nuisance has its roots in the rapid expansion of jet powered air services from the 1950s. Initially, the main concern regarding aircraft engine emissions was the impact on air quality in the vicinity of airports, as a result of which the International Civil Aviation Organisation (ICAO), following the US Environmental Protection Agency (EPA), developed standards for the control of smoke and NO_x , CO and UHC gaseous emissions through an engine certification scheme based on the Landing and Take-off (LTO) cycle (ICAO, 1981). The major aero engine manufacturing nations have adopted the standards which have been since regularly reviewed. More recently, however, there have been increasing concerns that these emissions may also be contributing to global atmospheric problems.

Subsonic aircraft operate primarily in the upper troposphere and lower stratosphere. Research surveys on the effect of aircraft engine emissions upon the atmosphere (Friedl, 1997 ; Schumann, 1994 ; IPCC, 1991), underline that emissions from high-flying global civil subsonic air traffic contribute to anthropogenic climate changes by increase of ozone and cloudiness in the upper troposphere therefore resulting in enhanced greenhouse effect, and to the destruction of ozone in the lower stratosphere. The major pollutants currently under scrutiny include nitrogen oxides, water vapour and carbon dioxide.

Emissions from aircraft engines constitute only a small proportion - in the region of a few per cent - of man-made and natural emissions into the atmosphere. However, such emissions have a great impact because they are emitted into the highly sensitive upper

troposphere and lower stratosphere where the gases are long-lived and where aircraft are the sole source of directly injected anthropogenic pollution (excluding the minor contribution from rocket emissions ; Schumann, 1994b ; Lieberherr, 1994). In comparison, higher volume emissions from natural sources (with the exception of those from sporadic volcanic eruptions) or generated by human activities on the ground remain contained in the troposphere where they will be eventually washed down back to the ground by weather processes.

Provided that global economic development is not halted by world-scale crises, global air traffic as of 1997 is expected to double early in the next millennium at around 2015 (ICAO, 1995a ; Boeing, 1996 ; Rolls-Royce, 1997). Technological developments will ensure to some extent that the emission growth rate will be lower than the fleet growth rate. However, the net result will be an increase in emissions and hence an increase in the environmental problems. In the absence of controls, its significance will become greater as air traffic grows and ground sources come under stricter control.

While the range of uncertainty regarding aviation's impact is indeed great, the accusation has been made that air transport may make a contribution to climate change out of all proportion to fuel use. Whether the significance of air transport contribution can be proved to be high or not may not be totally relevant : the finger of suspicion is being pointed at the civil aviation industry (estimated to account for 75% of all jet emissions), which operates in a highly competitive market against a background of declining yields. Declining yields are a combined result of growing long-haul travel, faster growth of leisure over business travel and improved airline productivity.

Most of the increase of aircraft pollution will be generated by high-flying long distance traffic (Schumann, 1994). This is because, while for a short haul flight of 900 km, cruise NO_x emissions typically represent 20% of the total, this rises to over 75% for a long haul flight of 8500 km (Lister, 1992). Supersonic transports (SST) are potentially more damaging because they cruise higher in the stratosphere (18-23 km) but will not be serious contenders before some time. This is because crucial technological and economical issues remain unresolved, making the development of an environmentally and economically acceptable high civil supersonic transport aircraft yet uncertain. There is only a handful of civil supersonic airliners presently in service (13 Concorde as of 1997) while a possible successor is unlikely to be introduced before 2015 (Rolls-Royce, 1998b ; Air et Cosmos, 1998). Should they enter commercial service thereafter, the total number of SSTs will still be limited by the production rate and the fraction of the market which they can occupy. Accordingly, subsonic high-flying aircraft will keep on dominating the air transportation system in the next century. Similarly, emissions from peacetime military operations and spacecraft such as rockets and reusable shuttles represent a minor contribution which has not been identified as posing a serious threat to the atmosphere (Schumann, 1994b ; Lieberherr, 1994).

With more evidence of air traffic emissions' adverse effects on the atmosphere being gathered, the introduction of emissions regulations not only covering the vicinity of airports but also the high altitudes is now more seriously discussed than before (Ralph et

al, 1996 ; Wright, 1995). Such moves will affect both engine and aircraft manufacturers as well as operators, in the way they build or fly aircraft. Most of current research in aircraft pollution reduction is concerned with the development of new low-emission engine combustors designed to lower pollutants based on the LTO cycle. While the need to control emissions around airports through the LTO cycle will remain, there will probably be further pressure to create a regulatory regime that addresses the global implications of high altitude aircraft emissions on the atmosphere. In order to support such developments, the contribution from an optimisation of the aero engine cycle and the flight operations must be thoroughly investigated.

Throughout the last decades, improvements in engine s.f.c. have been mainly achieved by the introduction of jet engines of higher bypass ratios. The introduction of these engines together with improvements in combustion technology, as a response to the ICAO recommendations as well as economic pressures, had environmental spin-offs with substantial reductions in smoke, UHC, CO as well as CO₂ and H₂O emissions. However, it has only been possible to maintain or slightly decrease NO_x emissions, due to the ever increasing cycle pressure ratios and combustor outlet temperatures necessitated by the design of those high bypass ratio turbofans. Nevertheless, further improvements in low-NO_x combustor technology are currently being investigated and hold promise for the future (Gupta *et al*, 1994 ; Lefebvre, 1995 ; AGARD, 1993). Yet it may be that these advances may not keep up with the trends of higher overall pressure ratios and turbine entry temperatures that the industry is to follow with current high bypass ratio turbofans in order to further reduce s.f.c. and drive up take-off and climb thrust. As a result, emissions may well become a pertinent cycle parameter in the preliminary design of aero gas turbine engines. At any rate, the effect of cycle parameters on emissions and the likely evolution in legislation should reveal if the future requirements can be met by combustor technology alone.

Current aircraft flight routes are defined by criteria such as high aircraft utilisation, route revenue-earning capability, minimising fuel consumption or because of considerations of airspace management including air traffic control restrictions. It is possible that alternative routes or operational practice with a different flight profile may result in less pollution or less damaging pollution. The life cycle of a civil aircraft covers about fifty years, with only the first ten years of basic and pre-competitive research where one can influence the final product (Topp, 1994). The "certification of airworthiness" windows, both for airframe and engine are a severe constraint and indeed very few innovative technologies are ever retrofitted. It may be that the atmospheric impact of flights will be found to be dependent on aircraft altitude or speed. In this respect, operating aircraft which have a substantial residual useful life on "low-pollution" routings might prove to be environmentally desirable, while low-emission technologies are being further developed for the next generations of aircraft.

In spite of the uncertainties as to the magnitude of aircraft pollution relative to other natural or anthropogenic sources, given the most serious long term consequences of pollutant emissions, the contribution of alternative routes to reduce the amount and the

impact of air traffic emissions such as aero engine cycle and flight operation optimisations deserve to be thoroughly investigated.

1.2 OBJECTIVES AND SCOPE

The research project's objectives are to explore the merits of two new alternative routes designed to reduce priority trace species at altitude, and investigate whether the current standards in their present form can assist the design of civil subsonic aero engines to achieve low flight emissions. The two routes under scrutiny include the optimisation of civil subsonic aero engine cycle and flight operations. Although the economic acceptability of cycle optimisations and operational measures to reduce pollution would eventually need to be thoroughly assessed, the present work proposes to focus on the environmental benefits (in terms of emission output) such measures could bring. The various emissions generated by aero gas turbine engines will be reviewed in Chapter 2. The thesis will focus on those species currently considered to exert the greatest impact on the earth's atmosphere.

Medium and long range civil subsonic jet transport airliners fly stage lengths over 3000nm (5556km). They will remain for some decades the highest-flying largest-emitting section of the global aircraft fleet (supersonic transports are potentially more damaging for the stratosphere but will not be serious contenders before some time). To illustrate this, the maximum fuel capacity and range of civil subsonic commercial jet aircraft types launched or in service as of 1997 are presented in Figure 1.1.

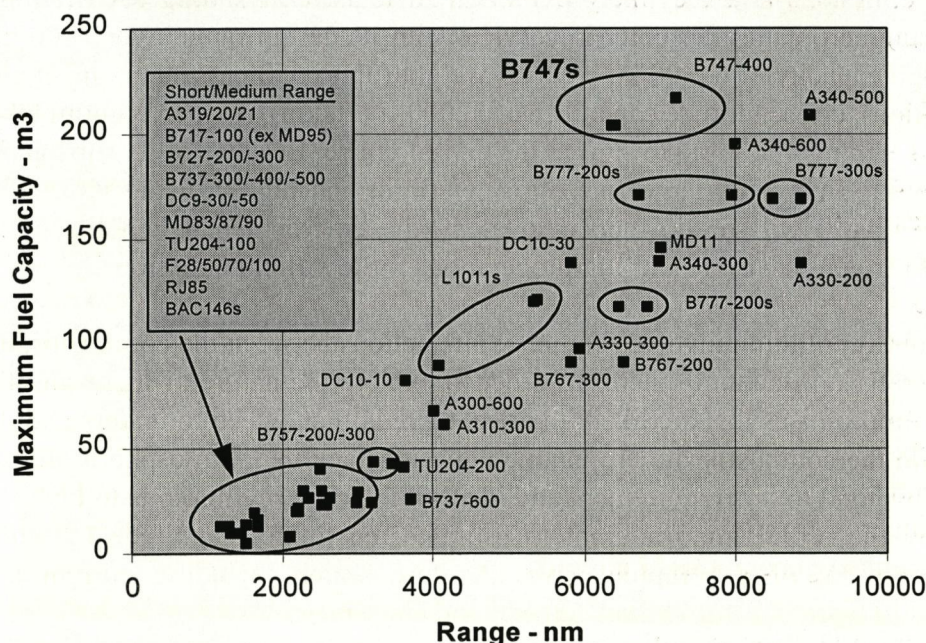


Figure 1.1 : Civil Subsonic Commercial Jet Aircraft in Service as of End of 1997

The fuel burnt over the corresponding range represents approximately 90% of the maximum fuel capacity (reserves account for 10% using typical international rules). The range indicated is the distance covered by the aircraft at maximum take-off weight and maximum fuel capacity. It will be generally higher than the design range. The longer the distance covered the higher the cruising altitude, while the higher the maximum fuel capacity, the larger the amount of emissions discharged in the atmosphere. Although the figure does not give credit to productivity (high capacity aircraft are likely to generate less pollutants per passenger), it nevertheless indicates that medium and long range aircraft discharge the largest amount of emissions per flight at the potentially most sensitive part of the atmosphere.

Medium/long haul routes represented in 1995 over 60% of the world civil scheduled passenger air traffic for only 13% of the total number of flights (Rolls-Royce, 1998b). They have maintained their share until 1998 and are expected to continue to do so in the future. The airliners operating these routes cruise at altitudes ranging from 30000 ft to 43000 ft. By virtue of their characteristics and substantial traffic share, they represent ideal candidates for an investigation into the optimisation of aero engine design and flight routes for low flight emissions.

In the medium/long range market segment, the Boeing 747 airliners held in 1995 8.5% of the world airline fleet with 942 units providing 22% of all airline capacity (Boeing, 1996). With such routes enjoying a higher average load factor at approximately 75% (to compare to a global average of 68.8% in 1995), this is equivalent to a quarter of the global civil passenger air traffic. Baughcum et al. (1996) have estimated that the 747 aeroplanes had burned in 1992 approximately 27% of the fuel consumed by world scheduled traffic. In the 747 family, the -400 series ranks among the longest-, heaviest- and highest-flying aeroplanes currently in service, with its design range over 7800 nm (14600 km), high capacity of 64800 kg payload weight (up to 550 passengers in single-class configuration), cruise altitude capability of 32000 ft (10 km) at the maximum take-off weight and reaching 45000 ft (13 km) at the end of cruise. Because of its substantial share of the global air traffic, large fuel burn per flight and high cruising altitude, a model of the 747-400 will be developed to study the environmental benefits of an optimisation of aero engine cycle and flight operations for low flight emissions.

The issue of aircraft pollution involves complex interactions between the combustor, the engine, the aircraft and the atmosphere. In order to explore the nature of these and the technological compromises that are likely to arise, there is first a need to understand the formation within the combustor of aero engine emissions and their atmospheric impact. Chapter 2 will respond to this requirement and identify the critical emissions to be taken into account by the project, and attempt to estimate the future magnitude of world aviation pollution out of a comprehensive literature search including current and predicted trends in world air traffic, fuel demand and emissions.

Secondly, there is a need to investigate what regulatory and technological measures have been adopted since the beginning of the jet age in the early 1950s to control those critical pollutants, as well as what the next decade holds in that respect. To this effect,

Chapter 3 should review regulatory standards and discuss the range of design and operational routes available to reduce emissions. The chapter will present the range of issues involved and provide a preliminary qualitative evaluation of the environmental benefits of subsonic aero engine design and flight operations in relation to other routes.

Evaluating the merits of such routes requires to estimate the effect of aero engine design (including deterioration) and aircraft flight parameters on flight emissions. Figure 1.2 presents diagrammatically the various design and operational factors influencing the production of flight emissions.

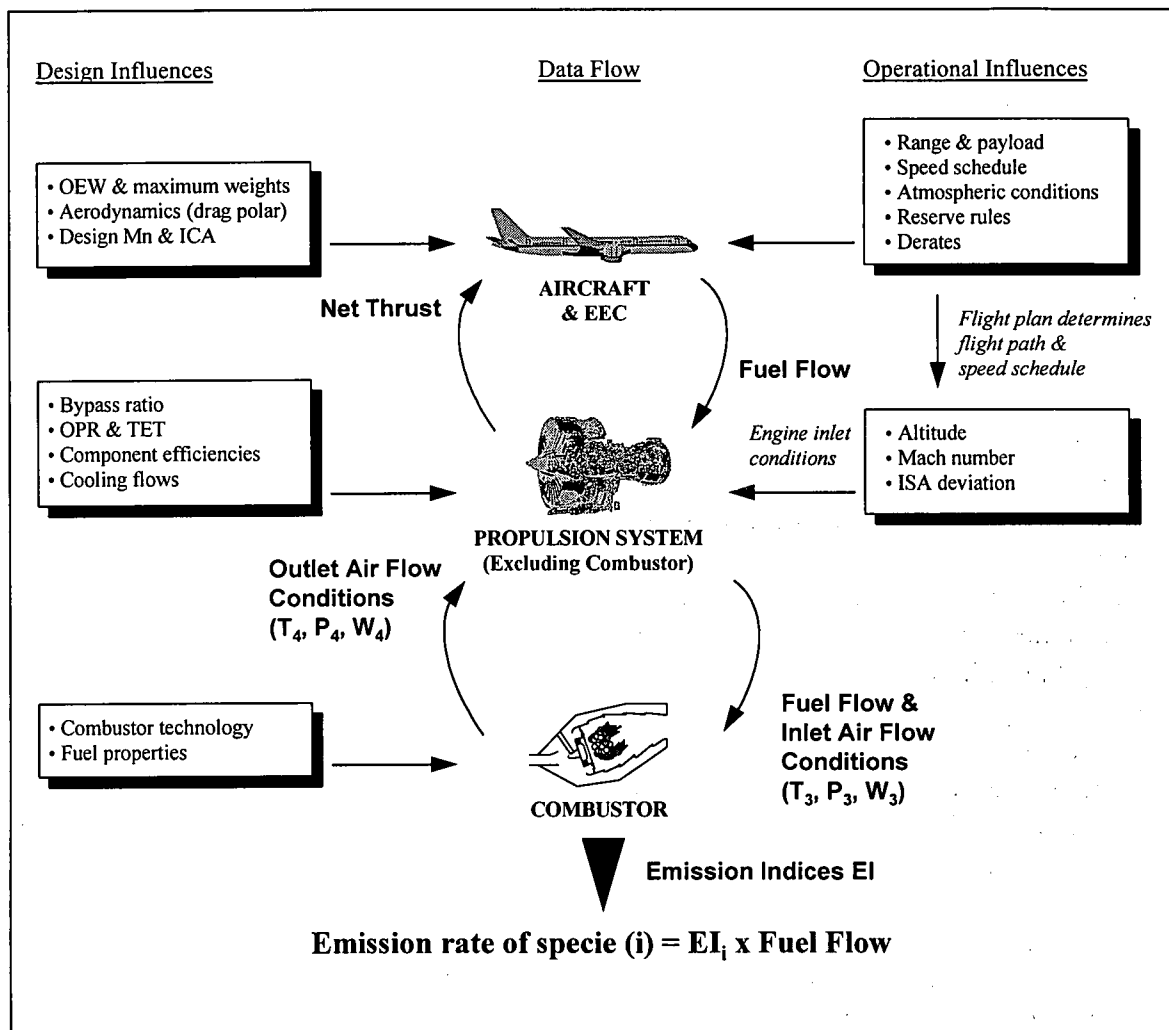


Figure 1.2 : The Estimation of Flight Emissions Generated by Jet Aircraft

In the light of the above figure, a computer simulation system integrating flight route performance, aero engine performance and the formation of the pollutants within the engine's combustor is required to quantify accurately and systematically the production of pollutants by large numbers of mission/aircraft/engine/combustor combinations in flight, and to study systematically the effects of changes in engine cycle, rating and aircraft flight parameters. Not only because of potentially large number of case studies,

the simulation system must take the form of a computer program for the following reasons :-

- For a given engine, emission indices depend on power level and engine inlet flow conditions. As a result, they can vary significantly throughout the flight. The NO_x index, for instance, may vary tenfold between idle and take-off (ICAO, 1993). It is therefore necessary to estimate fuel burn at sufficiently small flight intervals for a given aircraft/engine combination, range and payload. The estimation can be conducted through a "top-down" or a "bottom-up" approach. The "top-down" approach uses flight performance manuals to derive the data required to run the engine and emission models (e.g. Boeing, 1990). The approach is well suited to emissions calculation of existing aircraft/engine combinations. However, to study the effects of engine cycle parameters, it is necessary to employ a "bottom-up" approach, whereby flight route, engine performance and emissions formation are modelled through equations and databases derived from theory and experience. The level of complexity, detail and accuracy required, as well as the large number of parameters to be manipulated points towards the development of a flexible computer program and disqualify simpler calculation tools like the spreadsheet. The computer system simulating the combination of an aircraft, an engine and a combustor model, should be modular so that any engine cycle could be installed in the overall model.
- Because of the iterative nature of gas turbine off-design performance calculations which are based on empirical component characteristics, the simulation of modern aero gas turbine cycles are best performed by computer programs. One such gas turbine simulation system, Turbomatch, is available at Cranfield University (Palmer, 1983) and can be readily integrated into the overall simulation system to investigate the influence of main engine cycle parameters on flight emissions.
- Research aimed at assessing the effects of aircraft emissions on the gas concentrations of the troposphere and stratosphere, use a variety of mathematical models to describe the atmospheric transport, diffusion and complicated chemical reactions taking place within the earth's atmosphere. Because very little in-flight information is available, research groups produce their own profiles of pollutants from aircraft based on sea level emissions from the ICAO emissions databank. To assess the atmospheric impact either of a single civil subsonic flight or of the global fleet, it is important to accurately predict the amounts of emissions along the flight corridor with good spatial resolution. A flexible simulation computer program should therefore prove most useful to such crucial studies (Lee, 1996).

The computer system shall be run to evaluate flight emissions from any mission/aircraft/engine/combustor combinations of the user's choice and analyse the interplay between the engine design requirements of performance, fuel economy and low emissions. The detailed specifications and structure of the computer system developed will be discussed in Chapter 4. The computer simulation system shall be used to examine the optimum combination(s) of cycle parameter as well as the optimum 747-400 flight route(s) (Chapter 5) meeting performance, low fuel burn and low flight emissions requirements.

The variety of engines studied shall be installed on the 747-400 model resulting in different fuel burn at a given range and payload. Although each aircraft/engine combination should ideally be re-optimised to perform the required design mission, this represents a complex design exercise which shall not be tackled here. The airframe will be assumed fixed. The project will also attempt to investigate how environmental assessment of cycles can be made at an early stage of the preliminary design process.

Chapter 5 should consider aero engine design criteria inasmuch as they can translate into thermodynamic or flight and engine performance relationships, e.g. performance, fuel burn, and emissions. Other major requirements such as noise, manufacturing, life, reliability, maintainability and direct operating cost will be discussed where possible but are chosen not to be quantitatively included in the study in order to maintain the scope at a reasonable and achievable level. This chapter should also examine qualitatively what happens to emission concentrations beyond the engine nozzle outlet i.e. within the exhaust plume and aircraft wake and finally in the wider atmosphere. The software will be used to model the flight of the 747-400 airliner powered by high bypass ratio turbofans on a typical long range flight route. The emissions will be input into a 3-dimensional chemical transport model to study the passive distribution of critical emissions in the atmosphere. The implications on the atmosphere will be discussed.

Research in aviation's atmospheric pollution indicates that the time and location of injection (particularly the altitude relative to the tropopause and the latitude) into the atmosphere are key factors in assessing the atmospheric impact. However, given the current prevailing uncertainty as to the magnitude of such effects, it will not be possible to ascertain which design or operational solutions are least detrimental to the environment. The merit of such solutions will therefore be discussed on the basis of the amount of flight emissions discharged irrespective of the location, time, season or atmospheric dynamical conditions.

Finally, chapter 6 will incorporate the conclusions and recommendations for further work and will contribute to answer the following questions regarding the implications of civil subsonic aero engine design and flight operations on atmospheric pollution, i.e. :-

- What is the best combination of cycle parameters, i.e. the optimum aero engine design, regarding the minimisation of flight emissions? To what extent are those in conflict with usual subsonic aero gas turbine design requirements?
- What is the optimum flight profile with respect to the minimisation of flight emissions? To what extent is that in conflict with current operational practices?
- What is the influence of the in-service deterioration of aero gas turbines on the flight emission pattern? How does it compare with the contributions from cycle and operational optimisations?
- To what extent are the requirements of low near-airport and low high-altitude emissions in conflict? Does the current regime of the ICAO standard help to reduce high altitude emissions?
- Are low-emissions a pertinent cycle parameter to be employed at the preliminary design stage of aero gas turbine cycles?

1.3 PROGRAMME

The structure of the thesis reflects the work programme and schedule defined at the beginning of the research project. Given the nature of research work, the schedule initially defined was subject to a number of changes. In the course of the research project, some tasks turned out to require more attention and effort. For instance, the development of the computer simulation system needed more time than initially predicted. As a result, other tasks had to be shortened or cancelled altogether. In the light of the project's findings, those tasks have led to a number of recommendations for further work (Cf. Chapter 6). The tasks whose scope had to be reduced include the effect of post-combustor chemistry in the gas turbine and in the exhaust plume and the influence of engine deterioration, issues which are discussed in Chapter 3. Those tasks that had to be cancelled include the feasibility study of the reheat cycle (double-combustor cycle) and the development of a double annular combustor model.

In the light of the previous objectives and scope, the research programme was articulated around 5 main areas :-

1) Literature Search

The literature search, most of which was conducted initially, had to focus on the following key areas :-

- Flight route : flight route simulation, aircraft performance and aerodynamics, operational and ATC procedures.
- Aero engines : current technology and future developments, cycle definition, design procedure and requirements, design-point and off-design gas turbine performance simulation, deterioration.
- Combustion and pollution : aero gas turbine combustor design, low-emission technology, combustion and emission simulation, pollutant correlations, exhaust plume chemistry, atmospheric chemical and dynamical processes, impact of pollutants on the atmosphere.
- Legislation : evolution of legislation, ICAO, EPA, national regulations.
- Computing : Fortran 77 programming, VAX-VMS and DOS operating systems.

2) Calculation of Flight Emissions

The estimation of flight emissions produced by civil subsonic transport aircraft on medium to long range routes is chosen to be carried out by a computer program. The software will have to incorporate three modules i.e. the simulation of flight routes, aero gas turbine performance and the formation of the pollutants within the combustors. The specifications are to be carefully laid down prior to development. This computer simulation program is named SKY. While meeting the specifications, the approach shall be a compromise between development time, representativity of the required results, computing rapidity,

upgradeability and portability. The validation of the three modules shall be conducted separately.

3) Assessment and Comparison of Cycles at Design Point

A number of aero gas turbine cycles meeting the 747-400 thrust and mission fuel burn requirements shall be selected to investigate the effect of main engine cycle parameters such as bypass ratio, overall pressure ratio, turbine entry temperature, etc. on performance, fuel economy and LTO and flight emissions. In order to make a valid analysis, cycles using a similar level of technology shall be compared. In this respect, some of the cycle and combustor parameters will depend of the level of technology adopted. Other parameters will be constrained by the 747-400 design and mission requirements.

4) Assessment of Cycles over a Typical Flight Mission and Operational Optimisations

Where possible, the previously selected cycles shall be installed on a model of the 747-400 and flown on a typical long range sector (e.g. London to Tokyo) using the SKY computer simulation system to calculate the fuel burn and emission output. For a more limited number of cycles, varying flight profiles will be employed to explore how optimum operations could contribute to the reduction of flight emissions. The study should investigate the implications of optimising cycles for the ICAO regulatory levels (low near-airport emissions) on total flight emissions or mission emissions. Finally, some of the critical flight emissions generated on a typical flight mission over a given period will be input into a 3-D chemical and transport model of the Earth's Atmosphere to study the transformation and distribution of pollutants with time.

5) Discussion, Recommendations and Conclusions

The relative merits of aero engine cycle and flight profile optimisations possibly in comparison with other routes such as low emission combustor technology shall be discussed. Finally, a number of recommendations shall be raised in the light of the project's conclusions to assist further research in the field.

The Formation and Atmospheric Impact of Aero Engine Emissions

2

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2.1 INTRODUCTION

Many different species are emitted within the combustion chambers of aircraft aero gas turbines. Some are not considered to be a significant threat to the environment, because they are kept at low levels either because of the technical considerations that dictate combustor design (e.g. fuel efficiency) or thanks to low-emission technologies or because they are released in amounts insignificant in comparison to other sources (man-made or natural) with no relatively small atmospheric implications. Others are causing particular concern because they are conducive to poor air quality in the vicinity of airports or because of their potential large-scale effects including global warming and ozone depletion.

The chapter describes the formation of the major pollutants within the aero gas turbine combustion chamber as well as their subsequent evolution in the turbomachinery, the jet plume and aircraft wake. In the light of the current knowledge in atmospheric pollution by aviation, and in the context of world civil aviation traffic, fuel demand and emission predictions, the present and potential future impact of those major pollutants on the global atmosphere are discussed.

2.2 THE FORMATION OF EMISSIONS FROM AERO GAS TURBINES

The species emitted by commercial passenger jet aircraft are those resulting from the combustion of kerosene fuel in air (average kerosene formula : $C_{12}H_{24}$). By weight, dry air is composed of 76% nitrogen (N_2), 23% of oxygen (O_2), 1% of Argon (Ar) and 0.05% of carbon dioxide (CO_2). Traces of minor other airborne species are also present in negligible amounts. Small levels of humidity can be present with negligible effects on the engine performance and combustion process.

A short summary of the species resulting from the combustion of this hydrocarbon fuel and their importance to air pollution is presented in Table 2.1. This exhaustive list is not meant to indicate that aircraft are significant sources of all of these species, but simply that aircraft can discharge these species into the atmosphere.

Emissions of importance are water vapour (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (UHC), nitrogen oxides (NO_x i.e. NO and NO_2), sulphur dioxide (SO_2) and smoke/soot. For complete combustion, the emissions would contain mainly carbon dioxide (CO_2) and water vapour (H_2O), whose indices depend solely on the fuel stoichiometric composition. The H_2O index may be modestly higher depending on the level of ingested humidity. The impact of such emissions at high altitude will be addressed in Section 2.4.

<i>Emissions</i>	<i>Primary effects</i>
Carbon Monoxide (CO)	Toxic, reduces oxygen capacity of blood
Oxides of Nitrogen (NO, NO_2)	Toxic, photochemical smog, ozone layer depletion, Global warming by ozone formed by action of NO_x
Unburned Hydrocarbons (UHC)	Toxic (carcinogens), odorants, photochemical smog, can be inert (CH_4)
Oxides of Sulphur (SO_2 , SO_3)	Toxic, corrosion
Carbon Dioxide (CO_2)	Inert, possible weather modification
Water (H_2O)	Inert, ice, fog, possible weather modification
Oxygenated Hydrocarbons (Aldehydes)	Irritants, odorants, possible smog precursors
Smoke, Particulate	Visibility reduction, soiling, plume visibility, possibly carcinogenic
Lead (Pb)	Toxic
Metals (Mn, V, Na, P, etc.)	Toxic
Sulphur compounds (H_2S , etc.)	Toxic, odorants
Halogen Compounds (HCl, etc.)	Toxic, corrosion

Table 2.1 : Aero Gas Turbine Exhaust Emissions

The concentrations of pollutants in gas turbine exhausts can be related directly to the pressure, local temperature, local fuel-to-air ratios and residence time in the combustor, which result from the combustor design and the engine operating conditions. As shown in Figure 2.1, concentrations of CO and UHC will be highest at low-power conditions and diminish with increased power. This is because at idle conditions the residence time in the combustor is smaller than at full throttle and leads to incomplete combustion. In

addition, the performance of injection systems may deteriorate with decreasing pressure further leading to low efficiency and high CO and UHC. However, smoke and NO_x will feature an opposite behaviour and attain maximum values at higher power settings.

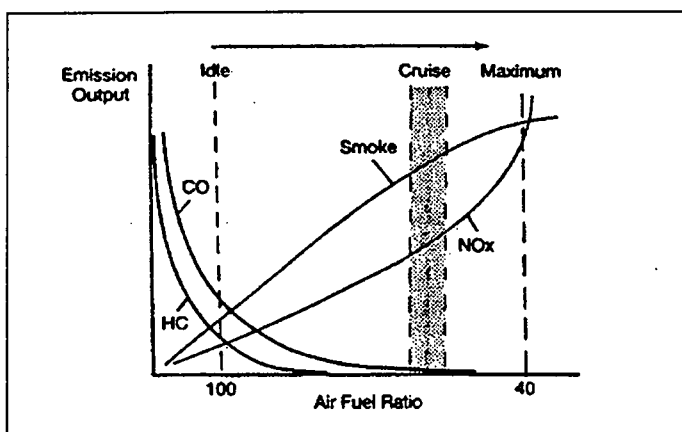


Figure 2.1 :
Typical Exhaust Emissions
Characteristics of Gas Turbine
Engines

For more details on each individual specie, Appendix B.1 presents the various mechanisms of formation for the main gas turbine combustor emissions identified above and, where relevant, tackle the changes they may subsequently undergo before leaving the engine exhaust nozzle. The possible chemical reactions occurring in the jet plume are studied in the section dealing with the atmospheric implications.

2.3 HISTORICAL TRENDS IN WORLD AVIATION TRAFFIC, FUEL USE & EMISSIONS

2.3.1 World Aviation Traffic

Trends in world air traffic, aviation fuel consumption and resulting emissions output are key parameters to assess the magnitude of aviation's current and future contribution to global environmental pollution. Regular statistics are available for world civil scheduled air traffic (passenger and cargo) from which trends can be derived. Such data does not include military and general aviation, non-scheduled and commercial charter flights.

Since 1960, growth in air transport has been much greater than economic growth but is closely linked with it (Singh, 1996). The 1995 ICAO Outlook to the Year 2003 (ICAO, 1995a) indicates that world civil airline scheduled passenger traffic (domestic and international) measured in terms of passenger-kilometres performed increased at an average annual rate of 9.4% for the 1960-1992 period. For the sub-periods 1960-1970, 1970-1980 and 1980-1992, traffic grew at an average annual rate of 13.4, 9.0 and 5.0 per cent respectively. Similar trends with slightly higher growth rates were observed with world airline scheduled freight traffic. The growth in passenger and freight traffic demand over the 1960-1992 period resulted in comparable growth in terms of aircraft seats and payload, while aircraft movements measured in terms of aircraft-kilometres grew at a much slower rate (2.7% per annum) due primarily to a large increase in

average aircraft size during the period. The scheduled civil aviation now accounts for almost 16,000 aircraft in commercial service today (excluding the former soviet union).

Aircraft and engine manufacturers, airlines and civil aviation institutions regularly publish assessments to estimate future demand on world air travel. Some recent long-term forecasts of growth in world scheduled traffic are given in Table 2.2. These forecast growth rates are in the range of 5 to 6.5% per annum for passenger-kilometres with freight tonne-kilometres generally forecast to grow at a slightly higher rate.

Source of Forecast	Forecast Period	Passenger-Kilometres (%)	Freight Tonne-Kilometres (%)
ICAO	1992-2003	5.0	6.5
Boeing	1997-2016	4.9	6.6
Airbus Industrie	1997-2016	4.6	-
Rolls-Royce	1996-2015	4.9	6.7

Table 2.2 : Available Forecasts of World Scheduled Air Traffic Growth (ICAO, 1995a ; Rolls-Royce, 1997 ; Airbus, 1997 ; Boeing, 1997).

Table 2.2 indicates a “most likely “ average annual traffic growth rate of 5% in the next 20 years with international traffic expected to grow faster than domestic traffic. Economic slowdowns may affect these figures in the near term but are not currently anticipated to alter the long term growth in world air traffic. Aircraft movements in terms of aircraft departures and aircraft kilometres flown for the period 1992-2003 are expected to increase at average annual rates of 2 and 3% respectively. Based on these growth figures, Figure 2.2 presents the growth forecast until 2020 for passenger traffic.

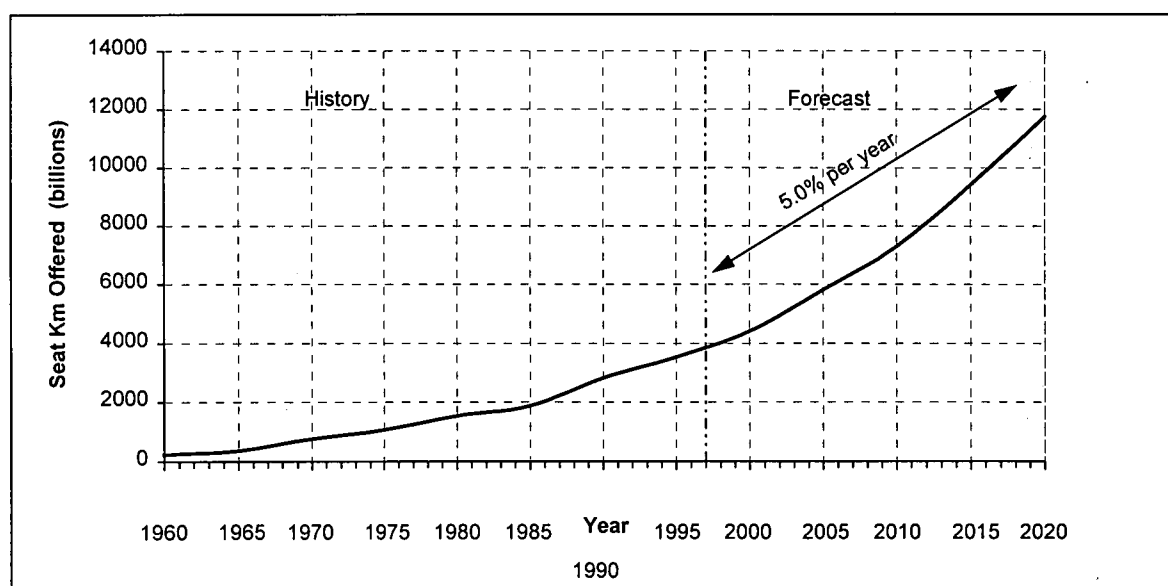


Figure 2.2 : Air Passenger Traffic Growth Forecast to the Year 2020 (Cook, 1997)

Provided that global economic development is not halted by a significant war or economic crisis, the demand for civil air transport is likely to continue to expand. Future growth of air transport will continue to depend primarily on world economic and trade growth and airline cost developments (which are in turn heavily dependent on fuel prices). The shape and size of the air transport system will also be affected by governmental decisions, notably those determining the type and extent of economic regulation of airlines. However, this growth will also be influenced by the extent to which the industry faces up to major challenges such as airport and airspace congestion, increasing capital investment needs, and environmental protection (both noise and emissions).

2.3.2 World Aviation Fuel Use

The continuing long-term rising trend in global aviation traffic implies a rising total fuel requirement, though at a lesser rate of increase because of the likely continuing introduction into the fleet of new aircraft and engines with improved fuel efficiency and, possibly, because of more favourable operating conditions and improved load factors. Further improvements in fuel efficiency through technology and operational techniques are indeed possible. They will be reviewed in detail in Chapter 3.

The world demand for aviation fuel accounts for 5 to 6% of total world oil consumption (Goodger, 1994 ; Balashov *et al.*, 1992 ; Schumann, 1995). The consumption by military operators represents about 25% of the global aviation fuel requirement (Kavanaugh, 1988 ; Schumann, 1993). General aviation and turboprops consume a mixture of jet fuel and aviation gasoline which accounts for an even smaller proportion at approximately 5% (Balashov *et al.*, 1992 ; Kavanaugh, 1988). The remainder or approximately 70% is attributable to commercial jet airlines. These numbers are in agreement with those presented by Friedl (1997). More accuracy is difficult to obtain given the uncertain contribution from China and the former Soviet Union. For the future, a reasonable assumption would appear to be that total military usage will remain approximately constant. As a result, the commercial jet fleet consumption is likely to increase above and beyond 70% of the total aviation fuel demand, and that against a historical background of constantly improving fuel efficiency.

Since the beginning of the jet era in the 1950's, there has been strong economical and operational incentive to improve aircraft fuel burn. The commercial jet era began with the Boeing 707-120 and the Comet 4 which made their first respective flight in 1954 and 1958. They carried about the same number of passengers as their piston-engined predecessors but at 50% greater speed. The Boeing 707-120 was powered by four Pratt & Whitney JT3D turbofan engines each developing 75.6 kN (17,000lbf) of take-off thrust. The Comet 4 was powered by four Rolls-Royce Avon engines that developed 46.7 kN (10,500lbf) of take-off thrust. Since then the commercial jet engine has been continuously developed and refined such that today's engines burn 40% less fuel per pound of thrust (see Figure 2.3) than the Avon. This 40% improvement in s.f.c. has translated into a 70% reduction in fuel burn for a given payload and distance to fly.

However, the rate of improvement has levelled off in recent years, indicating how difficult it will be to gain significant further improvements. Advances in airframe design, lower weight and drag have also accounted for aviation's improved fuel efficiency over the last 40 to 50 years.

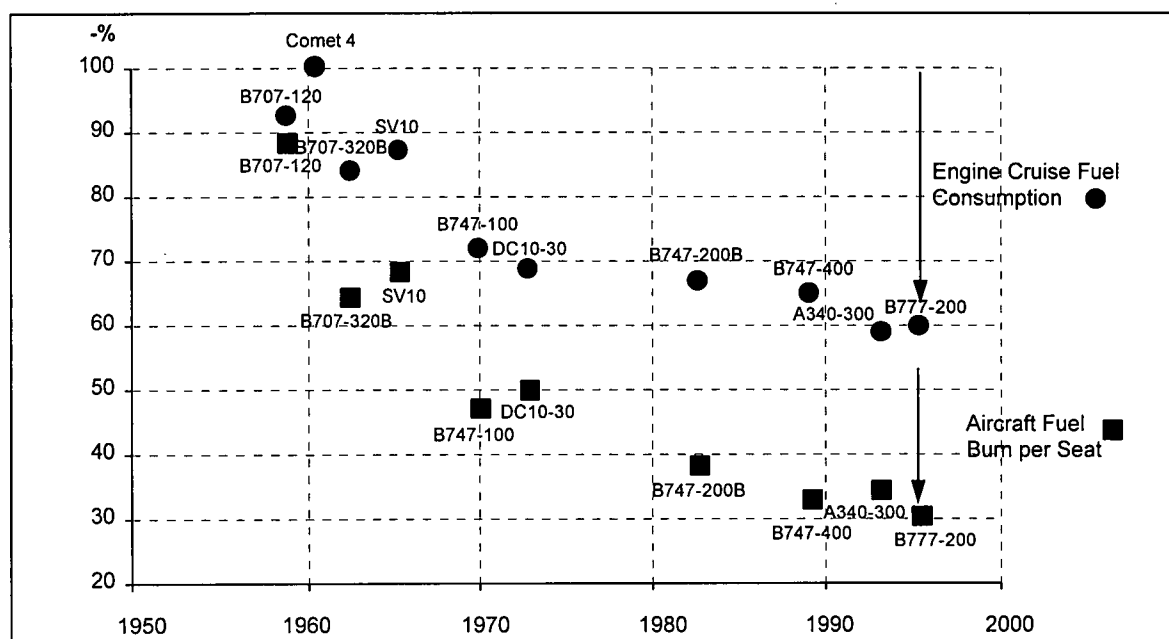


Figure 2.3 : Fuel Efficiency Comparison - Long Range Transport Aircraft (Cook, 1997)

Recent fuel demand forecasts prepared by the NASA and ECAC group of experts were reported to the third ICAO CAEP meeting in 1995 (Ralph and Newton, 1996). They show that the global civil aircraft fleet (passenger and cargo/freighter aircraft, excluding the former Soviet Union) consumed about 120 million tonnes of fuel in 1992.

According to Cook (1997), at today's technology levels, in order to meet the predicted growth in air traffic (likely average rate of 5% per annum), the global commercial aircraft fleet will need to increase from the current 16000 to over 26000 units by 2020, which will require approximately 360 million tonnes of fuel or 3.3 times the 1997 levels (average annual rate of 5%). This global commercial aircraft fleet includes passenger and freighter, jet and turboprop aircraft on scheduled and unscheduled services outside the former Soviet Union. Taking into account realistic improvements in fuel efficiency, the consumption would only rise to 280 million tonnes (2.6 times the 1997 levels, average annual rate of 4%).

Other studies have shown more conservative growth rates. Work carried out by ICAO in 1992 to quantify fuel consumption and to assess its future growth (Balashov *et al.*, 1992), predicted total civil aviation jet fuel consumption to grow at an average annual rate of about 2.5% over the period starting in 1990 and extending to 2010. Ralph and Newton (1996) predict that the civil fleet will consume 302 and 420 million tonnes of fuel by 2015 and 2040 respectively. Other studies covering periods up to 2025

(Schumann, 1994a ; Kavanaugh, 1988 ; Armstrong *et al.*, 1993) report a figure of between 2.2% (low fuel estimate scenario) and 3.6% (high fuel estimate scenario) annual growth, depending on various assumptions.

In spite of the predicted gains in fuel efficiency, the world aviation fuel burnt in the atmosphere is expected to rise strongly and steadily over the next decades at a likely average rate of 2.5% per annum. Unless the rate of reduction of emissions can match or exceed the expected growth in aviation fuel consumption, the implications of aircraft engine emissions on the atmosphere will become more significant in the future.

As will be discussed in Chapter 3, in terms of the balance between energy storage, operational properties, safety and economics, kerosene-type fuels do not appear presently to have strong contenders in prospect. As a result, the possible shortfall resulting from increasing aviation fuel demand and declining oil field production should be met by supplementation from other sources (tar sands, oils shales and natural gas) or by separate production of a manufactured kerosene-like fuel.

2.3.3 World Aviation Emissions

The restrictions regarding pollutant emissions in keeping with the internationally-accepted ICAO recommendations (Cf. Chapter 3) have resulted in the development and progress represented in Figure 2.4. The ICAO recommendations are applicable to NO_x, CO, UHC and smoke emissions.

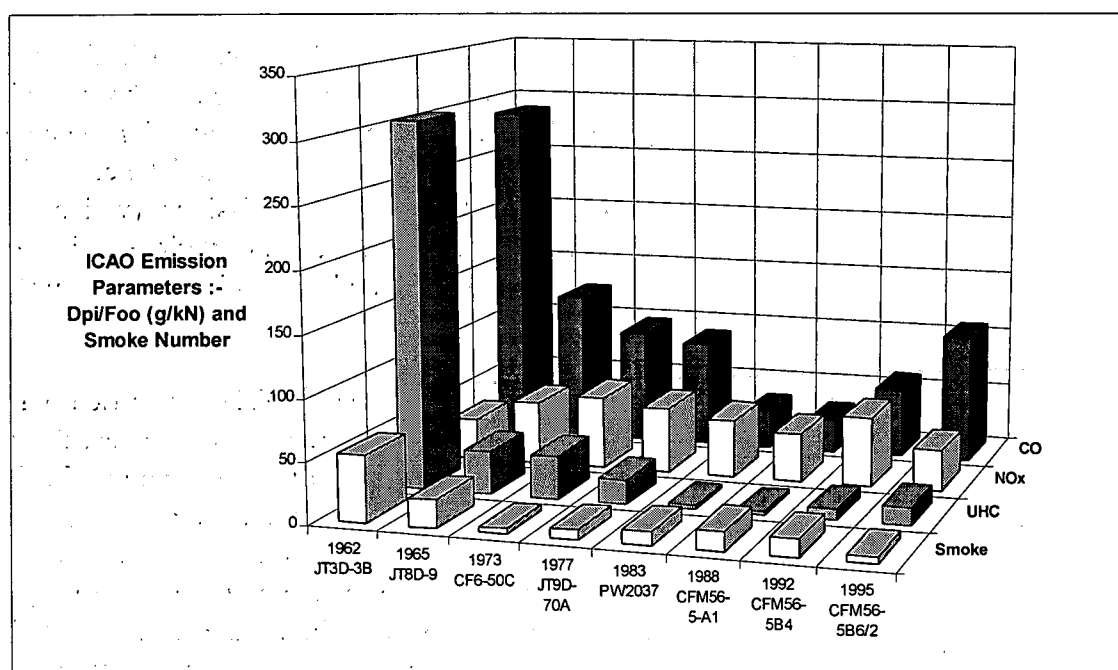


**Figure 2.4 : Development of Aero Engine Gaseous Emissions vs. Time
(ICAO LTO Cycle - ICAO Emissions Databank, 1993)**

In considering these figures, it is striking how in contrast to UHC and CO levels, which have been initially greatly reduced, there has been no similarly significant diminution in NO_x emissions. Improvements in jet engine fuel efficiency have resulted in much lower emissions of CO and UHC, but the higher combustion temperatures and higher overall pressure ratios which achieve have tended to push up the levels of NO_x. The more recent attempts to reduce NO_x levels have been carried out at the expense of CO and UHC.

Emission	Cruise Emission Index (g/kg fuel)	Emission Rates Mt/year in 1990	Comparable Emissions (Mt/year)	Remarks about the Comparable Emissions
Fuel	1000	176	3140	Total petrol consumption, extrapolated from 3095 Mt/yr in 1989
CO ₂	3150	554	20900	Burning of fossil fuels
H ₂ O	1260	222	45 525000	From CH ₄ oxidation in stratosphere Evaporation from Earth's surface
NO _x (as NO ₂)	18 (7-20)	3.2	2.9 ± 1.4 90 ± 35	Flux from the stratosphere All anthropogenic sources
CO	1.5 (1.5-10)	0.26	600 ± 300 1490	CH ₄ oxidation All anthropogenic sources
UHC	0.6 (0.2-3)	0.1	90	Ground anthropogenic emissions
Soot (C)	0.015 ± 0.014	0.0025		
SO ₂	1 (0.02-6)	0.176	0.0625 134	Required to sustain the background aerosol in the lower stratosphere Total from fossil fuel combustion

**Table 2.3 : Estimated Emission Rate from the World Aviation Fleet
(Schumann, 1993 and 1994a)**

Table 2.3 shows the estimated rates of the emissions released by aviation in the year 1990, and the comparable emissions from other sources, natural and anthropogenic (Schumann, 1993 and 1994a). The figures include civil commercial aviation, general aviation and military operators. They are meant to apply for long-distance cruise conditions. The most important uncertainty is that of NO_x emissions (which are quantified as if all emissions were NO₂), for which the upper bound of various estimates was selected. The total consumption of petrol is extrapolated from 1989 data from the International Energy Agency.

Looking to the future, the UK department of trade and industry (DTI) has carried out a study to attempt to assess possible future global cruise NO_x burdens over the near future (Ralph *et al.*, 1995). The study assumes a traffic growth rate of 5% per annum in the 1990's declining to 2.4% by 2040. Air traffic fuel efficiency trends were based on a number of studies. The work accounted for the change in fleet composition, as well as foreseen improvements anticipated by industry in engine technology, airframe weight and aerodynamics and air traffic management. As shown in Figure 2.5, the study illustrates the importance of fuel efficiency (two scenarios showed) and combustion technology improvements in reducing the NO_x emissions burden. The lower trends demonstrate the effects of introducing fuel-staged combustors featuring 30% lower NO_x

from 2005 for newly certificated engines and 2010 for all new deliveries. Ultra-low NO_x combustors achieving reductions of 70 to 85%, would be introduced in 2015 and 2020.

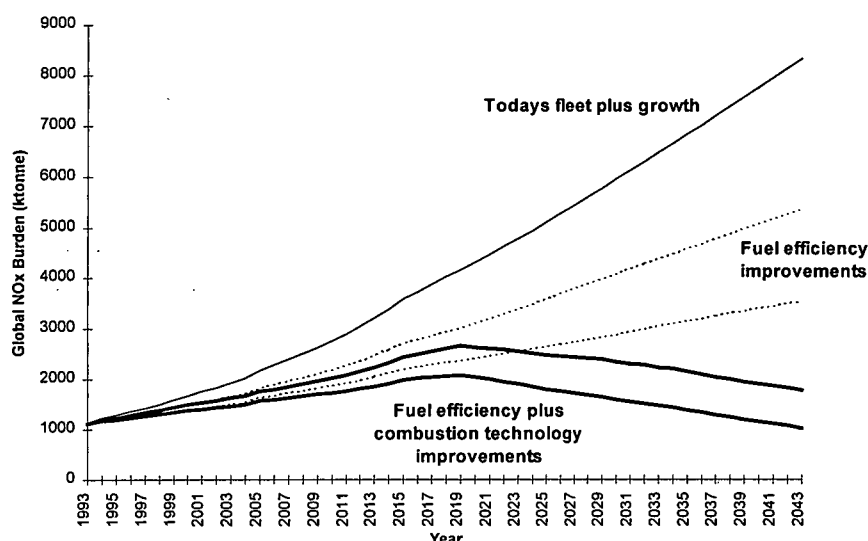


Figure 2.5 : Global Aircraft NO_x Burden Trend (Ralph *et al.*, 1995)

Another two studies of current and future emissions have been reported to the third meeting of the Committee on Aircraft Environmental Protection (CAEP) (Ralph *et al.*, 1996). The assessments were produced by the National Aeronautics and Space Administration (NASA) and the European Civil Aviation Conference (ECAC) group of experts on the abatement of nuisances caused by air transport (ANCAT) and are shown on Table 2.4. In broad terms, the studies show that the global civil aircraft fleet consumed about 120 Mt of fuel in 1992, and generated approximately 1.3 Mt of NO_x, 380 Mt of CO₂ and 150 Mt of water vapour. Assuming a traffic growth rate of 3.6, it is estimated that the more efficient fleet operating by 2015 will consume 2.5 times more fuel, producing 2.3 times more NO_x and 2.5 times more CO₂ and water vapour. As paralleled by the DTI study, the figure for NO_x in 2040 reflects the uncertainty about the ability of new technology to control such emissions.

Year	1992	2015	2040
Fuel	120	302	420
NO _x	1.3	3.0	2.4-4.4
CO ₂	380	953	1326
H ₂ O	150	372	517

In million tonnes ; The Forecast assumes traffic growth factor of 1.0 in 1992, 3.6 in 2015 and 6.5 in 2040.

**Table 2.4 : Predictions for Aircraft NO_x, CO₂ and H₂O Emissions
(Reported in Ralph *et al.*, 1996)**

Although any attempt to predict future trends over such a long time span carry large uncertainty, the various assessments show that fuel efficiency improvements only will

not be sufficient to reverse the trend of ever increasing global aviation NO_x . Low-emission technology providing NO_x reductions in excess of 30% and subsequently 80% over current levels will be necessary to reverse the trend. However, whether ultra low NO_x technology will be introduced remains uncertain. In this respect, given the long development timescales involved, new or alternative strategies to reduce the global NO_x burden and its impact - which may not be necessarily equivalent -, must be explored and assessed in parallel.

In addition to NO_x , low power emissions (CO and UHC) have been greatly reduced over the last decades. They may even be allowed to rise slightly to enable combustor technology to further reduce NO_x levels. Whether low power emissions can be further reduced with the current regulatory regimes will depend on the technical compromises arising from combustor technology, how the issue of air traffic congestion will be addressed, and the renewal rate of the global civil air fleet by new more fuel efficient aircraft. Finally, despite the strong economical and operational pressures to improve aircraft fuel burn, trends of increased carbon dioxide and water vapour global output are inevitable at an annual rate greater than 2.2% in line with the predicted fuel demand growth. Sulphur emissions should follow a similar pattern unless specific incentives are devised to remove it partially or totally by fuel treatment.

The future trends in global civil aviation emissions will ultimately depend on the environmental justification for reductions, the economic acceptability, the technologies available and the extent to which international agreement can be reached should the solution require operational measures. The past and possible future technical solutions and regulatory incentives to further reduce civil air traffic emissions are reviewed in Chapter 3.

2.4 THE ATMOSPHERIC IMPACT OF AERO ENGINE POLLUTANTS

2.4.1 Introduction

As presented in Section 2.2, important engine exhaust emissions include water vapour, carbon dioxide, nitric oxide and nitrogen dioxide (NO_x), sulphur oxides, carbon monoxide, unburned hydrocarbons and soot. The local environmental impact of such emissions in the vicinity of airports first drew public attention in the 1970's. A number of studies have since been carried out to assess the contribution of aircraft engines to emissions at and around airports (Williams *et al.*, 1979, 1981, 1990). Most of these studies concluded that the major emissions contribution was due to motor vehicle traffic, both at the airport and in the surrounding area, with air quality significantly better than at typical urban locations. However, as motor vehicle traffic has since come under stricter control, new studies will have to be carried out to re-assess the relative contribution of air traffic pollution in the vicinity of airports.

With attention now focusing on the global effects of Man-made emissions in the context of climate change, the emphasis has turned away from near-airport emissions towards aviation's global impact. In view of the expected major contribution from civil subsonic air traffic to aviation's total emissions output for the decades to come, the objective of this section is to investigate the impact of subsonic aero engine emissions at high altitudes in the upper troposphere and lower stratosphere. The effect of near-airport emissions as well as the impact of a future supersonic fleet of airliners have been chosen not to be addressed in this work.

The global environmental impact of these emissions depends on the relative change they induce in the background atmosphere and on their role in atmospheric photochemical, dynamical and radiative processes. Photochemical processing of such emissions can affect ozone and other important species. Climate change may result from changes in concentrations of radiatively important species (e.g. water, carbon dioxide, ozone and particles). Formation of contrails and cloud changes caused by subsonic air traffic emissions can also affect climate.

The fundamental implications of aircraft engine pollutants are presented in the following sections. Appendix B.2 will describe in more details the chemical processes and interactions leading to potential detrimental effects on the atmosphere. Following a description of some relevant properties of the atmosphere and an assessment of the chemistry occurring within the jet plume and the aircraft wake, the appendix reviews the atmospheric effects of each individual exhaust specie with an emphasis on those currently causing the greatest concern i.e. nitrogen oxides and water vapour.

2.4.2 Major Atmospheric Processes Affected by Subsonic Air Traffic

Chemical and radiative processes in the atmosphere can be affected by subsonic aircraft emissions. The most important ways in which these processes can be affected are :-

- The ozone balance in the upper troposphere and lower stratosphere can be perturbed by increases in NO_x and, to a lesser extent, by increases in carbon monoxide, water, hydrogen oxides (collectively referred to as HO_x) and non-methane hydrocarbons from aircraft. Aerosols produced from sulphur oxides, soot, and water emitted by aircraft may have an indirect effect on ozone concentrations through heterogeneous reactions that take place on aerosol surfaces.
- The radiative balance of the atmosphere can be affected both directly by the accumulation of carbon dioxide, water and other emissions from aircraft and indirectly through changes in ozone due to reactions involving NO_x and other emissions.

The radiative balance of the atmosphere can be further perturbed by aircraft-induced changes in aerosols and clouds. Chemical and physical processes occurring in the aircraft plume and wake produce aerosols and, under suitable conditions, rapid growth

of the aerosol particles produce visible "contrail" clouds. In addition to their direct radiative effects, these contrails may affect the radiative balance indirectly by increasing high cloud occurrence and/or changing cloud radiative properties.

2.4.3 Processes Occurring in the Jet Plume and Aircraft Wake

Research results to date (Friedl, 1997 ; Schumann, 1995 ; Louisnard, 1994 ; Schumann, 1993) indicate that the combined dynamical and chemical plume and wake processes have limited implications on engine effluents and in particular NO_x (see Appendix B.2). As knowledge stands at present, simple reacting plume models (simulating an isolated jet with no engine plume/aircraft vortices interactions) appear sufficient to bridge the gap between engine exhaust data and the global chemical and dynamical models. Using such models, maximum NO_x losses of some percent of the emitted NO_x have been observed. As to sulphur compounds, there are still uncertainties in the understanding of near-field nucleation processes. All other major species are not subject to significant chemical transformations in the wake. Beyond the exhaust plume and aircraft wake, exhaust emissions come to equilibrium with the ambient atmosphere.

2.4.4 Major Atmospheric Impacts of Subsonic Air Traffic

Climate impacts of aviation can be divided into *direct* and *indirect* effects. *Direct* climate effects caused by accumulation of water vapour, carbon monoxide, non-methane hydrocarbons, sulphur oxides, and soot emissions from the current and projected aircraft fleets are estimated to be small relative to aircraft carbon dioxide emissions. *Indirect* climatic effects of potential importance are related to ozone changes in response to aircraft NO_x injections and alteration of the formation and content of high-altitude clouds by aircraft particle injections. The magnitude of direct and indirect effects are still uncertain.

Both laboratory experiments and field campaigns have shown that the *direct* effect of NO_x on ozone is a complex function of background gas levels. Effects on ozone from aircraft emissions have not been discerned in existing long-term observational datasets, in part because of the year-to-year variability measured in tropospheric ozone. Furthermore, because of the large number of chemical species and reaction schemes in the atmosphere, there remains considerable uncertainty in the chemistry of tropospheric NO_x both in the gas and aerosol phase. Computer models are being continuously developed and improved to tackle the complexities involved and have offered valuable contributions to an initial poor understanding. The best computer tools are 3-D models that simulate the meteorological variability of the atmosphere and are able to represent the spatial and temporal variations in atmospheric processes. Such models are used to examine the impact of current and projected aircraft emissions on atmospheric chemistry and climate.

Studies undertaken by Friedl (1997) and employing a 3-D model suggests that current aircraft emissions contribute a significant fraction of the NO_x in the upper tropospheric region between 7- and 13-km : 5 to 10%, averaged globally and up to 20%, averaged between 30°N and 60°N. Although subject to substantial uncertainties, model studies suggest that emissions of NO_x from current aircraft have increased upper tropospheric concentrations of ozone, by about 1%, averaged globally, and 3% averaged between 30°N and 60°N. This corresponds to an increase in total column ozone of approximately 0.1%, averaged globally and 0.3%, averaged between 30°N and 60°N. Model calculations show that increases in ozone from growth in the subsonic fleet will be roughly proportional to the increased emissions of NO_x . Current emissions of NO_x from aircraft, through induced changes in atmospheric ozone (*indirect* effects), are estimated to have an effect on climate that is comparable to that from aircraft carbon dioxide emissions. As carbon dioxide and NO_x emissions increase in the future, the climate response will increase as well.

Current emissions of carbon dioxide from aircraft are 2.5% of the total emissions from fossil fuel use. Over the last 30 years, aircraft have contributed about 1.5% of the industrial increase in atmospheric carbon dioxide, or approximately 0.5 ppmv (parts per million by volume). In equilibrium this would lead to a calculated surface air temperature change of approximately 0.007°C. Current emissions of carbon monoxide and non-methane hydrocarbons do not have a significant effect on ozone in 3-D model calculations.

The *indirect* impact of increases in cloud cover due to air traffic are potentially significant relative to the *direct* effects of exhaust emissions accumulation. In some locations, high-altitude cloud cover has been observed to increase in conjunction with aircraft contrails. This correlation will have to be validated however by increased observational data and more knowledge on the physical interactions between aircraft exhaust and clouds. Because aerosol and cloud/contrail formation are non-linear processes with respect to environmental conditions and species concentrations, even small perturbations of H_2O , sulphur and soot may have significant impact. However, There are still large uncertainties in the understanding of such nucleation processes depending on location and microphysical conditions. As a result, the direct effects of particle injections, in the form of contrails, is difficult to predict.

Substantial improvements in the fundamental understanding and model treatment of upper tropospheric gas and particle sources and chemistry and transport processes are required before more credible quantitative ozone and climate predictions can be made. Future efforts are expected to focus on improving the predictive capabilities of 3-D chemistry and climate models through collection of critical field and laboratory datasets and further development of model parameterisations of atmospheric processes.

2.5 CONCLUSIONS

The major emissions generated by aero gas turbines burning kerosene fuel include water vapour (H_2O), carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbon (UHC), sulphur dioxide (CO_2) and smoke/soot/carbon particulates. Insignificant amounts of other trace species can also be found in engine exhausts which are ignored in this study.

CO_2 and H_2O pollutants are discharged in largest amounts with indices close to 3.1 and 1.3 kg per kg of kerosene fuel respectively. The water vapour index may vary slightly due to the ambient humidity level. The next largest emission outputs include NO_x , smoke, CO and UHC. CO and UHC are highest at low power during the start (sub-idle engine conditions), taxi, approach and descent flight phases (idle engine rating(s)). NO_x and smoke on the contrary attain maximum values at the higher power settings selected at the take-off, climb, one-engine-out and cruise regimes. The technology of the combustor and its operating conditions (local fuel-to-air ratios, inlet temperature, inlet pressure) will affect the magnitude of those emissions. Measured indices from recently certificated high bypass ratio turbofans ($\text{BPR} > 5$) show variations over the flight of 4 to 52 (NO_x), 0.05 to 46 (CO) and 0.005 to 5 (UHC) g per kg of fuel (1995 addendum to the ICAO emissions data bank).

Of such exhaust emissions, those currently considered to exert the greatest impact on the earth's atmosphere include NO_x , H_2O and CO_2 . The effect of CO, UHC, soot, smoke and SO_2 have and are being investigated and may prove in the future to play a part in the most critical pollution processes. However, as knowledge stands at present, they are not considered to play an important role and will be ignored in the present investigation.

It is estimated that subsonic aircraft contribute to about 3% of the global anthropogenic NO_x output. However, a significant proportion of the NO_x produced by medium and long range traffic is released at high altitude where generally there are no other sources of direct emissions. Aircraft NO_x generated by aircraft are responsible for tropospheric ozone increases and stratospheric ozone destruction mechanisms which contribute to global warming.

Water vapour is one of the most important greenhouse gases and volumetrically, is the most significant pollutant of the jet's exhaust stream. Air traffic contributes to only 0.04% of the global emission rate (natural and man-made). However, the water emitted by air traffic at high altitudes condenses into contrails. The resulting cloud coverage contributes to global warming. Furthermore, the frozen water can combine with NO_x to form polar stratospheric clouds or nitric acid clouds which lead to ozone destruction. The large residence time of both emitted water and nitrogen oxides enhance this process. Emitted water is therefore key to both increased global warming and decreased ozone protection.

Volumetrically, CO_2 is the second most significant pollutant of the jet's exhaust stream. It represents the principal anthropogenic greenhouse gas responsible for most of the

enhanced greenhouse effect. Because of the small contribution of air traffic to the global CO₂ inventory at approximately 2-3%, aircraft-generated CO₂ is often relegated to a secondary position. However, despite its small contribution to man-made yearly output, it remains important to consider because of its longevity, its abundance, its inevitability from jet fuel combustion, and its addition to an already CO₂ burdened atmosphere.

The current limitations in environmental science mean that assessing the impact of these three major pollutants is still subject to a huge range of uncertainty. In order to improve our understanding, further research into aviation's global impact will be required including direct measurements in-flight (which are in their infancy) and/or the use of the very few existing altitude simulation test cells (which are highly expensive). Nevertheless, at present, given the most critical long term implications, the routes to reduce aircraft-generated NO_x, CO₂ and H₂O levels deserve to be thoroughly investigated. The various routes and regulatory standards employed to date as well as envisaged for the future will be discussed in Chapter 3.

Civil aviation traffic and fuel demand are predicted to grow at an average annual rate beyond 5% and 2.2% respectively for the next 20 years or so. These forecasts account for changes in fleet composition and include assumptions of increased fuel efficiency credited to the global fleet. Given that it is widely acknowledged throughout the aviation industry that kerosene will remain the dedicated fuel for the jet-powered fleet (be it manufactured) during that period, trends of increased CO₂ and H₂O emissions are inevitable at an annual rate of 2.5% in line with the predicted likely average growth in fuel demand. The fate of global aircraft NO_x is more complex. To reverse its upward trend, it appears that low-emission technology providing NO_x reductions in excess of 30% and subsequently 80% over current levels will have to be introduced around 2010 and 2020 respectively. Such growth is likely to take place against a background of increasing public concern regarding the impact of aircraft engine emissions.

The evaluation of the impact of emissions from aircraft upon the atmosphere is based on the use of sophisticated global photochemical, radiative and dynamical models of the earth's atmosphere. To describe the atmospheric transport, diffusion and complex chemical reactions, these models require the amounts and composition of engine effluents as inputs to grid cells of the order of several hundred kilometres.

The limited computer simulations and local observations which have been made in the wake of airliners do not point out significant chemical transformations of engine effluents before they reach the grid size of global atmospheric models. In particular, CO₂ and H₂O reach the atmospheric background concentrations very rapidly while the maximum NO_x losses (occurring within the jet plume) appear to be about some percent of the emitted NO_x. These results would have to be confirmed by further studies introducing more gaseous and heterogeneous processes along the wake and in the contrails. As a result, it appears reasonable to use emission levels measured at the nozzle exit as inputs to the grid cells of global atmospheric models.

In the absence of comprehensive and published in-flight information, most research studies concerned with the simulation of global chemical processes produce their own profiles of pollutants from aircraft using data from the ICAO Engine Emissions Databank. These are fed as input to the models to study the resulting implications for the atmosphere. With the high-altitude emission data extrapolated from the near-airport data, there can be considerable discrepancy with the actual levels. This is reflected by the large variations among the emission indices used by various studies (e.g. range of 6-40 g/kg for NO_x). In order to assess the atmospheric impact of civil subsonic aircraft emissions either for a single flight or on a global scale, it is paramount to accurately predict the amount of emissions produced along the flight corridor with good spatial resolution. The present work will address this issue and establish a reliable method to estimate flight emissions (see Chapter 4).

Reduction of Aircraft Atmospheric Pollution : Legislation & Routes

3

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3.1 INTRODUCTION

In broad terms, the ability to reduce the global atmospheric pollution generated by the civil subsonic fleet depends on :-

- The global air traffic growth which is tightly linked to the world GDP growth.
- The fuel properties as well as combustor, aero engine and airframe technologies of the new aircraft introduced into the global fleet.
- The rate of replacement of polluting aircraft by new more environmentally efficient aircraft/engine combinations into the global fleet. This depends on the relative

competitiveness (cost, performance) of low-emission vehicles, the ability of the airline industry to finance new acquisitions and the traffic demand justifying such investments.

- The air traffic management system and airline operational practices as well as the productivity of the airline industry (load factors).
- The level of stringency and type of emission regulatory standards.

Ignoring the complex economic and supply/demand issues, this chapter describes the various regulatory, operational and technological measures available to reduce the global atmospheric effects of civil subsonic aircraft flight emissions. The review is based on the current state of knowledge on the subject. The possible technological routes include the alteration of kerosene properties, the use of alternative fuels, low-emissions combustor technology, aero engine cycle design and airframe design optimisations. The optimisation of engine cycle and flight operations represents two measures that will be tackled in detail in Chapter 5.

3.2 LEGISLATION

3.2.1 Introduction

Public awareness of air traffic as a nuisance source has its roots in the rapid expansion of jet powered air services from the 1950's. The public pressure towards air traffic grew against a background of severe air quality problems in urban areas due to the growth of ground-based transportation and power generation.

The first legislative moves appeared in the USA where some local areas initiated their own standards for air quality, until the US Federal Government enacted legislation to ensure a consistent application of standards and control methods across the country. Other nations were experiencing similar problems. As a result, the International Civil Aviation Organisation (ICAO) called for standards and controls to be agreed and applied on an international basis.

Aircraft smoke and fuel dumping were immediate targets, which, by the beginning of the 1970's, became largely controlled thanks to fuel system modifications and engine combustor retrofits. UHC, CO and NO_x were also identified as targets of likely controls. The fuel crises of the 1970's provided added impetus for aero engine manufacturers to improve the relatively poor idle efficiency of the prevailing engines, resulting in substantial reductions in UHC and CO emissions. NO_x proved far more difficult to control.

In setting standards, the difficulty faced by legislators lies in balancing both airport and global environmental protection, technological feasibility, appropriateness to type and economic acceptability. In addition, sufficient time must be allowed for the required technologies to be developed before those standards can be effectively enforced.

3.2.2 Early US Legislation

Passage of the US Clean Air Act in 1965 paved the way for the control of aircraft emissions. Following an amendment in 1970, the Environmental Protection Agency (EPA) was asked to establish standards applicable to emissions from any class of aircraft which it judged to contribute to pollution which endangers the public health or welfare. After public hearings, emission standards and test procedures for aircraft engines were formally agreed in June 1973 (Environmental Protection Agency, 1971, 1972 and 1973). The total cost to the American airline industry of implementing these requirements was estimated to represent an increase of at most 3% in the purchase cost of new commercial engines.

The EPA established engine classes to classify the various sizes and types of aircraft engines for regulation. The quantification of aero gas turbine pollutant emissions is based upon an operational airport cycle, defined as the Landing and Take-Off (LTO) cycle. The cycle includes all operations performed by the aircraft below 3000 ft (914 m) i.e. starting, taxi-out, take-off, climb-out to 914 m, approach from 914 m, landing and taxi-in. The altitude is typical of the thermal inversion in the atmosphere over major cities. The EPA emission standards specify maximum permissible levels for CO, UHC, NO_x and smoke. The gaseous emission limits are expressed in grams of pollutants per kilonewton of rated thrust per hour of operation (EPAP or EPA Parameter), and the smoke limit in smoke numbers which is a measure of visibility of the exhaust established by the Society of Automotive Engineers (ARP 1179, 1970).

While fuel venting and smoke standards were progressively to take effect from January 1974, the progress in developing low emissions technology was not rapid enough to meet the compliance schedule. These standards generated considerable controversy, with aircraft engine manufacturers arguing that the CO and NO_x regulatory levels could not be met without unacceptable cost and performance penalties with then-available technologies.

Work carried out by the two principal US manufacturers under contract to NASA in the Experimental Clean Combustor Program led to the design of two experimental staged combustion systems. Although these designs were capable to meet the EPA's proposed 1979 standards, the cost in combustor complexity was judged too large and the concepts were considered unable to meet potential low-NO_x requirements in the upper-atmosphere. In 1976, the EPA issued revised standards which lowered CO and UHC levels, followed, in December 1982, with the deletion of NO_x and CO restrictions which were never incorporated in the certification process, leaving only the regulations on smoke and UHC.

3.2.3 The ICAO Recommendations

3.2.3.1 The Concern Over Airport Air Quality : The LTO Cycle

Along the US regulatory developments, the International Civil Aviation Organisation (ICAO) was pursuing a policy of ensuring international agreement on the control of aircraft engine pollutants in the vicinity of airports. The ICAO initiated work related to the development of standards, recommended practices, procedures and guidance material dealing with the quality of the human environment from 1971. This led to the formation of the Committee on Aircraft Engine Emissions (CAEE) in 1971 to gather considerations from experts and member States on three identified issues : 1) the environmental impact of aircraft engine emissions, 2) the development of limiting levels and of a compliance procedure, and 3) the developments in instrumentation and measurement techniques. The standards had to be based on technical feasibility and economic acceptability with no compromise on airworthiness.

CAEE developed standards in 1980, which were adopted with a number of amendments by the Council after consultation with member States and became applicable in 1981. They became what is now known as the ICAO emissions recommendations (Annex 16, Vol. II - Aircraft Engine Emissions). The CAEE was then merged with the committee on noise to form the Committee on Aviation Environmental Protection (CAEP) to review and revise appropriately the recommendations. With the establishment of these international standards, the US accepted its obligation under the Chicago Convention on International Aviation, and amended the EPA standards to be as compatible as possible with ICAO standards.

The ICAO standards are based on the LTO cycle, an operational cycle around airports similar to the early EPA LTO cycle (see Figure 3.1). They are expressed in terms of a parameter that consists of the total mass in grams of any given gaseous pollutant emitted during the LTO cycle per kilonewton of rated thrust at sea level (see relationship 3.1). It can be seen that improving s.f.c. results in a direct reduction of the gaseous pollutant levels.

$$(3.1) \quad \text{ICAO Parameter} = \sum_{i=1}^4 \left(EI_i \times s.f.c._i \times \frac{F_i}{F_{00}} \times T_i \right)$$

Where :-

i	Mode (see Figure 3.1)
EI	Emission Index (g/kg of fuel)
s.f.c.	Engine s.f.c. (kg/s/kN)
F/F ₀₀	Power setting (see Figure 3.1) ; ratio of SLS net thrust in mode i to the SLS take-off net thrust.
T	Time in mode i in s (see Figure 3.1)

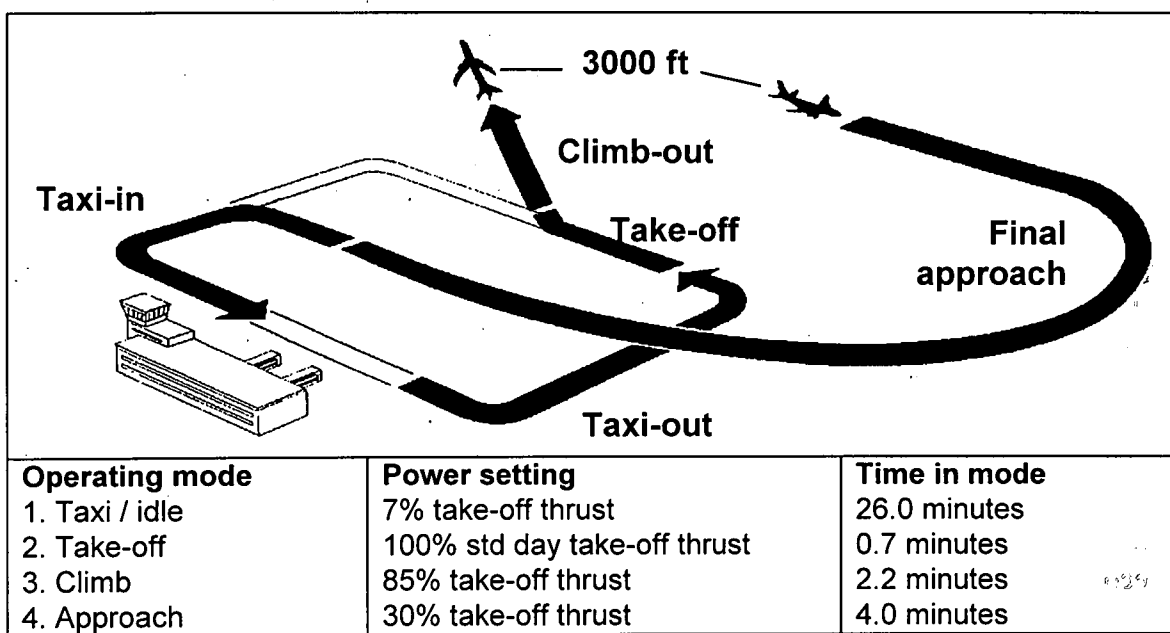


Figure 3.1 : The ICAO LTO Cycle

The historical evolution of the standards are presented in Table 3.1. They have been regularly reviewed since their introduction in 1981. Covering both subsonic and supersonic propulsion systems, they are related to engine rated take-off thrust and applicable to newly manufactured engines with rated take-off thrust greater than 26.7 kN. Type test certification is required for compliance.

CAEE/CAEP Meeting	Annex 16 Vol. 2 Amendments	NO _x	Change*	CO	UHC	Smoke
1981 (CAEE)	Issue 1	40+2 π_{00}	datum	118.0	19.6	min of 50 and 83.6(F ₀₀) ^{-0.274}
1986 (CAEP/1)	No amendments	-	-	-	-	-
1991 (CAEP/2)	Issue 2	32+1.6 π_{00}	-20%	-	-	-
1995 (CAEP/3)	Proposal rejected	19.2+1.6 π_{00}	-16%	-	-	-
1998 (CAEP/4)	Issue 3	See below	0 to -20%	-	-	-
Standards are applicable to newly manufactured turbojet/turboprop engines with rated take-off thrust greater than 26.7kN ; π_{00} = engine pressure ratio at take-off ; F ₀₀ = rated take-off thrust						
* : Variations are shown relative to the preceding levels and referenced against a pressure ratio of 30.						
CAEP/4 NO _x Standards						
Rated Thrust	0 < π_{00} < 30		30 < π_{00} < 62.5		62.5 < π_{00}	
F ₀₀ > 89 kN	19 + 1.6 π_{00}		7 + 2 π_{00}		32 + 1.6 π_{00}	
26.7 < F ₀₀ < 89 kN	37.572 + 1.6 π_{00} - 0.2087 F ₀₀		42.71 + 1.4286 π_{00} - 0.4013 F ₀₀ + 0.00642 π_{00} F ₀₀			

Table 3.1 : Evolution of the ICAO Standard for Subsonic Engines

The ICAO value for UHC and smoke are equivalent to the EPA standards. The NO_x standard makes allowance for the increase of this pollutant with increasing compressor outlet temperature. The intention of the smoke standard is to eliminate any visible

smoke from the engine exhaust. As smoke visibility depends on both the smoke concentration, as indicated by the value of SN, and on the viewing path length, the allowable SN of a high thrust engine is lower than for a low thrust engine because of its larger exhaust diameter.

CAEP has to date held four major review meetings in June 1986 (CAEP/1), in December 1991 (CAEP/2), in December 1995 (CAEP/3) and in April 1998 (CAEP/4). In so doing, the committee reviewed monitoring studies from a number of airports as well as current and future engine technologies able to reduce emissions together with the timescales for implementation. The adverse effects of increased stringency on both economics and airworthiness were also assessed.

In view of the continuing pressure to reduce NO_x emissions from all sources, the NO_x standards were made more stringent following the recommendation of the CAEP/2 meeting in 1991, with the original limits being reduced by 20% (against a reference pressure ratio of 30). The third meeting in 1995 (CAEP/3) proposed to the council a further 16% tightening of the NO_x standard referenced against the same pressure ratio of 30 with the allowance for pressure ratio remaining unchanged. The change was however judged too stringent for high pressure ratio engines which can offer low CO₂ emissions and the proposal was rejected by the council. A fourth meeting held in 1998 (CAEP/4) devised a set of five regimes to limit NO_x emissions. Their applicability depends on pressure ratio as well as rated thrust. An allowance is included for low-thrust engines (below 26.7 kN), which for reasons of physical size, have difficulty in incorporating the best low-NO_x technology. The proposed limits are applicable to new engine types first certificated after 31 December 2003.

Studies conducted in preparation of the CAEP/2 and CAEP/3 meetings have indicated that the situation around airports has not changed markedly since 1980 (Mortimer, 1996). A number of pollution surveys at Gatwick airport (Williams *et al*, 1990) conducted in preparation of the 1991 CAEP/2 meeting have shown that aircraft only contributed around 20% of the NO_x concentration at Gatwick main terminal. Road traffic travelling to or from the airport was responsible for 14% with the vast majority coming from non airport sources, nearby industries, motorways, railways, etc. Most aircraft now emit very low levels of smoke. In addition, typical modern engines have combustion efficiency in excess of 99.5% at idle, therefore producing very small amount of UHC and CO. As a result, the UHC, CO and smoke standards were maintained unchanged at the two last meetings. The benefits of attempting to improve these further may depend on the extent to which road traffic and non-airport sources have been able to curb emissions since the beginning of the 90's. Further reductions may be achieved at the airport through the use of electric vehicle to tow aircraft during ground operations. Further improvements to airport quality can be expected as the most polluting aircraft are phased out.

The adoption of the standards by the key nations manufacturing aero engines has meant that, at least in the Western world, all new aero engines meet ICAO recommendations. However, owing to the longevity of aircraft in service (up to 25 years), the full benefits

of improved technology only slowly feed through into the world's aircraft fleet. As a result of ICAO Recommendations, compared with 1970's technology, considerable reductions in UHC and CO have been achieved (typically 90% and 70% respectively), whereas only smaller NO_x reductions could be implemented (approximately 10%). Had there be no improvement in combustor technology, increases in NO_x levels would have been observed due to higher overall pressure ratios.

3.2.3.2 The Concern Over High Altitude Emissions

Through its committee on Aviation Environmental Protection (CAEP), ICAO has initiated contacts with other international organisations aimed at reaching a consensus regarding the extent to which aircraft engine emissions are contributing to global atmospheric pollution. This initiative has led to increased co-operation with those responsible for the IPCC and Montreal Protocol scientific assessment. CAEP is currently advising on inventories of aircraft emissions for use as inputs to atmospheric chemistry/climate models.

ICAO has to consider the future regulatory environment for civil aviation within the context of various international agreements and protocols. They include the Montreal Protocol on substances that deplete the ozone layer, the Framework Convention on Climate Change (FCCC) and the Sofia Protocol on NO_x (part of the Convention on Long Range Transboundary Pollution).

Beginning at its second CAEP meeting, ICAO has taken precautionary actions to reflect the increasing concern over the global impact of high altitude aviation emissions as well as the current uncertainty over the magnitude of the effects. Of the emissions currently covered by Annex 16, only NO_x has been considered by ICAO as possibly implicated. The tightening of the NO_x regulatory limit by 20% was agreed at its CAEP/2 meeting in December 1991. These changes were made to the existing certification regime based on the LTO cycle. Recognising that the impact of aircraft emissions on ozone depletion and global warming could have serious implications for the anticipated growth of the aviation industry, CAEP agreed that its third meeting in 1995 should address issues regarding high altitude subsonic aircraft emissions :-

- The environmental need for reducing aircraft emissions
- The technical feasibility, safety and economic acceptability of reducing pollutant emissions from civil aircraft and NO_x in particular
- Alternative operational procedures to reduce aircraft emissions

By the time of CAEP/3 in 1995, despite the development of a growing body of scientific data, no conclusive evidence of the environmental effects of aircraft-generated pollutants (in particular NO_x) was available. While accepting that the need for reducing NO_x standards had yet to be proved, CAEP/3 recognised that there was technical scope (Cf. Section 3.3) for increased stringency on the basis of the so-called "precautionary principle" (Mortimer, 1996). As used by United Nations agencies, this expression

means that where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing cost-effective measures to prevent environmental degradation. While the CAEP/3 proposal was rejected for being too strict for high pressure ratio engines, the ICAO Council accepted the less stringent CAEP/4 standard.

This is because controlling NO_x may well increase the production of some other engine exhaust species such as CO_2 , H_2O , SO_2 and particulates, reflecting the central dilemma facing engine designers involved in reducing NO_x . The high inlet combustor temperatures and pressures required to achieve peak efficiency and hence reduced fuel consumption (together with CO_2 , H_2O and SO_2), lead to increased oxides of nitrogen unless combustor technology can also be improved. Another reason for not recommending an increase in stringency was the need to allow manufacturers scope for the development of their engines. As the aircraft take-off weight rises during development, engine pressure ratios have to rise to provide the thrust and s.f.c. required to meet the aircraft payload-range capability. Such developments result in adverse effects to the engine ability to maintain low NO_x levels. This fact was recognised when the ICAO NO_x limits were developed and was allowed for by establishing a limit which is made less stringent as pressure ratio rises.

3.2.4 Sweden's Emission Tax

Sweden pioneered the use of pricing mechanisms to limit emissions from its scheduled domestic commercial aviation. The purpose was to create an incentive for airlines to introduce environmentally acceptable aircraft engines at Swedish airports (Westerberg, 1994). The emission tax was introduced in 1989 to the tune of Kr 12 per kilogram of NO_x and UHC emitted. In addition, Sweden also decided to tax CO_2 emissions at Kr 0.25 per kilogram, a pollutant not included in the ICAO emission standards. The tax gave an incentive to the biggest Swedish domestic carrier to change the combustors of its Fokker F-28 powerplants, which dramatically reduced UHC and CO emissions at major airports in the country. The tax however only affected 50% of Sweden's air traffic. As a consequence of European air traffic deregulation and the implementation of EU regulation in Sweden, the mechanism was suspended following Sweden's entry in the European Union.

3.2.5 Issues for Future Regulations

The adoption in the Western world of the ICAO standards has resulted in significant reductions in smoke, UHC (by approximately 90%), CO (70%) and more modest improvements in NO_x (10%) in the vicinity of airports. Further improvements in airport air quality can be expected as the most polluting aircraft are phased out. The pressure for even more stringent NO_x regulatory levels within the current certification regime will require extensive development of radically different combustors which will need to

gain the confidence of airworthiness authorities and customers, as no compromise on safety can be accepted (Lister, 1990).

As a result of the early concern for low airport air quality, the standards enacted since the beginning of the 1970's and currently enforced have been designed to control aircraft emissions below 3000 ft (915 m). Whilst it is questionable whether the current regime is well adapted to reduce high altitude emissions, given the large uncertainties surrounding the global environmental issues posed by aircraft, ICAO's precautionary response has been to tighten NO_x standards using the original LTO cycle regulatory regime. The project's contribution to this issue will be to investigate how the tightening of such standards affects the flight emission patterns of civil subsonic jet aircraft.

If air traffic continues to follow predicted growth rates, aviation's share of the global emissions burden may rise in spite of its current modest levels, as other emission sources come under stricter control. As a result, while the need to control emissions around airports through the LTO cycle will remain, there will probably be further attention by CAEP to creating a regulatory regime that addresses the global implications of high altitude aircraft emissions on the atmosphere (Wright, 1995).

The choice of action will depend on the level of certainty of scientific knowledge over global aircraft pollution issues especially from scientific assessment bodies such as UNEP/WMO on ozone depletion and IPCC on climate change. Aviation will continue to figure in considerations under the FCCC and Montreal Protocol, which in turn may influence future regulation. Water vapour, particulates and sulphate aerosols may well be added to the four species already considered by ICAO. One of the major resulting regulatory challenges is that the development of a future regulatory regime covering high altitude emissions, may require to move from an engine to an aircraft certification regime. The combination of engine, airframe and mission determines the flight emission levels. The same engine can power different airframes with quite different missions resulting in different impacts. In addition to further developments of ICAO Standards, other solutions that might need to be considered are operational measures and the possible use of pricing mechanisms (ICAO, 1995a).

3.3 ROUTES

3.3.1 Introduction

Measures that could contribute to reduce the atmospheric impact of aircraft emissions fall into two distinct categories : those designed to reduce the flight emission output and those designed to reduce the effects of these emissions. The present research work focuses primarily on measures designed to reduce the output of flight emissions. The reduction of the effects of such emissions requires to understand the chemical and physical processes in the atmosphere that could be adversely affected by aviation. Such effects have been discussed in Chapter 2 where it has been shown that large

uncertainties remain as to how best limit aviation's impact other than through low emissions technology and design. Based on the current state of knowledge, a range of possible measures to limit the impact are discussed in the literature, although not conclusively substantiated. They will be briefly explored in Chapter 5.

The possible routes to limit the output of flight emissions are reviewed in the following sections. Depending on the specie, the reduction of the flight emission output can be obtained either through fuel treatment, the use of alternative fuels, combustor design, aero engine design optimisation, airframe design optimisation or by implementing operational solutions. Because they will be subject to more detailed investigations in Chapter 5, two of these routes (aero engine cycle design and operational optimisations) will only be briefly introduced in this chapter.

The flight output D_p of any pollutant specie P can be integrated over the range covered R (ignoring the amount generated during start) :-

$$(3.2) \quad D_p = \int_0^R \frac{EI}{SAR} dr$$

Where the specific air range (SAR) can be expressed as a function of aircraft lift-to-drag ratio L/D , flight speed V_0 , engine s.f.c. and aircraft gross weight W :-

$$(3.3) \quad SAR = \frac{\frac{L}{D} V_0}{s.f.c. \times W}$$

The s.f.c. is taken here as the uninstalled s.f.c. with full account for the intake and exhaust effects. The propulsion system drag and weight are accounted for respectively in the lift-to-drag ratio and aircraft operational empty weight (OEW) terms.

Equations (3.2) and (3.3) show that minimising EI, maximising SAR at a speed and/or reducing the distances that needs to be flown can limit flight emissions. The emission index (EI) depends on fuel properties, combustor design and the engine operating conditions (combustor inlet temperature and pressure and fuel-to-air ratio). The engine operating conditions are a result of the choice of cycle. The fuel efficiency of an aircraft can be assessed through its specific air range (SAR) - also known as the fuel mileage - which represents the speed of travel divided by the aircraft rate of fuel consumption. To improve SAR at a speed, the s.f.c. must be reduced, the lift-to-drag ratio increased or the aircraft weight reduced.

Engine design has a direct effect on s.f.c. and contributes to the drag and weight of the aircraft. Lift to drag ratio and gross weight mainly depend on airframe design. The aircraft gross weight is the sum of the operational empty weight (including the powerplants weight), the payload weight (cargo and/or passengers), and the fuel weight. Because EI and SAR are interrelated, the cruise emission output is directly influenced by airframe and engine design as well as the way the aircraft/engine combination will be

operated. This will lead to conflicts between the requirements for low mission fuel burn and low flight emissions as will be seen in Chapter 5.

Chapter 2 identified NO_x , CO_2 , H_2O , CO and UHC as the pollutants at stake in this study. At cruise, medium to long haul subsonic civil aircraft (distance flown over 3000 nm) produce large quantities of NO_x , CO_2 and H_2O emissions (typically over 80% of the flight total) and smaller amounts of CO and UHC which are mostly emitted during low power operations in the vicinity of airports. Little can be done to reduce low power emissions (CO and UHC) other than through improvements in combustor technology or fuel quality as will be discussed further. Conversely, the amount of pollutant emitted at cruise is a valid yardstick to design and operate medium to long haul aircraft for a low output of NO_x , CO_2 and H_2O total flight emissions.

3.3.2 Kerosene Properties and Alternative Fuels

3.3.2.1 Kerosene Properties Affecting Pollutant Emissions

Smoke, CO, UHC, NO_x and SO_2 emissions can be affected by the quality of kerosene. The major properties influencing combustor exhaust emissions characteristics include hydrogen, aromatics, sulphur and fuel-bound nitrogen content, as well as viscosity and volatility.

Kerosene fuel properties can influence smoke production by encouraging the formation of local fuel-rich regions, and by exerting variable resistance to carbon formation (Lefebvre, 1995). The former is controlled by physical properties, such as viscosity and volatility, affecting the fuel mean drop size, penetration and rate of evaporation of the fuel spray, whilst the latter relate to molecular structure. It is also well established that smoking tendency increases with reducing fuel hydrogen content. A low hydrogen content (high C/H ratio) increases the kinematic viscosity, surface tension and specific gravity. The presence of aromatics is responsible for the formation of primary zone soot which enhances flame radiation and liner temperatures. The soot contributes to the production of exhaust smoke and has a detrimental effect on combustion performance and ultimately engine life.

Fuel volatility and viscosity control reaction time. For instance, falling volatility or increased viscosity will increase the fuel droplet lifetime and reduce the time available for chemical reaction resulting in higher CO and UHC emissions with associated poor combustion efficiency and ignition capability.

The production of NO_x within the combustor can be affected by the amount of organically bonded nitrogen as well as to some extent by the aromatics content. Light distillate fuels such as kerosene contains small amounts of fuel-bound nitrogen, less than 0.06%, but the heavy distillates may contain as much as 1.8% (Lefebvre, 1995). With current combustor technologies, the amount of NO_x resulting from fuel-bound

As petroleum resources diminish progressively and the aviation industry resorts to more viscous fuels, the quality of jet fuel slightly but steadily deteriorates. In the medium term, kerosene supplies could be supplemented from such alternative fossil sources as shale oil, tar and coal, but with associated continuing degradation in quality (Goodger, 1995). At a given combustor technology level, such a degradation is expected to cause small increases in smoke, SO₂, CO and UHC emissions as well as concerns with ignition and stability. The effect on NO_x is probably small.

The use of such alternative fossil fuels could require not only the re-design of combustor liners but also of the whole combustor so that these four species can be controlled (Blazowski, 1977). It is worth noting, however, that various routes for the production of synthetic kerosene-like fuels from natural gas have been recently examined (van der Burgt, 1989). The use of natural gas, one of the most abundant fossil energy sources, could avoid the substantial environmental problems associated with increasing exploitation of the tar sand and oil shale deposits (Armstrong *et al*, 1997).

3.3.2.3 Alternative Non-Fossil Fuels and Their Properties

In view of the expected long term future depletion of kerosene resources and recognising the specific difficulties in controlling emissions (especially NO_x) resulting from the combustion of that fuel, the use of alternative non-fossil aviation fuels such as methane or hydrogen is currently being investigated. Because the combustion of alternative fuels to kerosene are out of the scope of this work, this section presents only a brief discussion of those developments.

It can be observed from experience that, as a result of the lower flame temperature, fuels with low heat value generate lower NO_x levels at a given combustor technology (Bayle-Labouré, 1990). These fuels, however, result in higher s.f.c. requiring a larger fuel volume for the same mission. There is a benefit in using gaseous fuel in order to control NO_x at moderate flame temperatures (Snyder *et al*, 1994). Figure 3.2 illustrates the exponential dependence of NO_x on flame temperature for both gaseous and liquid fuels. Liquid fuels feature higher emissions because, even at relatively low equivalence ratios, near-stoichiometric combustion, with the resulting high temperature and consequently high NO_x formation, takes place in the region surrounding the fuel drops. At higher equivalence ratios, local conditions around the fuel drop approach the overall ambient conditions and both fuels generate similar levels of NO_x emissions.

nitrogen is small in comparison with thermal NO_x. In this regard, the reduction of fuel-bound nitrogen would provide few benefits.

The sulphur content of jet fuel is responsible for engine SO₂ emissions. The current jet fuel sulphur specification of 0.3 per cent weight is not a constraint for many refineries, as the sulphur content of the kerosene in the market place can be well below the limit in the region of 0.05% (Goodger, 1995). The technology to reduce or remove sulphur is available and could be implemented through increased stringency of the specification, should the environmental need and economic acceptability be demonstrated. Jet fuels can either be hydrotreated or wet-treated (Rivers, 1993). Hydrotreatment is the most effective but also more expensive process, removing sulphur compounds by converting them into hydrogen sulphide gas which can be separated off.

3.3.2.2 Kerosene Quality and Availability

The dwindling availability of the most suitable light petroleum crudes over the last 25 years has resulted in a general degradation in the quality of aviation kerosene, with adverse effects on emissions as well as combustion performance and engine life, except when combustor technologies emerged in parallel (Goodger, 1995). Indeed, the reduction of regulated engine emissions has so far been entirely catered for by combustor technology and not by improvements in existing fuel quality. The steady erosion of quality is confirmed by two surveys conducted between 1969 and 1992, as shown in Table 3.2 (Friedman, 1981 ; Bower *et al*, 1993).

Property			Jet A (US)			Avtur / Jet A-1 (UK)		
			1969	1979	Change	1984	1992	Change
Mercaptan Sulphur	% mass	0.003 max.	0.0002	0.0007	+0.0005	0.0004	0.0008	+0.0004
Total Sulphur	% mass	0.30 max.	-	-	-	0.0372	0.044	+0.0068
Aromatics	% vol.	20 max.	16	18	+2	-	-	-
		25 max.	-	-	-	18.7	18.7	0
Flash Point	°C	41/38 min	52.2	55.3	+3.1	-	-	-
	°C	38 min	-	-	-	43.71	44.2	+0.49

Table 3.2 : Recent Trends in Selected Properties of Jet Fuels
(Friedman, 1981 ; Bower *et al*, 1993)

Sulphur content is seen to have risen, and although aromatics content now appears unchanged, a rise has been noted within the intervening years. A slight reduction in volatility can also be observed. Rising sulphur and aromatics content and decreasing volatility may be expected in the future as greater reliance will need to be placed on the more severe refining of heavy crudes. While little treatment can be done to lower the aromatic content, the removal of the already low levels of sulphur generated by engines is technically feasible but expensive and would require more conclusive evidence about the global effects of SO₂. The observed property changes, although small, are yet undesirable from an environmental perspective.

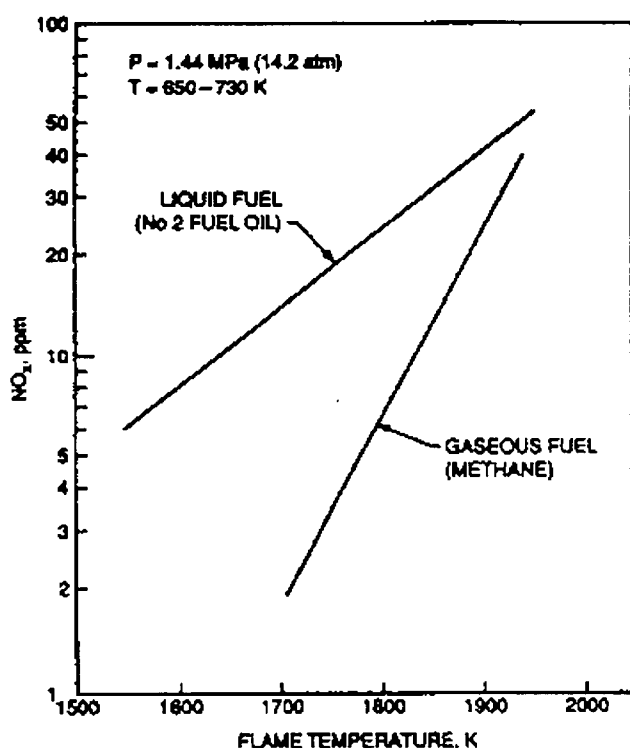


Figure 3.2 :
Dependence of NO_x on
Flame Temperature for
Liquid and Gaseous Fuels
(Snyder *et al*, 1994)

In the longer term, kerosene may be substituted by liquid methane or liquid hydrogen (Sosounov, 1989). In comparison with kerosene, methane produce less CO_2 while liquid hydrogen produces none. The N_2 based combustion products for hydrogen are much higher on a fuel mass basis but lower on an equal-energy basis. Finally, the flame temperature is lower with methane but higher with hydrogen, with the corresponding beneficial effects on NO_x .

However, the costs associated with the use of hydrogen are currently the key deterrent toward their use in commercial transport in the near future, with the most optimistic estimations higher than the price of kerosene (Gupta and Lilley, 1994). In addition to the basic fuel cost, account must be made to the ground and aircraft vapourised fuel losses and the provision of suitable infrastructure to distribute and store the fuel as well as to service the aircraft. Despite its advantage in specific energy, liquefied hydrogen is therefore unlikely to be introduced for large-scale use as an aviation fuel during the next 50 years (Armstrong *et al*, 1997), unless sever environmental constraints on carbon emissions force such a move.

3.3.3 Combustor Technology

3.3.3.1 Conventional Combustor Technology

As a response to emissions regulations, combustor technology has been until now the route to the reduction of smoke, CO, UHC and NO_x exhaust pollutants favoured by engine manufacturers. Because combustors are now designed with combustion efficiencies in excess of 99.5%, there is little the combustor designer can do to further reduce CO₂, H₂O and SO₂ emission indices. Further reductions would only be possible by means of improved aircraft fuel efficiency, the use of alternative fuels or the treatment of kerosene fuel (in the case of sulphur emissions).

In reducing smoke, CO, UHC and NO_x emissions, a technical compromise has to be found, not only between one specie and another, but also between one specie and the many other performance requirements such as size, low pressure drop, low wall temperatures, adequate ignition, altitude relight, blow out limits and outlet temperature distribution (pattern factor). It is possible to generalise and state that, with single annular technology, any change in operating conditions or configuration that reduces NO_x tends to exacerbate the problems of CO and UHC and vice versa.

As shown in Figure 3.3, during the past two decades or so, levels of smoke, CO and UHC have been successfully cut. This has been achieved through improvements in the fuel/air mixing (both aerodynamics and fuel atomisation) of single annular combustors (SAC) to prevent fuel reaching cooling films of air from being transported into the exhaust stream with little burning taking place. The efficiency of modern single annular combustors lies now above 99.5% producing low CO and UHC emissions, so that the benefits of further reductions seem unlikely. However, NO_x has proved far more intractable in spite of the various research efforts that took place since the early 1970s (see Figure 3.3). Because there has been an increasing demand for more powerful and fuel-efficient powerplants for twin-engined aircraft which have lead to increasingly adverse inlet combustor operating conditions, improvements in SACs have only been able to maintain or slightly reduce NO_x levels.

Today the pollutant emission of primary concern is NO_x. Low NO_x levels are readily achieved by lowering the peak flame temperature within the combustor. The challenge is to keep flame temperatures down at high-power conditions without incurring unacceptable penalties in combustion performance at low-power conditions.

The increased stringency of the ICAO standard for NO_x, which first became applicable in 1981, has been met by conventional single annular combustor technology through such measures as the use of advanced airblast fuel atomisation and aerodynamics and combustor shortening. With more recent high overall pressure ratio civil aero engine developments (such as those designed for the twin engine Boeing 777 application), advanced single annular combustor technology is still capable to cope with adverse

operating pressures and temperatures and meet the latest ICAO CAEP/4 standards adopted in 1998.

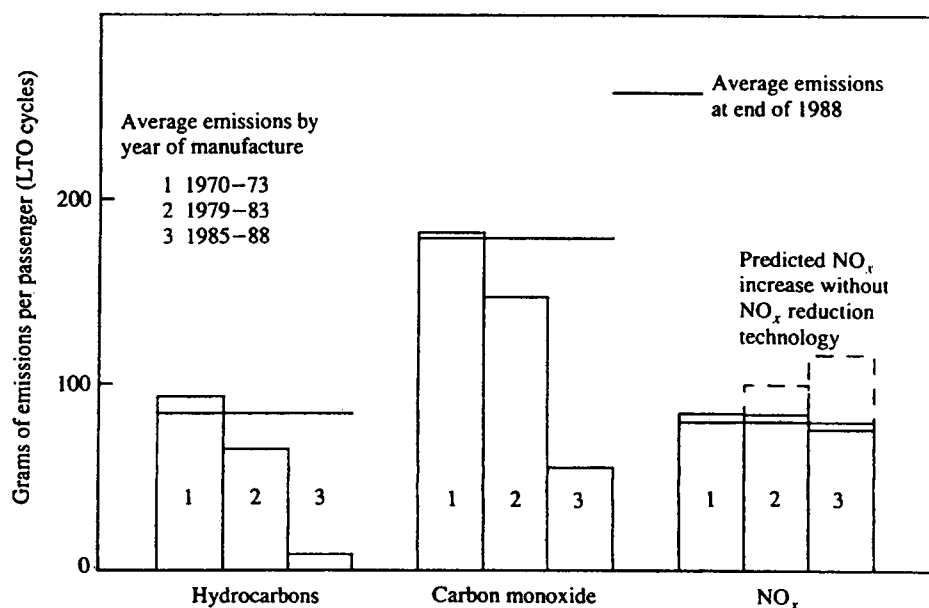


Figure 3.3 : Improvements in Emissions Levels with Time

3.3.3.2 Perspectives with New Low NO_x Combustor Concepts

Further tightening of the ICAO standards for NO_x beyond the 1995 proposal, such as a value of 30 g/kN with no allowance for the pressure ratio of the engine, would severely restrict the engine manufacturers design options with SAC technology. To approach this very low limit would require the adoption of complex staged combustors. Such technology has been proved to be capable to cut NO_x emissions by as much as 25-30% below levels attained by contemporary conventional single annular designs.

However, in anticipation of future tightening of the NO_x standards, manufacturers are actively investigating a range of ultra-low NO_x concepts which can reduce NO_x by between 30 and 80% relative to the current technology (RQL and LPP technologies appear currently more promising than catalytic combustion). Some of these combustors designed specifically for low NO_x first appeared in the 1970s, but remained on the shelf for another decade due to a greater interest during that time in reducing CO, UHC and smoke. Appendix C.1 discusses in detail the potential benefits and inherent penalties currently associated with these new technologies in relation to the currently widespread single annular design. The potential NO_x reductions and problems yet to overcome associated with these combustors are summarised in Table 3.3.

Combustion technique	Potential NO _x reduction	Problems to overcome
• Single annular (SAC)	datum	-
• Radial and axial fuel-staging	25-50%	Larger cooling requirement, increased complexity, high number of injectors, length of axially-staged designs, pattern factor of radially-staged designs
• Variable geometry	30-50%	Mechanical complexity, operational reliability, pattern factor
• Rich-burn, quick-quench, lean-burn (RQL)	60-70%	Radiation, exhaust smoke, quench mixer design, primary zone liner wall cooling, wall material thermal resistance
• Lean burn, premix, prevapourise (LPP)	80-90%	Autoignition and flashback at high OPR, acoustic resonance, variability requirement to maintain operability
• Catalytic	> 90%	Autoignition upstream of the catalyst, catalyst durability, variability requirement to maintain combustion efficiency

Table 3.3 : Future Low-NO_x Combustor Concepts

These techniques employ one of the two principal methods to reduce flame temperature and hence NO_x without unacceptable penalties in CO, UHC and smoke emissions as well as in combustion performance at low-power conditions : burning either fuel-rich or fuel-lean. While the former (RQL concept) has the advantage of offering a wide range of stable combustion operations, there is a difficulty in maintaining low levels of smoke. Furthermore, as excess air, not actively involved in the early reaction process, is added to the rich burning products, stoichiometric conditions are obtained that can lead to high NO_x. Fuel-lean combustion (remaining concepts) avoids these difficulties but can pose severe combustion stability and/or durability problems. There is also the added problem of ensuring as homogeneous a fuel-air mixture as possible in order to avoid locally stoichiometric or overrich regions that would generate large quantities of soot and NO_x.

Staged and variable geometry combustors are concepts founded on emissions reduction by control of flame temperature in fuel-lean conditions. The primary zone stoichiometry is controlled by adjusting the amount of fuel (radial and axial fuel staging) or air (variable geometry) going into the combustion zone. For the immediate future, staged combustors appear to be the most promising with the recent FAA certification of two GE dual-annular staged combustors. However, the realisation of their superior potential over single annular technology has so far been impeded by issues regarding durability (Mortimer, 1996).

At present, lean premixed prevapourised combustion (LPP) appears to be the only technology available to achieve ultra low NO_x emissions from practical combustors (Lefebvre, 1995). However, the problems of spontaneous ignition and flashback as well as acoustic resonance need to be fully addressed before the concept can be applied with confidence. The RQL concept is another ultra-low NO_x contender, whose prospects largely depends on the quick-quench design, a region where the combustion products

are moving from the rich primary zone to the lean dilution zone during a short period at high-temperature stoichiometric conditions. The RQL concept offers the widest combustion stability margins.

The concerns expressed for variable geometry and catalytic combustion at the operating conditions experienced by today's powerplants would appear to put them out of contention at this time, especially as both LPP and RQL techniques show almost equal promise with less risk. Considerable advances in high-temperature materials would be needed to raise the reliability of catalytic combustors to the standard required by aircraft engines.

3.3.4 Airframe Design

3.3.4.1 Improving Lift to Drag Ratio

As suggested by Equations (3.2) and (3.3), airframe design can contribute to low emissions by optimising specific air range (SAR). This can be achieved through the design of aircraft with high aerodynamic efficiency, the aim being to maximise the product of the speed by the lift-to-drag ratio at the desired cruise speed.

The aerodynamic deterioration of the aircraft surfaces must also be minimised over the lifetime of the aircraft. The degradation occurs as a result of deformations and dirt build up on the external surfaces (increasing skin friction drag). The deterioration of the aircraft lift-to-drag ratio generally accounts for one fifth of the total fuel burn deterioration, the remainder being related to the engine s.f.c. (Cook, 1996).

In cruise steady-level flight, lift balances weight while net thrust balances drag. The components of the total drag of a subsonic transport aircraft together with their typical contribution to the total are as follows :-

• Induced drag due to lift :	40%
• Skin friction drag due to viscosity of the air wetting the total aircraft surface area :	46%
• Pressure drag due to separation of the air flow from the surface at the afterbody and other regions :	6%
• Interference drag between components (e.g. engine and airframe) :	3%
• Parasitic drag due to miscellaneous effects such as surface area roughness and leakage from seals and gaps :	2%
• Wave drag due to compressibility effects of local transonic flows :	3%
• Total drag :	100%

Table 3.4 : Subsonic Transport Aircraft Drag Breakdown (Cook, 1997)

Improved aerodynamic design of aerofoils through the use of advanced Computational Fluid Dynamic (CFD) are anticipated to assist the reduction of the above drag components. The largest contributions to improved lift to drag ratio can clearly be made from reducing *skin friction* and *lift-induced* drag.

Advanced techniques are available to reduce *skin friction* drag through active or passive manipulation of the boundary layer including laminar flow control, turbulence management and the application of suction surfaces. Skin friction drag accounts for almost one half of the total drag in cruise. Laminar flow control consists in keeping the flow attached to the wetted surface to delay the onset of transition from laminar flows to high friction drag turbulent flows. The application of suction surfaces to the wing, fin and tail to achieve this could bring substantial benefits, even when suction pumping drag and power requirements are taken into account. The net benefits in total drag reductions may be as high as 40% (Cook, 1997). The main problems are with the need to keep the suction surfaces clean, the design and manufacture of the controlled aerofoils, the associated weight and cost penalties, and the reliability and maintainability of such a system in-service. Turbulence management works to manipulate the structure of turbulent flows to achieve drag reductions. This can take the form of a ribbed plastic film applied to the aircraft surface. Tests conducted by Airbus and 3M with this technique have achieved drag reductions of 1-2% (Szodruch *et al.*, 1990).

The *lift-induced* drag is the other main contributor to total aircraft drag, in this case about 40% of the total. It is inversely proportional to the wing aspect ratio, that is the ratio of the span of the wing to the average chord. Its magnitude can therefore be reduced by increasing the wing aspect ratio as well as by carefully designing winglets or wing tip fences that control the vortex flow. Recent advances in structural and aerodynamic design have increased aspect ratio such that values of 9-10 are now common. Winglets add effective span and hence aspect ratio. However, as aircraft become larger, the span constraints of existing airports will limit the leverage of aspect ratio in the reduction of total drag.

The Comet which made its first transatlantic flight in 1958 had a lift-to-drag ratio of 14.5, whilst that of the Boeing 777 and Airbus A330/340 family is close to 20. Further reductions in skin friction and induced drag can be expected in the next twenty years or so resulting in a predicted 10% increase in lift-to-drag ratio (Cook, 1997).

3.3.4.2. Reducing Aircraft Gross Weight

Another airframe design route leading to low fuel burn and hence emissions, resides in the reduction of aircraft gross weight whilst maintaining robustness and reliability. The Rolls-Royce Avon which powered the Comet had a thrust-to-weight ratio of over 3 whilst that of the Trent is over 5.

Of course, increasing the lift to drag ratio and improving the installed engine s.f.c. will result in a lighter aircraft to achieve a given mission. This will in turn require a smaller

propulsion system which will reduce the aircraft weight even further due to the snowball effect on engine and aircraft size.

The use of improved structural design and manufacturing and lighter materials can also contribute to reduced aircraft weight with a similar snowball effect between aircraft and engine weight. Future anticipated reductions in aircraft weight can be achieved by increased use of composite materials, advanced alloys such as aluminium-lithium and super plastically formed diffusion bonded (SPF-DB) titanium. Composite materials can offer 20% weight saving over a comparable light alloy structure. A 10% reduction in total structure weight could be achievable in the next twenty years or so (Cook, 1997), leading to a lighter, more fuel efficient aircraft exhausting less exhaust pollutants in the atmosphere unless the benefits are taken as an opportunity to introduce extra operational items such as inflight entertainment systems.

3.3.5 Aero Engine Design Optimisation

3.3.5.1 Introduction

The s.f.c., weight and drag of the propulsion system influence the specific air range (SAR) at entry into service and over the lifetime of the aircraft and as a result, affect the flight emissions. The weight and drag affect the gross weight and lift-to-drag ratio of the aircraft (see Equation 3.3). Besides, on the initial choice of cycle and materials for the engine as well as the airframe aerodynamic and structural design, depends the extent to which the flight emission levels will be maintained over the years. As an introduction to Chapter 5, the following sections will review qualitatively the effects of the s.f.c., weight and drag of the propulsion system on flight emissions, and explore the implications of engine degradation.

The propulsion system must offer sufficient thrust to meet the performance targets of the aircraft during all phases of its operation. Some of these targets are set against the requirements of the airworthiness authority certifying the aircraft whilst others may be determined by commercial competitive considerations. The regulatory authorities are concerned with the performance of the aircraft in the event of the failure of the most critical engine during take-off, approach to land and also en-route. The aircraft performance during these sectors of a flight is calculated from the declared maximum take-off and maximum continuous ratings of the engine. The maximum climb and cruise ratings are chosen to give acceptable level of operational performance assuming all engines operative. These ratings are often set by commercial requirements such as the time to climb and the engine ability to optimise the cruising altitude. The propulsion system must also offer adequate weight and s.f.c. to meet the aircraft payload-range capability. The weight and s.f.c. can be traded off against each other to meet the overall mission fuel burn target.

The choice of cycle to meet the performance and s.f.c. requirements will in turn affect the combustor inlet thermodynamic conditions and as a result CO, UHC and NO_x emission indices. Owing to the high efficiency of current combustors, CO₂ and H₂O indices, however, are a linear function of fuel flow and fairly insensitive to the main engine cycle parameters and combustor inlet thermodynamic conditions.

Although thrust, s.f.c. and weight are major requirements, a number of additional technical considerations constrain the cycle optimisation further narrowing the scope of candidate cycles. They include material capabilities (specific strength, thermal resistance, life, cost and availability), required engine life on wing, noise (which now poses serious constraint on the cycle's BPR), customer bleed air and power offtakes.

Economic factors can, however, ultimately well override these technical requirements and prevent the most attractive technical solution in term of SAR and flight emissions either not to be designed by the manufacturer or not to be selected by a specific operator. The profitability expected from the aircraft/engine combination will depend on the balance between customer revenue-earning capability and operating costs. In terms of operating costs, factors such as maintainability and reliability may well lead an operator not to select the most fuel efficient powerplant, provided that the reduced aircraft capability meet the operator's payload-range requirements.

3.3.5.2 Specific Fuel Consumption

Engine s.f.c. is inversely proportional to the thermal and propulsive efficiencies of the engine as illustrated by the following expressions :-

$$(3.4) \quad s.f.c. = \frac{V_0}{\eta_{ov} \times FCV}$$

$$(3.5) \quad \eta_{ov} = \eta_{th} \times \eta_{prop}$$

Where

η_{ov}	= Overall efficiency
η_{th}	= Core thermal efficiency
η_{prop}	= Propulsive efficiency
V_0	= Flight Velocity
FCV	= Fuel Calorific Value

Since the beginning of the jet era in the 1950's, there has been strong economical and operational incentives to improve aircraft fuel burn which have resulted in substantial improvements in engine overall efficiency and specific fuel consumption (See Figure 3.4) through increases in both thermal and propulsive efficiencies. Better thermal efficiency results from improvements in the engine thermodynamic cycle, in particular increased overall pressure ratio and turbine entry temperatures, while the higher bypass ratios are mainly responsible for the improvements in propulsive efficiency.

OVERALL EFFICIENCY

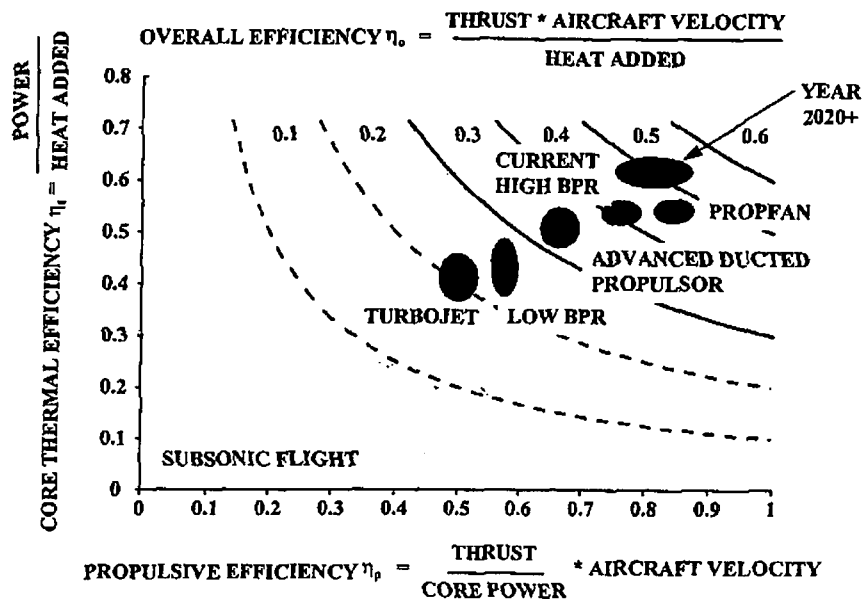


Figure 3.4 : Engine Cycle Thermal and Propulsive Efficiency Trends (Singh, 1996)

The early turbojets achieved overall efficiencies of about 20%. Low bypass ratio engines made available in the early 1960s offered overall efficiencies of 25% thanks to improved propulsive efficiency. Current high bypass ratio turbofans have achieved substantial improvements in both thermal and propulsive efficiencies and offer about 35% overall efficiency. Even higher overall efficiency, perhaps in the region of 50%, may be possible with ultra-high bypass ratio turbofans, such as propfans and advanced ducted propulsion systems. Increasing powerplant drag and weight may, however, negate the economic benefits of such increased propulsive efficiency.

Better thermal efficiency results from improvements in the engine thermodynamic cycle, in particular increased overall pressure ratio (OPR), turbine entry temperature (TET) and component efficiencies (see Figure 3.5). The arrow in Figure 3.5 indicates the trend of OPR and TET with time for large commercial turbofan engines since about 1970. The s.f.c. improvements are solely due to increased thermal efficiency. It reflects largely the progress made in materials and cooling technology, particularly in the high pressure turbine.

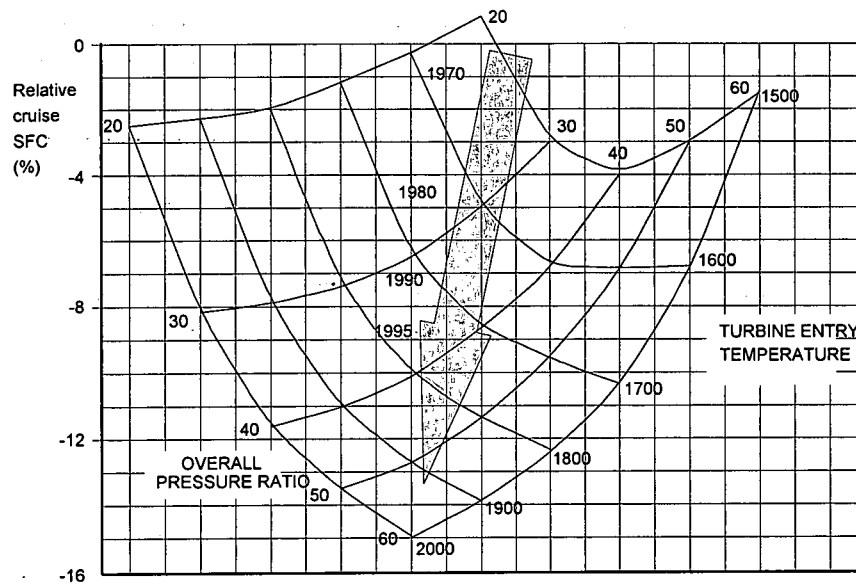


Figure 3.5 : Engine Cruise s.f.c. vs. Pressure Ratio and Temperature
(Le Dilosquer & Singh, 1998 ; Courtesy of Rolls-Royce plc)

A high bypass ratio (BPR) combined to a corresponding reduction in fan pressure ratio (FPR) is necessary to produce a high propulsive efficiency, whilst a high thermal efficiency requires to raise the work per unit gas flow through higher overall pressure ratio (OPR), higher component efficiencies and/or higher turbine entry temperatures (TET). Whilst absolute levels of water vapour, carbon dioxide and SO_2 emissions fall almost linearly with reductions in s.f.c., low NO_x requirements necessitate low combustion temperatures i.e. low OPRs and TETs. One of the objectives of the thesis will be to identify areas of conflict between low fuel burn (and hence low CO_2 and H_2O) and low NO_x requirements. Chapter 5 will review qualitatively the effects of the main engine cycle parameters on engine s.f.c. and emission indices with a particular emphasis on NO_x .

3.3.5.3 Propulsion System Weight

Determination of the optimum engine cycle for a specific aircraft requirement involves trade-offs among engine performance, noise, weight and dimensions. Most preliminary engine or engine/aeroplane design studies begin with a parametric study involving the main engine cycle variables. These variables include BPR, TET, OPR, air mass flow, design cruise Mach number and altitude, year of entry into service (reflecting the technology level). Such variables will influence the weight of the propulsion system (a component of the aircraft OEW) and hence flight emissions.

At a preliminary design stage, the propulsion system weight can either be determined from a general arrangement (component-by-component approach) or using semi-empirical correlations (overall engine approach). The former method requires a fairly detailed knowledge of the engine configuration. Although the component-by-component

approach can lead to an accumulation of errors, it is the most accurate of the two. The production of a general arrangement, however, requires detailed aerodynamic and mechanical design work using sophisticated design softwares. Given the timescales and wide objectives of the thesis, such an approach is not feasible. The overall engine approach determines the propulsion system weight based on the weight of existing engines. The method is statistical and based on a large number of designs spanning a long period of time (Gerend & Roundhill, 1970). It can also be based on the scaling of justifiably close engine designs. Given the timescales and for the purpose of predicting weights over wide ranges of cycle variables and configurations, the overall engine approach is considered to be superior and is described in Appendix C.2.

3.3.5.4 Propulsion System Drag

The net thrust calculated by a gas turbine simulation system is commonly referred to as the uninstalled thrust, which represents the bare engine streamtube net thrust corrected for inlet and exhaust nozzle losses. In order to assess the discrepancy between the uninstalled thrust calculated by the simulation system and the installed thrust which represents the actual forward force counteracting airframe drag, the drag generated by the installation of the propulsion system (nacelle and pylon) must be assessed, so that the aircraft drag polar can be corrected. Although propulsion system weight is included in the aircraft OEW throughout the thesis, the installed net thrust can sometimes also account for propulsion system weight.

Turbofan engines fitted to modern civil transport aircraft are typically housed in discrete nacelles mounted either on the wing or on the rear fuselage. The drag generated by the nacelle at a given flight condition very much depends on its dimensions and the location of the nacelle on the airframe. Airframe manufacturer's specifications such as the cruise drag rise Mach number and the engine-out requirement, as well as engine installation requirements including clearances, accessory positions and thrust reverser hard points will also affect the drag.

On the one hand, the choice of engine cycle influences the size and dimensions of the propulsion system's nacelle, governing as a result the external drag level of the isolated nacelle which contributes approximately 4-5% of the total aircraft drag (Rolls-Royce, 1998a). On the other hand, the dimensions and placement of the propulsion system on the airframe will be responsible for what is known as airframe/engine interference drag representing less than 1% of the total aircraft drag with a good installation. These two drag components make up the total drag generated by the installation of the propulsion systems and account for the discrepancy between uninstalled and installed thrust.

Nacelle and pylon isolated drag and interference drag affect the aircraft lift-to-drag ratio. From a modelling point of view, there are two ways to account for the total drag. The first is to correct the thrust of the isolated engine from an uninstalled to an installed figure that will be fed to the flight route model. The second is to correct the aircraft drag

polar for the propulsion system drag effects and feed the uninstalled net thrust to the flight route model. The latter approach is preferred.

Careful design is required to avoid excessive isolated nacelle drag particularly during cruising flight. Fundamentally, nacelle drag can be broken down into a number of components :-

- *Skin friction drag* arises from the viscosity of the air and is the largest single drag component of a well designed cowl at design conditions. It can be minimised by employing the smallest practical wetted area.
- *Form drag* (also known as boundary layer drag) is due to changes in surface pressure distribution which arise because the presence of the boundary layer changes the effective shape of the surface. It is usually a small proportion of the skin friction drag and is not a significant design parameter. The skin friction and form drag components make up the *profile drag*.
- *Spillage drag* occurs when the overspeed on the front of the nacelle either causes separation (low speed) or the formation of a shock wave (high speed). A good design will avoid operating in spillage at the design condition.
- *Wave drag* occurs when the freestream Mach number becomes high enough to give an area of transonic flow over the cowl, terminating in a shock wave. The drag increment is due to total pressure losses through the shock. The nacelle should have a drag rise Mach number which is high enough to avoid wave drag at cruise conditions.
- The presence of the jet gives rise to a modification of the surface pressures on the nacelle afterbody. These *jet effects* are a function of jet pressure ratio and freestream Mach number. The drag increments due to jet effects are relatively small for today's high bypass ratio engines.
- *Excrescence drag* is caused by steps and gaps on the nacelle external surface. It can be minimised by making these features as small as possible during manufacture.

When two bodies are placed in close proximity to one another, their combined drag is generally greater than the sum of their individual drag components, each measured in free flow. The difference $\Delta D = D_{1+2} - (D_1 + D_2)$ is termed the interference drag and is due to the mutual interaction between the bodies and resultant disturbances to the flows surrounding them. The disturbances manifests themselves by an alteration of the flow and pressure distribution over the entire aircraft, inducing forces on the external surfaces that increase the total aircraft drag. The interference drag is strongly dependent on the placement of the propulsion system on the airframe. With a well-designed nacelle and installation, interference drag can be minimised so that the total engine-related drag (isolated nacelle and interference) at cruise speed need not exceed by much the skin friction drag of a flat plate having the same wetted area as the nacelle (Williams, 1994).

The pod placements generally found in service can be fuselage-mounted (e.g. Boeing 717-200), tail-mounted (e.g. Lockheed Tristar L1011) or underwing-mounted (most commercial aircraft designs since the 1970's). The underwing mounting is now the preferred installation because it gives some bending relief to the wings, minimises aerodynamic engine/tail interference and offers the best compromise between low weight, adequate CG and wing location and one engine-out performance requirements. The position of the underwing pods are the result of a design compromise between powerplant weight, structural aspects of the powerplant/wing combination (e.g. torsional loads on the wing box), ground clearance and undercarriage length.

To put the propulsion system drag in perspective (nacelle and pylon) in relation to the total aircraft skin friction or profile drag, Figure 3.6 shows an example of a nominal breakdown of component drags for a four-engined long range aircraft with underwing pods. In this example, the share of the engine installation is 8% at cruise when the majority of the aircraft drag is due to skin friction (46% of the total).

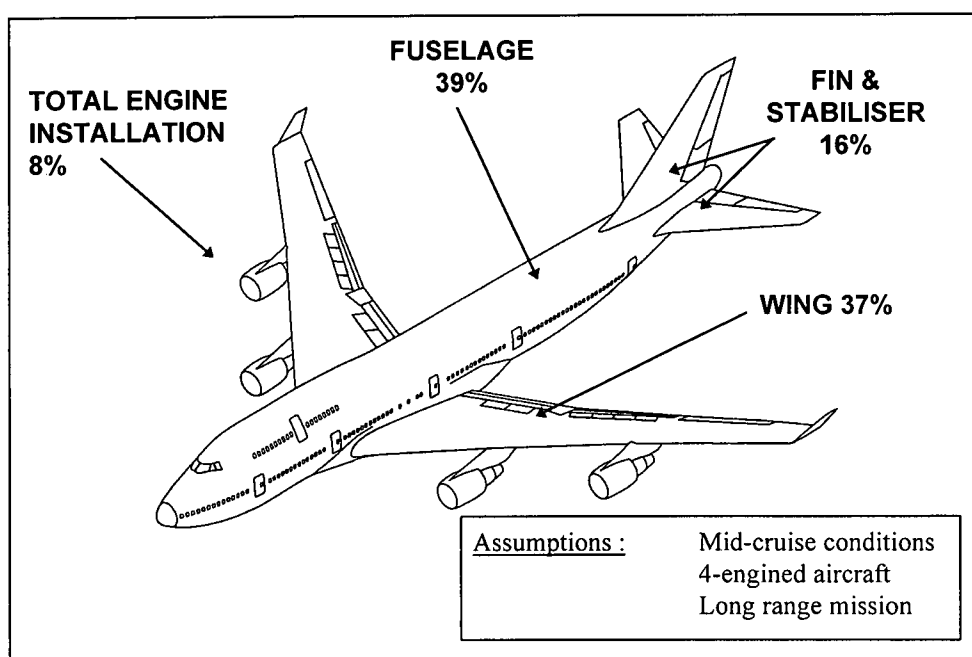


Figure 3.6 : Typical Aircraft Skin Friction Component Drag Breakdown (Rolls-Royce, 1998b)

3.3.5.5 Deterioration

On the initial choice of cycle and materials for the engine as well as the airframe aerodynamic and structural design, depends the extent to which the fuel burn and hence flight emission levels will be maintained over the years. The engine performance deterioration will generally account for 80% of the total aircraft fuel burn deterioration, with the remainder attributable to the airframe (Cook, 1998). The s.f.c. deterioration

stems from the necessity to maintain the aircraft take-off and climb performance with degraded engine components. Figure 3.7 shows the principal causes of degradations with erosion and clearance changes representing the major contribution to s.f.c. deterioration. Figure 3.8 shows where the degradation occurs within the engine (Singh & Hemeury, 1996).

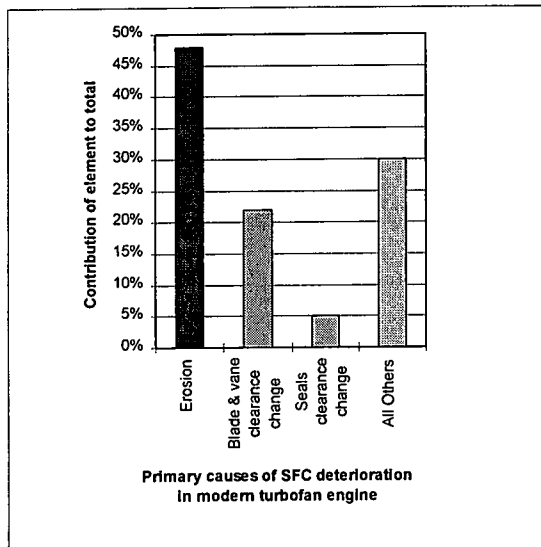


Figure 3.7 : Primary Causes of Performance Deterioration

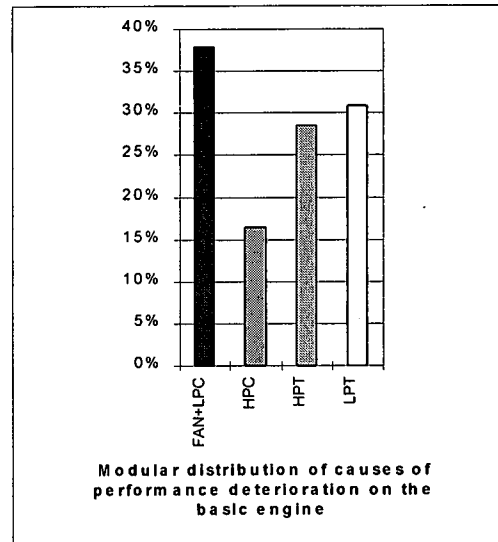


Figure 3.8 : Modular Distribution of Causes of Performance Degradation

Although the fuel burn deterioration will translate to an equal deterioration of the flight emission levels over the aircraft life cycle, the increased fuel flow to compensate for the loss in component efficiency will affect NO_x emission indices in various ways depending on the type of combustor. The increased combustor inlet pressure and temperature and equivalence ratio should lead to a higher NO_x emission index. Besides, NO_x emissions are more sensitive to non-uniformities in the fuel-air mixture at low equivalence ratio. As shown in Figure 3.9, LPP combustors burning lean mixtures are much more sensitive to changes in non-uniformities and mixture strength than current single-annular combustors.

As the engine components degrades, the deterioration of NO_x emission levels can therefore be expected to be more pronounced than that of fuel burn and any other pollutants, with engines incorporating LPP combustors showing higher NO_x increase than conventional ones. The effect on low power emissions CO and UHC should not be detrimental since deterioration of non-combustor components effectively result in hotter combustion at higher pressure. Because the increase in NO_x and possibly other trace species remain small relatively to H_2O and CO_2 emission levels, the deterioration in these latter emissions will be in line with that of fuel burn.

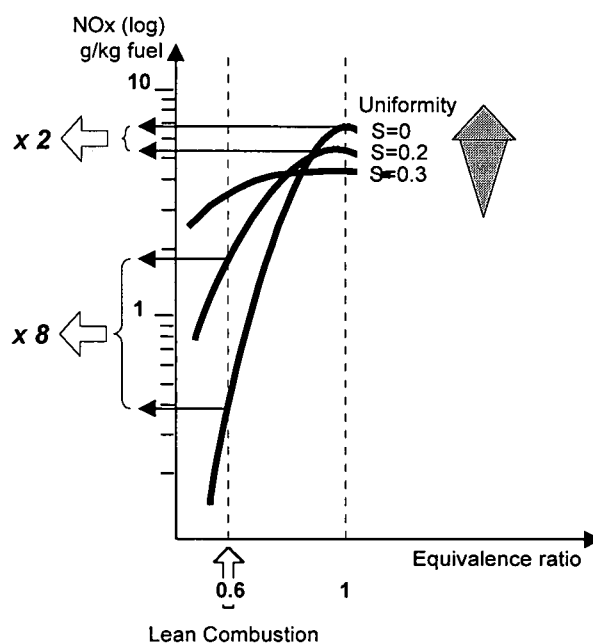


Figure 3.9 : Effect of Non-Uniformity in the NO_x Production of LPP Combustors
(Singh & Hemeury, 1996 ; Lefebvre, 1983)

3.3.6 Operational Measures

3.3.6.1 Introduction

Operational measures, i.e. alterations of the flight profile and/or engine rating to optimise the engine operating conditions for low emissions, that could contribute to environmental protection fall into two distinct categories : those designed to reduce the amount of aircraft flight emissions and those designed to reduce the effects of those emissions. The two routes are strongly linked. For example, an alteration to the cruise altitude for which the aircraft was optimised might be environmentally beneficial with respect to a number of pollutant species, but is likely to result in an overall increase in fuel burn and some flight emissions. Re-routing away from sensitive areas of the atmosphere is likely to lead to increased fuel consumption. Operational measures that can be considered are reviewed qualitatively in the two following paragraphs. The benefits to be derived from such measures will be investigated in Chapter 5.

3.3.6.2 Reducing the Amount of Flight Emissions

Much work is currently underway to streamline the way aircraft are controlled both on the ground and in the air. This will lead to fuel savings and operational as well as environmental benefits. A recent conference organised by the Confederation of European Aerospace Societies in Amsterdam (10th European Aerospace Conference, October 20, 21 and 22, 1997) has demonstrated that the technology, equipments and know-how are already available. Implementation however, will require the co-operation of air traffic control, pilots, airlines and politicians. Airlines will need to be convinced that there will be a reasonable time to offset the investment they will need to make for every aircraft in their fleet. The provision of the necessary ground stations or satellites to give world-wide coverage will be a matter largely for the governments and international organisations to resolve.

It is estimated that airlines burn 13% of their fuel bill in a non productive way of which 7% could be saved in the future (Cook, 1997). These inefficiencies are a result of :-

- *Low load factors* - Load factors have steadily improved since the end of the economic downturn of the early 90's with the advent of improved yield management techniques. Operations by the IATA member airlines showed an average load factor of 69.4% in 1996. Taking them beyond the 75 to 80% mark (yearly average) will affect the service flexibility required by the majority of the air travelling public (Ralph *et al.*, 1996).
- *High and less fuel efficient flight speeds* - The use of lower more fuel efficient aircraft speeds to cut fuel burn and emissions carries economical disadvantages. Airlines trade fuel burn against speed to improve aircraft utilisation and productivity.
- *Indirect flights with stopovers increasing total air distance per passenger* - Direct flights that bypass airline hubs, generally using much smaller regional aircraft, are more common now than in the past. The environmental benefits of this practice may be negative given the loss of economies of scale.
- *Air space congestion on the current network and air traffic control restrictions* - Air space congestion can prevent aircraft from using the best cruise altitudes. ATC restrictions on departure and arrival routings result in excessive taxi time, queuing on the taxi way and holding in stacks while waiting to land. Airport-related restrictions resulting in excessive taxi times, while offering real benefits around the airport, will have no effect on the issue of high altitude emissions. Excessive taxi times and unnecessary ground engine operations may be dealt with by the use of electric aircraft towing.
- *Avoiding bad weather encountered en-route*
- *International positioning of flight corridors and mandatory separations preventing aircraft to use the shortest routes and the best cruise altitudes* - Aircraft currently fly along prescribed corridors. These typically add 3% over the minimum great circle distance between the two airports. Political considerations may also affect the routings available. International relations or wars can preclude free civil flights.
- *Locally high fuel prices encouraging "tankering" practices* - Fuel price harmonisation and short sector prohibition (which burn more fuel per RPK than long-

distance flights) require international regulatory action, which is difficult to achieve in a global market-driven culture. The benefits would have to be weighed against the costs and what other solutions might bring. However, to some extent, it is possible for airlines to reduce the amount of fuel tankering by negotiating long-term bulk supplies (Somerville, 1996). In a number of cases, tankering can however be required if the destination airport is particularly isolated (e.g. located on an island).

Future Air Navigation Systems (FANS) based on highly accurate satellite Global Positioning Systems (GPS) are planned to make more efficient use of the available air space. The extent to which this might be achieved would depend upon harmonisation of ATC systems globally, as well as on how the issue of upgrades and modifications to the navigational equipment on all aircraft will be addressed. As a result of FANS, the available airspace will accept more traffic flying more fuel-efficient routes (Cook, 1997). The reduced separation will enable over 4 aircraft to use the airspace currently used by one. Aircraft will be able to fly along more direct flexible tracks thanks to, reduced separation minima (required vertical separation currently at 4000 ft or 1219 m), dynamic flexible re-routing to take into account of the weather situation in real time, cruising at optimum altitudes, speed adjustments to enable aircraft paths to cross without altitude adjustment, and the need to carry less contingency fuel. The system could be further developed to allow precision approaches to any airfield, making more airfields available as suitable alternates along the route.

3.3.6.3 Reducing the Effects of Flight Emissions

As indicated in Chapter 2, current data on the impact of air traffic are not adequate to permit definitive conclusions. However, as knowledge stands at present, a number of operational measures that could specifically reduce the effects of emissions include :-

- Reducing cruise altitude
- Restrictions on flight routes
- Reducing flights in daylight
- Widening (or narrowing) of flight corridors
- Repositioning of flight corridors (to use or avoid extreme weather systems)

Given the link between ozone chemistry and flight altitude, reducing cruise altitude for contemporary aircraft may lessen air traffic impact near the tropopause but will increase total flight tropospheric fuel burn and emissions, as such aircraft are optimised for specific flight profiles. Route restrictions to avoid sensitive atmospheric regions is likely to extend flight times and increase emissions as a result. Reducing daylight flights to restrict ultraviolet catalysis of some emissions imply severe practical difficulties and is unlikely to yield real benefits (Ralph and Newton, 1996). Widening or narrowing flight corridors will affect the concentrations of pollutants in the atmosphere. The benefits of such practice has however not been seriously studied.

Because such measures imply an increase in fuel burn and some emissions in order to reduce the environmental impact of other or those same emissions, careful assessments of the trade-offs by the scientific community, international regulatory bodies, governments and industry will be required.

The Calculation of Aircraft Flight Emissions by the SKY Computer System

4

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4.1 INTRODUCTION

The project's stated objective is to investigate the "*influence of civil subsonic aero engine design and flight operations on atmospheric pollution*". The project aims at evaluating the merits of aero gas turbine cycle and flight profile optimisations to reduce flight emissions produced by civil subsonic jet transports over medium to long range flight routes at altitude and in the vicinity of airports. The emissions of interest have been identified as NO_x , CO_2 and H_2O . As discussed in the conclusion of Chapter 2, when the additional effort is justified and reasonable, other species may be included in the assessment (e.g. CO, UHC or SO_2).

In order to quantify the production of the critical pollutants by mission/aircraft/engine/combustor combinations in flight, there is a need - as identified in Chapter 1 - for a computer simulation tool integrating flight route performance, aero engine performance and the formation of the pollutants within the engine's combustor. The system should be capable of evaluating the fuel burn and flight emissions of any combination of the user's choice in order to analyse the interplay between the engine design requirements of performance, fuel economy and low emissions.

In the light of this general outline, the specifications in terms of input and output requirements are described in the next section, followed by a description of the structure and the user interface of the SKY computer system developed to meet the specifications. The description is supported by Appendices D.1 to D.13.

4.2 SPECIFICATIONS

4.2.1 Output Requirements

SKY's primary requirement is to supply flight emission levels. In order to facilitate the environmental analysis, the output section shall include the ICAO regulatory parameter D_p/F_{00} (to allow comparison with the regulatory limits), the flight totals (absolute as well as on a per revenue passenger kilometres and per tonne-kilometres basis to account for utilisation), a phase breakdown and the average index per phase and per step of NO_x , CO_2 and H_2O (and possibly CO , UHC and SO_2) for each propulsion unit (that is the combination of the powerplant and combustor subsystems).

As part of the environmental analysis, the following flight and engine performance data, the calculation of which are required in overall computation process, shall also be included in the output section to support the environmental analysis :-

- **Mission and fuel burn analysis** : fuel carried, block fuel, mission fuel, reserve fuel, mission time, block time, still air range, specific range, revenue passenger miles, tonne nautical miles, specific RPM (RPM per tonne of fuel), specific TNM (TNM per unit of fuel).
- **Phase and step flight analysis** : phase and step breakdown of fuel burn, time and distance ; step breakdown of height, aircraft mass, Mach, true air speed (TAS), equivalent air speed (EAS), rate of climb, climb angle, aircraft net thrust requirement, drag, specific excess power, lift-to-drag ratio, lift and drag coefficients.
- **Aero engine performance analysis** : step breakdown of Mach, net thrust, fuel flow, and s.f.c ; plus any parameters selected by the user prior to computation (e.g. non-dimensional mass flows and pressure ratios to draw running lines on compressor maps).
- **Flight atmospheric conditions** : step breakdown of ambient pressure, temperature, density, speed of sound, wind speed, and ISA deviation.

4.2.2 Input Requirements

In order to meet the above output requirements, the input shall consist of the desired mission together with aircraft, gas turbine engine and combustor models assembled by the user. The system shall be modular so that the user can run any mission with any set of models in accordance with guidelines laid out in Chapter 1 Section 2 (*Objectives and Scopes*) and the introductory section of this present chapter. The user should also be able to power his/her selected aircraft with a set of distinct models of powerplant and combustors. This is of interest to examine the fuel burn and emissions of aircraft powered by a set of dissimilarly degraded subsystems.

To perform flight profile and engine cycle optimisations with respect to low flight emissions, the engine designer and the aircraft operator will need to determine the optimum combination of aircraft operational and aero engine cycle parameters. Whilst they represent the primary parameters that will be acted upon to meet the objectives of the thesis, some other input parameters are required to make the simulation possible. The various categories of input parameters required to achieve the objectives therefore include :-

- ***Aircraft operational parameters*** : payload, range, time schedule (for short flight phases excluding climb, cruise and descent), altitude profile, speed schedule (for climb, cruise and descent phases), reserve rules and simulation methods for each flight phase where available.
- ***Aircraft characteristics*** : weights, dimensions, drag characteristics, aircraft-specific performance data where required, aircraft fuel flow allowances (for short flight phases).
- ***Atmospheric conditions*** : wind components and ISA deviations along the flight path.
- ***Aero engine cycle configuration*** : engine architecture consisting of an assembly of components such as intake, compressor, combustor, turbine, nozzle (convergent and/or divergent), ducts, flow "splitter" and mixer. These components simulate the major thermodynamical processes taking place within the engine.
- ***Aero engine cycle parameters*** : parameters providing a numerical description 1) of the engine architecture (links between components) and 2) of each of these components such as component characteristics, bypass ratio, pressure ratios, pressure losses, component efficiencies, fuel flow(s), turbine entry temperature limit, and static pressure in the mixer.
- ***Combustor characteristics*** : emission correlations, and all parameters required to run those correlations such as constants, fuel properties, combustor dimensions, injector type and characteristics and primary zone flow conditions.

4.3 DEVELOPMENT

4.3.1 Introduction

SKY has been designed according to a number of programming principles laid out in Appendix D.1. Their application has minimised the development time, facilitated the validation process, and resulted in a detailed and modular yet user-friendly software with an inbuilt capability for further developments. The SKY computer system is written in Fortran 77 and is available to run under both the MS-DOS operating system.

It contains 14,600 lines of code excluding the Turbomatch Gas Turbine Simulation System (5,800 lines) run as a subroutine.

SKY incorporates three integrated modules which can be envisaged as having the structure of Russian dolls. They simulate the aircraft flight route, the performance of the powerplants and the formation of the pollutants within the combustors. The *Flight Route Module* computes the mission and reserve fuel carried by the aeroplane and calculates the flight parameters along the flight path. This module accounts for the weight and installation drag of the powerplants leaving the *Aero Engine Module* with the task of evaluating the uninstalled s.f.c. and net thrust. The *Emission Module* calculates the levels of pollutants generated by the engine.

Figure 4.1 describes SKY's structure and the data flow between the modules and the input and output sections. The program modules calculate detailed histories of the flight, engine and emission parameters at each step of each phase of the flight. Appendix D.6 explains how the 8 major parameters are calculated depending on the flight phase and the user's choice of simulation procedures. The modularity allows to model any subsonic commercial transport aircraft powered by gas turbine engines. SKY has the capability of evaluating the effect of using deteriorated engines.

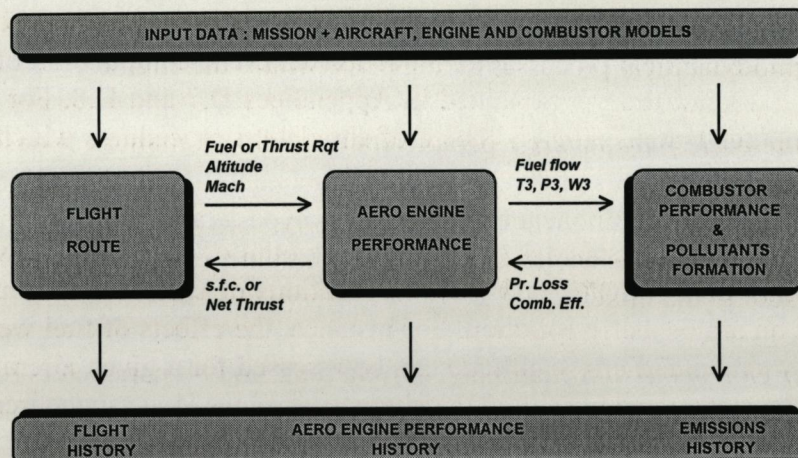


Figure 4.1 : SKY Computer System Architecture

4.3.2 Flight Route Module

The *Flight Route Module* - also known as FAST in publications prior to 1998 - employs the structure of FLTANAL, the flight route simulation module of an aircraft configuration design computer system developed at Cranfield University (Pasaribu, 1991). FLTANAL was based on a computer flight simulation program for aircraft preliminary design developed by NASA (Sliwa and Arbuckle, 1980). The SKY *Flight Route Module* uses a mixture of *analysis* and *interpolation* techniques. Analysis requires flight performance equations describing the aeroplane flight mechanics while

interpolation techniques derive the flight parameters through data tables. Both approaches are used by SKY to perform step-by-step calculations of fuel burn, time spent, distance flown, and up to over 15 flight parameters (excluding internal engine and combustor parameters). The flight phases are divided in a number of steps which can be either altitude steps (at climb and descent) or range steps (at cruise). Short phases (i.e. remaining phases) are simulated with a single step. All parameters are assumed constant on a step.

In return of atmospheric conditions, Mach number, altitude and either fuel flow (at take-off, climb and holding) or thrust requirement (at cruise), the *Aero Engine Module* supplies net thrust and s.f.c. to the *Flight Route Module*, allowing the computation of the flight parameters at any given step (see Figure 4.1). The start, taxi, descent, and approach phases employ fuel burn and fuel flow rate allowances rather than the *Aero Engine Module* which is currently unable to simulate engines at low power conditions. This is acceptable because on long range routes such phases will only make up about 10% of the total fuel burn.

While Appendix D.2 provides a detailed description of the aircraft flight route modelling (mission fuel burn and reserves prediction, aircraft configuration, engine requirements, performance equations simulating the various flight phases), Appendices D.3 and D.4 describe the *Flight Route Module* architecture by means of flow charts and subroutine trees. The module has been validated using 747-400 performance data on the London-Tokyo flight route (see Chapter 5 Section 5.3). The computation of atmospheric conditions and aircraft drag is explained in Appendices D.7 and D.8. For most phases, the SKY computer system offers a choice of simulation procedures which are listed in Appendix D.5.

The *Flight Route Module* supplies a substantial amount of mission data which, against emission levels, can be used to study the implications of various missions of different aircraft types on atmospheric pollution. For instance, the effects of fuel weight, mission range, cruise method and cruise altitude can be assessed for a given aircraft. It can also provide the user with some insight on the alternative routes long range aircraft could use in order to minimise their environmental impact.

4.3.3 Aero Engine Module

The current version of Turbomatch, Cranfield well-established gas turbine engine simulation system (Palmer, 1983), is used as the *Aero Engine Module* to run the engine model selected by the user to power the aircraft. It has been developed and validated by Cranfield School of Mechanical Engineering. The engine simulation system reproduces the fundamental thermodynamic processes taking place within aero gas turbines and performs design-point and off-design performance calculation for gas turbine engines. Provided it is supplied with representative input data, it can approach the performance of real engines by a few per cents.

This general-purpose program is built up of standard routines known as bricks corresponding to the various thermodynamic processes taking place within the gas turbine. It employs a simultaneous iterative method for off-design performance. The engine model, defined through an input data file, consists of a modular assembly of engine components such as intake, compressor, combustor, turbine, nozzle, and other components (see Figure 4.2).

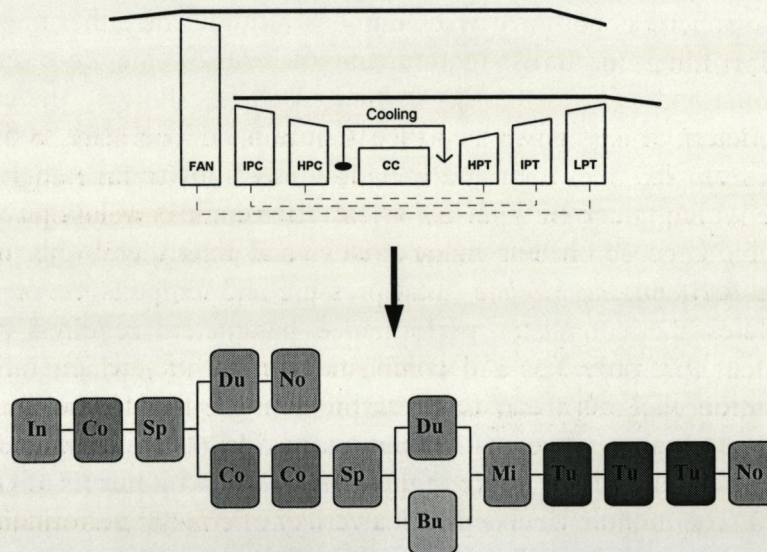


Figure 4.2 : Turbomatch representation of a typical turbofan engine
(In=intake, Co=compressor, Sp=splitter, Du=ducter, No=nozzle,
Bu=combustor, Mi=mixer, Tu=turbine)

If required by the user, Turbomatch can be run by the *Flight Route Module* at take-off, initial climb, acceleration, en-route climb, cruise and holding (the “high-thrust” phases) to provide :-

- Uninstalled fuel flow and net thrust to the *Flight Route Module* for each step. The propulsion system weight is accounted for in the aircraft OEW while the isolated nacelle and interference drag must be included in the aircraft drag polar.
- Combustor inlet thermodynamic conditions (P_3 , T_3 , W_3 and fuel flow) to the *Emission Module*.
- A selection of engine parameters of the user’s choice that can be made available in the output data file (e.g. non-dimensional parameters necessary to draw engine running lines).

The “low-thrust” phases (i.e. start, taxi-in, descent, approach and taxi-out), which the module is not able to simulate sufficiently accurately, are described by means of time, distance and fuel allowances and interpolation techniques within the *Flight Route Module*. It is possible to power the selected aircraft with a set of different engine models. This is of interest to examine the fuel burn of aircraft powered by engines with dissimilar performances (e.g. in terms of intakes, offtakes, degradations, etc.).

SKY can simulate any "high-thrust" phase without the *Aero Engine Module* system using interpolation techniques to derive fuel burn, time and/or distance from user-supplied aircraft performance data files. Such files contain fuel burn, time and distance step changes as a function of aircraft gross weight, altitude and ambient conditions. This is useful to validate a Turbomatch engine model of an existing powerplant in-service on each of the "high-thrust" phases as well as to optimise and use a cycle for a particular phase (e.g. cruise).

4.3.4 Emission Module

The *Emission Module* (also known as APPEM in publications prior to 1998) has been designed to evaluate the performance and emissions of gas turbine engine combustors burning kerosene fuel through semi-empirical emissions correlations. As shown in Figure 4.3, given some combustor characteristics and inlet thermodynamic conditions supplied by the *Aero Engine Module* (total pressure and temperature, air and fuel flow rate), it calculates the combustor performance parameters required by the engine simulation system (pressure loss and combustion efficiency) which the *Aero Engine Module* would otherwise assume constant throughout the flight. The module produces for every flight step the indices of carbon monoxide (CO), unburned hydrocarbon (UHC), oxides of nitrogen (NO_x), carbon dioxide (CO_2) and water (H_2O) emitted by the powerplant(s). The *Emission Module* offers a variety of emission correlations which can be adapted to the selected aircraft/engine combination.

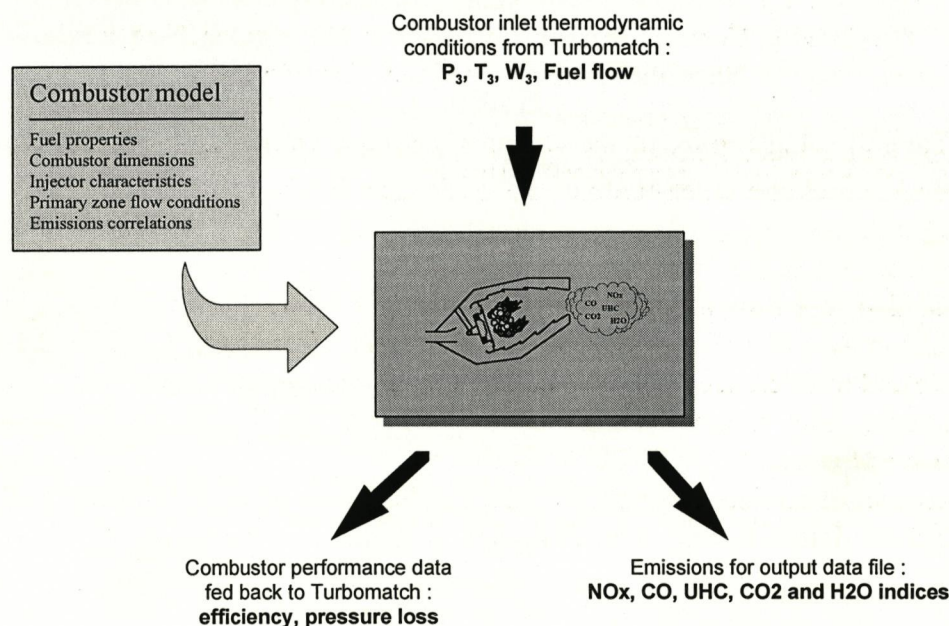


Figure 4.3 : Combustor performance and pollutants formation module

The description and validation of the correlations currently available are presented in Appendix D.9. The validation was conducted with data from the ICAO emissions databank (ICAO, 1993 & 1995b) and the AERONOX project for flight phases not

covered by the databank (Schumann, 1995). Appendices D.10 and D.11 describe the *Emission Module* architecture by means of flow charts and subroutine trees.

The subroutines incorporated in the module model the major physical phenomena that underpin combustor performance, combustion and emissions production. The approach has been one of adopting semi-empirical emissions models that could feature coherent behaviours within reasonable accuracy. They represent a compromise between accuracy of representation, ease of use, capability for further improvements via modularity, and computation rapidity as the module is designed to run as a subroutine of an already large program. The *Emission Module* is upgradeable so that in particular the best available published emission correlations can be readily incorporated.

In order to facilitate the analysis of flight emission, the emission data presented in the output section include the NO_x, CO₂, H₂O, CO and UHC emission indices at each step but also the ICAO regulatory parameter Dp/Foo, the flight total (absolute, per revenue passenger kilometres and per tonne-kilometres), the production per phase (particularly cruise) and per step.

4.4 USER INTERFACE

Depending on the simulation procedures selected for the run, up to 25 input data files may be required. Over two thirds of the files (16) relate to the particular aircraft selected for the run leaving 9 files and a minimum of 2 to generate or amend to study the influence of aero engine cycle on atmospheric pollution. The effect of the flight profile can be studied by altering a maximum of 2 files i.e. Aircraft/Mission and Engine Climb Rating. Currently all the aircraft files available pertain to the Boeing 747-400 (Boeing, 1990). The following Table lists the various types of input files required to run SKY and Appendix D.12 include copies of some of the files as examples.

Input file	Comments
<ul style="list-style-type: none"> • <u>'input.dat'</u> 	Names of required input data files (some will be optional according to the options selected by the user), number of propulsion units and distribution of total aircraft net thrust requirement among these units.
<ul style="list-style-type: none"> • <u>Aircraft/Mission</u> 	<ul style="list-style-type: none"> • <u>Aircraft Characteristics</u>: Operational empty weight (OEW), weight limits if available (MTOW, MLW, MZFW, OEW, MRW, MFC), aircraft fuel flow allowances (start, taxi-out, approach & landing, taxi-in), wing area, wing aspect ratio, drag polar, aircraft-specific performance data in cases not covered by the aero gas turbine performance simulation (e.g. phases requiring low thrust ratings and accounting for a negligible proportion of the total fuel burn and flight emissions). • <u>Mission</u> : No of passengers, payload weight, range, start fuel weight, time schedule (start, taxi-out, holding, approach & landing, missed approach, taxi-in), altitude profile (departure airport, initial climb start, en-route climb start, cruise flight levels, holding, end of descent, destination airport), speed schedule (climb EAS, cruise Mach number), descent angle, reserve policy (fixed reserve, ratio of final reserve to block fuel, diversion

	<p>distance, diversion initial cruise altitude, diversion Mach number, holding time), flight simulation procedures, phases step numbers, cruise distance step, computation convergence criteria.</p> <ul style="list-style-type: none"> • <u>Computation procedure</u> : Start weight estimation method, No of steps (initial climb, acceleration, en-route climb, step climb at cruise, descent), cruise distance step, tolerances for SKY's iterative processes.
<ul style="list-style-type: none"> • <u>Engine Model</u> 	<p>Weight, rated output and Turbomatch model consisting of :-</p> <ul style="list-style-type: none"> • <u>Engine cycle configuration</u> : Engine architecture consisting of an assembly of the following components : intake, compressor, combustor, turbine, nozzle, duct, flow mixer, flow splitter. • <u>Engine cycle parameters and component data</u> : Rated output, engine weight, intake pressure recovery, bypass ratio (turbofans), compressor characteristic and parameters (pressure ratio, efficiency, surge margin), overall pressure ratio, turbine entry temperature limit, turbine characteristic and parameters (cooling bleed, efficiency, power off-take), cabin bleed, duct pressure losses. • <u>Computation procedures</u> : Tolerances establishing when the engine thrust matches the aircraft required thrust at cruise, tolerances establishing the consistency between the engine's assumed combustor performance and that calculated by the Emission module, No of steps from one engine operating point to another (to ensure smooth off-design convergence).
<ul style="list-style-type: none"> • <u>Engine Climb Rating</u> 	Table of an engine handle (fuel flow, high pressure compressor speed, ...) as a function of Mach number and altitude.
<ul style="list-style-type: none"> • <u>Combustor Model</u> 	Fuel properties (formula, calorific value, temperature and density at injection, surface tension, viscosity), combustor dimensions (liner reference width, casing cross-sectional area, volume), injector type and characteristics, primary zone flow conditions (air fraction, turbulence level, pressure loss factor, gas velocity), emission correlations constants.
<ul style="list-style-type: none"> • <u>Emission Indices</u> 	Emission indices of each phase to be used for low-thrust phases as well as phases not covered by the engine and combustor models.
<ul style="list-style-type: none"> • <u>ICAO constants</u> 	Constants allowing the computation of ICAO parameters of the engine/combustor combination
<ul style="list-style-type: none"> • <u>ISA Deviations</u> 	ISA deviations along the flight path (i.e. as a function of altitude and range).
<ul style="list-style-type: none"> • <u>Wind Speeds</u> 	Wind speeds along the flight path (i.e. as a function of altitude and range).
<ul style="list-style-type: none"> • <u>Drag Polar</u> 	Drag coefficients as a function of lift-coefficients and Mach number.
<ul style="list-style-type: none"> • <u>Aircraft Performance Data (up to 14 Files)</u> 	Tables of fuel burn, time and/or distance as a function of aircraft mass, altitude(s) and/or ISA deviation. Each phase can be simulated by interpolation by means of such tables, therefore eliminating the need for the engine and combustor models.
<ul style="list-style-type: none"> • <u>Altitude Capability</u> 	Table of ceilings as a function of aircraft mass.
NB : some files may be optional depending on the user's choice of flight simulation procedures.	

Table 4.1 : SKY's Input Data Files

As shown in Appendix D.13 and further down (Table 4.2), the standard output data file includes a seven-part step by step and phase by phase output of flight, engine and combustor parameters, as well as phase breakdowns of fuel consumption, time, range, and emissions. The engine and emission data is presented for each category of propulsion units because the user may have chosen to model identical engine cycles with combustors of a different design or of the same design but dissimilarly deteriorated. Three additional files incorporating process and error messages pertaining to the *Flight Route* and *Engine Modules* are also generated to assist the user in diagnosing the causes of possible failures. They are named skymsg01.txt, skymsg01.txt and skymsg01.txt in the example file of Appendix D.13.

• <u>Part 1 : Case Study</u>	Basic information.
• <u>Part 2 : Data Files</u>	Filenames related to propulsion units, atmosphere, aircraft performance, emission simulation, output and messages.
• <u>Part 3 : Computation Status</u>	Running time, number of warnings (they can be read in the message files), number of iterations, tolerance sought, iteration details and simulation procedures.
• <u>Part 4 : Aircraft/Mission</u>	Flight analysis including overall performance results and phase and step breakdowns of up to 17 parameters.
• <u>Part 5 : Aero Engine Performance</u>	Main engine parameters, miscellaneous parameters selected by the user.
• <u>Part 6 : Combustion & Emissions</u>	Phase and step breakdown of NO _x , CO, UHC, CO ₂ and H ₂ O emissions expressed as mass and index for each propulsion units ; step breakdown of 17 major combustion parameters ; mission emission analysis featuring flight, cruise and LTO emissions.
• <u>Part 7 : Atmospheric Conditions</u>	Step breakdown of 8 atmospheric parameters including pressure, temperature, ISA deviation and wind speeds.

Table 4.2 : Structure of SKY Output Data File

4.5 CONCLUSIONS

Major research programs such as AERONOX (Schumann, 1995), MOZAIC (Marenco, 1994) or POLINAT (Schulte and Schlager, 1996) have taken place in the past to measure subsonic aircraft emissions and ozone concentrations. These measurement campaigns provide much needed inventories to validate ambitious 3D computer models of the earth's atmosphere as well as improve understanding on aircraft emissions and their interactions with the atmosphere.

However, smaller, complementary and flexible simulation and optimisation tools are needed to explore in a systematic way the technological compromises that will ultimately lead to low-emission designs as well as supply aircraft emission data with

good spatial resolution. SKY has been developed to this effect, and should prove a valuable tool to optimise in an integrated manner the mission/aircraft/ engine/combustor combination with respect to low emissions.

It can be employed to explore the relative implications of low-emissions combustor designs, engine cycles, and flight route details on atmospheric pollution, and therefore the relative merits of various routes designed to reduce emissions. It can also estimate the ability of engine/combustor combinations to meet current ICAO recommendations. For the specific purpose of the thesis, this tool is employed in the next chapter to explore the influence of aero engine design and flight operations on atmospheric pollution.

Influence of Subsonic Aero Engine Design and Flight Operations on Atmospheric Pollution

5

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5.1 INTRODUCTION

This chapter expands on issues covered qualitatively in Chapter 3 by reviewing and quantifying the effect of subsonic turbofan engine cycle and their flight operations on LTO and mission emissions. The engine cycles under consideration power long range widebody passenger transport aircraft and most of the data presented will pertain to a model of such an aircraft represented by the Boeing 747-400. The research results have been published by the author and are based on computational performance analysis using the SKY program (Le Dilosquer *et al.*, 1995a, 1995b, 1996 & 1998).

Section 5.2 examines the preliminary engine design requirements set out by the regulatory authorities certifying the aircraft as well as by commercial and operational considerations. The design of an engine cycle using Turbomatch is clearly presented. This lays the basis for the analysis of the interplay between the engine requirements for low fuel burn and low emissions. Section 5.3 then examines how the flight profile affects mission emissions in the case of a high bypass ratio turbofan powering the 747-400 model. Finally, Section 5.4 presents the advantages of using SKY data as an input to 3D models of the Earth's atmosphere in order to predict the dispersion and chemical transformation of pollutants at high altitude.

5.2 INFLUENCE OF SUBSONIC ENGINE CYCLE DESIGN ON LTO & MISSION EMISSIONS

5.2.1 Subsonic Aero Gas Turbine Design : Requirements and Process

5.2.1.1 Requirements

The aero engine design process is governed by commercial and regulatory considerations (see Figure 5.1) as well as available component technologies. The extent to which the commercial and regulatory requirements are met largely depends on the availability of enabling technologies commensurate with the aeroplane EIS date. Such technologies will impose aerodynamic, thermal and mechanical limits which set upper bounds on cycle pressure ratios and temperatures. They will generally be required to improve on aircraft currently available in the market and to deliver a competitive advantage over possible engine competitors on the same aircraft application.

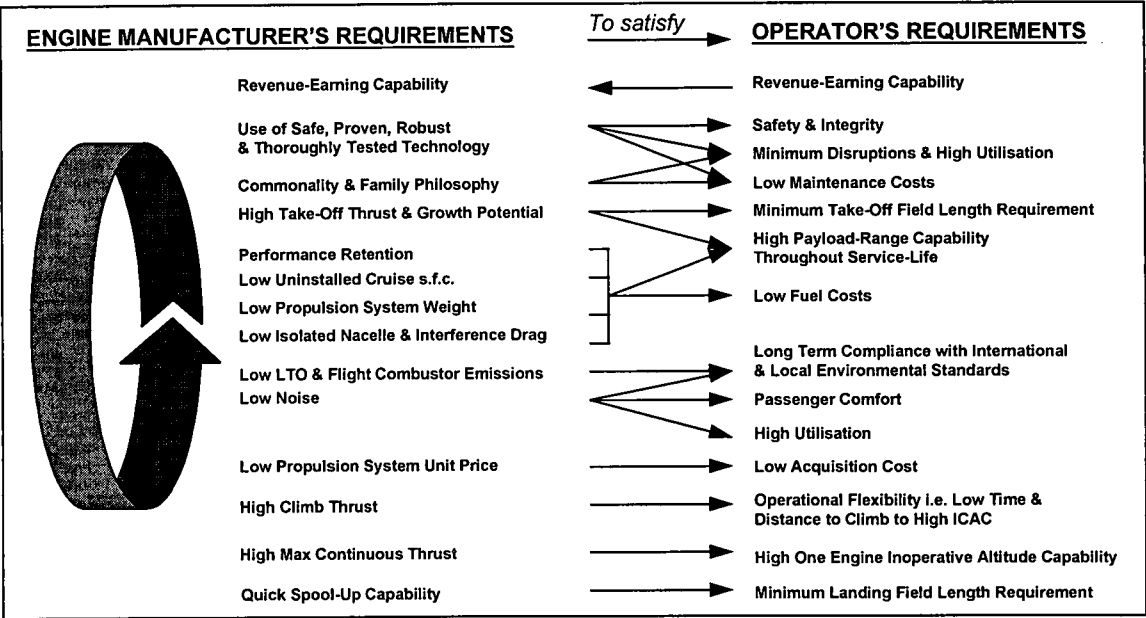


Figure 5.1 : Aero Engine Design Requirements

Regulatory considerations cover issues regarding safety, noise and emissions. The airworthiness authorities are concerned with the performance of the aircraft in the event of the failure of the most critical engine during take-off, approach to land and also en-route. The aircraft performance on such sectors is calculated from the declared maximum take-off and maximum continuous ratings of the engine. Noise requirements are set by international regulations (stage 3 limits) as well as by airport authorities (such as the London Heathrow quota counts). To minimise turbofan noise, the engine designer can employ a combination of the following routes : designing at the optimum bypass ratio to minimise exhaust jet noise without adversely impacting fan noise (which

predominates at low power), applying acoustic treatment to engine inner surfaces at suitable locations, and carefully choosing blade spacing and axial spacing between the fan rotor and stator blades. The final aircraft noise characteristics will depend on the engine noise characteristics and the aircraft flight profile and will have commercial implications (night curfews and fees are in force in an increasing number of airports around the world). Low emission requirements are currently applied to the aircraft operation in the vicinity of airports (LTO cycle). The nature of the requirements and the solutions adopted by engine manufacturers have been discussed in Sections 3.2 and 3.3.3 of Chapter 3.

Commercial considerations are mainly articulated around capability, operating costs and EIS date. The objective is to offer the customer a propulsion system with high revenue-earning capability throughout service life. To achieve this, minimum fuel consumption and long overhaul life are pre-eminent. Commercial considerations depend on the aircraft application, the planned service life and the mission operating requirements which include the extent of the intended flight envelope and the range of critical flight conditions for which performance must be assured. Take-off net thrust must be set against the take-off field length requirement and installed s.f.c. and underwing engine weight must both be minimised so as to meet the aircraft payload-range capability. Figure 5.2 illustrates how payload-range capability is affected by these three major engine characteristics.

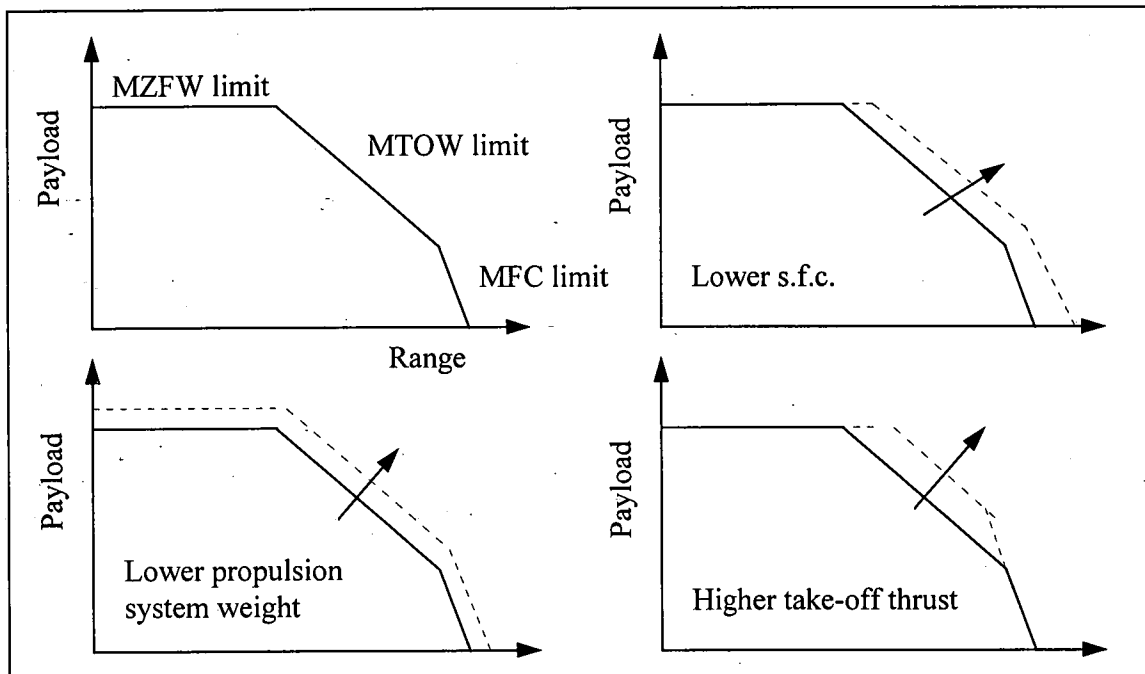


Figure 5.2 : Effect of Aero Engine Design on Aircraft Payload-Range Capability

In addition, operational flexibility is strongly desired with the max. climb and cruise ratings chosen to give acceptable level of operational performance assuming all engines operative provided that payload-range capability is not unduly affected. These ratings are often set by commercial requirements such as the time and distance to climb and the

initial cruise altitude capability. In designing an engine of the required capability, care must be taken in maximising service life and minimising maintenance costs and cost of ownership. The potential for growth must also be considered as customers are likely to require higher gross weight versions of the purchased aircraft in the future.

5.2.1.2 Preliminary Design Process Using Turbomatch

The preliminary design process aims at defining the optimum engine cycle and determining its performance, weight and noise characteristics based on the regulatory and commercial requirements mentioned previously. Cycles aimed at commercial transport aircraft are optimised for best s.f.c. at the aerodynamic design point (ADP) associated with top of climb operating conditions. This ensures that the engine bottom-of-loop s.f.c. coincides with the optimum aircraft lift-to-drag ratio at cruise hence delivering optimum specific air range throughout a phase of the flight that burns over 80% of block fuel on long haul flights. The cycles must also comply with hot day take-off thrust requirements (HDTO). The choice of ratings will determine the engine life, with the target life of the most critical components (e.g. HP turbine blades) leading to a compromise between the levels of maximum take-off, continuous and climb ratings.

Using SKY's *Aero Engine Module* (incorporating Turbomatch) it is possible to calculate cycle design point and off-design performance according to the following application- and technology-driven requirements (see Table 5.1). The engine model, defined through an input data file, consists of a modular assembly of engine components such as intake, compressor, combustor, turbine, nozzle, and other components. Figure 5.3 presents the cycle parameters that affect installed performance and emissions.

Turbomatch Parameter	Engine Cycle Requirement
MTO rating	TOFL at the required altitude and ambient conditions (to meet payload-range capability) and possibly noise targets (through faster take-off procedure). The take-off thrust is usually flat rated to ISA+15K.
MCT rating	One/two engine inoperative altitude capability to clear terrain depending on the number of engines. Four-engined aircraft may have identical MCT and MCL ratings.
MCL rating	Climb thrust profile to meet climb time and distance targets (to promote operational flexibility). The climb thrust is usually flat rated to ISA+10K.
MCR rating	The max. cruise thrust capability to enable operation at the airframer's recommended cruise Mach number within the flight envelope.
Idle rating	Used at descent, approach and landing. This requirement does not significantly impact cycle design and emissions and Turbomatch is unable to simulate it accurately.
Flight Mach number	Determined by the airframer, it represents a compromise between minimising flight time and maximising fuel mileage. The most important element is the cruise Mach number for which the wing is optimised.
Top-of-climb and initial cruise altitudes	Determined by the airframer to promote fuel efficiency and operational flexibility.
Compressor and turbine isentropic efficiencies	Depending on the technology available at the EIS date. This can be determined via the polytropic efficiency levels of each component.
Bypass ratio	This will depend on weight, installation and s.f.c. considerations.

Bleed offtakes	To meet cabin air conditioning and anti-icing requirements.
Power offtakes	To meet aircraft hydraulic power requirements, normally supplied by the HP spool.
Cooling air flow rate from compressor delivery	Depending on the Turbine NGV and rotor blade metal temperature capability and cooling technology adopted.
Fan pressure ratio	In the case of a separate exhaust turbofan engine this is the optimum fan pressure ratio for best s.f.c.
Inlet air mass flow at top-of-climb and MTO	Defined to meet the climb and take-off thrust requirements. It will set the intake and as a result nacelle size.

Table 5.1 : Translating Engine Preliminary Design Requirements Into Performance Parameters

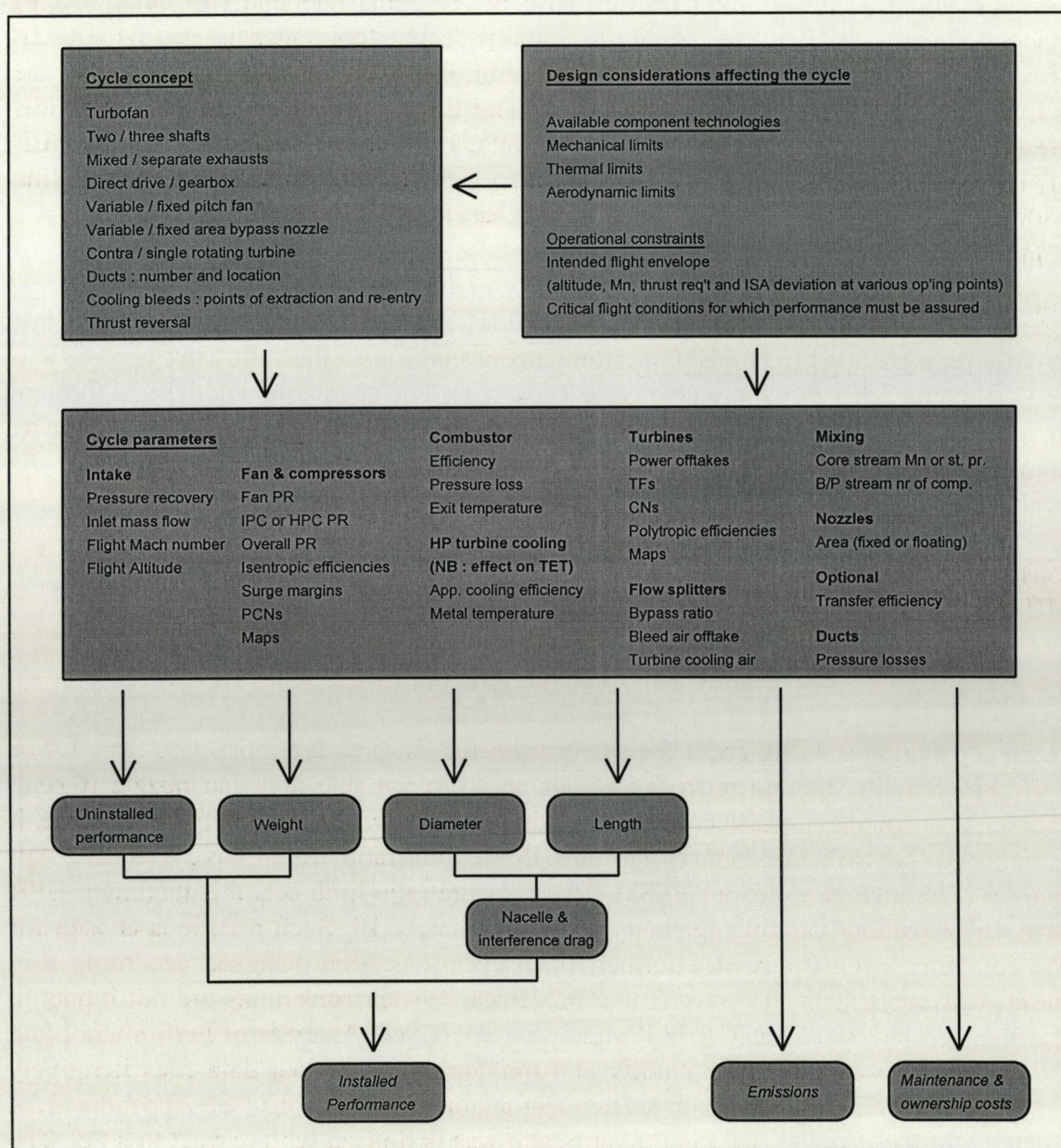


Figure 5.3 : Turbofan Performance Modelling with Turbomatch

5.2.2 Designing for Low LTO Emissions

The challenge with LTO NO_x is to keep flame temperature down at high-power conditions without incurring unacceptable penalties in terms of low power emissions, durability, flame stability and exit temperature distribution. Using single annular combustor technology, it has been seen that for a given combustor design and fuel injection system (i.e. a given fuel/air mixing quality), NO_x is primarily a function of combustor residence time and flame temperature. The flame temperature is mainly determined by inlet combustor temperature and pressure and zonal fuel-to-air ratio. Hence the NO_x emission index increases as engine thrust increases.

To examine the technical compromise between LTO emissions and fuel burn, it is of interest to associate common cycle preliminary design tools such as graphs of s.f.c. against specific thrust with means of evaluating emissions such as s.f.c. versus the fraction of the ICAO NO_x regulatory limit. The following figures, tables and results present such an approach (Le Dilosquer & Singh, 1995b). The cycle taken as the basis of this exercise incorporates a three-shaft arrangement with directly-driven front fan without variable geometry and with separate exhausts as illustrated in Figure 5.4.

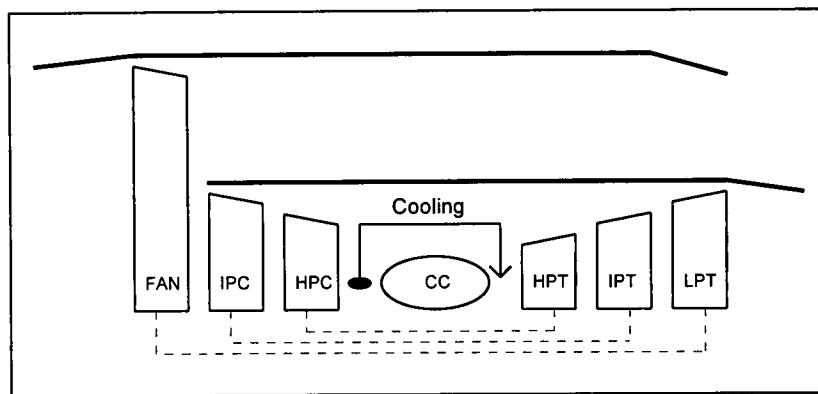


Figure 5.4 : Three-Shaft Direct Drive Turbofan with Separate Exhausts

Adequate engine stability and fan surge margin for fan pressure ratios less than 1.4 or 1.45 will require variable pitch fan blades and/or a variable area fan nozzle if peak efficiency is sought at cruise conditions. Although tests would ultimately be required, it is believed that a fixed geometry fan of 1.45 pressure ratio would have adequate stall margin (Zimbrick & Colehour, 1988). This pressure ratio limit sets the maximum BPR achievable without variable geometry to approximately 10. Such a BPR is chosen for the computed cycles presented further. Each cycle has been designed according to a number of constraints shown on Table 5.2. Because such constraints are not inputs to Turbomatch, the 5900-line CAPE Fortran program (Cycle Analysis of Performance and Emissions) was developed to modify and run Turbomatch input data files iteratively until the constraints are met without frequent manual interventions (see Appendix E.2). For each of these cycles, the fan pressure ratio was optimised with respect to s.f.c.. The amount of air taken from the HP compressor exit to cool the HP turbine blades and NGVs is calculated using a common level of cooling technology.

ISA SLS Take-off net thrust : 256 kN <i>Required by 747-400.</i>
Fan, IPC, HPC, HPT polytropic efficiency = 89% <i>Current compressor and turbine technology.</i>
IPT polytropic efficiency = 92% <i>Current turbine technology.</i>
LPT pol eff = 93% <i>Current turbine technology.</i>
Combustor pressure loss = 4.5% <i>Current technology.</i>
Combustor primary zone equivalence ratio = 0.8 <i>Current technology.</i>
Apparent turbine cooling efficiency = 100% <i>Current technology for combined film and convection cooling.</i>
Turbine rotor blade and NGV metal temperature = 1100 K

Table 5.2 : Constraints Imposed at Take-off for the Computed Cycles Incorporating Current Technology and Designed to Power a 747-400 Model

The combustor model is single annular with airblast fuel atomisation. The NO_x correlation used has been established by Lefebvre (1984) and modified (Le Dilosquer, 1995) to yield emission levels consistent with current high bypass ratio turbofans (ICAO, 1993) at the take-off and climb-out conditions defined by ICAO. It is a semi-empirical correlation that embodies the main variables of combustor size and inlet operating conditions. The effect of variations in combustor fuel-to-air ratio is also included via its influence on the primary zone temperature. The correlation is described in Appendix D.10. The figures illustrate the ability of current direct drive turbofans incorporating the highest achievable BPR to meet both fuel economy and low emissions requirements without variable geometry. Cycles on the right of the dotted line in Figure 5.5, have fan pressure ratios that do not necessitate the use of variable pitch fan blades and/or variable area fan nozzle. Each cycle has been designed according to requirements consistent with the cycle concept. The fan pressure ratio is optimised with respect to s.f.c..

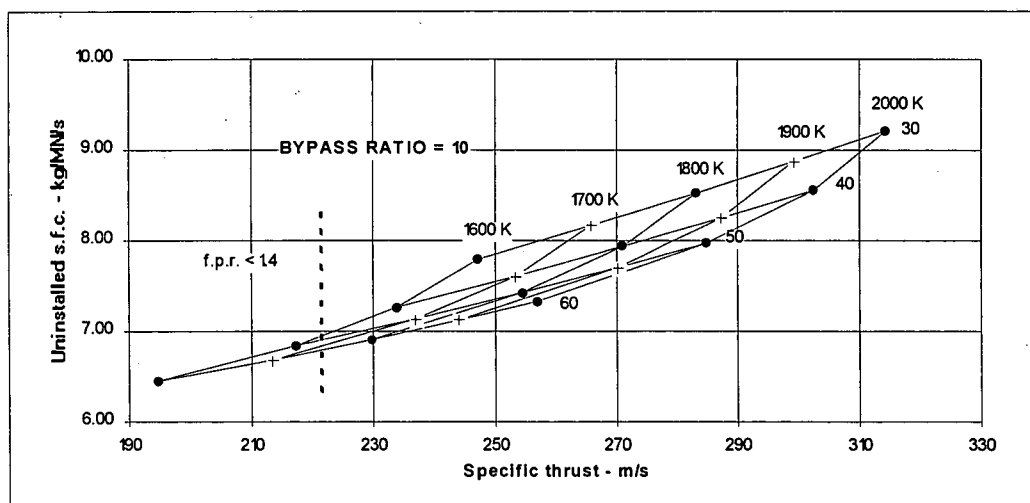


Figure 5.5 : Uninstalled s.f.c. Against Specific Thrust (Le Dilosquer & Singh, 1995)

The industry expects to further develop these cycles with OPR beyond 40:1 and TET over 1800K through improvements in material thermal capabilities and blade cooling (Peacock & Sadler, 1992 ; Ruffles, 1993). Although the current best single-annular technology would deliver lower emissions than the combustor model used for this study, Figure 5.6 indicates diagrammatically that the introduction of more advanced low- NO_x combustors is required to meet the latest CAEP/4 standard with more demanding cycles. The move to CAEP/4 means that the line of constant OPR are moved to the left by between 0% (approximately OPR=60) and 16% (OPR=30). The current investigations in staged and ultra low- NO_x combustors for high bypass ratio cycles by engine manufacturers exemplify this dilemma.

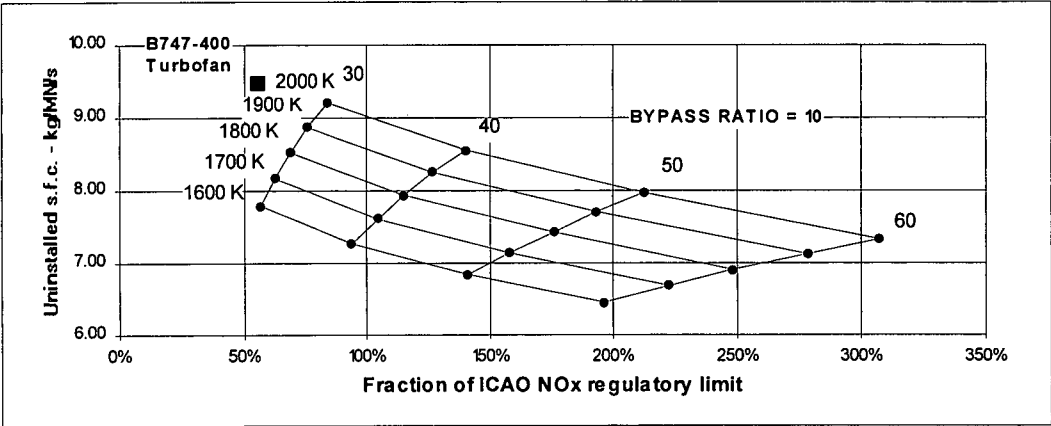


Figure 5.6 : Uninstalled s.f.c. Against the Fraction of NO_x ICAO CAEP/2 Regulatory Limit (Le Dilosquer & Singh, 1995) ;
NB : current 747-400 turbofans have bypass ratios below 5

5.2.3 Designing for Low Mission Emissions

The LTO emissions as a percentage of total flight cycle emissions are small and for long haul flights insignificant as shown in Table 5.3. Furthermore, LTO emissions are assessed statically by intrusive probes to the efflux on the test bed, there are no corrections to account for the effect of forward speed. Early engines certified by ICAO had very low bypass ratios, so that the effect of speed on emissions was small. Modern engines have much higher bypass ratios and the emissions can change significantly with forward speed. In this respect, the question arises whether the current standard is adapted to limit aviation’s impact at high altitude.

LTO as % of Total	Fuel	CO ₂	NO _x
Short Haul / 757 London-Glasgow (283 nm)	37	37	32
Long Haul / DC10-30 Los Angeles-Tokyo (4725 nm)	3	3	2

Table 5.3 : LTO Emissions as a Proportion of Total Flight Emissions

Figure 5.7 shows the NO_x characteristics of two different combustors. Engine B would produce much higher LTO NO_x than Engine A. However, at cruise, where a long range aircraft would burn over 85% of its fuel, the relative NO_x performance is reversed. With the current LTO based regulations, Engine B with the lower cruise NO_x emissions could fail the CAEP/4 recommendations, even though it could be argued that it has a better global environmental performance.

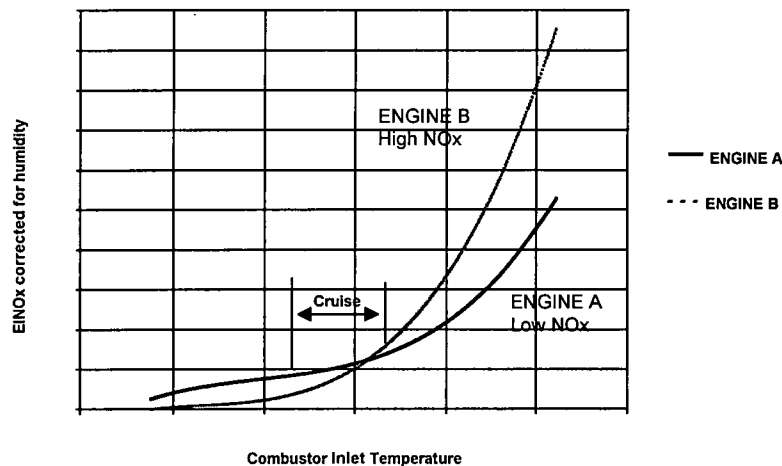


Figure 5.7 : NO_x Characteristics from 2 Hypothetical Combustors

Future emissions regulations must address such areas where the compliance with airport air quality is realised at the expense of high altitude environmental protection. This is not to say that all combustors with low LTO NO_x have high cruise NO_x . There are many cases where new technology combustors have been introduced into a particular engine which has resulted in better NO_x performance throughout the cycle.

Figure 5.8 shows the result of an engine preliminary design study undertaken by Rolls-Royce which looked at the performance and NO_x emissions of engines with a bypass ratio ranging from 6.5 to 13.5. The engines incorporate similar levels of combustor technology. All the engines are designed to give equivalent thrust at top of climb conditions as well as the same rated take-off thrust. At sea level static conditions, the higher BPR engines operate at less arduous conditions resulting in lower LTO NO_x . Conversely, the lower BPR engines have a greater propulsive efficiency gain as they are throttled back from climb to cruise rating. This is due to their lower thrust lapse rate with forward speed leading to lower NO_x emissions at cruise. The study concluded that whilst the higher bypass ratio engines would have lower LTO NO_x levels, the opposite was observed for cruise NO_x . Although time did not permit it, such a study could be carried out using the SKY computer system.

Irrespective of the NO_x issue, with today's technology levels, BPR greater than 9 are unlikely to deliver lower mission fuel burn for a given design maximum take-off weight (MTOW) due to higher weight and drag. At today's levels of technology, the optimum bypass ratio with respect to mission fuel burn lies between 6 and 9 depending on the installation. Noise requirements may dictate the final choice of BPR.

Furthermore, ultra low- NO_x concepts such as the Lean Premix Prevapourised combustors are under study for subsonic applications. However, doubts remain whether they will be able to operate in very high pressure engines due to limitations of auto ignition delay time. This may force the industry to choose between further fuel efficiency (and hence low CO_2 and H_2O emissions) and NO_x control.

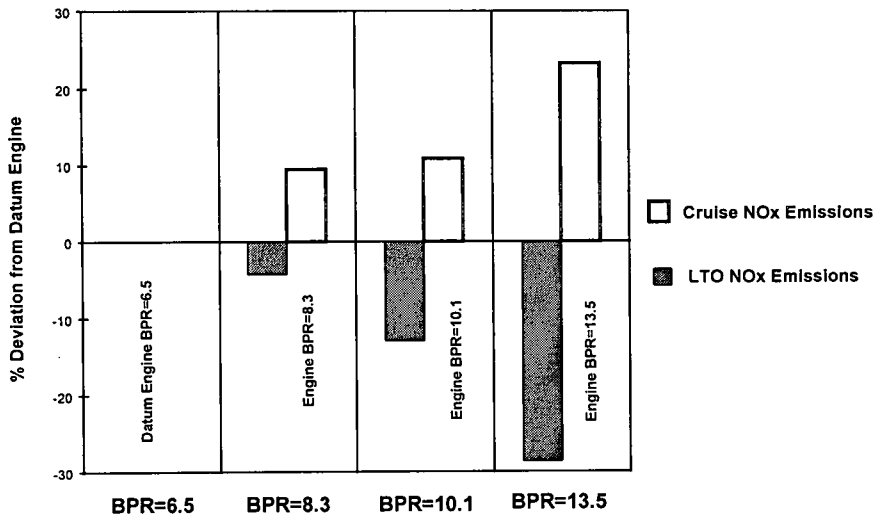


Figure 5.8 : Deviation of LTO and Cruise NO_x Emissions with Engine Bypass Ratio (Courtesy of Rolls-Royce plc ; Le Dilosquer & Singh, 1998)

5.3 INFLUENCE OF FLIGHT OPERATIONS ON MISSION EMISSIONS

5.3.1 Profile of NO_x Emissions on a Typical Long Range Flight Route

Emissions of NO_x from a 747-400 powered by high bypass ratio turbofans on the long range London-Tokyo flight route are presented in this section. If air traffic control (ATC) does not prevent the aircraft to cruise climb, SKY estimates that a typical London-Tokyo flight produce around 1320 kg of NO_x pollutants, with the largest part of it (around 85%) being emitted at cruise as shown in Table 5.4 (Le Dilosquer & Singh, 1995b). In practice, climb cruise is not allowed as aircraft are restricted to flight corridors with minimum vertical and horizontal separations. This means that the emission predicted here is optimistic and will not be achieved in reality with the same aircraft/engine combination producing more than 1320 kg on a step-cruise profile.

As the aircraft becomes lighter while gaining altitude and the thrust requirement diminishes, the reducing fuel flow rates into the combustors are responsible for a proportionate reduction in NO_x emissions. At the same time, they produce lower combustion temperatures and NO_x reaction rates, resulting in lower indices. This beneficial dual effect originates from the burnout of the fuel carried and the possibility for the aircraft to cruise climb. The amount of NO_x rejected per cruise step eventually

levels off as the fuel lost over one step is small in comparison with the total aircraft gross weight (see Figure 5.9).

Flight phase	NO _x emissions	
	kg	% total
Take-off (I)	15	1.1
Climb out to 457m (I)	15	1.1
Climb (457m to 9.5km) (II)	158	12.0
Cruise (9.5km to 11.8km) (II)	1113	84.3
Descent (II)	5	0.4
Approach (I)	7	0.5
Taxi / ground idle (I)	8	0.6
Total	1321	100
(I) : ICAO data from 747-400 engines (ICAO, 1993). (II) : SKY simulation. Flight conditions : cruise Mn = 0.85, initial cruise altitude = 9.845 km, cruise method = climb cruise, payload weight = 50835 kg (III). (III) : 1992 average scheduled air traffic data from 747 airliners on the London-Tokyo route (ICAO, 1992).		

Table 5.4 : Typical NO_x Emissions per Flight Phase for a 747-400 Powered by High BPR Turbofans on the London-Tokyo Route (Le Dilosquer & Singh, 1995b)

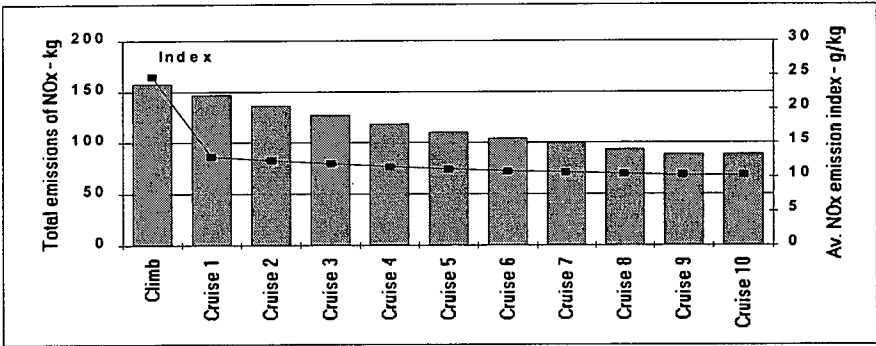


Figure 5.9 : Climb and Cruise NO_x Emissions (Le Dilosquer & Singh, 1995b)

The average and inherently less accurate indices used as inputs to large 3D chemical and dynamical models of the Earth’s atmosphere compare favourably with the above indices calculated by SKY at high altitude (see Table 5.5). In such areas of research, SKY’s advantage will obviously be to provide accurate distribution of emission output along the flight path.

0-9 km Altitude Band			9-13 km Altitude Band		
NO _x	CO	UHC	NO _x	CO	UHC
25.8	8.9	1.6	13.9	1.0	0.4

Table 5.5 : Boeing 747-400 Average Emission Indices ; NB : these number are irrespective of the engine type (Baughcum et al, 1996)

Validation of the flight and engine performance has been achieved on long range routes such as London to Hong-Kong (Le Dilosquer, 1993). The high bypass ratio turbofan

engine model features consistent behaviour on such a route with its actual performance characteristics. No discrepancy on thrust and fuel consumption larger than 3% was observed on this route, with climb showing the largest differences with the actual performance of the RB211-524G, a similar in-service engine (see Figures 5.10 and 5.11).

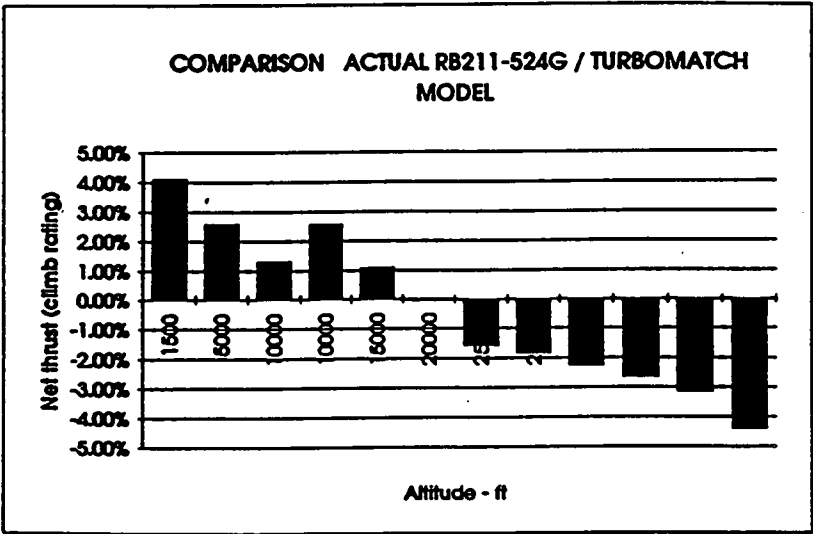


Figure 5.10 : 747-400 Turbofan Engine Model Climb Thrust Validation, Comparison with the RB211-524G Climb Thrust (Courtesy of Rolls-Royce plc)

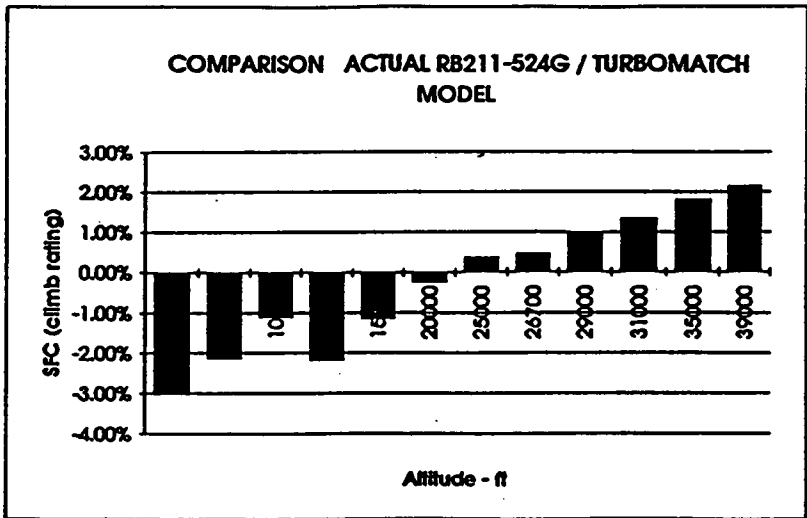


Figure 5.11 : 747-400 Turbofan Engine Model Climb s.f.c. Validation, Comparison with the RB211-524G Climb s.f.c. (Courtesy of Rolls-Royce plc)

5.3.2 Effect of Operational Factors on Mission NO_x Emissions

5.3.2.1 Effect of Cruise Mach Number and Initial Cruise Altitude

It can be seen from Figure 5.12 that optimising the cruise speed can result in a reduction of NO_x mission emissions of approximately 10% over the standard flight profile at a Mach number of 0.85. The 0.85 Mach number is selected by 747-400 aircraft in service because it offers for most airline operations the best operating economics at the expense of a relatively small penalty in fuel burn (optimum balance between the cost of fuel and the cost of time). The model used for this study is assumed to retain an identical optimum speed. The determination of such a parameter depends on airline economic factors and would lie out of the scope of this work.

Figure 5.12 shows that a reduction of the standard cruise Mach number of 0.85 to 0.80 is beneficial with respect to fuel burn and NO_x mission emissions. The reduction in fuel burn (-2.5%) stems from a slightly higher specific air range at 0.80. The reduction in NO_x mission emissions is more significant (-10%) indicating that the fall in NO_x emission index (i.e. combustion chamber running cooler) is responsible for most of the environmental benefit. Slowing the aircraft down would however penalise flight time (+40 minutes with Mn=0.80 over Mn=0.85) passenger appeal, utilisation and as a result operating costs. The payload-range capability is not affected.

At the 0.85 Mach, the optimum initial cruise altitude for best mission fuel burn lies at 11km (see Figure 5.13). Higher altitudes would be greater than the 747-400 buffet initial cruise altitude capability (ICAC) and are chosen not to be investigated. In the case of the actual 747-400, the buffet ICAC is more limiting than the maximum climb and cruise thrust ICAC, because the engine has been rated to maintain short climb time and distance for the heavier growth variants of the 747 family. The evaluation by SKY shows that the benefits of starting cruise at the optimum altitude for mission NO_x (10.5km) are not significant (< 1%). It can be argued that the optimum initial cruise altitudes for best mission fuel burn and NO_x coincide in this case.

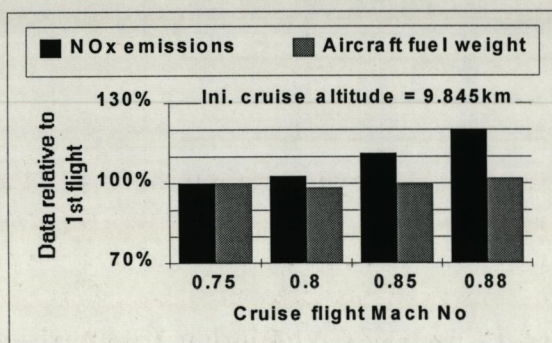


Figure 5.12 : Effect of Cruise Mach Number on Mission NO_x

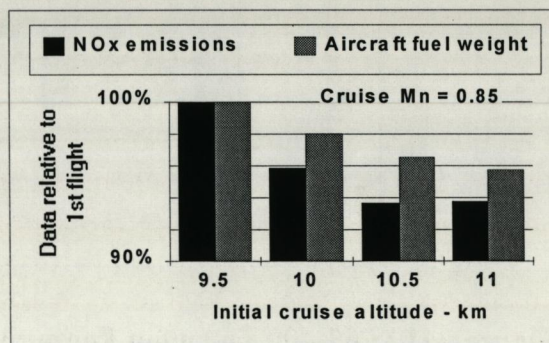


Figure 5.13 : Effect of Initial Cruise Altitude on Mission NO_x

Data for both Figures from London-Tokyo Route (Le Dilosquer & Singh, 1995b)

For the range of cruise speeds and altitudes studied, the take-off weights computed by SKY lie between 359 and 365 tonnes. At those weights, the actual 747-400 would start cruising at 9.6-9.7km representing the optimum altitude at a 0.85 Mach number (Boeing, 1990), whilst the model's optimum lies higher at 11km. The aircraft model drag polar and the engine model s.f.c. and rating structure are therefore not matching exactly the actual 747-400 performance. This should however not affect the conclusions which are based on comparisons between missions using the same model.

Although the aircraft is allowed to cruise climb in these model simulations, actual 747-400 operations would employ a step-cruise procedure burning more fuel and generating more emissions. Similar discrepancies between missions are nevertheless expected with the standard procedure, so, again, this should not affect the conclusions.

It is worth mentioning that the application of climb derates to save engine life in cases where the aircraft take-off weight is sufficiently low would not affect the aircraft altitude capability. Such derates would reduce climb NO_x emissions and promote the retention of the engine NO_x indices throughout service life. It would also preserve the aircraft ability to choose an optimum altitude for NO_x control, although, the benefits would be limited as this case study shows. Moreover, a high initial cruise altitude may be at variance with spacing requirements from current ATC, with the higher initial cruise altitude meaning that the rapid 747-400 aircraft model will have to share airspace with the slower short-range twin-engined aircraft unless a speed reduction is applied to bring the aircraft in line with twins.

If aircraft were to be proved more damaging above the tropopause, maintaining the flight profile in the troposphere may become be desirable as it has been discussed elsewhere (Haberland *et al.*, 1994) but would carry detrimental effects on fuel consumption, CO_2 and H_2O pollution, direct operating costs, and NO_x emission output, raising aviation's contribution to total tropospheric pollution. More research on the impact of aircraft emissions into the atmosphere in relation with altitude is required before any attempt to optimise operational factors can be made. For all that the optimisation of aircraft flight profile can bring in terms of emissions, large benefits should be derived from ATC improvements (as discussed in Chapter 3).

5.3.2.2 Effect of Maintaining a Constant Altitude at Cruise

Emissions of NO_x from a 747-400 model powered by high bypass ratio turbofans on the London-Sidney route are presented in this section. The aircraft performs two separate flights with a stopover at Bangkok. The cruise procedures adopted for the seven London-Bangkok flights and two Bangkok-Sidney flights computed by SKY (Le Dilosquer & Singh, 1995a) are detailed on Table 5.6. Table 5.7 presents the air traffic data used for the simulation of each leg.

Flight	Leg	Mn	Ini. cr. altitude (km)	Method
A	L-B	0.85	9.5	CC
B	L-B	0.85	10.5	CC
C	L-B	0.80	9.5	CC
D	L-B	0.80	10.5	CC
E	L-B	0.85	9.5	CA
F	L-B	0.85	10.5	CA
G	L-B	0.85	11.5	CA
H	B-S	0.85	9.5	CC
I*	B-S	0.85	9.5	CC

L-B = London-Bangkok ; B-S = Bangkok-Sidney ; CC = cruise climb ; CA = constant altitude
 * : with same payload weight and number of passengers as on London-Bangkok.

Table 5.6 : Cruise Method and Main Parameters for the Computed Flights

Flight route	London-Bangkok	Bangkok-Sidney
Range (km)	9546	7542
Av. pax load factor (%)	78	62
Av. no. of pax carried	305	240
Av. payload weight (kg)	52,582	50,721

Table 5.7 : 1992 Scheduled Air Traffic Data from 747 Airliners on the London-Bangkok and Bangkok-Sidney Routes (ICAO, 1992)

If air traffic control does not prevent the aircraft to cruise climb, SKY estimates that the two legs A and H would discharge respectively 1,370 and 1,070kg of NO_x into the atmosphere, with the largest part of it (83-85%) being emitted at cruise (see Table 5.8). This is comparable to the London-Tokyo results presented earlier. The emission profile as well as the NO_x index for both legs is shown on Figures 5.14 and 5.15. The cruise steps are 900 and 700 km long for flight A and H respectively.

Flight phase	NO _x emissions (kg)	
Take-off (1)	15	1.1
Climb out to 457m (1)	15	1.1
Climb (457m to 9.5km) (2)	155	11.3
Cruise (9.5km to 11.8km) (2)	1,162	85.0
Descent (2)	5	0.4
Approach (1)	7	0.5
Taxi / ground idle (1)	8	0.6
Total	1,367 kg	100 %

(1) : ICAO data from B747-400 engines (ICAO, 1993) ; (2) : SKY Flight A

Table 5.8 : NO_x Emission Flight Profile for a 747-400 Model Powered by High Bypass Ratio Turbofans on the London-Bangkok Route (flight A)

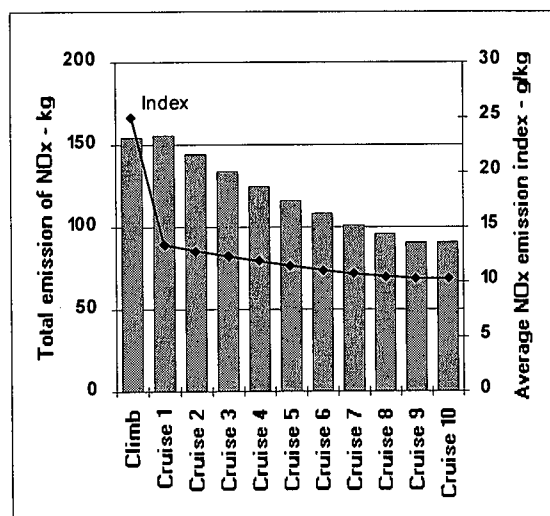


Figure 5.14 : London-Bangkok (A)

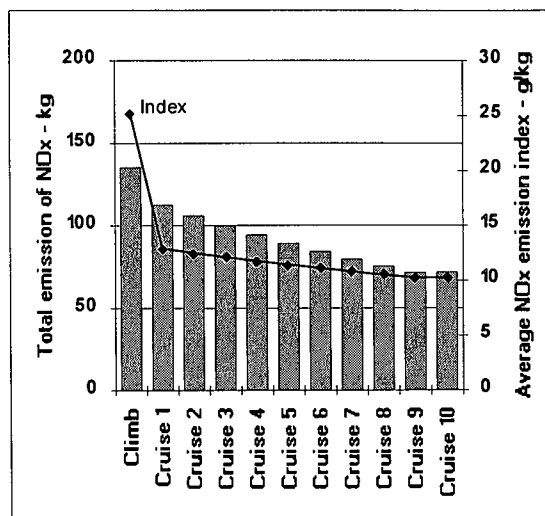


Figure 5.15 : Bangkok-Sidney (H)

NO_x Emissions & NO_x Index at Climb and Cruise (10 steps)

The amounts of NO_x discharged by each flight are presented on Table 5.9 and Figure 5.16. According to SKY calculations, the best scenario regarding the minimisation of NO_x emissions is flight D (0.80Mn and 10.5km).

Flight -	Leg -	Mn -	ICA km	Method	Fuel Used t	Cruise NO _x kg	Mission NO _x kg
A	L-B	0.85	9.5	CC	131.6	1162	1367
B	L-B	0.85	10.5	CC	127.1	1062	1283
C	L-B	0.80	9.5	CC	129.4	1044	1248
D	L-B	0.80	10.5	CC	127.2	992	1213
E	L-B	0.85	9.5	CA	140.8	1421	1633
F	L-B	0.85	10.5	CA	133.3	1185	1410
G	L-B	0.85	11.5	CA	128.9	1072	1318
H	B-S	0.85	9.5	CC	106.2	884	1069
I	B-S	0.85	9.5	CC	106.7	891	1077
A+H	L-S	0.85	9.5	CC	237.8	2046	2436
A+I	L-S	0.85	9.5	CC	238.3	2053	2443

Table 5.9 : Fuel Burn and Mission NO_x Emissions for the Computed Flights (Le Dilosquer & Singh, 1995a)

In terms of fuel burn, Flight B at a slightly higher cruise speed (0.85Mn and 10.5km) is marginally better indicating that in this study case, best specific air range does not coincide with best cruise NO_x emission index. At 10.5km, the aircraft specific air range or fuel mileage is higher at Mach 0.85 than at 0.80. The optimum fuel mileage depends on the aircraft gross weight, the altitude and the Mach number. At 10.5 km, for example, the optimum cruise Mach number lies between 0.78 and 0.85 depending on the aircraft gross weight (Boeing, 1990). In practice, a 0.85 Mach number will be maintained for

optimum operating costs at the expense of mission NO_x . To fly from London to Bangkok, the 10.5km initial cruise altitude used by flight D is aerodynamically optimum with lower fuel burn and mission NO_x than equivalent flight C at 9.5km.

Unless close to the optimum cruise altitude for specific air range, flights hold at a constant altitude (E at 9.5km, F at 10.5km) burn more fuel and generate more NO_x , as well as CO_2 and H_2O than the equivalent flights performing a cruise climb procedure (A at 9.5km and B at 10.5km).

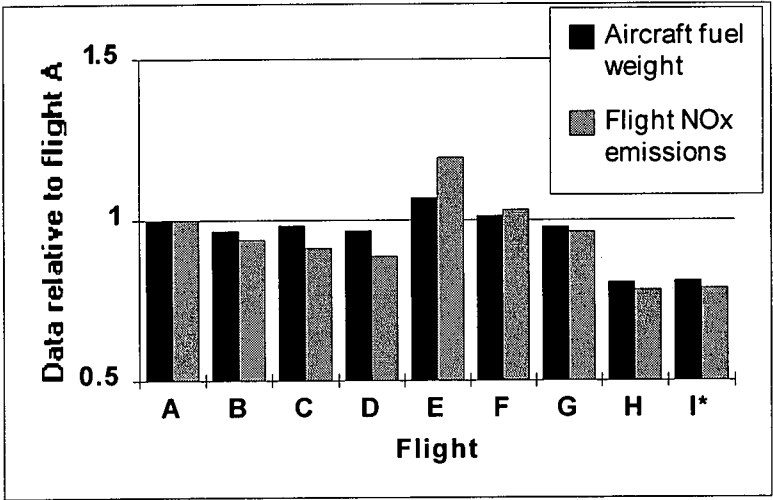


Figure 5.16 : Fuel Burn and Mission NO_x Emissions Relative to Flight A for the Computed Flights (Le Dilosquer & Singh, 1995a)

Emissions of NO_x per revenue passenger kilometre or tonne kilometre are a measure of emissions related to aircraft productivity i.e. the aircraft ability to carry passengers or payload on a given range. Any attempt at formulating a regulatory standard aimed at controlling mission NO_x would have to consider this parameter in order not to penalise the most efficient aircraft/engine combinations. As illustrated by Table 5.10, the two parameters are not particularly sensitive to a range variation of 2000 km (flight A and I).

Flight	NO_x emissions per RPK mg/RPK	NO_x emissions per TKM mg/TKM
A	0.47	2.72
H	0.59	2.80
I	0.47	2.72
A+H	0.52	2.75
A+I	0.47	2.72

Table 5.10 : Flight NO_x Emissions per Seat-Kilometre and per Tonne-Kilometre for Some Computed Flights (Le Dilosquer & Singh, 1995a)

5.4 DISPERSION OF NO_x EMISSIONS INTO THE ATMOSPHERE

5.4.1 Introduction

SKY is used in this section to simulate the flight of a 747-400 model powered by high bypass ratio turbofans on the London-Tokyo long range flight route (as modelled in the previous section). The calculated cruise NO_x emissions are input into the TOMCAT 3-dimensional chemical transport model to study the passive distribution of NO_x and HNO₃ in the atmosphere. The implications on the atmosphere are discussed.

The chemistry governing the formation or destruction of ozone by action of NO_x is non-linear (Lin *et al.*, 1988). The concentration of NO_x is not zonally symmetric and there is much variability in the NO_x mixing ratio on the synoptic time scale. A meaningful and accurate assessment of the effects of aircraft emissions on atmospheric ozone can only be performed with 3-D models able to resolve synoptic scale phenomena. Additionally, the effects of the pollutants depend strongly upon the flight altitude, calling for accurate estimates of the amount of pollutants and the corresponding discharge altitude throughout the flight.

The section presents a preliminary study of the transport of NO_x emitted by air traffic over the London to Tokyo great circle flight route (middle latitude path). As the statistics of scheduled international services for passenger flights suggest (ICAO, 1992), the 747-400 can be selected as a representative aircraft for this route. The SKY simulation system performs the integrated simulation of the aircraft performance, the engine performance and the emissions. The calculated cruise NO_x emissions are then input to the TOMCAT atmospheric chemistry model to perform the three-dimensional dispersion calculation of NO_x and nitric acid HNO₃ (resulting from the reaction between nitrogen dioxide NO₂ and the hydroxyl radical OH). The integration in this preliminary study covers only a period of one month sufficient to characterise the short term dispersion of the exhaust wake.

5.4.2 Modelling of Atmospheric Chemistry and Transport

The TOMCAT (Toulouse Off-line Model of Chemistry And Transport) three-dimensional atmospheric chemistry model has been used for studies of stratospheric chemistry (Chipperfield *et al.*, 1993, 1994 & 1995 ; Lee, 1996). The model includes transport by advection, vertical diffusion, and convection.

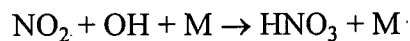
TOMCAT is an off-line model, that is it does not calculate the atmospheric circulation itself which is driven by data from the ECMWF (European Centre for Medium-range Weather Forecasts), UKMO (United Kingdom Meteorological Office) or other physical data from an on-line model. For the simulations presented here, a horizontal resolution of 2.8°×2.8° (T42) was used. In the vertical domain, the model has 19 levels, extending from the surface up to the 10 hPa level (31 km height).

The TOMCAT model treats advection of tracers using a second order moments scheme (Prather, 1986). This scheme, although costly in terms of computer time, is non-diffusive and is able to maintain sharp gradients in the tracer distributions. For the convective fluxes (Tiedtke, 1989), the occurrence of convection is calculated every six hours, using the instantaneous fields of temperature and specific humidity obtained from the analyses. The convection is applied to the tracer fields at every model time steps. Turbulent diffusion is parameterised (Louis, 1979). The diffusion coefficients are dependent on wind shear and the static stability of the atmosphere.

Wet and dry deposition schemes have also been included in the model. For wet deposition due to weather processes (Giorgi & Chameides, 1985 ; Jonson & Isaksen, 1992), a modified first order loss proportional to the concentration of the species being removed is used.

In this scheme, wet loss is tied to the specific humidity obtained from ECMWF profile; it depends upon the species solubility and takes into account the episodic nature of the wet removal process through the inclusion of a storm cycle. The storm cycle is an attempt to simulate the number of rainy days during which the wet removal is active. For dry deposition (absorption by vegetation and soil), the model uses a parameterisation with prescribed deposition velocities in the layer nearest to the ground. Deposition velocities vary according to different vegetation categories around the globe (Wilson *et al.*, 1985).

The major sink of NO_x , HNO_3 , is parameterised using an exponential decay process with an altitude dependent lifetime. The chemical reaction generating nitric acid out of nitrogen dioxide is the following :



5.4.3 Distribution of NO_x and HNO_3 Emissions in the Atmosphere

As described previously, the simulations were performed using ECMWF data on the grid corresponding to a T42 truncation for July 1990. The northern summer period is simulated with a time step of 0.5 hours and spin-up period of 1 month. The forcing data is obtained as spectral coefficients of vorticity, divergence, temperature, specific humidity and surface pressure. Flights from London to Tokyo and back using the same route are considered. The estimated average total number of flights is 10.3 per day (ICAO, 1992). From SKY calculations, each aircraft has emitted 1110 kg NO_x at cruise, which makes a total of 11430 kg. The distribution of NO_x emissions along the flight track is shown in Figure 5.17.

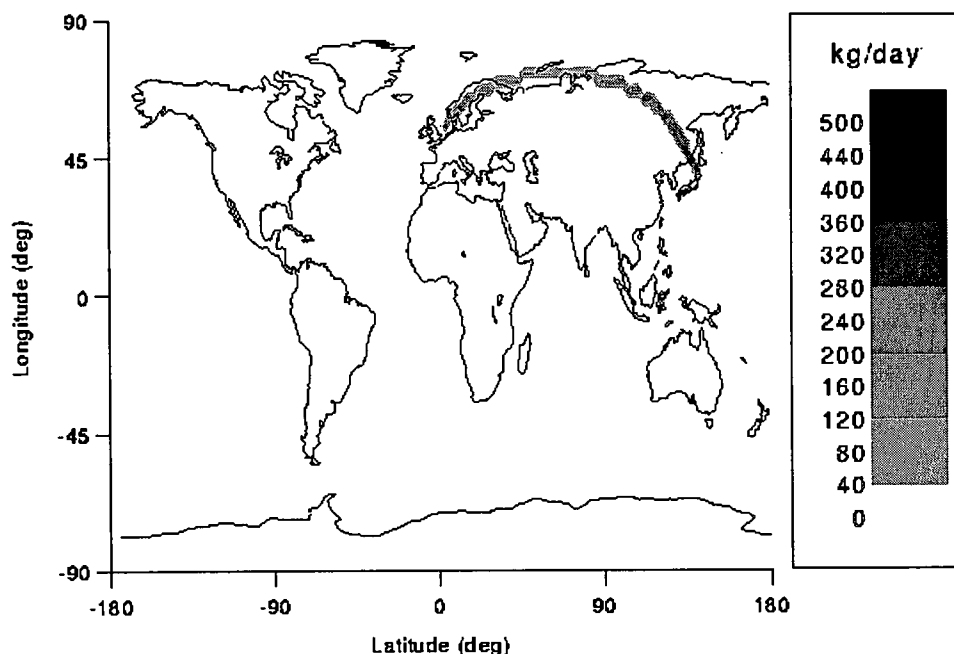


Figure 5.17 : Cruise NO_x Distribution per Day Along the London-Tokyo Flight Route (Le Dilosquer *et al.*, 1996)

The resulting distributions of NO_x and HNO_3 are considered next. For this short integration (approximately one month) of the TOMCAT model, we examine the immediate short-term dispersion of the emissions, and investigate the speed of the transformation from NO_x to HNO_3 .

Figures 5.18 and 5.19 show the distribution of NO_x and HNO_3 at approximately 10 km altitude (the model level closest to the maximum emissions) for the month of July. The largest NO_x mixing ratios are confined close to the flight track with some advection further to the east in the westerly jet stream. Very little NO_x from this particular flight track is found over the Atlantic. The chemical transformation to nitric acid is much faster than the advection. The nitric acid distributions show more substantial zonal mixing than for NO_x . The lifetime against wet deposition is long enough for air parcels rich in HNO_3 to be advected long distances.

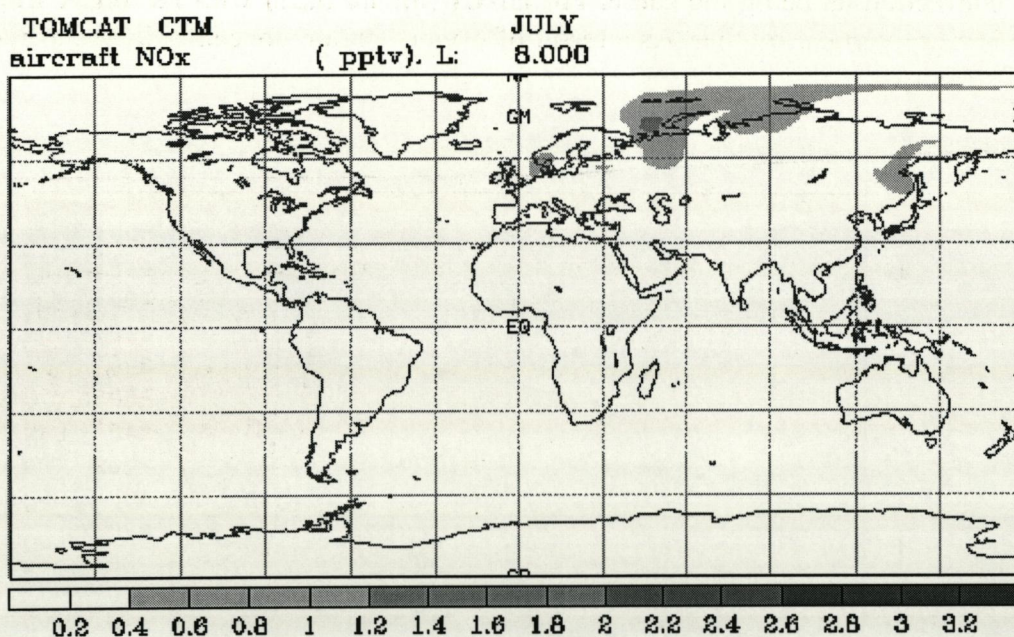


Figure 5.18 : Latitude-Longitude NO_x Distribution at 10 km Height in July
(Le Dilosquer *et al.*, 1996)

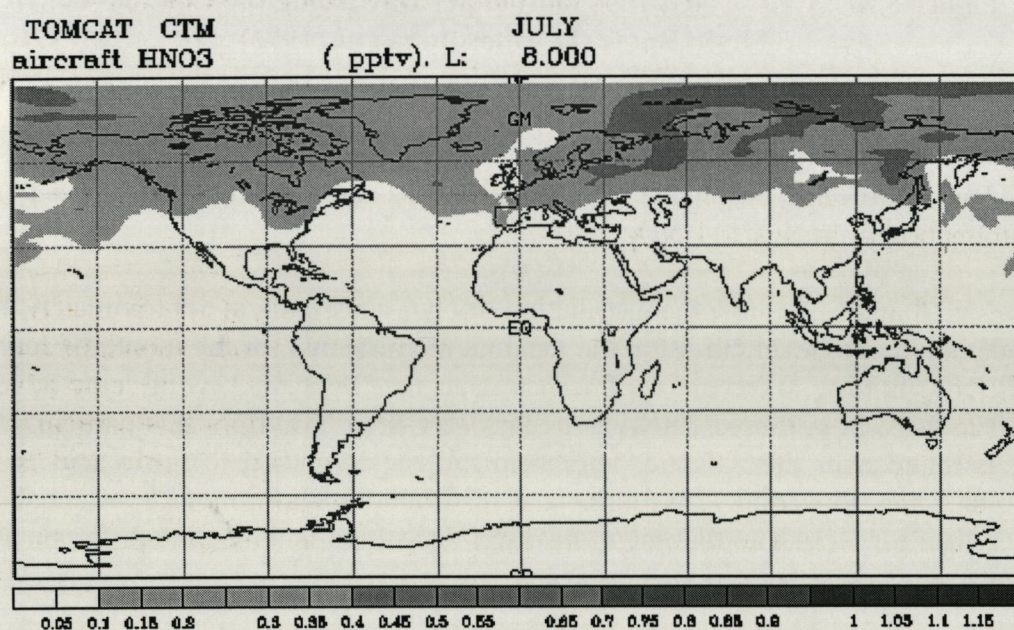


Figure 5.19 : Latitude-Longitude HNO₃ Distribution at 10 km Height in July
(Le Dilosquer *et al.*, 1996)

Figure 5.20 shows zonally averaged plots for both species in July (mixing ratios averaged on the longitude). In the case of NO_x, little transport to the surface is effected. The transport that has occurred is close to the latitude of the emissions and points to

deep convection as being the cause. For HNO_3 (Figure 5.21) with its longer lifetime, there is more vertical mixing. As a result of dry deposition concentrations close to the surface are low.

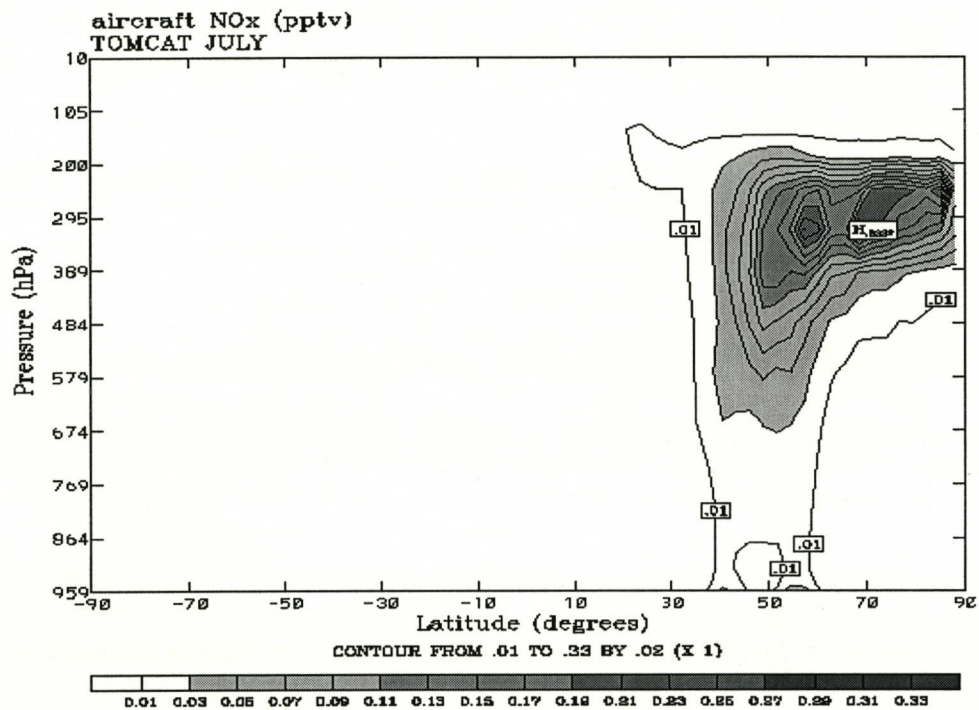


Figure 5.20 : Zonal Mean NO_x Distribution in July (Le Dilosquer *et al.* 1996)

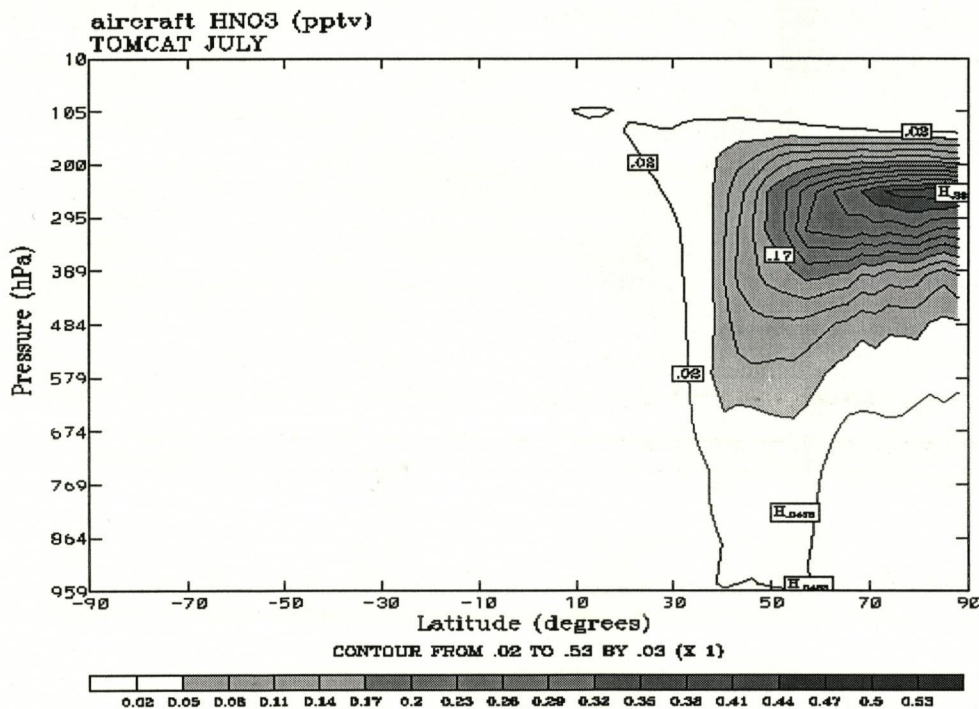


Figure 5.21 : Zonal Mean HNO_3 Distribution in July (Le Dilosquer *et al.* 1996)

Discussions, Conclusions and Recommendations for Further Work

6

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6.1 DISCUSSIONS

A number of objectives were set out at the beginning of this work to examine the influence of civil subsonic aero engine design and flight operations on atmospheric pollution (see Chapter 1). They included :-

1. To determine the best combination of turbofan cycle parameters with respect to the minimisation of mission emissions and examine if this is in conflict with traditional subsonic aero gas turbine design requirements ; to assess the environmental penalty of in-service engine deterioration ; to determine if low mission emissions would be a pertinent cycle parameter at the preliminary design stage.
2. To identify the optimum flight profile with respect to the minimisation of mission emissions and examine if this is in conflict with current operational practices.
3. To examine the regulatory implications and in particular if the current ICAO LTO standard is an adequate regime to minimise mission emissions.

The computer simulation system named SKY integrating flight route performance, aero engine performance and the formation of the pollutants within the engine's combustor was developed to meet the above objectives. Through the evaluation of mission NO_x , UHC, CO, CO_2 and H_2O emissions, SKY can be used to optimise in an integrated manner mission/aircraft/engine/combustor combinations so as to minimise any of the aforementioned pollutant emissions over a given mission. SKY can be employed to explore the relative merits of any technological and operational routes and study systematically the effects of changes in combustor technology, engine cycle, rating structure and flight path (altitude profile and speed schedule). It can also estimate the ability of engine/combustor combinations to meet ICAO LTO standards as well as supply flight emission data with good spatial resolution as inputs to 3-dimensional chemical transport models of the Earth's atmosphere to study the impact of air traffic pollution on a regional or a global scale.

Ignoring the complex economic considerations which lie out of the scope of this work, the technological and operational routes designed to reduce the amount of civil aviation emissions have been identified as : the alteration of kerosene properties and the use of an alternative fuel, low emissions combustor technology, airframe design,

aero engine design and optimisation of the flight profile. It is worthwhile to review the individual environmental merits of the first three options to put in perspective aero engine cycle and operational optimisations.

- *Alternative fuels and kerosene properties*

In terms of the balance between energy storage, operational properties, safety and economics, kerosene-type fuels do not seem to have strong contenders in prospect. The possible shortfall resulting from increasing aviation fuel demand and declining oilfield production should be met by supplementation from other sources (tar sands, oils shales and promisingly natural gas) or by separate production of a manufactured kerosene-like fuel. As to the properties of the current kerosene, at a given combustor technology level, the predicted degradation in its quality may be expected to cause small increases in smoke, SO₂, CO and UHC emissions, whilst the effect on NO_x is probably small. Accurate data would be required to formulate definite conclusions on that matter.

- *Low emissions combustor technologies*

As a response to the ICAO LTO standards, the reduction of aviation emissions has until now focused on the development of low emission combustors by aero engine manufacturers to address the issue of airport air quality. NO_x reductions of between 30 and 80% over the current single annular combustor technology may be expected from future low-NO_x combustors, depending on their ability to achieve their full potential in service. A number of impending technical problems will have to be resolved before these techniques can gain the acceptance of airworthiness authorities as well as airlines. These new types of combustors do not envisage further reductions in CO, UHC and smoke beyond the current ICAO LTO levels and will certainly maintain high combustion efficiency levels therefore not affecting the direct relationship between fuel burn and CO₂ and H₂O emissions.

- *Airframe design*

Maximising the lift-to-drag ratio and minimising the aircraft empty weight lead to improved specific air range and therefore emissions. In the next 20 years or so, it is estimated that further reductions in skin friction and induced drag can be expected, resulting in a predicted 10% increase in lift-to-drag ratio. Additionally, the use of improved structural design, manufacturing and lighter materials can contribute to reducing aircraft weight. Lighter material include composites, advanced alloys and super plastically formed diffusion bonded titanium. A 10% reduction in operational empty weight could be achievable in the next 20 years. The cumulative 20% improvement in fuel burn will lead to a similar reduction in all emissions.

Because it may become environmentally desirable in the future to actively curb the global production of flight NO_x emissions, and because combustor technology may not deliver on its own the required balanced global reductions across all relevant species (in particular NO_x, CO₂ and H₂O), the benefits of alternative routes such as aero engine design and flight route optimisations for low emissions deserve to be

thoroughly investigated. The principal conclusions regarding aero engine cycle optimisations are as follows :-

- Although single annular technology has shown it is still capable to cope with current operating pressures and temperatures and meet the latest ICAO CAEP/4 standards, the introduction of more advanced low- NO_x combustor technologies will be required as the industry expects to push Overall Pressure Ratios beyond 40:1 and Turbine Entry Temperatures over 1800K. The current investigations in staged and ultra low- NO_x combustors for high bypass ratio cycles by engine manufacturers exemplify this dilemma.
- The LTO emissions as a percentage of total flight cycle emissions has been shown to be small and for long haul flights insignificant in the region of 2% for NO_x and 3% for CO_2 and H_2O whilst approximately 85% of such emissions are produced at cruise. However, with the current LTO based regulations, the optimum engine/combustor combination with respect to cruise NO_x may be one that could fail the CAEP/4 standard, even though it could be argued that it has a better mission environmental performance. Similarly, it has been demonstrated that for a given aircraft application, as engine bypass ratio is increased, LTO NO_x levels are improved, but the opposite is observed for cruise NO_x . For engines with a bypass ratio which does not require variable pitch fan blades and/or variable area fan nozzle (in the region of 9-10), variations of the order of 10% in cruise NO_x emissions between the best and the worst engine can be observed. For engines with a bypass ratio greater than 10, up to 20% higher NO_x levels appear possible over the best engine. Although the study showed that the optimum bypass ratio was approximately 6-7, that may depend on the application. As a result, the current ICAO regulatory regime is not adequate to control mission NO_x and future standards must address areas where the compliance with airport air quality can be potentially realised at the expense of global environmental protection.
- At any rate, with today's technology levels, bypass ratios greater than 9 are unlikely to deliver the lower mission fuel burn required to offer improved payload-range capability due to greater propulsion system weight and installation drag that limit the benefits of improved propulsive efficiency. At today's levels of technology, the optimum bypass ratio with respect to mission fuel burn lies between 6 and 9 depending on the installation. Noise requirements may however dictate the final choice of bypass ratio at the expense of fuel burn.
- The continuing pressure for low streamtube s.f.c. can only be met by raising the cycle pressure and temperatures to increase thermal and/or propulsive efficiencies, because only limited returns can be obtained from improvements in component efficiencies. A reduction of 10% in s.f.c. is achievable in the next 20 years or so. This approach yields obvious benefits in terms of H_2O and CO_2 but would result in higher combustion temperatures and higher NO_x levels for a given combustion technology. As a result, the reduction of CO_2 and H_2O on the one hand and NO_x on the other hand are in conflict. Furthermore, doubts remain whether ultra low- NO_x concepts such as Lean Premixed Prevapourised combustors will be able to operate in very high pressure engines beyond 40:1 to 50:1 due to limitations of auto

ignition delay time. This may limit the thermal efficiency as well as the level of bypass ratio achievable and force the industry to choose between further fuel efficiency (and hence low CO₂ and H₂O emissions) and NO_x control. In the future, the nature of the compromise between the requirements of engine performance, fuel efficiency and low NO_x, CO₂ and H₂O emissions will depend on the type of combustor technologies that will emerge and gain acceptance by airworthiness authorities and airlines.

- The engine deterioration will generally account for 80% of the total aircraft fuel burn deterioration, with the remainder attributable to the airframe. The deterioration in H₂O and CO₂ mission emissions over the aircraft life cycle will be in line with that of fuel burn. However, because of increased combustor inlet pressure and temperature and equivalence ratio, as the engine components degrade, the deterioration of NO_x mission emissions can be expected to be more pronounced than that of fuel burn and any other pollutants. In particular, Lean Premixed Prevapourised combustors burning lean and highly homogeneous mixtures are much more sensitive to changes in non-uniformities and mixture strength than current single-annular combustors. Although they will offer a better NO_x index than current technology on new engines, the index rate of deterioration may be worst as a result. This technical issue will have to be addressed. The effect of deterioration should be slightly beneficial to CO and UHC low power emissions.

The principal conclusions regarding the optimisation of flight operations are as follows :-

- Based on the simulation of a model of a 747-400 airliner powered by high bypass ratio turbofans on the long range London-Tokyo route, a reduction in cruise Mach number has shown to lead to an improvement in mission NO_x emissions of more than 10% over the standard speed. This standard speed is generally selected higher than the optimum for fuel mileage to offer greater passenger appeal and lower direct operating costs. The optimum Mach number for NO_x control is likely to be lower than that for mission fuel efficiency. As a result, it should be possible to apply a more modest cruise speed reduction benefiting NO_x control as well as fuel burn and hence CO₂ and H₂O emissions. Although the payload-range capability would be maintained, the economic penalty may not be insignificant. These considerations are valid for existing aircraft and may vary if, for instance, the aircraft wing, cruise speed and altitude were designed to minimise mission NO_x.
- Based on the same mission/aircraft/engine combination at the standard cruise Mach number, computer evaluations by SKY show that beginning cruise at the optimum altitude for mission NO_x rather than for fuel efficiency does not offer significant benefits (< 1%). The optimum initial cruise altitude has not been examined for lower cruise speeds.
- Unless close to the optimum cruise altitude for specific air range, flights hold at a constant altitude are detrimental to fuel burn as well as all emissions including NO_x, than the equivalent flights performing a cruise climb procedure. Step-cruise procedures would lie in between.

- Maintaining the flight profile at sufficiently low altitude to avoid the tropopause (if that was to be proved environmentally desirable) to minimise the stratospheric effects of NO_x would be severely detrimental to fuel burn, payload-range capability and direct operating costs as well as raise aviation's contribution to total tropospheric CO_2 and H_2O pollution. Furthermore, depending on the stage length, it may also worsen tropospheric NO_x pollution on polar routes where the tropopause height is likely to lie below the optimum altitude for minimum NO_x . In this respect, more research on the atmospheric impact of NO_x , particularly in relation to altitude, are required.
- It has been estimated that airlines burn 13% of their fuel bill in a non productive way of which 7% could be saved through more efficient air traffic management procedures and the use of satellite-based future air navigation systems. The inefficiencies are a result of air space congestion, indirect routings and ATC restrictive rules. Such savings would translate to equivalent reductions in all emissions.
- In cases where the aircraft take-off weight is sufficiently low, the application of climb derates to save engine life would reduce climb NO_x emissions. Given that climb makes up only 10-15% of long range mission NO_x , the benefits would be limited for new engines. However, the application of take-off and climb derates in service, which can amount to up to 25% and 10% respectively, would promote the retention of the NO_x index, significantly minimising the mission NO_x emissions generated by mature engines.
- Emissions of NO_x per revenue passenger kilometre or tonne kilometre are a measure of emissions related to aircraft productivity i.e. the aircraft ability to carry passengers or payload on a given range. Any attempt at formulating a regulatory standard aimed at controlling mission NO_x would have to consider this parameter in order not to penalise the most efficient aircraft/engine combinations.

The effects of the various technological and operational improvements on the global emission burden in the next 20 years can be summarised thus :-

- A cumulative improvement in fuel efficiency (fuel burn improvement for a given payload) of around 45% is achievable in the next 20 years or so. This will result from operational measures (-7% in fuel burn) as well as from airframe/engine design advances i.e. engine s.f.c. (-10%), airframe structural weight (-10%) and aerodynamic improvements (+10% lift-to-drag ratio). The 45% improvement is achievable if the air traffic growth is accompanied by more efficient navigation practices to avert the congestion of airports and flight corridors. With no account for s.f.c. reductions, the potential total fuel burn improvement reduces to 30% (cumulative figure). Because emission indices are not strongly affected by non-s.f.c. improvements, this should translate into a 30% reduction in all pollutants.
- At today's level of combustor technology, NO_x emissions would be however adversely affected by the potential 10% improvement in s.f.c.. The prediction is based on traditional design rules with no attempt at optimising the engine cycle for

low NO_x emissions. However, a 10% variation in mission NO_x may result from engines with bypass ratios between 6 and 10 (those likely to deliver optimum aircraft fuel burn), implying that aero engine cycle optimisations could deliver mission NO_x reductions of up to 10% over cycles designed for low LTO NO_x emissions. The benefits are not negligible but smaller in comparison to the 30% reduction due to the overall fuel efficiency improvements as well as to the 30-80% potential advances in low-NO_x technology.

- Developments in combustion technology alone indicate that NO_x emission indices may be reduced in the future by between 30 to 80% whilst further cuts in other emission indices such as CO and UHC are not currently on the agenda. The CO₂ and H₂O indices depend on the kerosene stoichiometric composition and would not be affected.
- Operational measures such as speed reductions could bring further reductions of the order of 10%. Some of the improvement would be made at the expense of fuel burn, CO₂ and H₂O emissions, as well as payload-range capability and direct operating costs. Although larger benefits may be obtained by designing the airframe/engine combination to minimise mission NO_x, the benefits of the operational route are not negligible but, as for cycle optimisations, comparatively smaller than what the overall fuel efficiency improvements and the potential advances in combustion technology may offer in the next 20 years or so.
- With air traffic expected to double in the next 20 years, global NO_x on a revenue-passenger or tonne-kilometre basis may be expected to fall dramatically thanks to these advances. However, reversing the trend of the ever-increasing absolute global NO_x burden is unlikely to happen, unless ultra low NO_x technology is introduced.
- Depending on the technological compromise realised by future low-NO_x cycle/combustor combinations and provided that this is not made at the expense of fuel burn, H₂O and CO₂ emissions may be expected to reduce by up to 30-40% in the next 20 years or so. Similar trends should be followed by CO and UHC emissions.

SKY has been used to simulate the 747-400 model powered by high bypass ratio turbofans. Flights from London to Tokyo and back over the month of July 1992 are considered. The aircraft have performed the efficient climb cruise procedures at altitudes between 9.8 and 12.1km providing optimistic estimates of emissions. The calculated cruise NO_x emissions have been input into the TOMCAT 3-dimensional chemical transport model of the Earth's atmosphere to study the passive distribution of NO_x and HNO₃ in the atmosphere. For this short integration, most NO_x is found close to the location of emission. Longer-lived nitric acid is mixed more evenly in the zonal direction. The results lead to a number of implications for the atmosphere which are of course specific to the selected aircraft/engine combination and route :-

- In the stratosphere, some of the advected NO_x emissions that survive the chemical transformation to nitric acid may destroy ozone, which might lead to increased fluxes of solar ultra-violet radiations (UV-B) at the earth's surface and cause damage to human health and the biosphere.

- However, in the troposphere, NO_x participates in the formation of ozone. The excess ozone produced absorbs infra-red radiation and contributes to global warming.
- The physical removal of nitric acid, either by dry or wet deposition, acidifies the atmosphere. In the upper troposphere (for temperatures below 195K), if HNO_3 encounters water vapour it may be transformed into nitric acid trihydrate (NAT) and contribute to Polar Stratospheric Cloud (PSC) formation. It can therefore impact the ozone destruction process in the stratosphere and contribute to the polar ozone hole.

In these preliminary calculations, the distribution of exhaust products is sensitive to the model formulation of chemistry, long-range transport by the meridional circulation, deep convection and wet and dry deposition processes. Comparison of the model with measurements of the aircraft exhaust and background emissions should allow to test these aspects of model formulation. The consequences of the results are potentially important and should be studied in longer integrations including more detailed chemical schemes.

6.2 CONCLUSIONS

The SKY computer simulation system has been developed to examine the potential benefits from optimising aero engine cycles and flight operations for low emissions. A model of the high capacity Boeing 747-400 powered by Turbomatch high bypass ratio turbofan models and simulated on long range routes such as London-Tokyo has been selected for this work. The principal conclusions are as follows :-

- The commercial requirement for further s.f.c. reductions as well as possible future regulatory pressures for low CO_2 and H_2O emissions can be met via increased cycle pressures and temperatures. This approach is however in conflict with the minimisation of LTO and mission NO_x calling for more advanced combustors.
- At today's levels of technology, the optimum bypass ratio for mission fuel burn lies between 6 and 9 depending on the installation. In this range, mission NO_x reductions of up to 10% over designs optimised for LTO NO_x are possible, indicating that the current ICAO regulatory regime is not an adequate criterion to control mission NO_x .
- The deterioration in H_2O and CO_2 mission emissions over the aircraft life cycle will be in line with that of fuel burn. The effect of degradations should be slightly beneficial to CO and UHC levels. However, the deterioration of NO_x mission emissions can be expected to be more pronounced than that of fuel burn. In particular, Lean Premixed Prevapourised combustors will offer a better NO_x index than current technology, but the rate of deterioration may be worst. This technical issue has to be addressed.

- Operational measures such as cruise speed reductions could bring further reductions of the order of 10%, but some of the improvement would be made at the expense of fuel burn, CO₂ and H₂O emissions, payload-range capability and direct operating costs. With the aircraft type, engine type and route selected for the study, the benefits from optimising the cruise altitude do not appear significant.
- Maintaining the flight profile at sufficiently low altitude to avoid the tropopause to minimise the potential stratospheric effects of NO_x would be severely detrimental to fuel burn, payload-range capability and direct operating costs as well as raise aviation's output of tropospheric NO_x and CO₂ and H₂O greenhouse gases. More research on the atmospheric impact of NO_x in relation to altitude is required.
- When applicable, take-off and climb derates can not only enhance engines life cycles but also promote the retention of the NO_x index throughout the flight, significantly minimising the mission NO_x output generated by mature engines.
- The benefits from engine cycle and flight profile optimisations are therefore not negligible but smaller in comparison to the 30 to 80% potential cuts from future low-NO_x technology, as well as to the 30% reduction due to cumulative improvements anticipated in the next 20 years or so in airframe weight and aerodynamics and more efficient navigation practices.
- With air traffic expected to double in the next 20 years, global NO_x on a revenue-passenger or tonne-kilometre basis may be expected to fall dramatically thanks to these advances. However, reversing the trend of the ever-increasing absolute global NO_x burden is unlikely to happen, unless ultra low NO_x technology is introduced.

6.3 RECOMMENDATIONS FOR FURTHER WORK

- *Improvements to the SKY computer simulation system*

A number of potential improvements can be made to facilitate the optimisation of mission/aircraft/engine/combustor combinations as well as increase the software's computation rapidity. It may be of interest to supply SKY with data files containing the engine performance data, which the flight route module could interpolate rather than allowing Turbomatch to run as a subroutine. This would help the user to control the quality of the engine data, prevent the computer system to fail when Turbomatch does not converge and accelerate the convergence of take-off weight to a final solution. The user would have to construct input data files including the engine thrust and s.f.c. as a function of altitude, Mach number and ISA deviation. This approach would also permit SKY to use engine data from another source than Turbomatch.

A number of emission correlations have been published in the report concluding the AERONOX project (Schumann, 1995). The best correlations could be coded in Fortran and added to SKY alongside those of Lefebvre. In addition, it would be of interest to model a staged combustor. This would be theoretically straightforward

and offer the possibility to assess the LTO as well as mission emissions of engines with this recently introduced combustor. The practical issues and implications on engine design would have to be considered. Lean Premixed Prevapourised and Rich-burn Quick-quench Lean-burn combustors would deserve similar attention.

- *Further research on the influence of subsonic aero engine design*

The effect of bypass ratio on mission emissions could be further investigated using SKY and Turbomatch. The assessment would have to incorporate up-to-date and valid methods to assess the installed drag and weight of the very and ultra high bypass ratio powerplants. Several engine cores could be employed for such a study depending on technology levels commensurate with a number of hypothetical Entry Into Service dates. The engines under consideration could be aimed at powering an aircraft of the class of the 747-400 for the reasons expressed in Chapter 1.

For that particular application, it would be of interest to study the effect of using 2, 3 or 4 engines to meet the 747-400 thrust requirements on mission emissions. The implications of engine deterioration as well as thrust derates on NO_x indices throughout service life deserve to be investigated in more details.

The reheat gas turbine engine cycle is a cycle with two combustion chambers separated by a turbine. At present, only a electricity-generating stationary version has been developed. Because the two combustors run cooler than the combustor of a conventional turbofan providing an equivalent output, this concept may lead to significant reductions in mission NO_x emissions. The two points of fuel input in the engine would provide useful means of variability. A proper assessment of this type of cycle including emissions, fuel efficiency, weight, drag and performance retention, should be considered for an aeronautical application.

- *Further research on the influence of flight operations*

The investigation into low pollution routings should be expanded. Further investigations should be conducted to assess to what extent the conclusions regarding the effect of altitude and speed can be applied to other aircraft and engine types. The aircraft cruise speed is optimised with regards to such requirements as operating economics, fuel efficiency, payload-range capability and operational flexibility, but it is possible to determine the best cruise speed for minimum NO_x . At this cruise speed, it would then be possible to define the optimum cruise altitude profile (i.e. profile minimising the ratio of Emission Index over Specific Air Range). The benefits in NO_x as well as the penalty in other emissions, fuel burn and payload-range capability could be assessed. The approach may deliver more than the 10% improvement calculated in Chapter 5. To be independent of the flight route, the profile could be defined in terms of optimum altitude against aircraft take-off weight. This study could be applied to an existing aircraft. Using an aircraft design optimisation program, the approach could also be applied to new designs where the aircraft/engine/combustor combination is fully optimised for low NO_x emissions.

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NB : The numbering convention for appendices is tied to the referring chapter (Chapter 1 with Appendices A.x, 2 with B.x, etc. with *x* starting at 1). As chapter 1 does not refer to any appendices, there are no appendix numbers starting with A.

Appendix B.1

The Formation of Aero Gas Turbine Exhaust Emissions

1. INTRODUCTION

The species emitted by aircraft are those resulting from the combustion of jet fuels in air which encompass kerosene and wide-cut fuels. Kerosene makes up the major part of the world civil and military jet fuel consumption. Wide-cut fuels appeared in the USA in 1968 as a result of their availability and lower cost at that time. The civil specifications Jet A, Jet A-1 and Jet B appeared in 1958. A small number of other fuel variants such as aviation gasoline exists but their use remains globally insignificant. All jet fuels are, in fact, kerosene based, the several variations having emerged for reasons of availability and operational requirement (Goodger, 1994). The various kerosene and wide cut fuel specifications and designations are given in Table 1. The present research project deals with emissions generated by the chemical reaction of kerosene in air.

<i>Fuel Type</i>	<i>Specification</i>			<i>Designation</i>			
	US MIL	US CIVIL	UK (DERD)	NATO	US MIL	US CIVIL	UK (JSD)
<i>Kerosene</i>	-	ASTM D1655	-	-	-	Jet A	-
	-	ASTM D1655	2494	F-35	-	Jet A-1	Avtur
	T-83133	-	2453	F-34	JP-8	-	Avtur/FSII
<i>Wide Cut</i>	-	-	2486	-	-	Jet B	Avtag
	T-5624	-	2454	F-40	JP-4	-	Avtag/FSII

Table 1 : Current Specifications and Designations for Kerosene and Wide-cut Jet Fuels (Goodger, 1994)

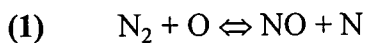
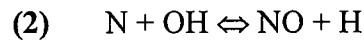
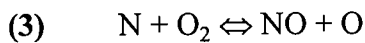
2. NITROGEN OXIDES (NO_x)

Oxides of nitrogen (NO_x) encompasses nitric oxide (NO) and nitric dioxide (NO₂), the result of the subsequent oxidation of some of the nitric oxide. In the gas turbine combustor, NO_x initially only include nitric oxide NO. These oxidation reactions are slower than those of the fuel combustion under the gas turbine operating conditions. It follows that the concentrations obtained are far from the chemical equilibrium and are therefore almost proportional to the residence time. In contrast to CO and UHC, NO arises only in the hot central regions of the combustor with levels highest at full-power conditions.

Nitric oxides can be produced in the combustor by four different mechanisms :-

- Thermal NO produced by oxidation of atmospheric nitrogen in the post flame gases
- NO produced by oxidation of nitrous oxide (N_2O)
- Prompt NO produced by high-speed reaction at the flame front
- Fuel NO produced by oxidation of nitrogen originally bounded in the fuel

Thermal NO is produced by oxidation of atmospheric nitrogen in the post flame gases and is controlled largely by flame temperature. It is formed at a significant rate only at temperatures above around 1850 K. In conventional gas turbine combustors with residence time less than a few milliseconds, NO increases linearly with time but does not attain its equilibrium value. NO formation proceeds by the extended Zeldovich chain mechanism as follows :-



NO is found to peak on the fuel lean side of stoichiometric. Although flame temperature is a maximum on the rich side of stoichiometric, the available oxygen is then all consumed preferentially by the fuel whose reaction proceeds at a higher rate.

Figure 1 (opposite →) : Effect of Residence Time on NO_x in a Premixed Fuel-Air System (Anderson, 1975)

Figure 2 (below ↓) : Influence of Inlet Air Temperature on Nitric Oxide Emissions (Rink *et al*, 1989b)

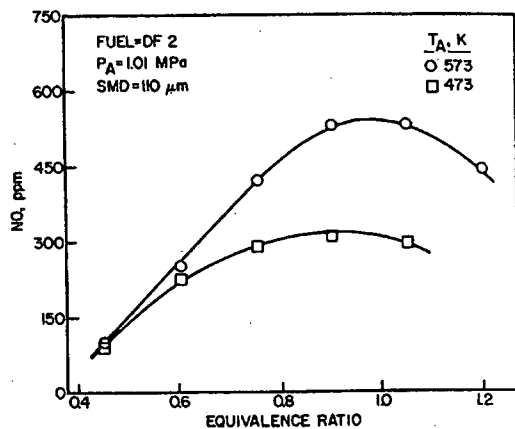
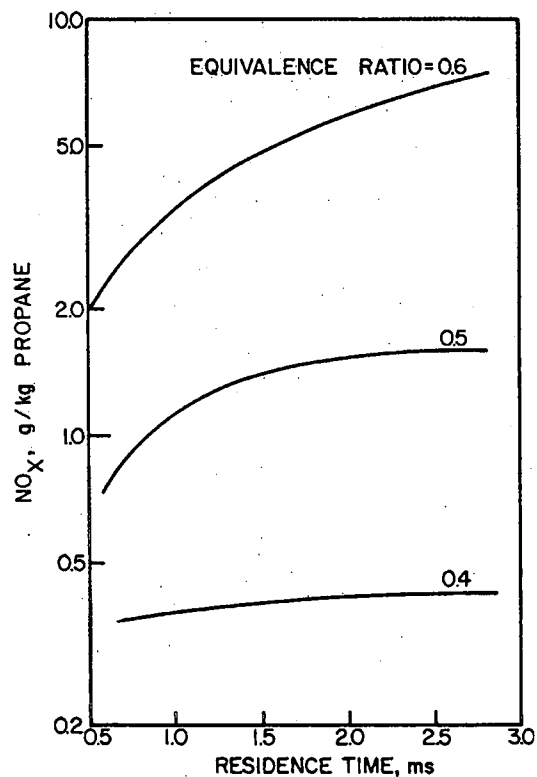


Figure 2 illustrates the effect of combustor inlet temperature on NO_x for a large number of engines, using a time- and temperature-dependent correlation. This correlation on combustor inlet temperature is important only insofar as it influences the flame temperature. The effect of residence time on NO_x emissions is shown on Figure 1. The data is obtained from experiments using a premix-prevapourise combustor burning gaseous propane fuel. The results show an increase in NO_x emissions with an increase in residence time, except for very lean mixture (equivalence ratio 0.4), for which the rate of formation is so low that it becomes insensitive to time. Such findings confirmed by several other research results have important implications to the design of lean premix prevapourise (LPP) combustors.

Fuel injection and atomisation mechanisms are also a determining factor. Improved mixing prior to combustion through better fuel atomisation and placement, and higher pressure drops across the liner result in more homogeneous combustion. The consequence may be lower or higher NO_x levels, depending on the combustor overall average fuel/air ratio.

Although thermal NO makes up the larger part of the NO_x emission count from current gas turbine combustors, three other varieties of NO are generated albeit in smaller amounts. They include :-

- NO produced by *oxidation of nitrous oxide* (N_2O) : according to Nicol et al (1992), the mechanism is initiated by the reaction between nitrogen (N_2) and atomic oxygen (O) and the N_2O formed is then oxidised to NO by three different, the most powerful of which is $\text{N}_2\text{O} + \text{O} \Leftrightarrow \text{NO} + \text{NO}$.
- *Prompt NO* : under certain conditions, NO is found very early in the flame region, a fact that is conflict with the idea of a kinetically-controlled process (Lefebvre, 1995). The reaction mechanism involving N_2 , CH, HCN, CN and NCO is proposed by Nicol et al (1992). Although prompt NO is difficult to predict, it may be a significant contributor to the NO_x emissions produced in lean premixed combustion at operating conditions giving very low levels of thermal NO.
- *Fuel NO* : this variety is generated by the combustion of fuel containing organically bonded nitrogen. The proportion of nitrogen undergoing this change increases only slowly with increasing flame temperature. Although heavy distillate fuels may contain as much as 1.8 per cent of organic nitrogen, light distillates contain less than 0.06 per cent (Lefebvre, 1995).

Nicol et al (1992) have examined the relative contribution of the various mechanisms of NO formation to the total NO_x production by a lean-premixed combustor burning methane fuel containing no organically bonded nitrogen (Table 2). The results of their study is summarised in the following table. Such results are of great importance to the design of ultralow NO_x lean-premixed combustors. As thermal NO comes under control, and in order to further reduce total NO_x emissions, combustion technology will have to understand and learn to control new mechanisms of NO formation.

Temperature	Equivalence Ratio	Thermal NO	NO from N ₂ O	Prompt NO
1900 K	0.8	60%	10%	30%
1500 K	0.6	5%	30%	65%

Table 2 : Contributions of Various Mechanisms to the Production of NO_x (Nicol *et al*, 1992)

Because of the trends toward engines of higher overall pressure ratio to meet the need for increased take-off and climb thrust as well as low s.f.c., the influence of pressure on NO_x is crucial. However, the experimental data obtained on different combustor types are conflicting and suggest that the relationship is combustor specific. The data vary from no effect of pressure on NO_x to quite significant increases in NO_x with increases in pressure. Conventional combustors show that NO_x is proportional to Pⁿ with n ranging from 0.5 to 0.8 (Lefebvre, 1995). Experiments conducted with laboratory combustors highlight the influence of flame temperature on the pressure dependence of NO_x formation, and hence the exponent n (Maughan *et al*, 1994 ; Leonard and Corea, 1990). The results appear to suggest that nitrous oxides and prompt mechanisms, which are independent of pressure, dominate in low temperature flames and are modelled with a low exponent n. Homogenous mixing of the fuel with air tends to further attenuate the pressure dependence in lean premixed. At higher combustion temperatures, however, the larger NO_x levels are due to thermal NO mechanisms, which exhibits a square root dependence on pressure (n = 0.5). Comparatively little is known about the pressure dependence of NO_x formation in fuel-rich flames. Experiments on an RQL combustor (Rizk and Mongia, 1991) suggest that for this type of combustor at least, the exponent increases to about 0.7 at an equivalence ratio of 1.4.

NO, the original form in which the nitrogen oxides are created, can be oxidised to NO₂ as soon as the low temperatures required for this reaction are reached. The conversion from NO into NO₂ occurs in zones of considerable excess air. At full load the fraction of NO₂ formed within the combustor and the engine is very small (10% is reported by Friedl, 1997), but at idle conditions the NO₂ levels can be as great as 50% of the total NO_x.

From the combustor through the turbine stages, small amounts of NO will be depleted to N₂, CO and CO₂ as a result of both heterogeneous NO/soot interactions and NO+CO homogeneous reactions which are active above temperature close to 950 K (Schumann, 1995).

3. CARBON MONOXIDE (CO)

The main factors influencing the mechanisms of CO formation have been widely investigated (Bahr, 1982 ; Bayle-Labouré, 1991 ; Koff, 1993 ; Lefebvre, 1995) and include :-

- Primary zone equivalence ratio
- Combustor inlet air temperature
- Combustion pressure
- Ambient air temperature

Carbon monoxide is strongly dependent on *primary zone equivalence ratios* within the combustor. Low CO levels can only be found in a very narrow range of equivalence ratios (typically 0.7-1.0). In this region, the beneficial effects of high *inlet air temperature* and *combustion pressure* in reducing CO are maximised.

By order of importance, the influence of *primary zone equivalence ratio* should be mentioned first. In fuel-lean conditions (typically below 0.7-0.8), the high levels of CO emissions are due to the slow rates of oxidation associated with low combustion temperatures. CO emissions therefore diminish with increase in equivalence ratio reaching a minimum value at an equivalence ratio of between 0.7-0.8 (Rink *et al*, 1989a) and 1.0 (Sturgess *et al*, 1993). The discrepancy is due to the experimental difficulty in estimating accurately the amount of air participating in primary combustion (Lefebvre, 1995). Beyond this point any further increase in equivalence ratio causes CO emissions to rise. If the primary zone mixture is stoichiometric or slightly fuel-lean (typically 1.0), then significant amounts of CO are produced due to the dissociation of CO₂. In fuel-rich conditions (i.e. equivalence ratios beyond 1.0) large amounts of CO will be formed owing to the lack of oxygen to complete the reaction to CO₂.

In principle, it should be possible to reduce this CO to a very low level by the staged admission of additional air downstream of the primary zone to achieve a gradual reduction in burned gas temperature (Lefebvre, 1995). In practice, whilst at high-power conditions CO formation within the combustor follows the equilibrium theory, at low power CO emissions are found to be much higher than predicted from equilibrium calculations and to be highest than at high power, because burning rates and peak temperatures are relatively low.

The effect of *combustor inlet air temperature* is to reduce CO in fuel-lean conditions as illustrated in Figure 3. The resulting increase in flame temperature accelerates the conversion of CO to CO₂. Beyond stoichiometric equivalence ratios, however, the effect is opposite and the higher flame temperature promotes the formation of CO through dissociation. Figure 4 demonstrates that the effect of *combustion pressure* is similar to that of inlet temperature. At high equivalence ratios, increase in pressure reduces CO, albeit to a lesser extent. Similarly to inlet air temperature, the effect can be opposite at the highest equivalence ratios. CO emissions are also very sensitive to *ambient air temperature* in a similar manner to combustor inlet air temperature (Lefebvre, 1995).

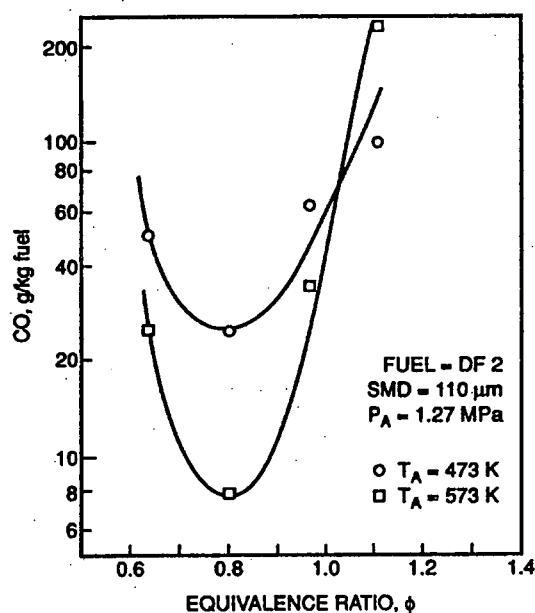


Figure 3 : Influence of Inlet Air Temperature on CO Emissions
(Rink et al, 1989a)

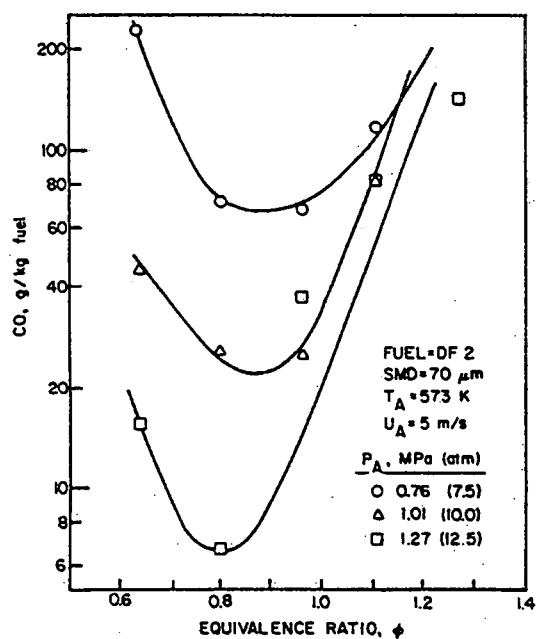


Figure 4 : Influence of Combustion Pressure on CO Emissions
(Rink et al, 1989a)

At any given set of combustor operational conditions, a number of factors related to the combustor geometry and aerodynamics as well as to the atomisation process can promote the formation of CO. This may be caused by one or more of the following reasons :-

- Inadequate burning rates due to locally too low FAR and/or insufficient residence time.
- Inadequate mixing of fuel with air or air distribution in the flame tube producing overweak and overrich regions.
- Quenching of the post flame products by entrainment with the liner wall cooling air or dilution air. The use of more efficient film-cooling techniques (or even ceramic liners) in the primary zone is effective in reducing CO.

4. UNBURNED HYDROCARBONS (UHC)

Unburned hydrocarbons include fuel that emerges at the combustor exit in the form of droplets or vapour, as well as the products of the thermal degradation of the parent fuel into species of lower molecular weight, such as methane and acetylene. Data on hydrocarbon composition are limited. Spicer *et al.*, (1990) measured methane as the dominant hydrocarbon in the exhaust (in particular for low power settings) but at concentrations lower than in the ambient air indicating that aircraft are a net sink for methane in the atmosphere. Alkanes were the most significant hydrocarbons at all

power levels whilst alkene, aldehyde and ketone concentrations were much lower at higher power settings than at idle conditions. The content of non-methane hydrocarbons, mainly alkanes, decreases with the load factor of the engine.

As for CO, the presence of UHC in the exhaust gases is a manifestation of incomplete combustion. Their formation is associated with poor atomisation, inadequate burning rates, and/or the chilling effects of film cooling air. The reaction kinetics of UHC formation are more complex than for CO formation, but it is found generally that those factors that influence CO emissions also influence UHC emissions in much the same manner (Lefebvre, 1995). CO and UHC pollutants respond in a similar manner to variations in equivalence ratios and are reduced by increases in inlet air temperature and combustion pressure. At high power conditions, atomisation quality improvements and mainly higher inlet temperature and pressure result in improved chemical rates in the primary zone.

5. CARBON DIOXIDE (CO₂) AND WATER VAPOUR (H₂O)

H₂O and CO₂ are the primary products of oxidation of fuel carbon and hydrogen through interaction with atmospheric oxygen, and as a result are an inevitable consequence of jet fuel combustion. The emission levels are determined by the fuel consumption, combustion efficiency and the fraction of hydrogen and carbon in the fuel. They represent the easiest principal emissions to estimate as the emission indices can be accurately calculated from simple chemistry and do not change significantly with operating conditions (unlike NO_x, UHC and CO). Like SO₂, CO₂ and H₂O are a fuel-dependent pollutant, i.e. its emission increases or decreases in direct linear relation to the amount of fuel consumed.

Outside the idle engine conditions encountered in flight during descent, approach, landing and taxiing, which account for a small proportion of the aircraft mission fuel consumption, modern gas turbine combustors run with combustion efficiencies close to 100% (at take-off, climb and cruise), and during normal operation, those combustors burn lean mixtures of fuel and air. In this respect, the amount of carbon dioxide and water vapour will be very near 3.14-3.16 and 1.24-1.28 kilograms per kilogram of fuel respectively (see Appendix D.9 and Friedl, 1997). The H₂O index may be subject to some slight variation depending on the level of humidity ingested by the engine.

6. SULPHUR DIOXIDE (SO₂)

As a minor emission, the exhaust contains sulphur dioxide (SO₂), because aviation fuel is allowed to contain up to 0.3 per cent weight of sulphur (IATA, 1988). Fuels can vary with low sulphur contents (less than 0.01 per cent weight), if they have been manufactured by a hydroprocessing route, to levels around 0.2 per cent weight if they have been chemically processed. The average content of jet fuel world-wide is around 0.04 to 0.05 per cent weight, resulting in between 0.8g and 1g sulphur dioxide per kg of

fuel burnt (Schumann, 1993 ; Goodger, 1995 ; Friedl, 1997). Emissions are highest during take-off and climb-out where fuel consumption rates are high. Sulphur is one of the few principal emissions not to be routinely measured when aircraft engines are tested.

Sulphur is also responsible for the formation of particle emissions in the form of sulphuric acid aerosols produced indirectly by the oxidation of sulphur dioxide in the near-field behind the aircraft. Another specie generated in the combustor, namely sulphur trioxide (SO₃), has been suggested by some atmospheric observation to lead to sulfate generation in the near-field (reported by Friedl, 1997).

7. SMOKE, SOOT AND CARBON PARTICLES (C)

Exhaust smoke is an unburnt product emitted under high pressure conditions and caused by the production of finely divided soot particles in fuel-rich regions of the flame. Such conditions are prevalent in the combustor zones where the local fuel-to-air ratio is high, i.e. mainly in the primary zone. It is the primary zone which governs the rate of soot formation, and the intermediate zone (and, on modern high-temperature engines, the dilution zone also) which determines the rate of soot consumption. The dominance of one zone over the other results in the observed soot or smoke concentration.

The main factors which individually or in combination influence the mechanisms of smoke formation include :-

- Combustion pressure
- Fuel properties (viscosity and volatility)
- Atomisation process

Smoke levels strongly increase with *combustion pressure* because this factor affects the limit of flammability, the chemical process and the atomisation spray characteristics. This is clearly illustrated by Figure 5. Increased pressure extends the limit of flammability, so that soot is produced in regions that, at low pressures, would be too rich to burn. In addition, chemical reaction rates are exacerbated with pressure, so that combustion is initiated earlier and a larger proportion of the fuel is burned in the fuel-rich region adjacent to the fuel spray.

With pressure-swirl atomisers another adverse effect of an increase in pressure is to reduce the spray penetration and cone angle. This encourages soot formation by raising the local fuel-to-air ratio. With airblast atomisers, the fuel distribution in the primary zone depends on the liner airflow pattern, which is insensitive to pressure.

Fuel properties can influence smoke production by encouraging the formation of local fuel-rich regions, and by exerting variable resistance to carbon formation (Lefebvre, 1995). The former is controlled by physical properties, such as viscosity and volatility, affecting the fuel mean drop size, penetration and rate of evaporation of the fuel spray,

whilst the latter relate to molecular structure. It is well established that smoking tendency increases with reducing fuel hydrogen content.

The production of smoke within the primary zone strongly depends on the adopted *atomisation process*. With pressure-swirl atomisers, the main soot-forming region lies inside the fuel spray, at the centre of the combustor. This is the region where local pockets of fuel vapour are enveloped in recirculating oxygen-deficient gases at high temperature. Most of the soot produced in the primary zone is consumed in the well-oxygenated high temperature regions downstream. The now widely used prefilming airblast atomiser is capable of producing fine atomisation and a virtually smoke-free exhaust at high combustion pressure.

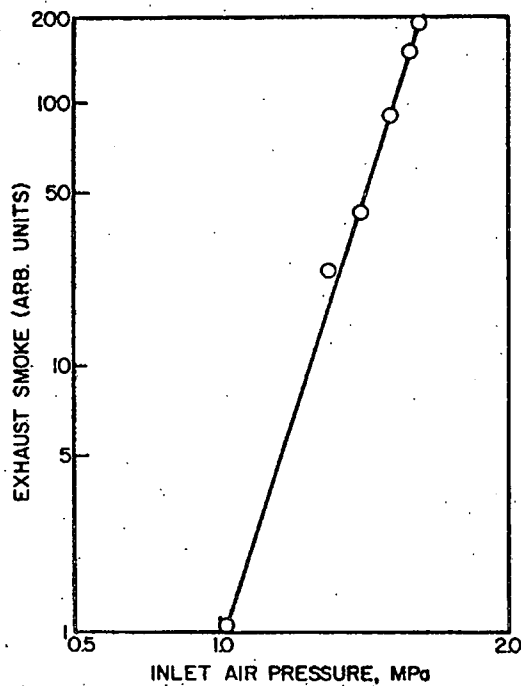


Figure 5 :
Effect of Pressure on Exhaust Smoke
(Lefebvre, 1995)

Appendix B.2

The Impact of Aircraft Exhaust Emissions on the Atmosphere

1. INTRODUCTION

As presented in Chapter 2, engine emissions from subsonic aircraft include NO_x , H_2O , CO , CO_2 , UHC, SO_2 , soot and other trace gases. The most outstanding effects of each individual pollutant is presented in detail in the following sub-sections. Based on recent surveys and studies, the review will first describe the chemical and dynamical processes occurring in the aircraft wake before tackling the chemical processes and interactions leading to potential detrimental effects on the atmosphere.

The environmental impact of aircraft engine emissions in the vicinity of airports first drew public attention in the 1970's. A number of studies have since been carried out to assess the contribution of aircraft engines to emissions at and around airports (Williams *et al.*, 1979, 1981, 1990). Most of these studies concluded that the major emissions contribution was due to motor vehicle traffic, both at the airport and in the surrounding area, with air quality significantly better than at typical urban locations. However, as motor vehicle traffic has since then come under stricter control, new studies will have to be carried out to re-assess the relative contribution of air traffic pollution in the vicinity of airports. With public attention now focusing on the global effects of Man-made emissions in the context of ozone depletion and global warming, the emphasis has turned away from near-airport emissions towards aviation's impact at the higher where typical subsonic air traffic cruise (8-13 km).

At the higher altitudes of the stratosphere, it is possible that a future fleet of supersonic aircraft, cruising at 18-23 km, holds the potential for creating what NASA calls 'significant global-scale radiative effects'. However, crucial technological and economical issues remain unresolved, making the development of an environmentally and economically acceptable high civil supersonic transport aircraft yet uncertain. A negligible number of air vehicles currently fly above subsonic air traffic's altitude. They include military operations, a small fleet of Concorde airliners and spacecraft such as rockets and reusable shuttles. As knowledge stands at present, such emissions represent a minor contribution which has not been identified as posing a serious threat to the atmosphere (Schumann, 1994b ; Lieberherr, 1994).

Recognising the current public concern towards current aviation's global impact at high altitude, and the expected major contribution from civil subsonic air traffic to aviation's total emissions output for the future decades, the effect of near-airport emissions as well as the impact of a future supersonic fleet of airliners are chosen not to be addressed. The objective of this section is to investigate the impact of subsonic aero engine emissions at high altitudes, i.e. beyond the airport vicinity at typical cruise altitudes. Following a description of some relevant properties of the atmosphere and an assessment of the

chemistry occurring within the jet plume and the aircraft wake, the sub-sections review the atmospheric effects of each aero engine specie with an emphasis on those currently causing the greatest concern i.e. nitrogen oxides and water vapour.

2. SOME RELEVANT PROPERTIES OF THE ATMOSPHERE

The concentrations resulting from emissions depend on the product of emission rate and residence time as well as on the mass of the atmosphere over which the emissions are dispersed. The concentration change can be estimated from :-

$$(1) \quad \text{Volumetric concentration change} = \frac{\text{Emission rate} \times \text{Residence time} \times M_{\text{air}}}{\text{Mass of atmosphere} \times M_i}$$

where M_i is the molecular weight of the individual gas (CO_2 , H_2O , NO_2 , CO , SO_2 or air). The residence time and the relevant mass of atmosphere depend strongly on the emission altitude and on the manner by which the emitted quantities are mixed and removed from the atmosphere.

The region of the atmosphere where aircraft activity occurs is structured in three distinct bands : the boundary layer (0-1 km), free troposphere and stratosphere (Brasseur and Solomon, 1986 ; Fabian, 1990). Due to an inversion in the atmosphere's temperature profile, a boundary, known as the tropopause, which limits the exchange of air mass, occurs between the troposphere and the stratosphere. Depending on day, season and latitude, the location of the tropopause varies between 9 and 17 km, compared with typical subsonic cruise altitudes of 8-13 km. With respect to chemical and dynamical aspects, stratosphere and troposphere are extremely different.

The lower troposphere contains approximately 80% of the mass of the atmosphere. In the troposphere, the temperature decreases with height so that this layer is only weakly stably stratified. In this region, turbulence and convection provide effective vertical mixing. Weather processes in connection with the water cycle of evaporation, cloud formation and precipitation act as a cleaning mechanism where particles and soluble gases are washed out by precipitation. Above the tropopause, within the stratosphere, the temperature increases with height. Therefore, this layer is stably stratified with much weaker vertical mixing. As a consequence of these properties and of the conversion into soluble forms, species such as nitrogen oxides have a short residence time of the order of 1 to 4 days in the troposphere. Pollutants such as NO_2 are oxidised by OH to form HNO_3 which is removed from the troposphere by wet and dry deposition. With a residence time less than 4 days, NO_2 (and its precursor NO) is not distributed very far from its emission sources.

Because of its vertical temperature structure, the stratosphere acts as a huge inversion thus suppressing vertical mixing. Consequently, the stratospheric residence time of inert tracers quickly increase with height above the tropopause and reaches values in excess of one year (Fabian, 1990). For the present subsonic air traffic at altitudes below 13 km,

the residence times is probably below 6 months. The tropopause altitude is strongly dependent on latitude and variable from day to day and from season to season (Hoinka *et al.*, 1993). The average height is about 8 km over the polar regions and about 16 km at the equator. Hence, the residence times of aircraft emissions depend strongly on whether the aircraft flies above or below the tropopause.

The residence time depends also strongly on the latitude because the lower stratosphere exhibits mean rising motion near the equator and, to first approximation, mean sinking motion elsewhere, and because of strong tropospheric-stratospheric exchange at mid-latitudes (Schumann, 1993). The global exchange of air mass and water vapour between the troposphere and the lower stratosphere tend to reduce average stratospheric residence times. Tropospheric air enters the stratosphere mainly in the tropics in ways that are closely connected with cumulonimbus convection. Stratospheric air enters the troposphere mainly in middle and high latitudes, some or all of it via structures called tropopause folds, part of the weather-front structures found in middle-latitude cyclones.

In view of long stratospheric residence times, the effect of aircraft emissions in the lower stratosphere can not be considered as negligible. The impact may be out of proportion to the modest air traffic global contribution (0.9-3%). The chemical reactions involving those emissions therefore deserve to be thoroughly investigated.

3. DYNAMICS AND CHEMISTRY IN THE AIRCRAFT WAKE

3.1 INTRODUCTION

The evaluation of the impact of emissions from aircraft upon the atmosphere is based on the use of sophisticated photochemical radiative and dynamical global models. These studies use a variety of mathematical models, such as box, 1-D, 2-D and 3-D models, to describe the atmospheric transport, diffusion and complex chemical reactions (Lee, 1996c). These chemical and dispersion models of the earth's atmosphere require inputs of aircraft engine exhaust emission levels into grid cells of the order of several hundred kilometres. Before engine effluents reach the grid size of those models, they may be subject to potential chemical modifications and short term evolution of their composition, as they expand with the aircraft exhaust and come to equilibrium with the atmosphere.

Emissions from individual aircraft are initially highly localised within the aircraft's exhaust plume and wake. Concentrations of combustion products in the plume and wake are typically much greater than the corresponding ambient concentrations. These high concentrations do not persist very long, however, since the plume and wake rapidly expand and mix with the surrounding atmosphere on time scales of minutes to hours. The potential for important chemical changes to take place in short-lived aircraft plumes and wakes has been actively investigated. This is because a number of non-linear chemical and microphysical processes, which do not typically proceed under the low

concentration conditions of the background atmosphere, may occur in species-rich plumes and wakes. Such short processes may lead to global-scale effects if they result in irreversible changes in exhaust compositions.

Most of the research carried out in the past 30 years on the physico-chemical processes taking place in the aircraft wake has been related to supersonic applications as part of the HSCT and SST programs. Most of this work is based on what the CIAP initiated in the 70's and is currently led by Aerodyne Research Inc. in the USA. However, some substantial research work with subsonic aircraft wakes has been carried out since the beginning of the 1990's in Europe as part of the DLR Falcon campaign (Schlager *et al.*, 1994 ; Arnold *et al.*, 1992-1994 ; Schumann, 1994 ; Busen *et al.*, 1994) and especially as part of the AERONOX programme (Schumann, 1995). Based on current the knowledge on the subject (Friedl, 1997 ; Schumann, 1995 ; Louisnard, 1994 ; Schumann, 1993), this section discusses the various dynamical and chemical processes occurring in the aircraft wake and the change in composition of the emissions pattern. Because those processes are only beginning to be understood, the discussion is mainly qualitative but incorporates some orders of magnitudes given further in Table 1 and 2.

3.2 WAKE DYNAMICAL PROCESSES

The investigation of the dynamical processes along the different parts of the wake is essential prior to assessing the local temperature, water condensation and local chemical processes that will affect the concentration of the different species. These species are a mixture between the emissions coming out from the engine and the natural atmosphere. The aircraft wake can be divided into three regimes corresponding to the flow dynamics that control the structure and growth of the wake (CIAP, 1970 ; Louisnard, 1994 ; Myake-Lye, 1991 ; Schumann, 1995) :-

1. *The jet regime.* The engine effluents are rapidly cooled down from the hot jet conditions and turbulently mixed with the ambient air. The effluents are confined to individual exhaust jets or plumes. In the case of a high bypass ratio engine, this phase lasts fractions of a second and is limited to the first 30 metres behind the engine. During that phase, it is assumed that the jet temperature is not influenced by the aircraft vortex environment. The simulation of the chemical processes is based on Navier-Stokes equations and temperature-dependent chemical kinetics. Figures 1 and 2 presents the axial profiles of both temperature and dilution factors behind a typical B747 high bypass ratio turbofan engine during that phase. The data was generated by the NATUR code which was employed for the AERONOX Project (Schumann, 1995). The computer code solves the full Navier-Stokes equations and incorporates the k- ϵ turbulence model.
2. *The vortex regime.* The individual exhaust jets merge with the two trailing aircraft vortices. The temperature of the effluents is now close to the background level. The aircraft and in particular the wing tips generate turbulences in the form of trailing vortices which interact with the exhaust jets and can trap the engine effluents. The

jet/vortex interaction is both a crucial and complex dynamical phenomenon. By modifying the local exhaust temperatures, this interaction controls the condensation process and the development of contrails. Furthermore, the velocity gradients in the vortices can give rise to temperature variations and further chemical processes for the engine pollutants trapped. This regime persists in an increasingly oscillating manner - the Crow instability - (Crow, 1970) until the trailing vortex pair becomes unstable and brakes up into a less ordered configuration (vortex decay) at about 10 km.

3. *The dispersion regime.* In this regime, the atmospheric shear motions and turbulences as well as the buoyancy from the jet exhaust heat or the differential heating by radiation in contrails, contribute to further mixing. The vortices have decayed to the point where vortex-induced velocities are comparable to or smaller than the turbulent fluctuations of the atmosphere. This phase lasts several hours. Daytime and night-time chemical schemes must be separately envisaged, with many of the night-time processes being slow compared to the photolytical daytime reactions.

As shown in Figure 3, the importance of the jet/vortex interaction in the vortex regime is very much dependent on the type of aircraft under consideration. With heavy four-engined aircraft, the vortex begins to significantly affect the plume a short distance behind the engine (0-100m), whereas for smaller twin-engined aircraft significant plume vortex interaction is unlikely (Schumann, 1995). Irrespective of the interaction mechanism, after a distance of about 10 km both jet plume and vortex are likely to have fully decayed resulting in a large stationary cloud of gas. The composition of that gas will eventually equate that of the local atmosphere but the time scales for this process depends upon the atmospheric state.

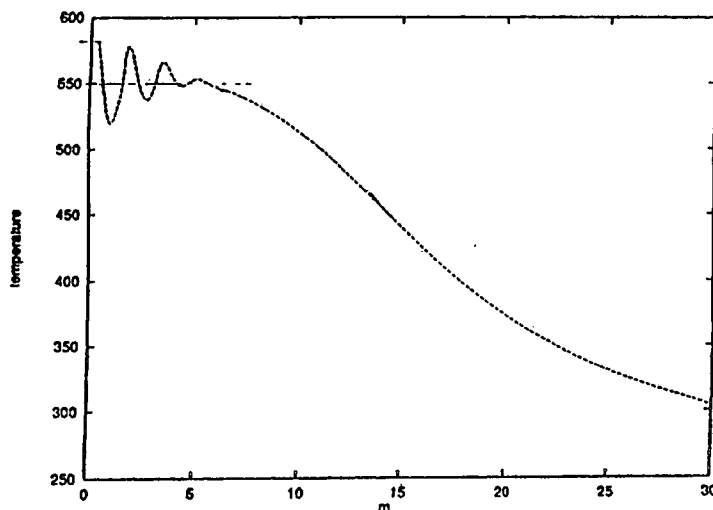


Figure 1 :
Axial Temperature
Profile Behind a Typical
B747-400 Turbofan
(Schumann, 1995)

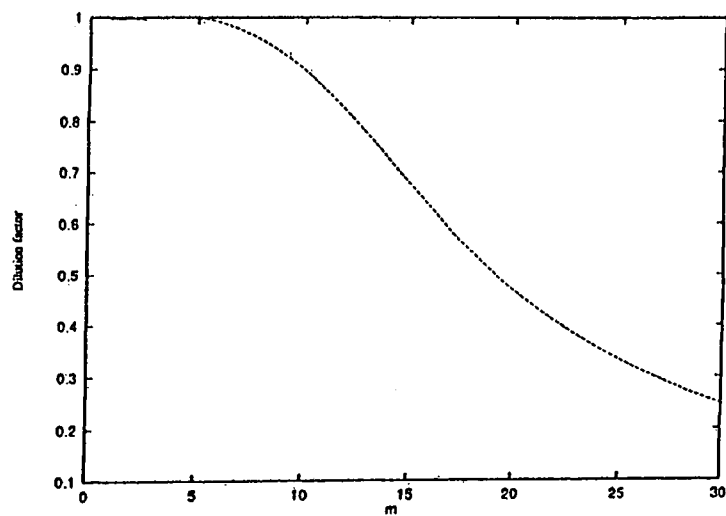


Figure 2 :
Axial Dilution Factor
Profile Behind a Typical
B747-400 Turbofan
(Schumann, 1995)

	Burner exit	Nozzle exit ⁽⁴⁾			Jet	Vortex	Dispersion	Ambient atmosphere (Mn0.85, 10668 m)
		Core	Bypass	Mixed	Aircraft wake regimes ⁽²⁾			
Static temperature (K)	1300	580	250	310	310 - 230	230 - 219	219	219
Static pressure (kPa)	980	28.7	32.5	23.8	23.8	23.8	23.8	23.8
Velocity ⁽⁶⁾ (m.s ⁻¹)	120	228	58	90	90-45 (isolated jet ⁽³⁾) 40 at 30 m (vortex)	45 - 3 (isolated jet) 40 - 3 (vortex)	Atmospheric fluctuations	Atmospheric fluctuations
Mass flow all engines (kg.s ⁻¹)	180	200	920	1120	-	-	-	-
Effective cross section of mixing all engines (m ²)	0.25	2.6	6.4	9	8 to 3600-5400 ⁽⁵⁾	3600-5400 to 21000-52000 ⁽⁵⁾	> 21000-52000 ⁽⁵⁾	-
Distance (m)	-1.75	datum	datum	datum	0 - 30 m	30 m - 10 km	> 10 km	-
Duration	datum	5 ms	5 ms	5 ms	≈ 0.1 s	≈ 40 s	> 1 hour	-
Remarks :- 1. The engine data are calculated from a Turbomatch model of a typical B747 high bypass ratio turbofan at cruise conditions (Mn=0.85, Altitude 10668m, ISA day). 2. The figures related to the three aircraft wake regimes apply to the B747 at the flight conditions given and have to be taken as order of magnitudes rather than precise values. They are derived from computer modelling of B747 wake dynamics up to 10 km behind (Schumann, 1995). 3. Downward motion due to the lift is 2.3 m.s ⁻¹ . 4. The nozzle is fully expanded. The exhaust conditions are shown in the case of mixed and separated jets. To obtain the centreline jet velocities relative to the atmosphere, the velocities relative to the engine have been reduced by 252 ms ⁻¹ . 5. Schumann, 1993 ; Myake-Lye, 1991. 6. Combustor exit velocity is relative to engine ; all other velocities are relative to atmosphere.								

**Table 1 : Typical Thermodynamic Figures through the Engine and in the Wake of a B747 airliner
(Mn=0.85/252m.s⁻¹, altitude 10668m, ISA conditions)**

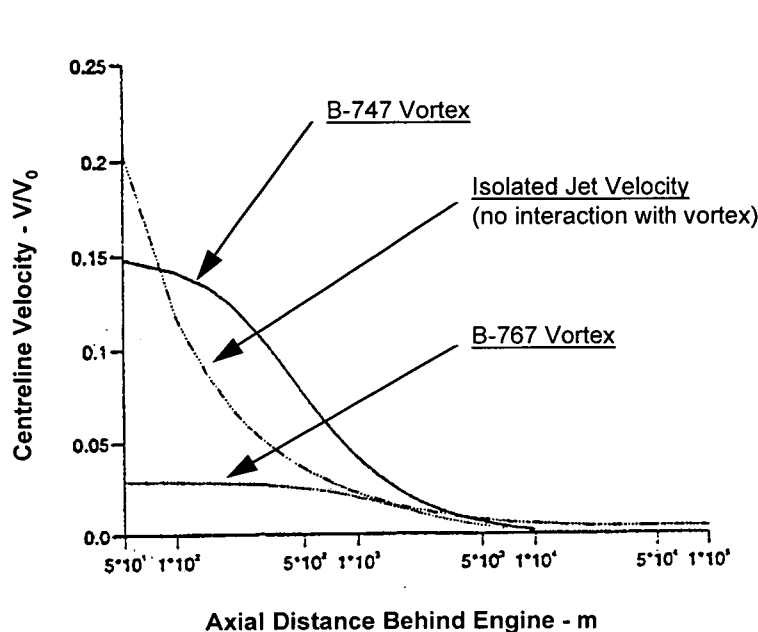


Figure 3 :
Jet Centreline Velocity
Decay Using Computer
Simulation
(Schumann, 1995)

3.3 WAKE CHEMICAL PROCESSES

The main chemical transformations are made in the jet regime while the jet/vortex interaction of the vortex regime controls the condensation process and the production of contrails. In the absence of inflight measurements in the near field behind the engine (up to the first kilometres of the vortex regime), only ground measurements, laboratory experiments and numerical approaches have until now been available to investigate the wake chemical processes. The chemical processes occurring in the three regimes considered to be affecting with various magnitudes the final composition include :-

- Homogeneous chemical transformations i.e. chemical reactions between engine effluents and between effluents and atmospheric species in the gas state.
- Heterogeneous chemistry on the surface of particles originating from water, sulphur or soot emissions from hot (> 1300 K) to ambient temperatures (219 K at 10668 m).
- Water vapour homogeneous or heterogeneous condensation i.e. ice nucleation and growth process from soot or sulphuric particles that will form contrails in the atmosphere.
- Sulphuric bimolecular nucleation that will increase the local aerosol burden ; this process has an impact on the cloudiness and may have an impact on the radiation budget, but it can lead to further heterogeneous processes.
- Absorption of some of the species by liquid water or ice particles which can lead to elimination of some of the soluble species such as NO_x by sedimentation followed by re-evaporation or wet deposition.

The important chemical families to consider in the hot jet and the cold wake include NO_y (NO , NO_2 , HNO_3 , HNO_2 , N_2O and N_2O_5), HO_x (primarily OH), SO_x (primarily H_2SO_4) and CH_x . The main processes are given below with respect to pollutant species.

- NO_x - The Zeldovitch mechanism which describes the formation and destruction of NO inside the combustor is not efficient at the engine nozzle exit temperatures ($< 600 \text{ K}$). The heterogeneous NO /soot interaction and the homogeneous $\text{NO}+\text{CO}$ reaction which could both reduce the amount of NO , appear unable to significantly deplete NO in the hot jet (Schumann, 1995). The transformation of NO_x in the hot jet ($\approx 0.1 \text{ s}$) is effectively dominated by the OH chemistry which is responsible for the transformation of NO_2 into HNO_3 , HNO_2 and N_2O_5 . As a result, the maximum NO_x losses during the jet regime are about some percent of the emitted NO_x (Schumann, 1995). Because the OH mixing ratio decreases rapidly after the nozzle exit, this limited NO_x consumption should not be sensitive to the shape of the temperature and mixing ratio profiles along the jet. This is in broad agreement with measurements at a distance of 2 km behind a DC-9 engine showing that more than 80% of the NO_x is composed by NO , approximately 20% by NO_2 and 0.05% HNO_3 (Arnold *et al*, 1992). As shown in Table 2, following the jet phase, and taking into account dilution, NO_x emissions are delivered to the atmosphere several orders of magnitude above the background level.
- H_2O - The rapid temperature drop to only tens of Kelvins above the ambient temperature results in the homogeneous and heterogeneous formation of solid water particles (contrails) and liquid supercooled water particles. The production of contrails by nucleation on the local soot is however limited by the dilution factor and the temperature field during the jet/vortex interaction and do not appear very sensitive to the initial soot distribution. The liquid water will constitute a wet support for the dissolution of NO_y gases during the dispersion regime.
- CO & CO_2 - At the beginning of the vortex regime in the cold wake, CO , CO_2 emissions are close to the background levels.
- UHC & soot - Soot is hydrophobic and a poor candidate for cloud or ice nucleation (Friedl, 1997). Little conclusive data are however available on the chemical processes affecting these families of pollutants.
- SO_2 - As shown in Table 2, following the jet phase, and taking into account dilution, SO_2 emissions are delivered to the atmosphere several orders of magnitude above the background level. The production of sulphuric acid water aerosol is limited by the dilution factor and the temperature field during the jet/vortex interaction. Unlike the NO_x conversion case, the fate of sulphur compounds is significantly affected by near-field processes (Friedl, 1997). Plume/wake model results have shown that a large number of small particles can form via homogeneous nucleation of sulphur compounds (Miake-Lye, 1994). The creation of numerous small particles, rather than the condensation of SO_2 onto existing large particles, will result in greater ambient

aerosol surface area for catalysing heterogeneous chemistry. Schumann (1993) estimates that about 20% of SO_2 appear to be converted to sulphuric acid H_2SO_4 .

	8km behind engines	Background atmosphere
NO_x (all NO_2)	78 ppbv	0.01-0.05 ppbv
CO	17 ppbv	40-100 ppbv
H_2O	14 ppmv	20-400 ppmv
CO_2	14 ppmv	354 ppmv
SO_2	1-3.1 ppbv	0.03-0.15 ppbv
Remarks : altitude 10668 m, Mn 0.85, ISA conditions.		

Table 2 : Typical Mean Concentrations (Mixing Ratios) of Major Pollutants in the Wake of a B747 during the Vortex Regime (Schumann, 1993)

3.4 CONCLUSIONS

The analysis of research results to date indicates that the combined dynamical and chemical processes have limited implications on engine effluents and in particular NO_x in the jet and vortex regimes.

While the jet/vortex interaction is crucial with respect to condensation and the production of contrails, its chemical implications appear to be insignificant, because for the interaction to be completed takes only 40 s and most reactions will require time scales of several minutes or hours (Schumann, 1995).

At the beginning of the dispersion regime, most species apart from NO_x and SO_2 have reached the background level (see Table 2). The dispersion regimes will feature chemical reactions akin to those accounted for by global atmospheric chemical and dynamical models but with higher mixing ratios in the case of NO_x and SO_2 .

As a result, as knowledge stands at present, simple reacting plume models (simulating an isolated jet with no vortex interactions) appear sufficient to bridge the gap between engine exhaust data and the global chemical and dynamical models. Using such models, the maximum NO_x losses to less reactive forms of nitrogen oxides during the jet regime appear to be about some percent of the emitted NO_x . As to sulphur compounds, there are still uncertainties in the understanding of near-field nucleation processes (Friedl, 1997). All other major species are not subject to significant chemical transformations in the wake.

4. NITROGEN OXIDES (NO_x) AND ITS INTERPLAY WITH OZONE (O₃)

One of the worst effect is the addition of NO_x into the atmosphere. At the jet exit, most of the emitted NO_x is in the form of NO. In the exhaust plume, the emissions are mixed with the ambient air, and react with O₃ to form NO₂. A photochemical equilibrium between NO and NO₂ is soon reached in the plume after several minutes.

Because of the characteristics of the region where air traffic cruise, such as low background concentrations, low temperature, large residence time, large radiative efficiency, etc. (Johnson *et al.*, 1992), the implications of aircraft-generated NO_x on the chemistry of the atmosphere will be quite different from the effects of similar amounts of pollution emitted at ground level. The effects summarised in Table 3 strongly depends on the aircraft emission rates, the location of injection, the time of injection, and the conditions of the atmosphere.

Location	Effect
Upper Troposphere	Global warming by ozone formed by action of NO _x
Lower Stratosphere	Ozone destruction (increased UV-B radiation)
Factors affecting the magnitude of the effects	
1) Aircraft emission rate	Design, engine rating, operations, traffic mix
2) Location of injection	Altitude, latitude*
3) Time of injection	Season, day*
4) Atmospheric conditions	Background concentrations, temperature, residence times, sun light, PSCs
* : items 2 and 3 determine the aircraft position relative to the tropopause	

Table 3 : A Summary of the Concern Over NO_x from High Altitude Air Traffic

It is estimated that subsonic aircraft contribute to about 3% of the global anthropogenic NO_x output (Schumann, 1995). However, a significant proportion of the NO_x pollutant produced by medium and long range air traffic is released at high altitude where generally there are no other sources of direct emissions. The NO_x pollutants generated by non-aircraft sources (road traffic, wood and straw, lightning, microbiological, power generation, manufacturing industries, domestic) are removed by weather processes and do not reach the high air traffic cruise altitudes.

Tropospheric NO_x reacts with the hydroxyl radical OH to produce nitric acid HNO₃, which, in turn, will be removed by precipitation or dry deposition. As a result, NO_x and HNO₃ have a short tropospheric residence time of approximately 1 to 4 days, while in the stable lower stratosphere the residence time is much longer, of the order of several months to a year (Schumann, 1994a). Table 4 shows NO_x equilibrium concentrations which are computed using Equation 1 expressed in Section 2.

Location	Residence Time	Emission Rate	Mean Conc. Increase	Background Conc.
a) 8 km	4 days	2.5 Mt/year	4.1 pptv	10-50 pptv
b) 14 km	0.5 year	0.63 Mt/year	0.4 ppbv	0.2-0.5 ppbv

1) Aviation NO_x concentration increases are a) mixed over the whole troposphere and b) mixed over the northern stratosphere. 2) These computations neglect any chemical transformations. 3) Assumption for the stratosphere : 1/5 of the fuel (total 176Mt/year) burned within 1/10 (only northern stratosphere) of the atmosphere's mass (total 58.10⁸ Mt). 4) Assumptions for the troposphere : 80% of all fuel burned and distributed over 4/5 of the atmosphere's mass (i.e. below 200 hPa). 5) Residence times and background concentrations from Schumann and Reinhardt (1991).

**Table 4 : Estimated NO_x Concentration Increases due to Aviation Emissions
(Schumann, 1993 ; Schumann *et al.*, 1991)**

The atmospheric ozone layer is known as the Earth's shield because it prevents UV-B radiation from penetrating the biosphere, thereby protecting the Earth's surface from harmful solar radiation. The absolute ozone density between 8 and 12 km altitude exerts the greatest influence on the troposphere-surface climate system (Johnson *et al.*, 1992). The lower half of this band is the cruise altitude of jet-powered civil subsonic air traffic, and it can be expected that a large amount of NO_x (or ozone precursors) has already been injected at this critical altitude.

Stratospheric ozone is formed at altitude above 20 km by photodissociation of O₂ by solar ultraviolet radiation. Most of the O₃ generated is reconverted into O₂ by a large variety of reaction chains involving radicals such as O_x, HO_x, ClO_x and others. The efficiency of additional NO_x in these chains depends on the degree of reactions between these radicals and the rate of conversion of NO_x into less reactive NO_y compounds at the surface of aerosols (Schumann, 1995). Because of low stratospheric background concentrations (0.2-0.5 ppbv), the added aircraft NO_x may contribute to the break-up of the ozone layer through catalytic cycles (Johnston *et al.*, 1989). The effect is to alter the temperature of the Earth's surface via, (1) increases of the solar radiation flux to the Earth's surface thus contributing to the surface warming, and (2) cooling of the stratosphere by less long wave radiation emission to the troposphere, consequently cooling the Earth's surface.

In the troposphere, the hydroxyl radical (OH) formed by photodissociation of ozone, is responsible for the oxidation of air pollutants such as CO, CH₄ and NMHC, ultimately to CO₂ and H₂O. Ozone plays a key role in cleaning the troposphere from these pollutants. However, increases in NO_x concentrations enhance complex photocatalytic reactions involving HO_x and CO or CH₄, and lead to net ozone production at high NO_x background concentrations, and reduced ozone destruction rates in low NO_x background concentrations (Crutzen, 1988 ; Bojkov, 1995). The effect will tend to warm the Earth's surface by absorption of the outgoing long wave radiation.

On a global basis, the mechanisms of ozone production dominate relative to the stratospheric photocatalytic sinks up to an altitude of between 10 and 20 km. The net effect from tropospheric ozone increases and stratospheric destruction mechanisms contributes to global warming (Schumann, 1995).

Upper tropospheric ozone increases of about 1.5% per annum have already been reported at some ozone stations and it is considered to be consistent with the increases in nitrogen oxides (Lee, 1996c). Model results also predict a decrease in ozone in the lower stratosphere of less than 1% (Ko *et al.*, 1992). It appears that air traffic is responsible for most of the observed ozone increase in the upper troposphere. Although the contribution of ozone to global climate change is difficult to quantify, the absolute warming effect caused by present aircraft emissions is estimated by model calculations to be of the order of 0.01 to 0.02K (Johnson *et al.*, 1992) and might reach a figure of 0.2K by the year 2050 (Brühl et Crutzen, 1988). However, these estimates remain uncertain, due to the yet limited knowledge on the actual distribution of the emissions, on the mixing and conversion processes in the wake and on the global effects which require three-dimensional (3-D) models (Schumann, 1995).

5. EMITTED WATER VAPOUR AND CLOUD FORMATION

The water vapour (H₂O) generated by air traffic in the atmosphere contributes only 0.04% of the emission rate of H₂O which evaporates from the surface. However, it represents a large source when compared to the amount of H₂O released into the stratosphere by methane oxidation. H₂O is by itself one of the most important greenhouse gases. The strong radiative sensitivity of the atmosphere with respect to its concentrations has been demonstrated elsewhere (Schumann and Wendling, 1990). The greenhouse effect of added water vapour is strongest when added near the tropopause (Lacis *et al.*, 1990). Table 5 indicates that the global contribution of aircraft-generated water vapour emissions is small in comparison to the background state but has a knock-on effect on water vapour generally in the atmosphere (from whatever source), in that concentrations increase in response and in turn enhance the global warming process.

Location	Residence Time	Emission Rate	Mean Conc. Increase	Background Conc.
a) 8 km	9 days	177 Mt/year	0.002 ppmv	20-400 ppmv
b) 14 km	0.5 year	44 Mt/year	0.07 ppmv	5-20 ppmv

1) Aviation H₂O concentration increases are a) mixed over the whole troposphere and b) mixed over the northern stratosphere. 2) These computations neglect any chemical transformations. 3) Assumption for the stratosphere : 1/5 of the fuel (total 176Mt/year) burned within 1/10 (only northern stratosphere) of the atmosphere's mass (total 58.10⁶ Mt). 4) Assumptions for the troposphere : 80% of all fuel burned and distributed over 4/5 of the atmosphere's mass (i.e. below 200 hPa). 5) Residence times and background concentrations from Schumann and Reinhardt (1991).

**Table 5 : Estimated H₂O Concentration Increases due to Aviation Emissions
(Schumann, 1993 ; Schumann *et al.*, 1991)**

Even larger changes occur if the water emitted by air traffic at high altitude condenses into contrails and forms thin ice clouds. For 0.4% additional cloud coverage by contrails, which is the presently observed value, computer simulations predicts an increase in surface temperature by about 0.01 to 0.05K (Schumann, 1993). In terms of global warming, a few per cent increase in artificial cirrus clouds equal a doubling of CO₂. Much of the high-flying air traffic takes place at the tropopause where the formation of contrails is very likely, in particular in the northern hemisphere in winter. The residence time of such contrails depends strongly on the relative humidity of the environmental air and the amount of mixing with the contrail. As a result, the upper troposphere is more likely covered by large amounts of artificial cirrus clouds induced by aircraft than the lower stratosphere.

In the cold air of the higher troposphere and lower stratosphere, water freezes and combines with NO_x, to form polar stratospheric clouds (PSCs) or nitric acid clouds which lead to ozone destruction (NASA, 1992). The large residence time of both emitted water and nitrogen oxides enhance this process. Stratospheric water is therefore key to both increased global warming and decreased ozone protection.

6. CARBON DIOXIDE (CO₂)

Carbon dioxide, a greenhouse gas, is an inevitable product of the combustion of fossil fuel. It is produced directly from jet fuel combustion as well as indirectly through the conversion of carbon monoxide (CO) and unburned hydrocarbons (UHC). Volumetrically, CO₂ is the second most significant pollutant of the jet's exhaust stream (water vapour coming first). It represents the principal anthropogenic greenhouse gas responsible for most of the enhanced greenhouse effect (Archer, 1993). The global warming effect of carbon dioxide raises the earth's surface temperature and reduces the stratosphere's temperature, therefore increasing the formation of polar stratospheric clouds (PSCs). In this respect, global warming encourages ozone depletion.

Location	Residence Time	Emission Rate	Mean Conc. Increase	Background Conc.
a) 8 km	10 years	443 Mt/year	0.7 ppmv	354 ppmv
b) 14 km	10 years	111 Mt/year	1.4 ppmv	354 ppmv

1) Aviation CO₂ concentration increases are a) mixed over the whole troposphere and b) mixed over the northern stratosphere. 2) These computations neglect any chemical transformations. 3) Assumption for the stratosphere : 1/5 of the fuel (total 176Mt/year) burned within 1/10 (only northern stratosphere) of the atmosphere's mass (total 58.10⁸ Mt). 4) Assumptions for the troposphere : 80% of all fuel burned and distributed over 4/5 of the atmosphere's mass (i.e. below 200 hPa). 5) Residence times and background concentrations from Schumann and Reinhardt (1991).

**Table 6 : Estimated CO₂ Concentration Increases due to Aviation Emissions
(Schumann, 1993 ; Schumann *et al.*, 1991)**

The chemically inert carbon dioxide is removed only slowly resulting in very long lifetimes. As shown in Table 6, CO₂ features the longest atmospheric life of all the pollutants emitted by jet engines. Despite the average estimate of 10 years by Schumann, the longevity of CO₂ cannot be ascertained precisely because it depends on highly fluctuating absorption rates by the ocean and biosphere (IPCC, 1990). Atmospheric lifetimes up to 120 years are also given (Houghton *et al.*, 1992). Because of its longevity, and unlike the other pollutants, its effects are relatively insensitive to altitude and the location of injection.

Because of the small contribution of air traffic to the global CO₂ inventory at approximately 2-3% (Schumann, 1993), aircraft-generated CO₂ is often relegated to a secondary position. However, despite its small contribution to man-made yearly output, it remains important to consider because of its longevity, its abundance, its inevitability from jet fuel combustion, and its addition to an already CO₂ burdened atmosphere.

7. CARBON MONOXIDE (CO)

Carbon monoxide is not a major pollutant of aero engine exhaust and does not add greatly to the global CO inventory. The CO contributed from aviation is very small in comparison to the global budget of CO. It reaches only 0.03% of all anthropogenic sources. However, by virtue of several atmospheric chemical reactions, it does contribute indirectly to global warming. It is discussed here in second place because although on its own it may not have a significant impact, (1) it appears alongside NO_x as a precursor to ozone formation and (2) its control in the past has pushed up emissions of NO_x even further. Until the end of the eighties, the combustor technology adopted to reduce CO and UHC exhaust pollutants from jet engines involved raising engine temperatures and , as a result, increasing the output of NO_x.

Emissions of CO are highest at ground level when aircraft are taxiing and idling. CO pollution from aircraft in and around airports forms a very small part of a region's total air pollution from all sources. As an example, aircraft operations at Manchester airport contribute about 0.5% of CO emissions in the greater Manchester conurbation (Raper, 1990). As a result, the issue of CO emissions in the vicinity of airports will not be addressed here.

While gross emissions are relatively small, CO, like NO_x, is an indirect greenhouse gas. The global warming effect is achieved through three routes (Archer, 1993). Firstly, CO is readily oxidised to CO₂, the principal greenhouse gas. Secondly, like NO_x, it chemically reacts to lessen the tropospheric OH concentrations by removing the radical, thereby effectively increasing the lifetime of CH₄, a potent greenhouse gas for which OH is a major sink. Thirdly, CO is one of the three gases (together with CH₄ and NMHC) which control the chemistry of ozone in the presence of reactive NO_x. It contributes to ozone production through photooxidation in the presence of large NO_x concentrations, and to ozone destruction in the presence of small NO_x concentrations. Processes two and three interact in a complex fashion. Concentrations of the OH

hydroxyl radical - which control the atmospheric lifetime of NMHCs and CH_4 as well as the oxidising capacity of the atmosphere - can be enhanced by increased O_3 or suppressed by increases in CH_4 , CO and NMHC. As the IPCC states (IPCC, 1990), for any understanding of O_3 and its precursor gases, it is essential to understand tropospheric OH. And to assess trends in OH concentrations requires knowledge of regional emissions of CH_4 , CO and NMHC and NO_x , as well as transport of O_3 between source regions and the remote troposphere.

Because of this complex reaction scheme, the gas's short tropospheric lifetime, and the lack of accurate data as input to models of the atmosphere, its distribution and long-term trends and impact are difficult to ascertain. The atmospheric perturbation both in the troposphere and the lower stratosphere from aircraft-generated CO is at present knowledge, nevertheless thought to be minimal.

8. UNBURNED HYDROCARBONS (UHC)

Unburned hydrocarbons emitted by air traffic comprise methane (CH_4) and non-methane hydrocarbons (NMHC). They contribute to smog formation on the ground and to global warming. UHCs contribute to global warming on several counts :

- (1) Catalytic ozone production in the stratosphere ;
- (2) Conversion of NO_x into reservoir gas (N_2O_5), hence lessening O_3 destruction in the stratosphere ;
- (3) Reduction of OH concentrations therefore increasing the atmospheric lifetime of methane CH_4 ;
- (4) Conversion to CO_2 ;
- (5) Conversion to H_2O , the most powerful of the greenhouse gases.

However, the amounts involved in aircraft exhausts within the troposphere today are not reckoned to be especially worrying compared with other sources of pollutants. At higher altitude, as with NO_x , aircraft are the only source of man-made hydrocarbons in the free troposphere. Hydrocarbons, like CO, play an important role in HO_x chemistry (OH, HO_2). The exact impact of a pollutant comprising large amounts of various species on the complex and delicate chemistry of the high atmosphere has yet to be unveiled.

9. SULPHUR DIOXIDE (SO_2)

The emission of sulphur from aviation is much smaller than from surface emissions and negligible in terms of the resulting acid rain but may be important if emitted at high altitudes. Aircraft-generated sulphur may contribute substantially to the observed rise in non-volcanic stratospheric sulphate aerosol of about 5% per year (Hofmann, 1991 ; Bekki *et al.*, 1992). As suggested in Table 7, at high tropospheric altitude (8 km), aircraft emissions of sulphur are very small compared with other sources.

Sulphur present in aviation fuel is oxidised to SO₂ during combustion. By reaction with OH or H₂O it is then transformed into H₂SO₄ (sulphuric acid), which in turn forms into sulphate aerosol particles which stay in the atmosphere between 5 days (troposphere) and half a year (stratosphere). Aerosol particles play an important role in the climate system either directly, because they scatter and absorb solar and terrestrial radiation, or indirectly, because they attract water vapour to condense therefore altering the microphysical properties of clouds and hence their radiative function. Cloud droplets form exclusively through condensation of water vapour on cloud condensation nuclei (CCN), i.e. aerosol particles. In this respect, clouds carry more droplets in the presence of sulphur emissions and are more reflective as a result. Such clouds can thus counteract to some extent the enhanced greenhouse effect being caused by the other pollutants. Sulphur emissions could then be regarded as a positive factor, to be weighed against the negative environmental impact of acid rain.

In the troposphere, the short lifetime makes long-term accumulation impossible, and implies large spatial and temporal variability in the concentrations of aerosol particles. In the stratosphere, the aerosols' lifetime is much longer. Although these aerosols can significantly affect the net radiation balance of the earth when present in sufficient quantities, the subsonic air traffic flying in the lower stratosphere do not currently have a significant impact in this regard. Natural sources such as volcano eruptions, which can increase the sulphate aerosol burden by a factor of 100 or more, are much more worrying.

A still large degree of uncertainty surrounds the effect of global sulphur emissions on the atmosphere (IPCC, 1990). For the troposphere, aircraft-generated SO₂ emissions are consequently thought to be negligible and of little environmental significance. Any impact they do have will be regional and probably greater in the northern rather than the southern hemisphere. Both in the troposphere and the lower stratosphere, subsonic air traffic SO₂ emissions represent a small perturbation in comparison to the larger, though sporadic, contribution from volcano eruptions.

Location	Residence Time	Emission Rate	Mean Conc. Increase	Background Conc.
a) 8 km	5 days	0.14 Mt/year	0.21 pptv	30-150 pptv
b) 14 km	0.5 year	0.035 Mt/year	16 pptv	30-100 pptv

1) Aviation SO₂ concentration increases are a) mixed over the whole troposphere and b) mixed over the northern stratosphere. 2) These computations neglect any chemical transformations. 3) Assumption for the stratosphere : 1/5 of the fuel (total 176Mt/year) burned within 1/10 (only northern stratosphere) of the atmosphere's mass (total 58.10⁸ Mt). 4) Assumptions for the troposphere : 80% of all fuel burned and distributed over 4/5 of the atmosphere's mass (i.e. below 200 hPa). 5) Residence times and background concentrations from Schumann and Reinhardt (1991).

**Table 7 : Estimated SO₂ Concentration Increases due to Aviation Emissions
(Schumann, 1993 ; Schumann *et al.*, 1991)**

10. SMOKE, SOOT OR CARBON PARTICLES (C)

The absolute amount of soot induced by aircraft into the atmosphere is much smaller than those of other sources (Schumann, 1993). Moreover, this class of emissions has been reduced already considerably in the past. However soot contributes significantly to the CN concentration in the lower stratosphere, providing condensation sites for aerosols and clouds. It also acts as a third body for chemical reaction or surface for heterogeneous reactions. Such effects encourage ozone depletion in the lower stratosphere.

In conclusion, although more research is required into the role of heterogeneous chemistry and these condensation nuclei and their contribution to atmospheric chemical reactions involving more critical pollutants, soot emissions from air traffic at altitude are very small and, by themselves, not a cause for concern as knowledge stands at present.

Appendix C.1

Low Emissions Combustor Technology

1. CONVENTIONAL COMBUSTORS : DESCRIPTION

There are two basic types of conventional gas turbine combustors : tubular and annular. A tubular chamber is composed of a cylindrical liner mounted concentrically inside a cylindrical casing. Most of the early jet engines featured tubular chambers, usually in numbers varying from seven to sixteen per engine. The tubular design offers advantages of accessibility and maintainability. For aircraft applications, the tubular system is now regarded as too long and too heavy and the annular system is now the automatic choice for all new engines. The annular combustor comprises an annular liner mounted concentrically inside an annular casing. In many ways, it represents an ideal form of chamber, since its "clean" aerodynamic layout results in a compact unit of lower pressure loss than other combustor designs.

The volume contained within the liner of a conventional combustor incorporates three main zones : primary, intermediate and dilution. The function of the primary zone is to anchor the flame and to provide sufficient time, temperature, and turbulence to achieve essentially complete combustion of the fuel. The hot combustion products issuing from the primary zone flow into the intermediate zone, which provides a region in which combustion can proceed to completion upstream of the dilution zone. The role of the dilution zone is to admit the air remaining after the combustion and wall cooling requirements have been met, and to provide an outlet gas stream with a mean temperature and a temperature distribution that are acceptable to the turbine. The locations of the three main zones in relation to the various combustor components and the air admission holes are shown in Figure 1.

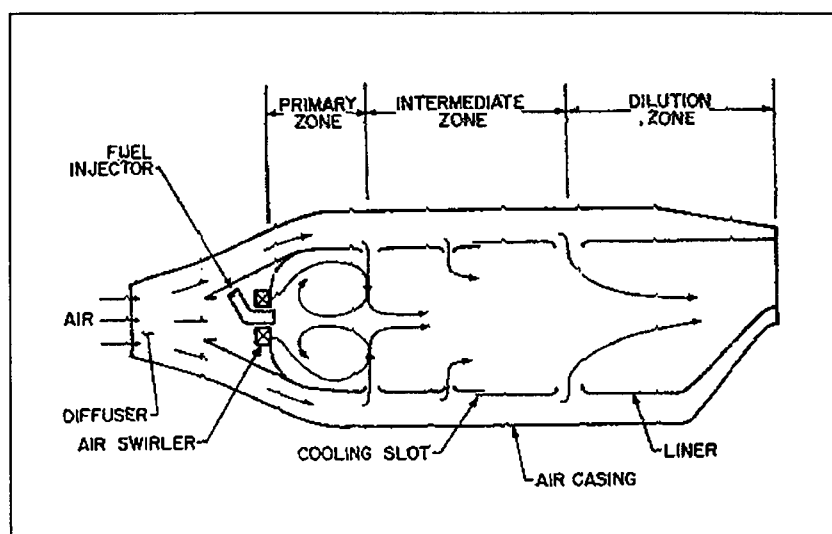


Figure 1 : Main Components of a Conventional Gas Turbine Combustor

Because the liquid fuels must first be atomised before being injected into the primary zone, a high relative velocity between the liquid to be atomised and the surrounding air or gas is needed. Pressure atomisers accomplish this by discharging the liquid at high velocity into a relatively slow-moving stream of air. An alternative approach generally known as airblast atomisation is to expose a slow moving liquid to a high-velocity airstream.

Pressure atomisers are usually of the dual-orifice type, as shown in Figure 2. This atomiser incorporates a small and a larger orifices, arranged concentrically. The design gives satisfactory atomisation over a wide range of fuel flows without calling for excessive fuel delivery pressures. While dual-orifice atomisers offer good mechanical reliability, their drawbacks include potential plugging of the small passages and orifices by contaminants in the fuel and a tendency toward high concentrations of exhaust smoke at high combustion pressures.

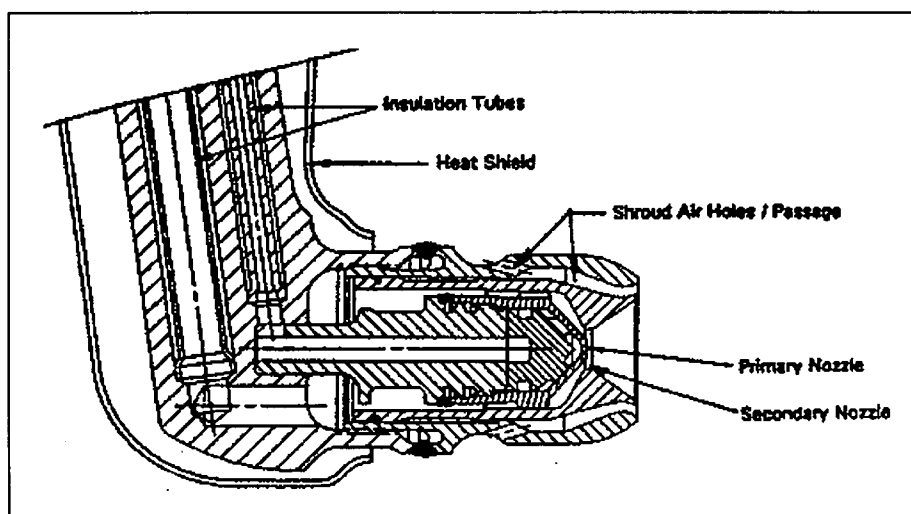


**Figure 2 : Dual-Orifice Pressure-Swirl Atomiser (Lefebvre, 1995 ;
Courtesy of the Parker Hannifin Corporation)**

The most widely used type of airblast atomiser is illustrated in Figure 3. In this design the fuel is first spread into a thin continuous sheet, a process called “prefilming”, and then exposed to high-velocity, swirling air streams on both sides of the sheet. Such atomisers are capable of producing a virtually smoke-free exhaust at high pressures, and fine atomisation quality over the entire operating range. With a dual-orifice injector, there is always a range of fuel flows over which atomisation quality is poor. As a result, throughout the operating range, the airblast injectors will be more effective to reduce CO and UHC emissions. The main drawbacks include poor lean blowout performance and poor atomisation during engine start-up when air velocities are low. these problems can be overcome by incorporating a pilot or primary nozzle. At low fuel flows, all of the fuel is supplied through the pilot nozzle, and a well-atomised spray is obtained, giving efficient combustion at start-up and idle. At higher power settings, fuel is supplied to both the airblast and pilot nozzle. By this means, the performance requirements of wide burn range and low exhaust smoke are both realised.

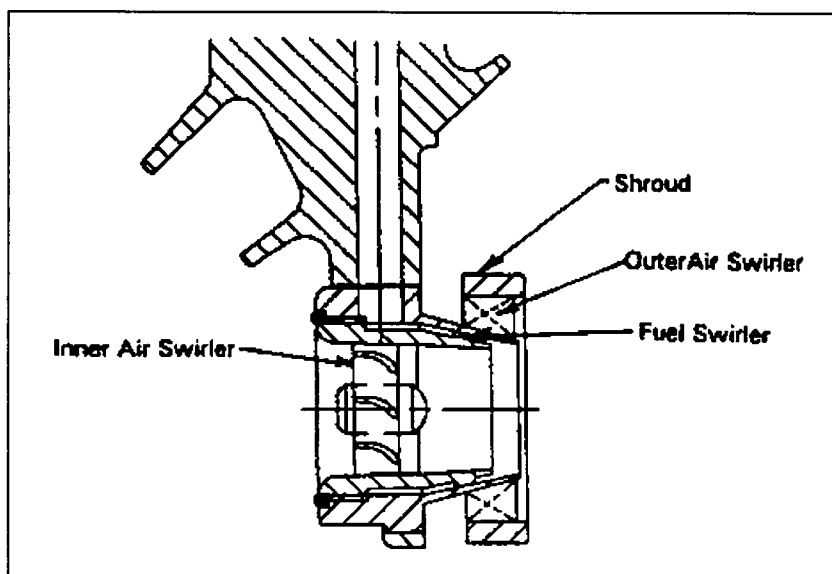


**Figure 3 : Prefilming Airblast Atomiser (Lefebvre, 1995 ;
Courtesy of the Parker Hannifin Corporation)**

2. CONVENTIONAL COMBUSTORS : DESIGNING FOR LOW EMISSIONS

Analysing the effects of the various combustor thermodynamic and geometric parameters shows that designing a conventional combustor involves much compromise, not only between one specie and another, but also among the many other performance requirements such as size, low pressure drop, low wall temperatures, adequate ignition, altitude relight, blow out limits and outlet temperature distribution (pattern factor). It is possible to generalise and state that any change in operating conditions or configuration that reduces NO_x tends to exacerbate the problems of CO and UHC and vice versa.

The main factors controlling emissions from conventional combustors include :-

- *Primary zone temperature and equivalence ratio* : the overall combustion temperature depends on the inlet air temperature and pressure as well as the equivalence ratio. It will govern the chemical reaction rates that produce or consume the various pollutants.
- *The degree of homogeneity of the primary zone combustion process* depending on the fuel atomisation quality and the optimisation of the air and fuel distribution. Pollutant levels largely depend on the performance of the injection system. The quality of the fuel-to-air ratio and its distribution in the primary zone will determine the degree of homogeneity of the fuel-air mixture as well as the local temperature at which the mixture will burn. Pollution levels also strongly depends on the fuel-air mixing prior to combustion and the air distribution in the flame tube.
- *Residence time in the primary zone* controlling the duration of the various chemical reactions producing or consuming the pollutants.

- *Liner-wall quenching and entrainment in the wall cooling air* which can freeze chemical processes.

In considering practical design methods for pollutant reduction, attention is focused first on individual pollutant species for which the various reduction routes are detailed in Table 1. The beneficial effects of an optimisation of combustor inlet thermo-dynamical conditions also discussed, although such routes are to this day ignored and form part of the constraints the combustor designer has to work with. The mechanisms of formation have been described earlier in Chapter 2.

Species	Reduction Route
CO and UHC	<ul style="list-style-type: none"> • <u>Raising combustion efficiency</u> : this can be achieved by re-distributing the airflow to bring the primary zone equivalence ratio around 0.8. A higher equivalence ratio (up to around 1.0) would enhance burning rates but the resulting scarcity of oxygen would push up CO and UHC levels. • <u>Ensuring good primary zone fuel-air mixing</u> : at the optimal equivalence ratio, poor mixing could produce overweak or overrich regions. • <u>Reducing the amount of liner wall-cooling air</u> especially in the primary zone : the use of new materials and cooling techniques (such as effusion and transpiration cooling) allow the liner to operate at higher temperatures with less cooling air. • <u>Improving fuel atomisation quality</u> : reductions in SMD enhance evaporation rates except at low equivalence ratio where the influence of drop size is less pronounced.
Smoke	<ul style="list-style-type: none"> • <u>Raising combustor inlet air temperature</u> : this promotes both the soot-forming and soot-burnout processes, but usually results in a net reduction in smoke. • <u>Reducing combustion pressure</u> : so that the slower chemical reaction rates allow more fuel to evaporate and mix with the air before burning. With pressure atomisers, decreasing pressure beneficially raises the cone angle of the fuel spray. • <u>Injecting more air in the primary zone and promoting mixing</u> : this approach is limited, owing to the adverse effects on ignition, stability limits and CO and UHC emissions at idle. • <u>Premixing the fuel with air prior to combustion</u> which airblast atomisers achieve more effectively than pressure atomisers • <u>Improving fuel atomisation quality</u> : so that the heat penetrating the droplet during evaporation has not enough time to raise the droplet temperature and promote the formation of carbon at the centre. However, if improved atomisation leads to a reduction in spray penetration (as occurs with pressure atomisers), the smoke output may actually increase. Airblast atomisers exhibit better atomisation quality than dual-orifice pressure atomisers.
NO _x	<ul style="list-style-type: none"> • <u>Adding more air into the primary zone</u> to lower the reaction temperature. This can be achieved through the use of new materials and cooling techniques allowing to operate combustors with less cooling air. • <u>Increasing liner pressure drop</u> to promote better mixing and eliminate hot spots from the combustion zone. • <u>Improving fuel atomisation quality for lean mixtures</u> : according to Lefebvre (1995), even at low equivalence ratios and high pressure where evaporation time is small in comparison to residence time, an increase in SMD means that a larger proportion of fuel drops are capable to support "envelope flames". These envelope flames burn in a diffusion mode at near-stoichiometric fuel-air ratios where the high local combustion temperatures produce appreciable

quantities of NO_x . As the mixture becomes stoichiometric, the local fuel-air ratio adjacent to the fuel drops approaches the overall premixed value and drop size has generally no influence on NO_x (Rink and Lefebvre, 1989b).

- **Shortening the combustor** allows to reduce residence time therefore limiting the formation of NO_x emissions. The flame tube flow aerodynamics must be improved to maintain low levels of unburnt products and smoke as well as deliver acceptable exit temperature profiles. This technique has been extensively used to prevent increases in NO_x levels as a result of higher engine overall pressure ratios (Bayle-Laboure, 1990).

Table 1 : Reduction Techniques for Smoke, CO , UHC and NO_x

Figure 4 shows the cross section of a typical modern single annular combustor developed by Rolls-Royce for the Trent series of engines. The combustion system comprises a dump diffuser feeding air via deep annuli to a pin mounted annular combustor. The primary zone is optimised to ensure satisfactory altitude relight in the smallest volume to minimise residence time and NO_x emissions. Airblast fuel injection and mixing chutes minimise NO_x and smoke emissions. In order to achieve long mechanical durability, machined ring film cooling is employed in conjunction with external convection ribs, selective angled effusion cooling and thermal barrier coatings.

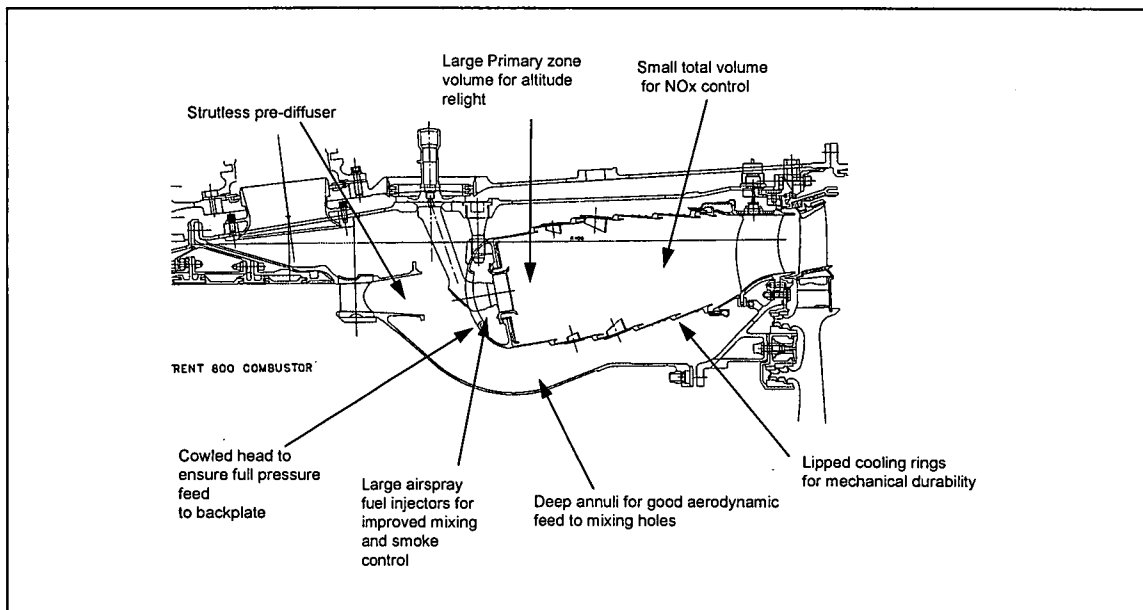


Figure 4 : Modern Single Annular Combustor (Courtesy of Rolls-Royce plc)

Raising the combustor exit temperature is usually the first choice in upgrading an engine's thrust (a requirement known as throttle-push) at the expense of the liner and the turbine nozzle which must improve their effectiveness or suffer a life penalty (Clouser & Kamin, 1993). The focus is for the combustor to withstand the highest possible temperature limit that the materials, fuel injection system and liner designs can support. To that end conventional materials such as Floatwall, Multihole, Lamilloy and Lycolite have been developed utilising every type of heat transfer mechanism available to dissipate the temperature and maintain materials integrity. Fuel injector design requires

to push a sufficient amount of fuel and still maintain some level of operability. Higher combustor exit temperatures responding to improvements in thrust levels leads to necessary innovations in operability and durability.

3. FUEL-STAGED COMBUSTORS

The main parameter governing pollutant emissions is the temperature of the combustion zone. With conventional combustors this can range from 1000K at low power operation to 2500K at high power operation, as illustrated in Figure 5. The figure indicates that only in a fairly narrow band of temperatures between 1670 and 1900K, are the levels of CO and NO_x below 25 and 15 ppm, respectively (Lefebvre, 1995).

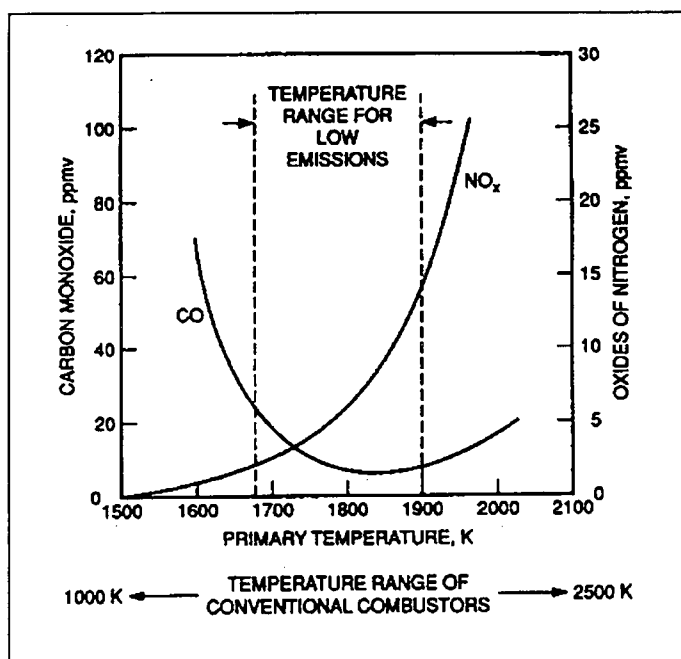


Figure 5 :
Influence of Primary Zone
Temperature on CO and NO_x
Emissions

The solution to low emissions can therefore reside in maintaining the combustion zone within a narrow band of temperatures over the entire engine power operating range. This can be achieved by switching the fuel flow from one zone to another during the operation without changing the air distribution in what is known as staged combustors. Such combustors can be circumferentially, radially or axially staged.

One simple method of fuel staging known as circumferential staging or selective fuel injection is to supply fuel to selected combinations of fuel injectors at lightoff, relight and engine idle conditions. Only above idle conditions are all injectors employed. The objective of the technique is to raise the equivalence ratio and temperature of the localised combustion zone at low power operating conditions. Relative to conventional combustors, this technique presents the following advantages and drawbacks :-

Advantages :-

- Low pollutant emissions .
- Lean blowout limit extended to lower equivalence ratios.

Drawbacks :-

- Non-uniform exit temperature distribution leading to reduced turbine efficiency.
- Chilling effect occurring at the edges of the localised combustion zones which restricts the reduction of unburnt products.

The limitations have led to the development of staged combustors where two or more zones are employed, rather than trying to achieve the combustion objectives in one single zone. The principle of staged combustion (illustrated in Figure 6) allows the combustor to operate over the entire power range while keeping the combustion temperatures within the low-emissions window. As soon as the combustion temperature approaches a level above which NO_x levels become excessive, the fuel flow is diverted to the next zone. The staged combustor can feature either radial- or axial-staging. Two such concepts were developed by the principal US aero engine manufacturers under contract to NASA in the Experimental Clean Combustor Program. Although they were capable to meet the EPA's proposed 1979 standards, the cost in combustor complexity was judged too large and the concepts were considered unable to meet potential low- NO_x requirements in the upper-atmosphere.

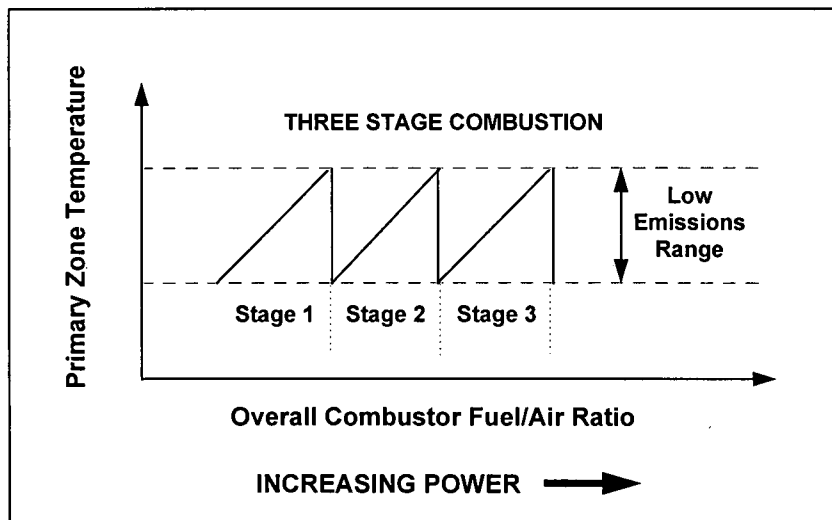


Figure 6 : Principle of Staged Combustors

A typical radially staged combustor uses two zones as shown on Figure 7. The pilot zone occupies a large volume (long residence time) to optimise the primary zone stoichiometry at start-up, altitude relight and idle conditions, therefore producing little CO and UHC emissions. Conversely, the main zone features small volume (i.e. short residence time) supplied with a large quantity of air from the compressor in order to achieve lean combustion and low residence times at high power in order to minimise the formation of NO_x and smoke. Immediately after the primary zone exit, the gases are strongly diluted by a row of dilution holes as well as by the air flowing from the "idle" zone to rapidly quench the chemical reactions leading to the formation of NO_x .

This technique presents the following advantages and disadvantages relative to conventional combustors :-

Advantages :-

- Low pollutant emissions with NO_x as low as 50-70% of levels attained with conventional combustors. CO and UHC down by over 30% (Bayle-Labouré, 1990 ; Lefebvre, 1995).
- Combustor design requirements met within the same length as a conventional combustor (advantageous for retrofitting) leading to low engine weight and high performance retention (Bahr, 1987).
- Pilot fuel can be used to cool main stage fuel.

Drawbacks :-

- Increased complexity and higher number of injectors.
- Larger liner wall surfaces requiring more cooling and/or new more temperature-resistant materials.
- Difficulty to achieve satisfactory performance at intermediate ratings where the two zones are out of their optimum design.

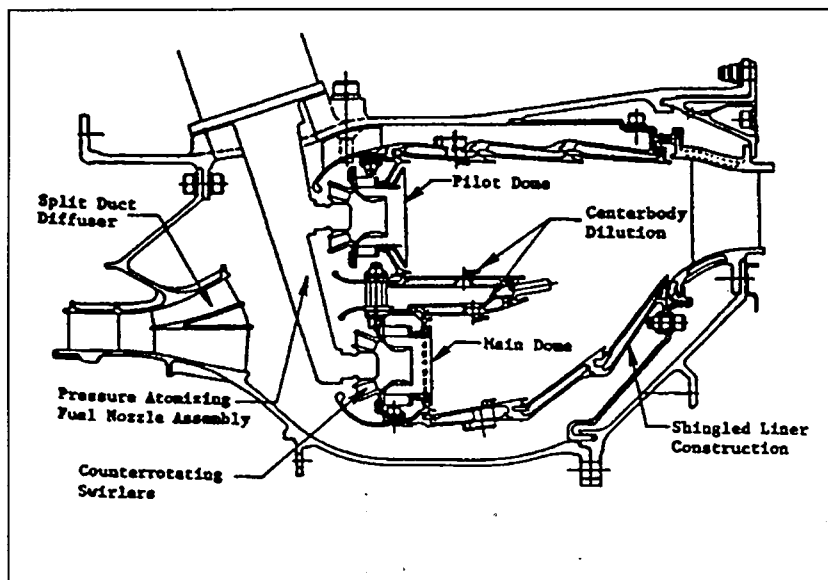


**Figure 7 :
General Electric
Dual-Annular
Combustor**

Radially-staged combustors are now in service on a number of General Electric engines including the CFM56-5B and the GE90-76B/-84B. It has shown the hoped-for reduction in NO_x on the CFM56-5B engine (powering the Airbus Industrie A320 and A321), but on the more recently certificated very large, very high compression ratio GE90 engine, it has proved a disappointment. The reason appears to be that there is not enough air passing through the engine core to both control NO_x and cool the combustor walls to maintain tolerable temperatures (Mortimer, 1996). The need to balance these two requirements has until now prevented the realisation of the anticipated NO_x reduction over conventional single annular designs.

Figure 8 shows an axially-staged combustor developed by the Pratt and Whitney company (Koff, 1993) and designed to fit into the existing P&W B2500-AS engine. A portion of the fuel is injected into the pilot zone, which is a conventional primary combustion zone designed to provide wide stability limits and high combustion

efficiency (i.e. low unburnt products) at low power. Its function is similar to that of the radially-staged combustor pilot zone. At higher power settings, additional fuel is injected downstream into the main combustion zone. At high power, the function of the primary zone becomes one of providing the heat to initiate rapid combustion of the fuel supplied to the second stage. In combination, the pilot and main zones operate at low equivalence ratio ensuring low NO_x emissions at high power.

The advantage and drawbacks of the axially-staged design relative to conventional combustors can be summarised as follows :-

Advantages :-

- Low pollutant emissions with NO_x as low as 50-70% of levels attained with conventional combustors.
- Rapid and reliable ignition of the main stage directly from the pilot.
- High combustion efficiency even at low equivalence ratio.
- Simple control of radial temperature distribution.
- No thrust lag when fuel is first introduced into the main zone.

Drawbacks :-

- Length due to in-line arrangement (retrofit difficult).
- Liner surfaces to cool larger than in conventional combustors.
- Two separate fuel injector feed arms.

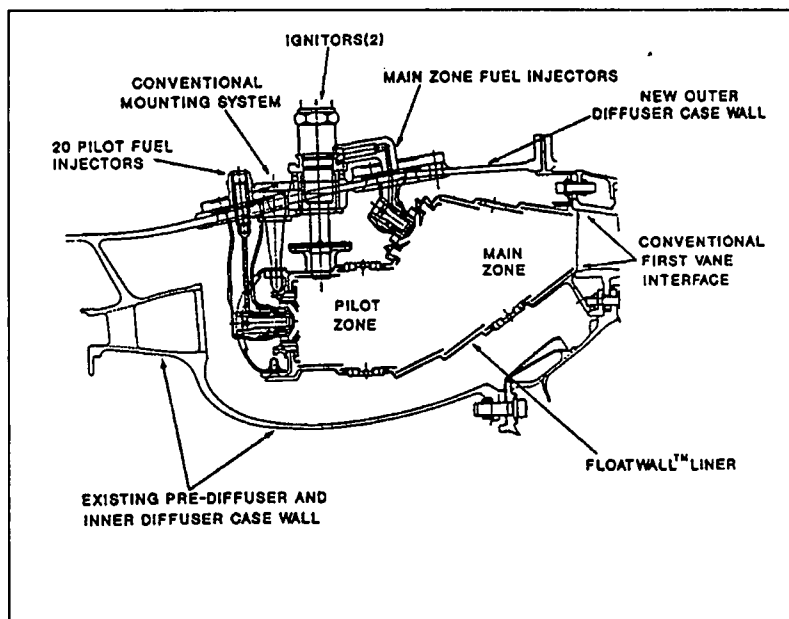


Figure 8 :
Pratt and Whitney
Axially Staged
Combustor

4. VARIABLE GEOMETRY COMBUSTORS

Variable-geometry was first considered long before its advantages to control pollutant emissions were recognised, as a means for improving the altitude reight capability of aircraft engines. The technique was never implemented in service because of the mechanical complexities involved.

Variable-geometry combustors maintain fuel-air ratio and the flame temperature within fairly narrow limits by adapting the airflow in the primary zone to each operating conditions. The variation in airflow distribution include the use of variable-area swirlers to control the amount of air flowing into the combustion zone (Bayle-Labouré, 1990), variable air openings into the dilution zone (Roberts *et al*, 1982 ; Jamieson, 1990 ; see Figure 9), or a combination of these.

The techniques have the potential for reducing silmutaneously all the main pollutant emissions without unacceptable compromise with other combustor design requirements. Variable-geometry could ideally be used in conjunction with premix-prevapourise fuel injection systems, to avoid local high temperature regions resulting from the presence of large fuel droplets. Although this technique has been used in some large industrial gas turbines, there have been few aero applications due to the disadvantages listed below.

Advantages :-

- Low pollutant emissions.
- Reduced combustor volume leading to low engine overall dimensions and weight.
- Enlarged fuel-air ratio operating range (wide stability limits).
- Improved altitude relight capability.

Drawbacks :-

- Mechanically-complex control mechanism leading to increased weight, size and cost and reduced operational reliability.
- Pattern factor can suffer from possible variations in liner pressure drop.

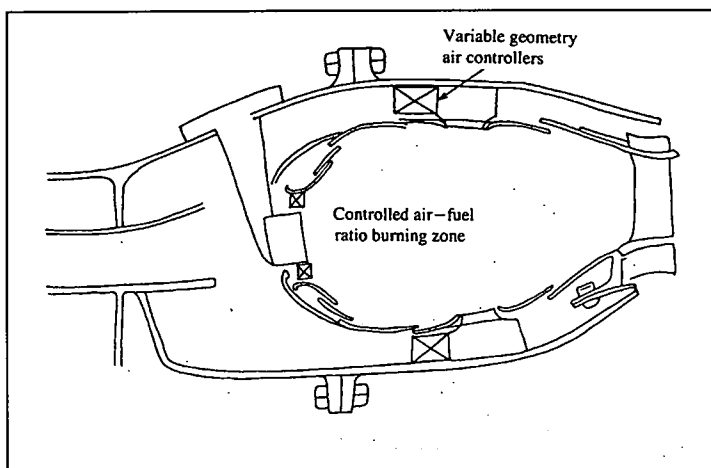


Figure 9 :
Variable Geometry Injection
(Jamieson, 1990)

5. LEAN-BURN PREMIX PREVAPOURISE COMBUSTORS

It has been demonstrated that the presence of fuel drops in the primary zone of conventional combustors gives rise to conditions in which combustion proceeds at near-stoichiometric equivalence ratios regardless of the average equivalence ratio in the combustion zone (Rink and Lefebvre, 1989b). The various types of lean premix prevapourise combustors attempts to eliminate those fuel drops by mixing the fuel and air upstream of the combustion zone to achieve ultra low NO_x . The combustion zone is supplied with a highly homogeneous fuel-air mixture and operate at an equivalence ratio

which is very close to the lean blow-out limit. The smaller the margin between stable combustion and flame blowout, the lower will be the output of NO_x .

A typical LPP (see Figure 10) combustor can be divided into three main regions. The first region is for fuel injection, fuel vaporisation and fuel-air mixing. In the second region, the flame is stabilised by the creation of one or more recirculation zones. Combustion is completed in this region and the resulting products then flow into the third region, which may comprise a fairly conventional dilution zone.

The main advantages and disadvantages of this technique are listed below :-

Advantages :-

- Low pollutant emissions with NO_x potentially as low as 10-20% of levels attained with conventional combustors.
- Short residence time allowing to limit NO_x formation.
- NO_x formation is insensitive to residence time with flame temperatures below 1900K (Anderson, 1975). LPP combustors can be designed with long residence time to control CO and UHC as well.
- Almost no carbon formation, therefore reducing the need for liner wall cooling air which can be used for controlling NO_x and improving pattern factor.

Drawbacks :-

- Autoignition and flashback upstream of the flame stabilisers at high pressure ratio because of the long time needed for fuel evaporation and fuel-air mixing.
- Some form of piloting device may be required to facilitate ignition and sustain combustion at arduous operating conditions.
- The airflow rate needed at high power may lead to flame blow-out when the engine is slammed to low power conditions. Some form of variability (fuel staging or variable geometry) is usually required.
- Acoustic resonance is encouraged by the improvements in fuel-air mixing and result in noise and mechanical vibrations.

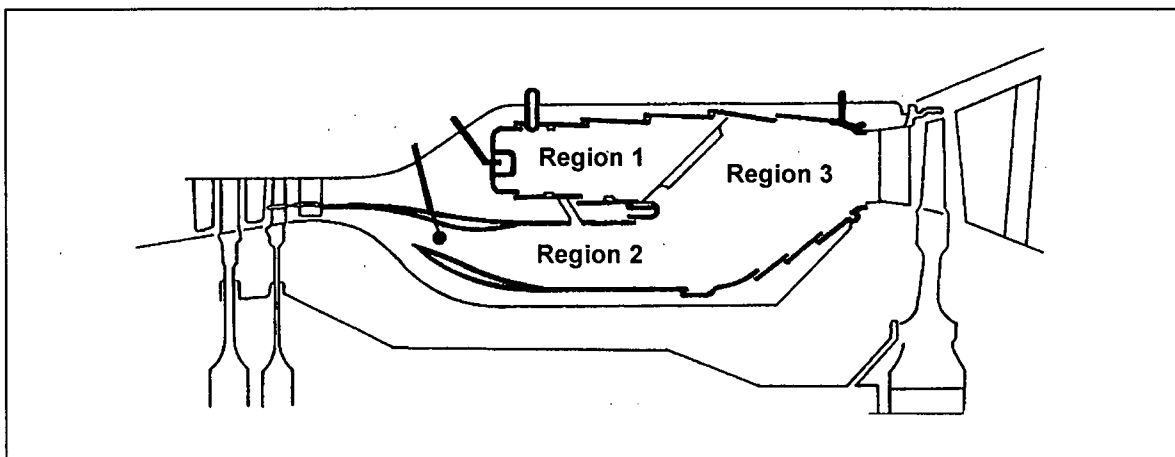


**Figure 10 : Typical Lean-Burn Premix Prevapourise Combustor
(Bayle-Labouré, 1991)**

LPP combustion has remarkable potential for ultra low NO_x emissions. Levels below 10 ppm have been reported (Lefebvre, 1995). However, the incorporation of such combustors in service particularly in high pressure ratio engines will depend on the extent to which the major issues of autoignition and acoustic resonance are dealt with.

6. RICH-BURN, QUICK-QUENCH, LEAN-BURN COMBUSTORS

NO_x emissions can in principle be reduced by achieving combustion at equivalence ratios largely over the stoichiometric value thereby reducing flame temperature as well as the available oxygen. Originally designed for industrial engines, the RQL concept uses this principle of staged burning as shown on Figure 11. Combustion is initiated in the fuel-rich primary zone at equivalence ratios between 1.2 and 1.6. Higher levels would yield even lower NO_x emissions but could lead to excessive soot formation and smoke. A homogeneous and uniform fuel-air mixture and the absence of localised flow recirculation zones in the primary zone, are required to effectively control NO_x emissions. The fuel-rich combustion products are then rapidly diluted in the stoichiometric zone to limit the formation of nitrogen oxides. The combustion process is then completed in the lean-burn zone which operates at equivalence ratios between 0.5 and 0.7 in order to eliminate the remaining CO, UHC and soot but without encouraging the formation of NO_x . This technique presents the following advantages and disadvantages :-

Advantages :-

- Low pollutant emissions with NO_x potentially as low as 30-40% of levels attained with conventional combustors.
- Only one stage of fuel injection is required.

Drawbacks :-

- Quench mixer design to be improved.
- High soot formation in the primary zone leading to high radiation and exhaust smoke.
- Air cannot be injected into the primary zone as part of the liner wall cooling, because it will lead to the formation of high temperature zones.

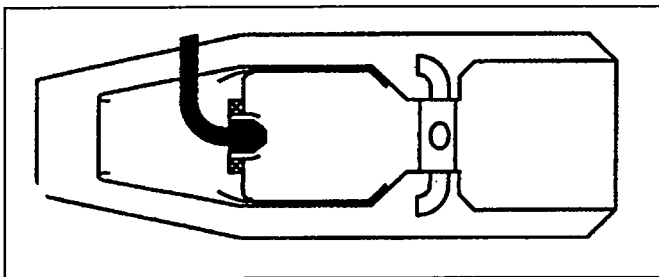


Figure 11 :
Typical Rich-Burn Quick-Quench
Lean-Burn Combustor

7. CATALYTIC COMBUSTORS

Because NO_x emissions are lowest when the combustion zone operates at equivalence ratios close to the lean blow-out limit, another NO_x reduction technique consists in incorporating a combustion-enhancing catalyst within the combustor which could meet the required level of engine operability. Catalytic combustion occurs without flames at temperatures well below the lean flammability limits of the kerosene-air mixture.

Figure 12 illustrates the principle of catalytic combustion. The reactor may consist of several sections, each made of a different kind of catalyst. The inlet section should be active at low temperatures while the remaining ones should provide good oxidation

efficiency. The reactor inlet must be supplied with a homogeneous and uniform mixture with regard to temperature, composition and velocity profile.

Most of current research work regarding catalytic combustors is focused on stationary gas turbine applications. The high pressure and high temperature conditions experienced by aircraft gas turbines lead to serious and still unresolved concerns over the catalyst durability and reliability. LPP and RQL concepts appear to show equal promise with less risks (Lefebvre, 1995). Advantages and disadvantages of the technique are as follows :-

Advantages :-

- Low pollutant emissions.
- Extended flammability limits.

Drawbacks :-

- Tendency toward autoignition of the fuel upstream of the catalyst due to locally fuel-rich regions near the fuel injector.
- Limited life expectancy of catalysts under typical high pressure and temperature conditions.
- High combustion efficiency over a narrow range of operating temperatures requiring catalytic combustion to be combined with variable-geometry or fuel staging.

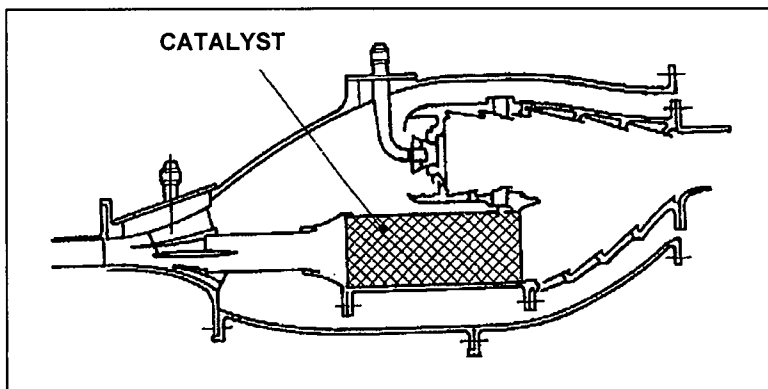


Figure 12 :
Schematic representation
of a Catalytic Combustor

8. LOW EMISSION TECHNIQUES FOR STATIONARY GAS TURBINES

A number of techniques specific to industrial gas turbines can be used to reduce NO_x emissions. They include water or steam injection, ammonia injection, exhaust gas recirculation and the use of alternative fuels.

Water or steam injection into the combustor can lower the local flame temperature and result in reductions in NO_x levels by a factor of four with similar water and fuel flow rates. The water must be of high purity to prevent deposits and corrosion in the hot sections downstream of the combustor. The drawbacks associated with this form of control has led to the development of the so-called “dry low NO_x ” combustors.

Another solution, known as selective catalytic reduction, consists in trying to eliminate NO_x by injecting a reducing agent such as ammonia. Nitrogen oxides react with ammonia to produce nitrogen (N_2). The technique requires the detection of the NO_x concentration in the exhaust, a control system metering the flow of the agent to be injected and a chemical reactor having a sufficient volume to allow the reaction to take place.

The recirculation of cooled exhaust products into the inlet of a gas turbine combustor reduces the emissions of NO_x . With this method, little re-development of conventional combustors is required. Its main drawbacks, however, lie in the need for very clean fuels as well as for an intercooler between the exhaust and inlet. This virtually rules it out for simple gas turbines which have high exhaust temperatures.

Industrial gas turbines have shown to operate with various fuels such as domestic fuel oil, natural gas, lean gas or alcohol. As a result of the lower flame temperatures, low heat value fuels generate less NO_x for a given combustor structure. CO and UHC emissions may however be higher. Moreover, such fuels result in higher specific consumptions.

Although all these solutions are possible for industrial gas turbines, they have not been implemented on aero engine applications because a number of requirements specific to the aero applications such as low weight, reliability and operability are not successfully addressed.

Appendix C.2

Evaluation of Propulsion System Weight

As the implications of main engine cycle parameters on engine weight is a complex issue, the following table only presents the major aspects as described by Gerend & Roundhill (1970). Table 1 will sometimes refer to the minimum gage effect. This occurs where minimum standard material sizes, the ability to manufacture and handle parts or operational considerations limit the feasibility of designing lighter components as the gas generator core airflow is reduced. This happens for instance when blade trailing edges cannot be made thinner from a practical manufacturing standpoint.

Cycle Parameter	Engine Section Affected	Major Effects of increase in Parameter (unless stated otherwise)
BPR	Fan section Engine	<ul style="list-style-type: none"> Ratio of fan section weight to total weight increases with BPR. Ratio of engine weight to total airflow reduces as the relative portion of air entering the core diminishes.
OPR	Gas generator	<ul style="list-style-type: none"> More compressor and turbine stages. Use of usually heavier more temperature-resistant materials in casing and structural components. Increased bearing and shaft weights. Minimum gage effects : small engines (small airflow) have higher rate of change of GG weight with OPR than large engines. Low rate of increase at low OPR because of increased combustor volume and no further benefits with single-stage HP compressor.
FPR	Fan section	<ul style="list-style-type: none"> The influence of FPR can be accounted for through BPR.
TET	Gas generator	<ul style="list-style-type: none"> Lower allowable stresses resulting in increased weight. Advances in materials and blade cooling alleviate the upward trend of weight with TET.
Core airflow (i.e. core diameter)	Gas generator	<ul style="list-style-type: none"> Assuming constant engine weight per volume and airflow per unit frontal area : a) scaling with constant GG length shows weight scales linearly with core airflow (scaling exponent 1), b) scaling with constant ratio of GG length to diameter shows scaling exponent of 1.5. The assumptions are less valid with small engines where fixed weight components predominate. Minimum gage effects : GG weight per unit of airflow rises with airflow for large engines, but reduces for small engines.
Total airflow	Engine	<ul style="list-style-type: none"> Engine weight increases with increased total airflow.
Flight Mach number	Engine	<ul style="list-style-type: none"> Engines designed for supersonic flight speeds tend to be heavier than subsonic and low supersonic engines primarily because of the higher operating temperatures. the variation of weight between one subsonic design and another is negligible.
Fan duct	Fan section	<ul style="list-style-type: none"> Obvious effect.
Noise	Fan section	<ul style="list-style-type: none"> Low noise designs tend to increase weight. They include low fan tip speeds, larger fan rotor/stator spacings, additional acoustic materials.
Life	Engine	<ul style="list-style-type: none"> Designing for shorter lives leads to lighter engines.

EIS year	Engine	<ul style="list-style-type: none"> Due to technological advances over the years, engine manufacturers have been able to design and build progressively lighter engines with equivalent cycles.
	Gas generator	<ul style="list-style-type: none"> Increased TET with time at no weight penalty owing to technological advances.
<u>Definitions :-</u> <ul style="list-style-type: none"> Fan section : fan, fan casing, turbines required to drive fan, fan spool shafts and bearings but excludes any compressor stages on the fan spool (e.g. booster). Gas generator : all components of the engine which are not part of the fan section. 		

Table 1 : Major Effects of Cycle Parameters on Propulsion System Weight

Appendix D.1

SKY Program Design Principles

1. PROGRAMMING STYLE

Requirements : Software integrity
Rapid validation process
User-friendliness
Capability for further improvements

- Preparation : A top-down design method is adopted where the main program consist of invocations of subprograms. Before writing the program, flowcharts using pseudo-code are produced.
- Modularity : The program is segmented into a sequence of modules with each subprogram performing a clearly-defined task.
- Before a run, the input data are checked by the program.
- Upon entry to any subprogram, all input arguments are written in a dedicated file. Back in the calling module, all returned results are written in the same file. The file is maintained to a reasonable size by keeping only the most recent data. The file is useful to the validation process.
- Direct comparisons of reals are not allowed to avoid round-off errors.
- Iterative computations are controlled and programmed with a maximum number of loops and a failure path leading to some form of diagnostic message.
- Declaration : Each variable is explicitly declared. Constants are only declared in the main program.
- Compiling : The main program is compiled and checked out first before the subsequent levels.
- Memory requirements and computing rapidity : The array sizes are minimised to reduce memory requirements. The iteration procedures optimised for minimum computing time.
- Validation : The modules are validated separately as well as together. All input data are echo-printed during the validation process.

2. USER-FRIENDLINESS

Requirements : Minimised memory requirements
Computing rapidity
Rapid assessment of failures
Clarity and easy manipulation of output data

- Memory requirements and computing rapidity : The array size is minimised and the iteration procedurs optimised for minimum computing time.

- Control of argument passing : Upon entering and after leaving any subprograms, the arguments are written in a dedicated file to assist the user in assessing the causes of a failure.
- Failure control : Before a run, the input data are checked by the program. If a problem is encountered during execution, some form of diagnostic message is written in a dedicated file presenting error messages. The messages enable the user to track the origin of the error.
- Output data : The output section is clearly presented with text and numbers segregated to allow for easy manipulation by spreadsheets.

3. CAPABILITY FOR FURTHER DEVELOPMENTS

Requirements : Popular programming language and operating system
 Program modularity
 Comprehensive and user-friendly documentation

- Programming language : Common and popular programming language (Fortran) and operating system (DOS or VMS) are selected.
- Modularity : well-documented modules can be easily modified.
- Documentation : Flowcharts, subroutine trees and variable's dictionaries are made available to enable a rapid and efficient understanding of the source code for further improvements. To this effect, comments are largely included in the program. The variable dictionary includes the list of variables, an explanation of their meaning and the units used.

Appendix D.2

SKY Flight Route Module - Modelling Description

1. INTRODUCTION

The *Flight Route Module* is an upgraded version of FAST (Flight Analysis of Subsonic transport) which formed part of SKY's predecessor (Le Dilosquer, 1993). Most of FAST was re-written to closely reflect the actual flight profile of subsonic transport aeroplanes according to the design rules established in Appendix D.1. FAST originally employed the structure of FLTANAL, the flight route simulation module of an aircraft configuration design computer system developed at the College of Aeronautics in Cranfield University (Pasaribu, 1991). FLTANAL was itself based on a computer flight simulation program for aircraft preliminary design developed by NASA (Sliwa and Arbuckle, 1980).

The SKY *Flight Route Module* uses a mixture of *analysis* and *interpolation* techniques. Analysis requires flight performance equations describing the aeroplane flight mechanics while interpolation techniques derive the flight parameters through data tables. Both approaches are used by SKY to perform step-by-step calculations of fuel burn, time spent, distance flown, and up to over 15 flight parameters (excluding internal engine and combustor parameters). The flight phases are divided in a number of steps which can be either altitude steps (at climb and descent) or range steps (at cruise). Short phases (i.e. remaining phases) are simulated with a single step. All parameters are assumed constant on a step.

In return of atmospheric conditions, Mach number, altitude and either fuel flow (at take-off, climb and holding) or thrust requirement (at cruise), the *Aero Engine Module* supplies net thrust and s.f.c. to the *Flight Route Module*, allowing the computation of the flight parameters at any given step. The start, taxi, descent, and approach phases employ fuel burn and fuel flow rate allowances rather than the *Aero Engine Module* which is currently unable to simulate engines at low power conditions. The module has been validated using 747-400 performance data on the London-Tokyo flight route (see Chapter 5 Section 5.3). For most phases, the computer system offers a choice of simulation procedures which are listed in Appendix D.5. The output section includes not only the current step by step output of over 15 flight parameters but also phase breakdowns of fuel consumption, time and range.

2. FUEL BURN PREDICTION

2.1 Mission Fuel Burn Prediction

The program primary task is to iteratively predict the aircraft fuel mass required to fly the mission specified by the user. The fuel requirement includes the mission fuel burn and the reserves. Once the start mass required to perform the mission is known, the program launches the final iteration to output the computed flight, engine and emission data.

The mission can be divided into a number of elements each of which makes particular demands on the airframe-engine combination. The basic elements of the mission can be considered in terms of their requirements on the engine thrust and mission fuel. For civil operations the basic mission profile for a specified stage length is outlined in Figure 1. The program follows this flight plan to calculate the fuel consumption of each phase : start, taxi-out, take-off and climb-out, initial climb, acceleration, en-route climb, cruise, descent, holding, approach and landing and taxi-in. The user decides whether holding occurs at all and if so at which point of the descent phase. The holding and taxi-in fuel are taken out of the reserves and therefore not accounted for in the aircraft fuel mass prediction.

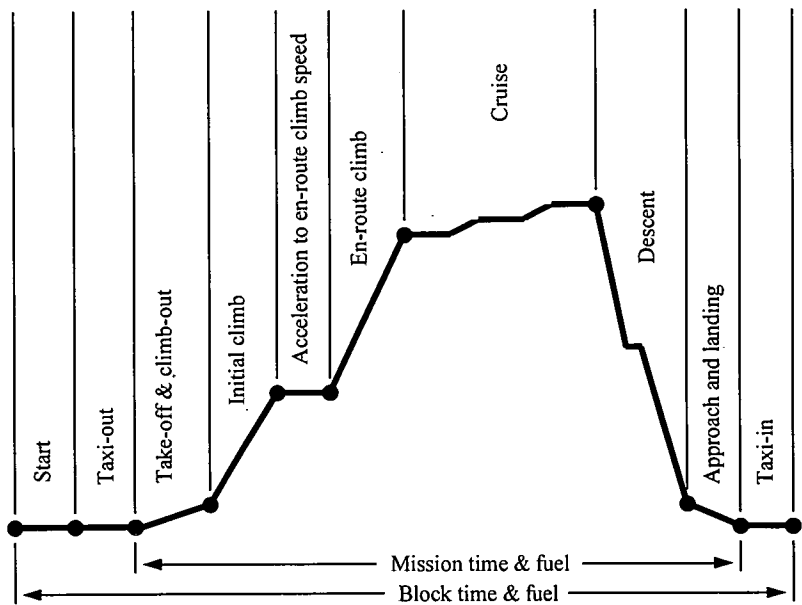


Figure 1 : Mission Flight Profile

2.2 Reserve Fuel Burn Prediction

Minimum fuel reserve loads are specified in FAR 91.23 (IFR operations) and FAR 91.207 (VFR operations), but in airline practice the quantity of reserve fuel is usually greater. The reserve fuel will include items such as : an extra hour of cruising, a percentage of the block fuel (e.g. 5%), a diversion flight (e.g. 200 nm), or a 30 or 45 mn hold. Depending on the type of operation, a reserve policy will combine several of these items, in accordance with FAR rules or company policy.

The fuel reserves intended for international operations (range exceeding 3,000 nm) specified by the FAR and ATA and typically adopted by airlines, incorporate the amount of fuel required to fly from the destinate airport to an alternate airport 200 nm distant, and various contingencies described as reserves segments in Figure 2 and detailed in Table 1. An alternative reserve fuel policy may be to continue the basic flight profile for two hours.

As an initial contingency, ATA and FAR recommend to continue the flight for 10% of the flight time at end of cruise conditions. Airlines typically make an allowance of 5% of mission fuel (SKY's *final reserve*). The second contingency is a 30-minute holding procedure performed at 1,500 ft with the power setting for maximum endurance. The diversion flight profile is illustrated on Figure 2. The diversion cruise power setting may be equal to 99% of maximum subsonic range, the cruise speed from the basic mission being used. The diversion cruise altitude must be optimum for best range, except that it must not exceed the altitude where cruise distance equals the climb plus descent distance. SKY reserve fuel computation is based on the typical international policy (shaded part of Table 1).

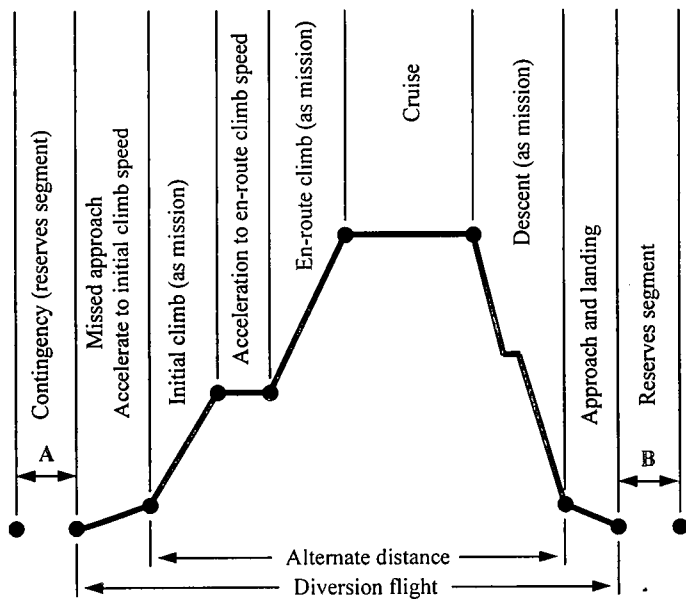


Figure 2 : Reserves Segments and Diversion Flight Profile

Policy	Reserve Segment	
	A	B
FAR domestic	Not used	45 mn continued cruise at long range cruise Mach and end mission altitude, starting at end alternate weight
ATA domestic	1 hr continued cruise at long range cruise Mach at end of cruise altitude and cruise weight	Not used
Typical - Int ^{al}	5% of mission fuel	30 min hold at 1,500ft
FAR - Int ^{al}	10% Flight time at long range cruise Mach at end of cruise altitude and weight	30 min hold at 1,500ft

Table 1 : Typical Reserve Fuel Policies

3. MISSION AND DIVERSION AIRCRAFT CONFIGURATION AND ENGINE REQUIREMENTS

The mission and diversion can be divided into a number of elements each of which makes particular demands on the aircraft aerodynamic configuration as well as on the powerplant thrust, bleed and power offtakes. The typical requirements corresponding to each element of the flight plan are outlined in Table 2 (next page).

Phase		Altitude	Speed	Flap setting	Under-carriage	Thrust Rating	Power offtake ⁽⁹⁾	Bleed offtake ⁽¹⁰⁾
Taxi-in/-out		R'way elevation	-	En-route	Down	Idle	40	0
Take-off	Initial segments	R'way elevation to 1,500 ft	0 to 250 KCAS	Take-off	Down	MTO initially	75	0
	Final segment	400 ft to 1,500 ft	< 250 KCAS	En-route	Up	MCL-MCT ⁽⁸⁾	75	0
Initial climb		1,500 ft to acceleration altitude	250 KCAS ⁽¹¹⁾ (ATC requirement)	En-route	Up	MCL	75	1.4
Acceleration		10,000 ft (typical)	250 KCAS to en-route climb speed	En-route	Up	MCL	75	1.4
En-route climb		10,000 ft to ICA	280-340 KCAS ⁽³⁾	En-route	Up	MCL	75	1.4 to 1.1
Cruise		ICA to final altitude ⁽⁴⁾	Cruise Mn ⁽⁷⁾	En-route	Up	< MCR	40	0.8 to 0.7
Climb to higher cruise altitude		As required	Cruise Mn	En-route	Up	MCL	75	1.1
Descent		End of cruise altitude down to 1,500 ft	Cruise Mn down to 250 KCAS ⁽⁵⁾	En-route ; approach below 10,000 ft	Up	Idle	40	1.1 to 1.4
Approach		1,500 ft to touchdown	Initial to final approach speed	Approach	Down	> idle ⁽⁶⁾	75	1.4
Landing		R'way elevation	Final approach speed to 0	Landing flap	Down	Idle and/or Rev. Thrust	75	1.4
Missed approach and acceleration to initial climb speed		R'way elevation to 1,500 ft	Final approach speed to 250 KCAS	En-route	Retracting	Idle to MTO	75	1.4
Holding		Between 1,500 and 25,000 ft dep. on ATC requirements	0.15 to 0.60 Mn ⁽¹²⁾	En-route	Up	< MCR	40	0.9
Remarks : (1) Percentage thrusts are typical figures and expressed relative to uninstalled ISA SLS take-off net thrust. (2) Power requirements and offtakes are controlled by the user. (3) Depend on passenger aircraft type. (4) Final cruise altitude depends on aircraft SAR at end of cruise. Cruise flight levels are of two types : westbound (260 280 310 350 390 430 470 510) or eastbound (250 270 290 330 370 410 450). (5) Maximum cabin depressurisation rate is limiting factor. Typical decsent profile would be 0.855Mn/280KCAS/250KCAS (747-000). (6) As required for 3 degree glide slope (7) Cruise Mn can be long-range, economical or high-speed. (8) The MCT rating is only selected in the event of an engine failure. (9) kW per engine, normal operation. (10) Typical widebody values in kg/s from each engine, all air conditioning packs on, the APU may be used at taxi (11) The initial climb speed can be greater that 250 KCAS if the stall margin is not met. (12) Typical 747-400 figures, optimum Mn depends on gross weight and altitude.								

Table 2 : Civil Jet-Powered Passenger Aircraft Configuration and Engine Requirements During a Typical Flight

4. SIMULATION OF FLIGHT PHASES

4.1 Introduction

The prediction of the fuel requirement for a flight route necessitates the computation at each step of the flight phases of four major parameters : fuel burn, time, distance and altitude change. The process is described by Figure 3. Over a step, all flight parameters remain constant. A system of equations appropriate to the conditions in which the aircraft flies and closed by a number of constraints, is used to calculate the variations in the aircraft mass (Δm), time (Δt), distance (Δr) and altitude (Δh). The four parameters are then incremented so that the *Flight Route Module* can perform the next step simulation.

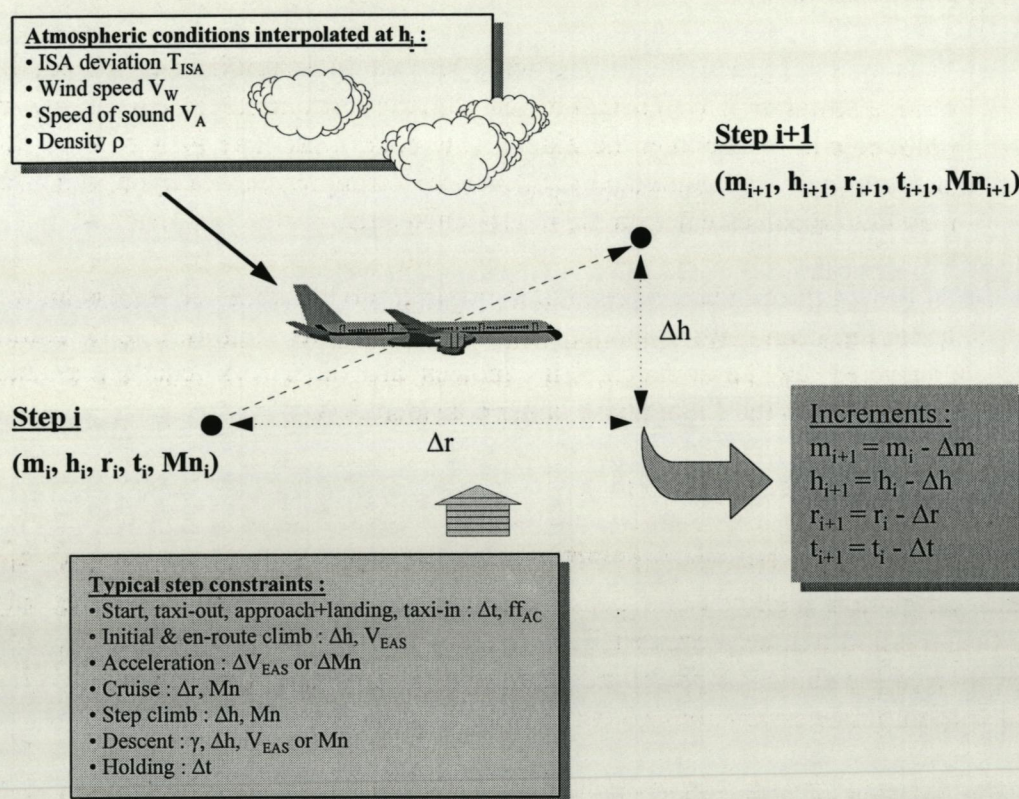


Figure 3 : Flight route simulation over a step

Each phase employs a particular method to compute the four parameters. The method may be unique or controlled by the user prior to the run. The various methods or simulation procedures differ from each other through the way they compute fuel burn, distance, time, fuel flow, speed, engine handle, thrust requirement and emission indices. Appendix D.6 classifies these parameters by calculation procedures for every flight phases. The calculation procedures are the following :

- 1) Analysis : the parameter is calculated by means of an equation or analytical expression related to other parameters.
- 2) Interpolation : an input data file is used to interpolate the parameter with respect to up to three variables.
- 3) Allowance : the parameter is a user input or originates from the program's previous computations.
- 4) Turbomatch (coupled) : the gas turbine simulation system is used to compute engine net thrust, fuel flow and the engine handle (in cases where it is not fuel flow). Flight and engine performance are coupled that is the thrust and fuel flow are fed to the *Flight Route Module* to compute fuel burn and the aircraft position analytically.
- 5) Turbomatch (de-coupled) : in cases where the fuel burn is interpolated, the gas turbine simulation system can be fed with the resulting fuel flow rate and run to produce combustor inlet thermodynamic conditions. The *Flight Route Module* does not need the computed net thrust which represents an approximation and may not be consistent with the interpolated data.
- 6) APPEM : the emissions prediction program produces the five emission indices. It can only run if it is supplied with combustor inlet thermodynamic conditions computed by Turbomatch. The indices are otherwise read on a data file depending on the flight phase under consideration.
- 7) Nil : the parameter is set to 0.

The next paragraphs will present in detail how each flight phase is modelled. In case several simulation methods and hence systems of equations are available, only the analytical method will be presented. The reader is advised to refer to Appendix D.5 for a description of the choice of procedures. This approach should bring the required level of detail without unnecessary confusions.

The computation of atmospheric data (density, wind speed, speed of sound and ISA deviation) and the interpolation of the aircraft drag coefficient by means of a drag polar will not be described in the following sections. The required explanations can be found in Appendices D.7 and D.8.

4.2 Start, taxi-in, approach/landing, taxi-out and missed approach

These phases account for a negligible proportion of the total fuel burn, distance flown and time spent. As a result, the approach of employing aircraft fuel flow and time allowances specified by the user to derive the fuel requirement is preferred. The distance

and time increments of each of these phases is considered as negligible. Most other parameters are set to 0.

The variations in aircraft mass, time, distance and altitude for such phases are therefore :

$$\Delta m = ff_{AC} \times \Delta t$$

$$\Delta t = \text{user allowance}$$

$$\Delta r = 0$$

$$\Delta h = 0 \text{ (start, taxi - out, taxi - in, missed approach)}$$

$$\Delta h = 1,500\text{ft} \text{ (approach / landing)}$$

4.3 Take-off and climb-out

The fuel, distance and time to take-off to 35 ft (10.7 m) and then climb out to 1500 ft (457 m) are interpolated from a performance data table with respect to airport altitude and aircraft mass. The average fuel flow is derived and may be fed if required to the Turbomatch engine simulation system to compute engine performance and emission data. The thrust computed may of course not be consistent with the interpolated data and in such circumstances must be considered only as an indication.

Having interpolated Δm , Δt , Δr and Δh being known, SKY can compute the various flight parameters. The aircraft fuel flow, the rate of climb and the true air speed first derive from these variations :

$$ff_{AC} = \frac{\Delta m}{\Delta t}$$

$$ROC = \frac{\Delta h}{\Delta t}$$

$$V_{TAS} = \frac{\Delta r}{\Delta t}$$

Once the atmospheric conditions (density ρ , speed of sound V_A and wind speed V_w) are determined at the starting altitude, it is possible to compute Mach number, the climb angle and, as a result, the lift coefficient :

$$Mn = \frac{V_{TAS}}{V_A}$$

$$\gamma = \arcsin\left(\frac{ROC}{V_{TAS} + V_w}\right)$$

$$C_L = \frac{mg_0 \cos \gamma}{\frac{1}{2} \rho V_{TAS}^2 S_w}$$

At the take-off configuration (undercarriage down, take-off flaps), the drag coefficient is interpolated with respect to the lift coefficient and the Mach number. The aircraft drag can be expressed as :

$$D = \frac{1}{2} \rho V_{TAS}^2 C_D S_w$$

To be relative to the ground, the distance increment must be corrected with respect to wind speed :

$$\Delta \mathbf{r} = \Delta \mathbf{r} + \mathbf{V}_w \Delta t$$

4.4 Initial and en-route climb

The optimum climb performance may require either minimum time or minimum fuel usage to a given altitude. Operational or other limitations may well override these optimum conditions. Initial climb starts from the end of climb-out at 1500 ft (457 m) with take-off flaps and undercarriage up. Acceleration to the required en-route climb speed follows at an altitude of usually 10,000 ft. En-route climb is then performed with clean configuration up to the initial cruise altitude.

Airline practice is to perform both climb portions at constant calibrated air speed CAS (CAS being greater on the en-route climb portion). Above a certain altitude it will be necessary to continue en-route climb at cruise Mach in order to avoid undesirable compressibility effects. For low subsonic speed, CAS is approximately equivalent to the equivalent air speed or EAS. A climb at constant EAS results in a steadily increasing TAS (True Air Speed) and Mach with increasing altitude (see equation below).

$$V_{EAS} = V_{TAS} \sqrt{\frac{\rho}{\rho_0}}$$

The simulation of the aircraft acceleration will be presented in the next section. This section presents the analytical simulation of a climb step whereby the thrust and fuel flow are supplied by Turbomatch and the aircraft EAS is a user-input constant. Three extra procedures are available that are described Appendix D.5.

Climb performance is computed by means of a step-by-step calculation procedure using the following equation, for an appropriate engine rating usually specified by the engine manufacturer. For most conventional subsonic aircraft the angle of climb is limited to roughly 10°-15°. For such small climb angles the rate of climb over a flight step is given by :

$$ROC = \frac{(T - D)V_{TAS}}{mg_0 \left(1 + \frac{V_{TAS}}{g_0} \frac{\Delta V_{TAS}}{\Delta h} \right)}$$

This equation is instrumental in calculating the variations in aircraft mass, time and distance :

$$\Delta t = \frac{\Delta h}{ROC}$$

$$\Delta r = (V_{TAS} + V_w) \Delta t$$

$$\Delta m = n_{eng} ff \Delta t$$

In order to evaluate the rate of climb, it is first necessary to compute the aircraft net thrust, drag and the initial and final TASs. The aircraft initial mass is used in the equation. Given that EAS is constant within any of the two climb portions, the initial and final TASs can be easily calculated as follows.

$$\text{Initial TAS : } V_{TAS} = V_{EAS} \sqrt{\frac{\rho_0}{\rho(h)}}$$

$$\text{Final TAS : } V'_{TAS} = V_{EAS} \sqrt{\frac{\rho_0}{\rho(h + \Delta h)}}$$

$$\text{Therefore : } \Delta V_{TAS} = V'_{TAS} - V_{TAS}$$

Mach number and the lift coefficient are derived as in the previous section :

$$Mn = \frac{V_{TAS}}{V_A}$$

$$C_L = \frac{mg_0}{\frac{1}{2} \rho V_{TAS}^2 S_w}$$

Given that the aircraft climbs with a clean aerodynamic configuration, the drag coefficient can then be interpolated with respect to the previous two parameters :

$$D = \frac{1}{2} \rho V_{TAS}^2 C_D S_w$$

Finally, given altitude, Mach number and the appropriate engine rating (interpolated from a data table), Turbomatch can supply net thrust T and the fuel flow rate ff. All the data required to compute the rate of climb are now available.

In case the aircraft reaches the initial cruise altitude before attaining the specified cruise Mach number, an single-step acceleration is performed at this altitude. The step will be part of the en-route climb phase.

4.5 Acceleration

Acceleration from the initial climb EAS to the required en-route climb EAS is performed at a constant altitude of usually 10,000 ft. This section presents the analytical simulation of an acceleration step whereby the thrust and fuel flow are supplied by Turbomatch and the EAS increment is a user-input. Two extra procedures described in Appendix D.5 are available.

The variations in aircraft mass, distance and time can be expressed as :

$$\Delta t = \frac{m(V'_{TAS} - V_{TAS})}{(T - D + ff_{AC} V'_{TAS})} \quad \Delta m = ff_{AC} \Delta t \quad \Delta r = \frac{1}{2}(V_{TAS} + V'_{TAS} + 2V_w)$$

Given the increment in equivalent air speed EAS, the initial and final true air speeds are calculated thus :

$$V_{TAS} = V_{EAS} \sqrt{\frac{\rho_0}{\rho(h)}} \quad V'_{TAS} = (V_{EAS} + \Delta V_{EAS}) \sqrt{\frac{\rho_0}{\rho(h)}}$$

The Mach number and lift coefficient are derived with data from the initial step as in the previous section (initial and en-route climb) to yield the drag coefficient and hence the aircraft drag D. The thrust T and aircraft fuel flow ff_{AC} are supplied by Turbomatch.

4.6 Cruise and step climb

The optimum cruise performance requires the aircraft to gradually gain altitude as it becomes lighter. This procedure known as climb cruise is the most fuel efficient. In practice, however, the aircraft is constrained by air traffic control (ATC) to fly on internationally-agreed flight levels and can change from one corridor to another only if it is able and permitted by ATC to do so. This procedure is known step cruise procedure and is presented in this section. The climb cruise method as well as other cruise procedures are also available to the user (see Appendix D.5).

Step cruise starts when the aircraft reaches the user-specified cruise initial altitude and Mach number. It is performed at constant Mach number and altitude with clean configuration up to the point where the remaining distance to the destination airport is deemed appropriate to start descent (see next section). The aircraft changes altitude if :- 1) the climb, cruise and buffeting ceilings are free ; 2) and the specific range is better at the upper altitude. If the requirements are met, climb is performed using the engine climb rating. The procedure is similar to the one described previously, except that the aircraft maintains a constant Mach number rather than a constant EAS.

The determination of the various flight parameters over the step starts with :

$$\Delta h = 0$$

$$\Delta r = \text{user input}$$

$$ROC = 0$$

$$\gamma = 0$$

The true air speed and the lift coefficient must be calculated first leading to the familiar expressions :

$$V_{TAS} = M n_{cr} \times V_A \quad C_L = \frac{mg_0}{\frac{1}{2} \rho V_{TAS}^2 S_w}$$

The time increment can be derived as follows :

$$\Delta t = \frac{\Delta r}{V_{TAS}}$$

Given that the aircraft climbs with a clean aerodynamic configuration, the drag coefficient can then be interpolated :

$$D = \frac{1}{2} \rho V_{TAS}^2 C_D S_w$$

Turbomatch is run to find the aircraft fuel flow rate required by the powerplants to match the drag. The resulting specific fuel consumption is :

$$sfc = \frac{ff_{AC}}{T}$$

The well-established Breguet's range equation is finally used to evaluate the fuel burn (equation below). It is of interest to note that the fuel burn could as well be calculated using the fuel flow and time increment previously estimated. This method would however not be as accurate since s.f.c. vary much less over cruise than fuel flow.

$$\Delta m = m \left(1 - \exp \left(- \frac{sfc \times \Delta r \times V_{TAS}}{\frac{C_L}{C_D} g_0} \right) \right)$$

4.7 Descent

Descent starts when the computer system recognises that the remaining range to fly to the destination airport is satisfactory as regards to the fuel efficiency, speed schedule and descent rate requirements. The low thrust requirement currently prohibiting the use of Turbomatch, the descent phase simulation is carried out using a data table to interpolate the Mach number, fuel burn, distance and time with respect to altitude, altitude change and the aircraft mass.

The following set of equations is used to compute the whole range of flight parameters :

$$V_{TAS} = Mn \times V_A$$

$$ROC = \frac{\Delta h}{\Delta t}$$

$$\gamma_{air} = \arcsin\left(\frac{ROC}{V_{TAS}}\right)$$

$$\gamma_{ground} = \arcsin\left(\frac{ROC}{V_{TAS} + V_W}\right)$$

$$C_L = \frac{mg_0 \cos \gamma_{air}}{\frac{1}{2} \rho V_{TAS}^2 S_W}$$

$$D = \frac{1}{2} \rho V_{TAS}^2 C_D S_W$$

$$T = D - mg_0 \sin \gamma_{air}$$

4.8 Holding

When requested by the user, holding is simulated using a data table to interpolate the recommended holding Mach number and fuel flow with respect to altitude and aircraft mass. The variations in aircraft mass, time, distance and altitude are therefore :

$$\Delta m = ff_{AC} \Delta t$$

$$\Delta h = 0$$

$$\Delta r = 0$$

$$\Delta t = \text{user input}$$

The flight parameters are computed using the following expressions :

$$V_{TAS} = Mn \times V_A$$

$$ROC = 0$$

$$\gamma = 0$$

$$C_L = \frac{mg_0}{\frac{1}{2} \rho V_{TAS}^2 S_W}$$

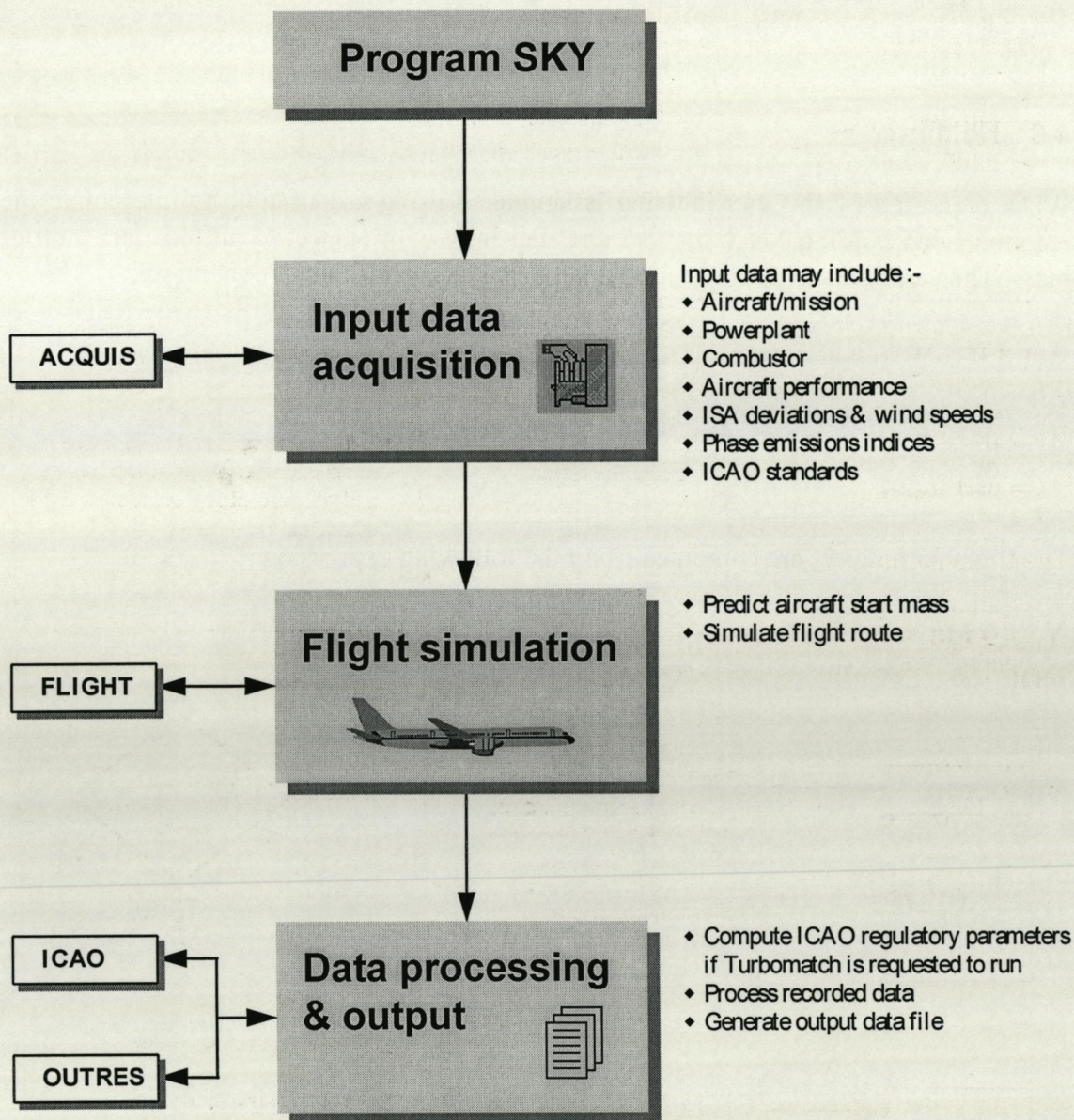
$$D = \frac{1}{2} \rho V_{TAS}^2 C_D S_W$$

Appendix D.3

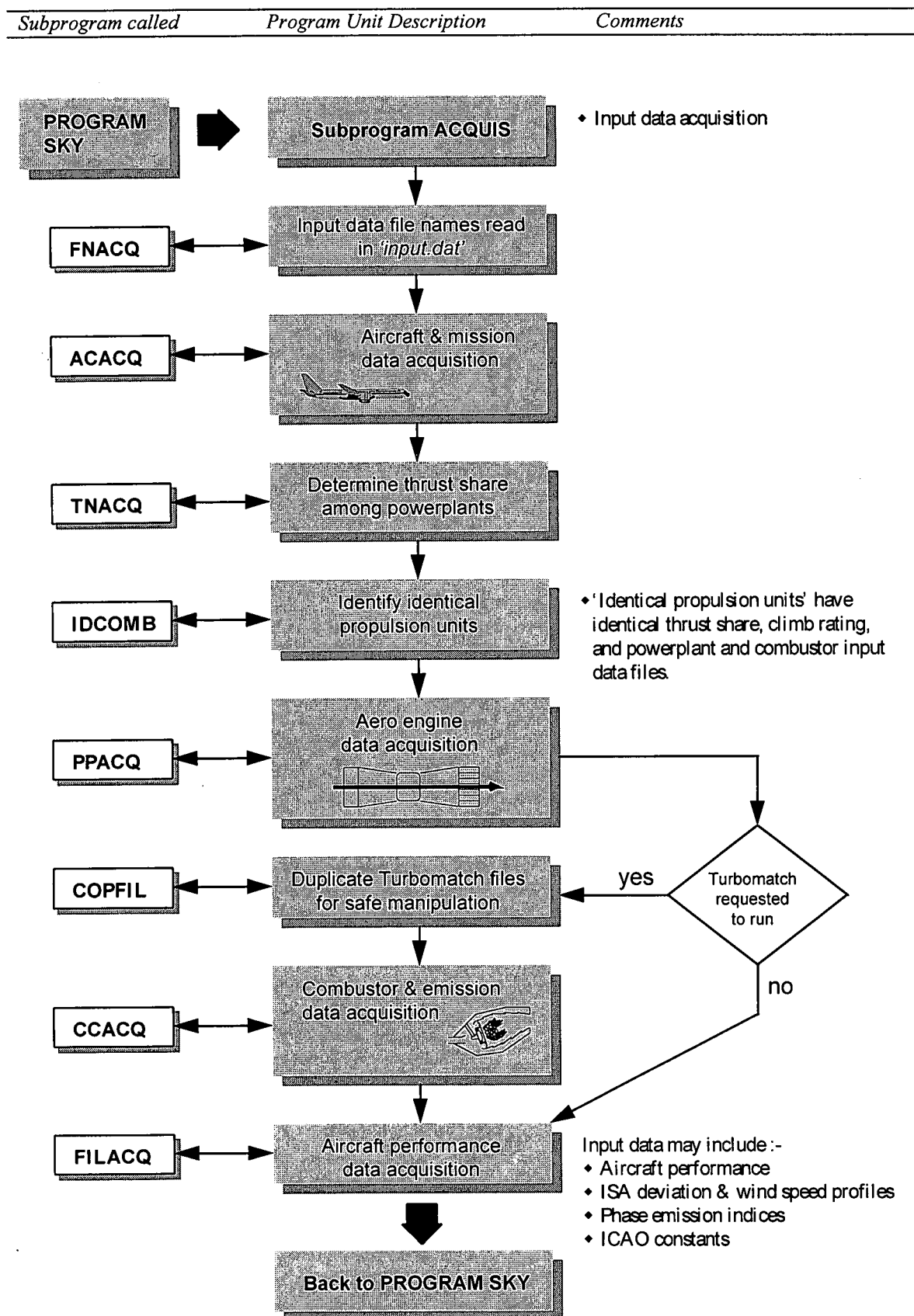
SKY Flight Route Module - Flow Charts

1. MAIN PROGRAM

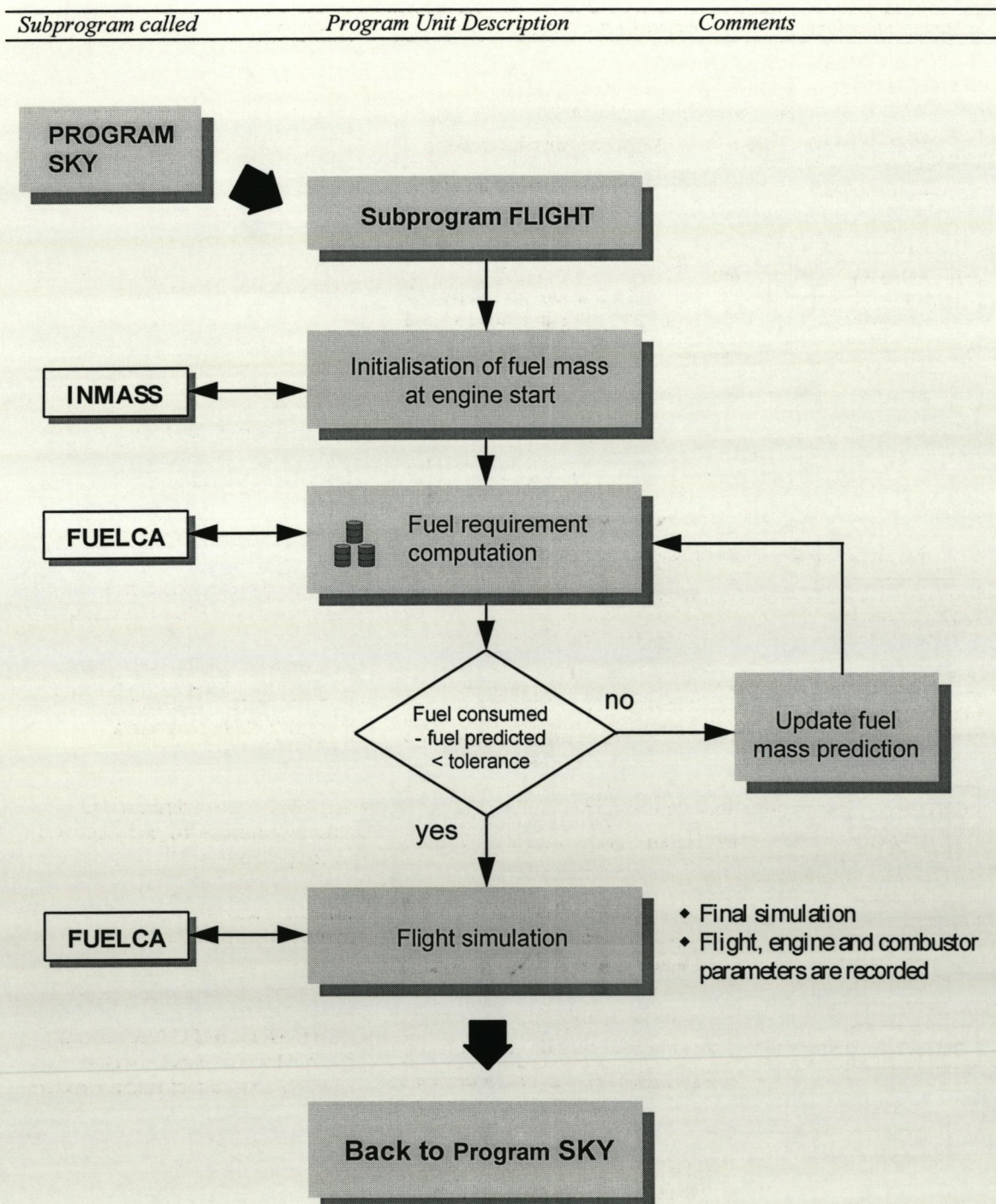
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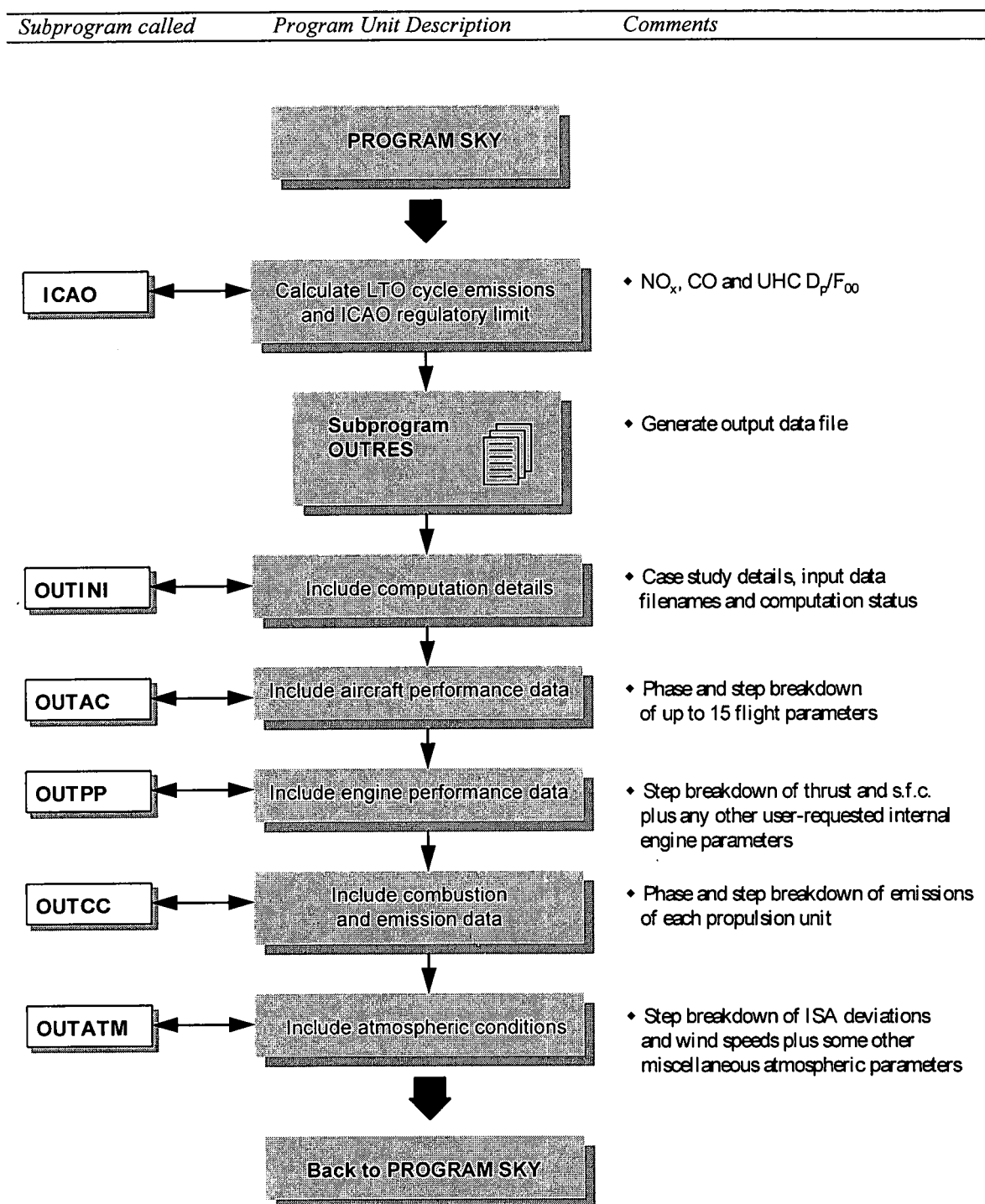
2. INPUT DATA ACQUISITION



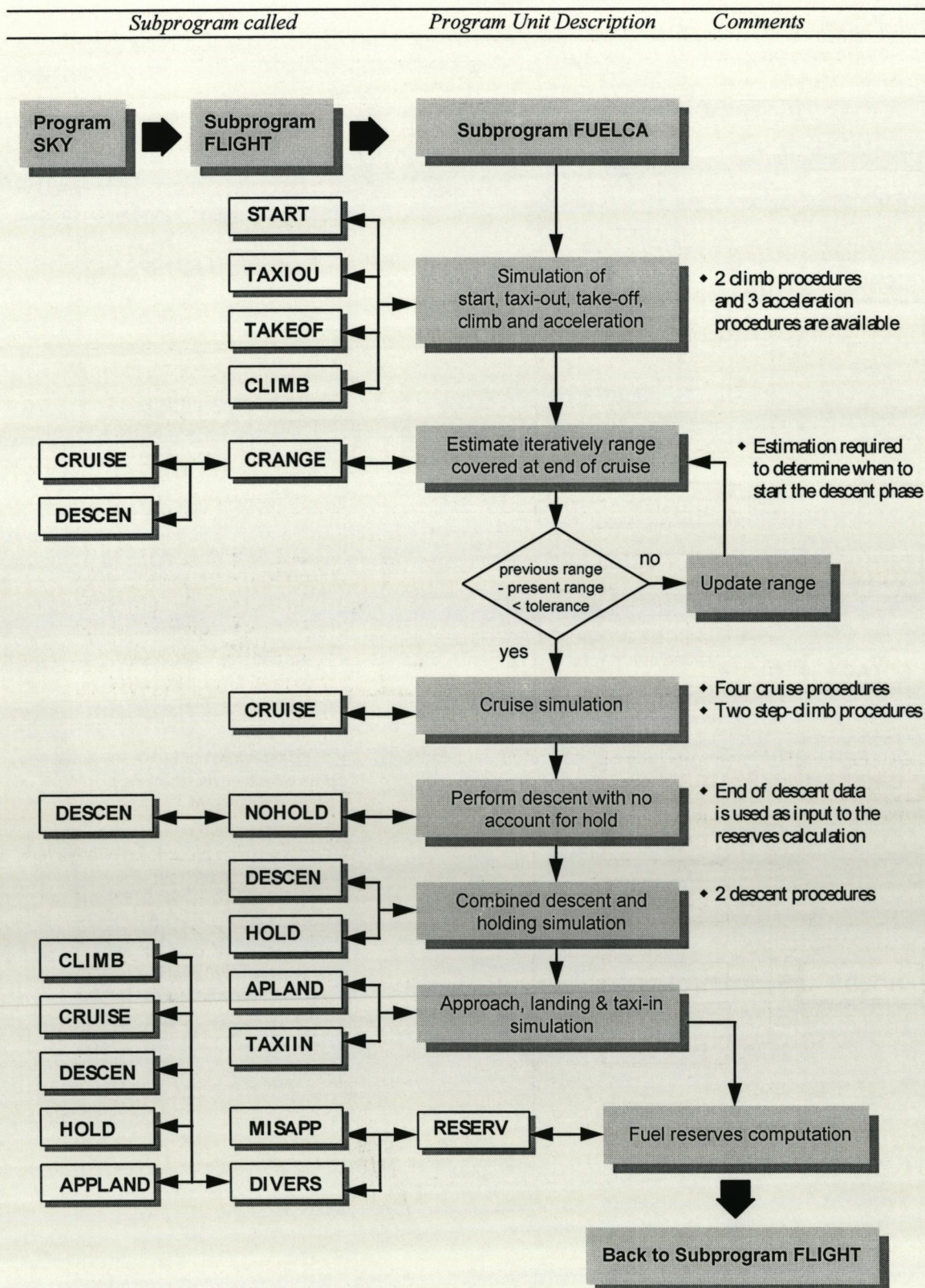
3. FLIGHT ROUTE SIMULATION



4. DATA PROCESSING AND OUTPUT



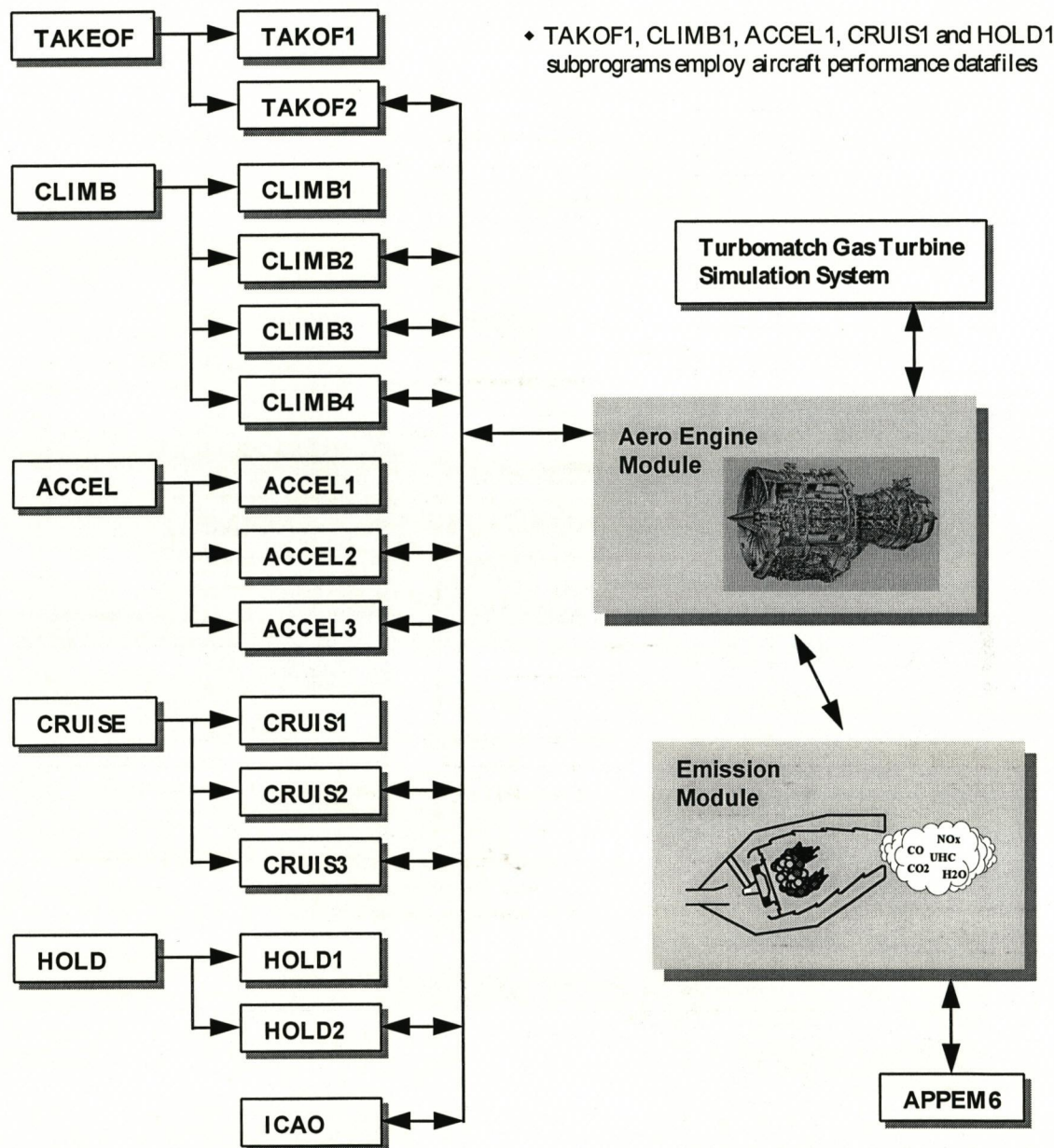
5. FUEL REQUIREMENT COMPUTATION



6. SUBPROGRAMS CALLING THE AERO ENGINE AND EMISSION MODULES

Subprograms calling the Aero Engine and Emission Modules

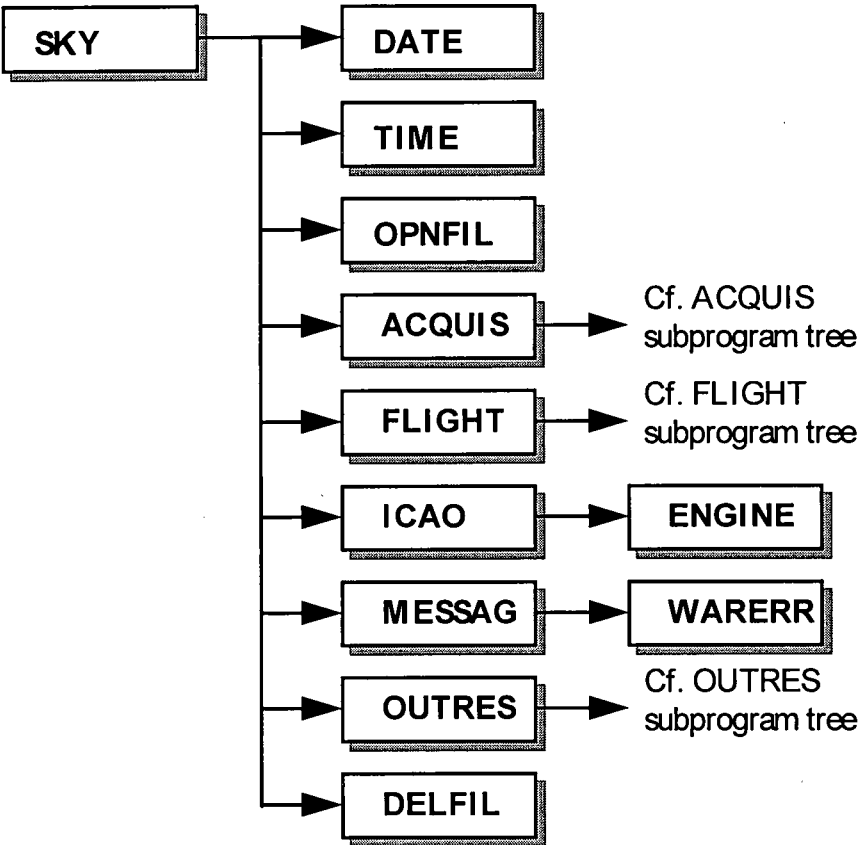
- Aero Engine and Emission Modules
- Comments



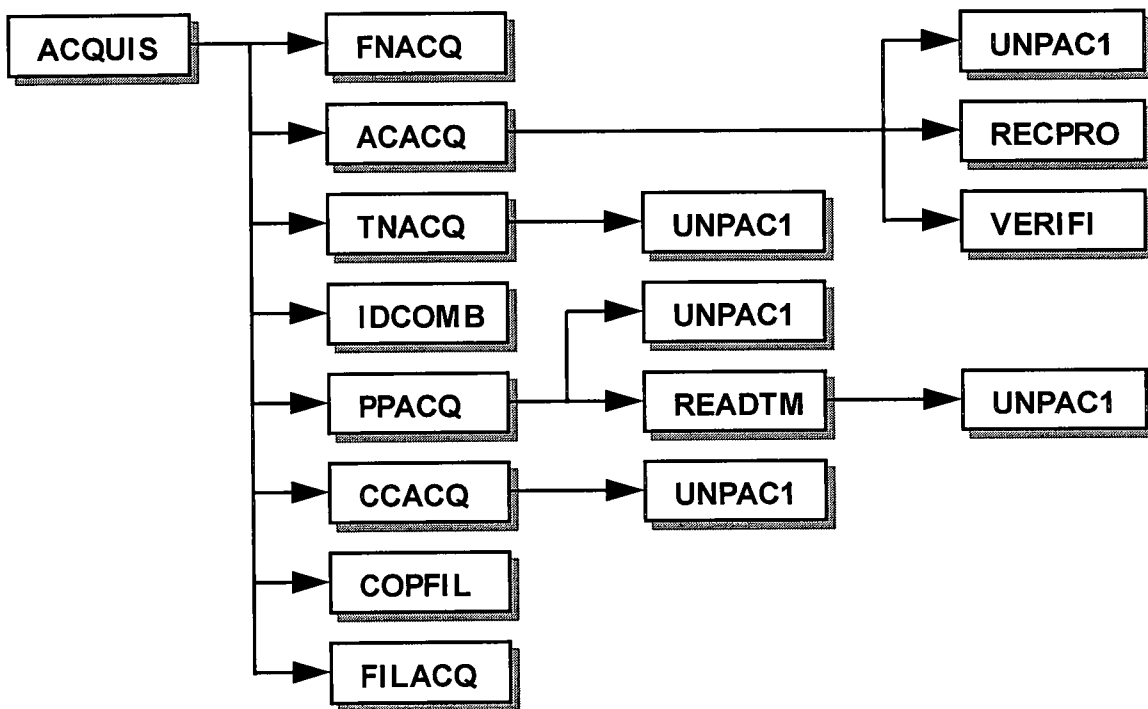
Appendix D.4

SKY Flight Route Module - Subroutine Trees

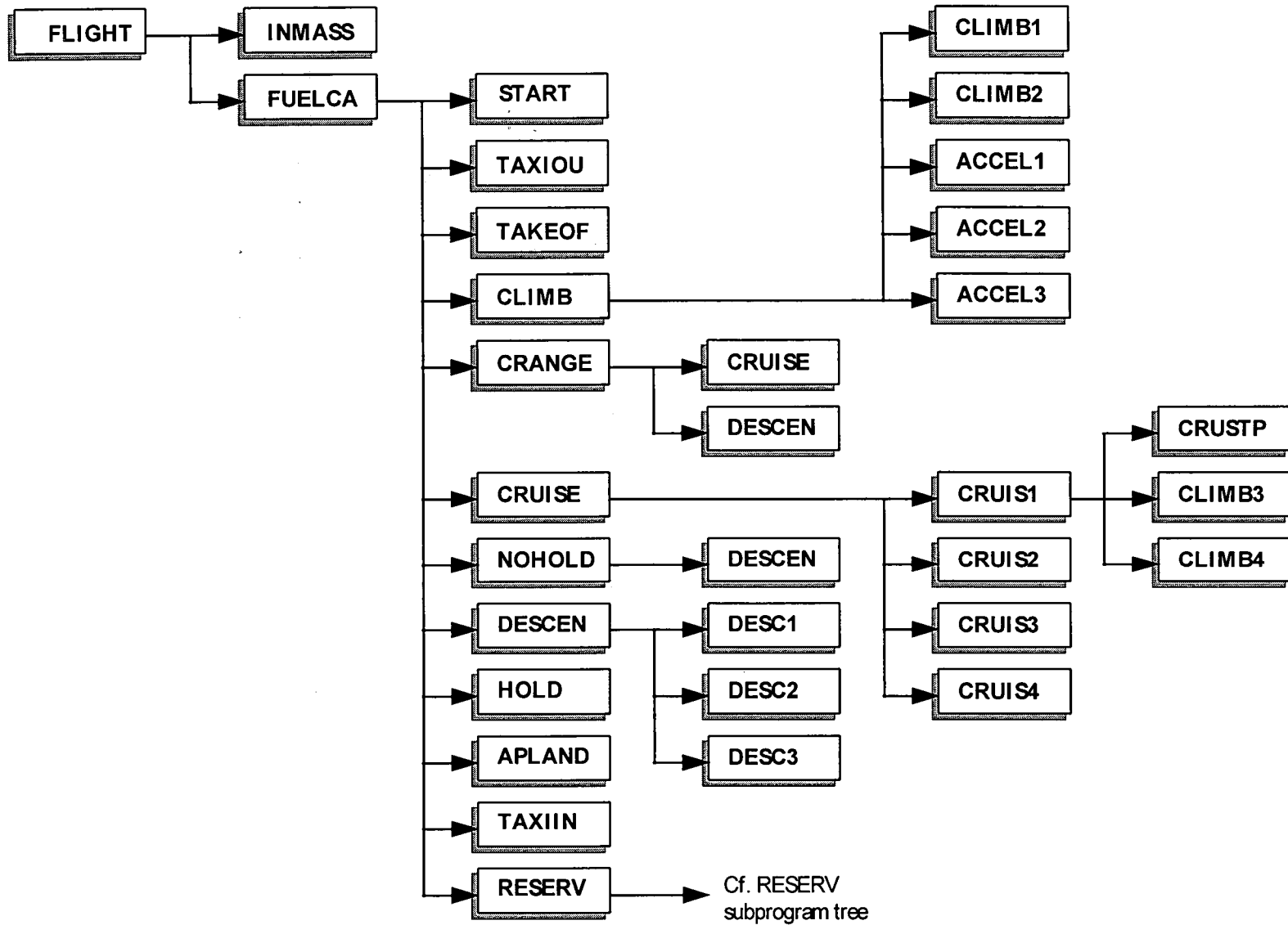
1. MAIN PROGRAM SKY



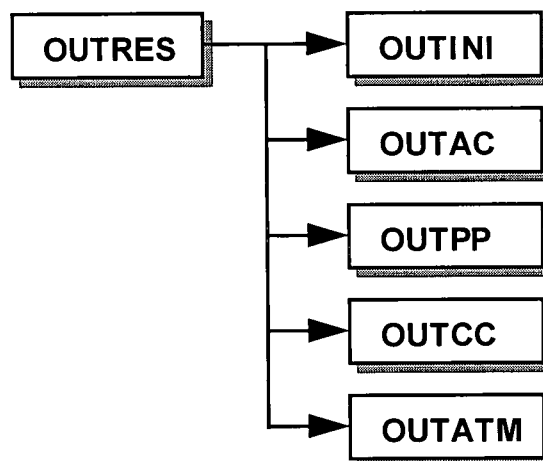
2. INPUT DATA ACQUISITION



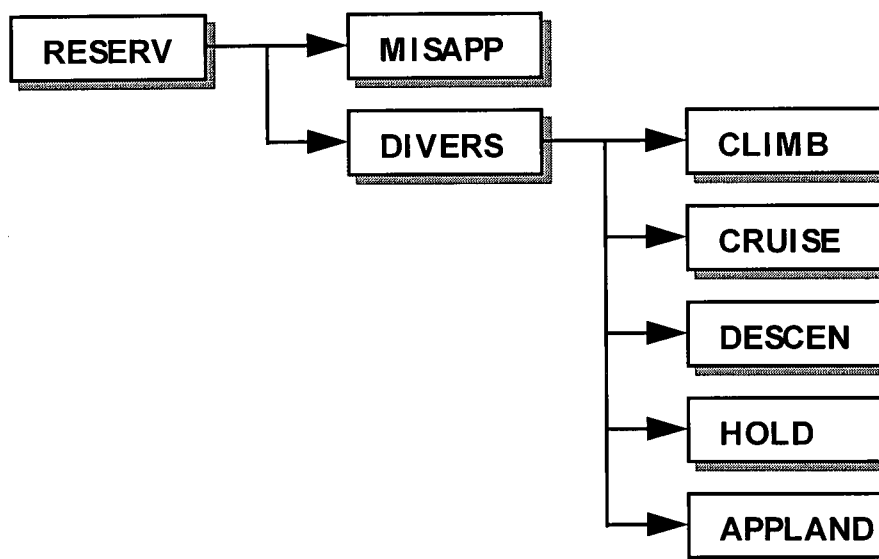
3. FLIGHT ROUTE SIMULATION



4. DATA PROCESSING AND OUTPUT

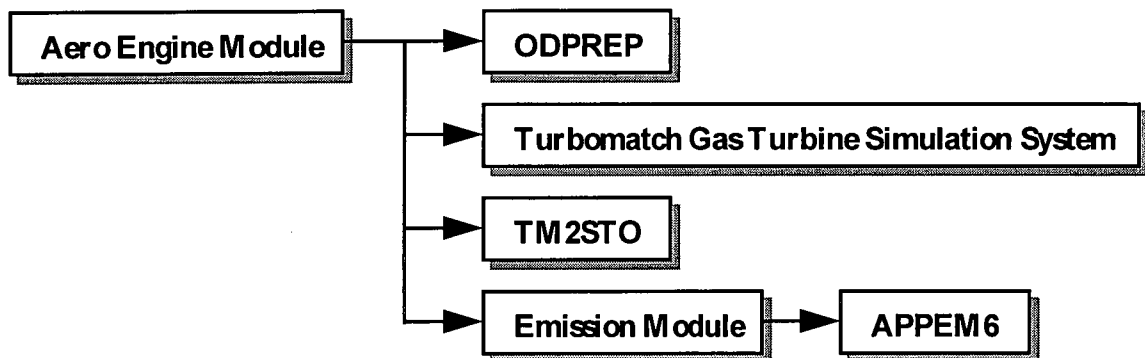


5. FUEL RESERVES EVALUATION



NB : Only subprograms simulating flight phases are shown

6. AERO ENGINE AND EMISSION MODULE



NB : The *Aero Engine module* is called by subroutines TAKEOF, CLIMB2, CLIMB3, CLIMB4, ACCEL2, ACCEL3, CRUIS2, CRUIS3, CRUIS4 and HOLD.

Appendix D.5

SKY Flight Route Module Simulation Procedures

This section presents the range of methods available to the user to simulate take-off, initial climb, acceleration, cruise, step climb (between two cruise altitudes) and holding.

Phase	Description of main features
Take-off 1	a) Turbomatch not run. b) Emission indices are phase allowances read from a data table.
Take-off 2	a) Turbomatch run to supply inlet combustor data to APPEM. b) Emission indices calculated by APPEM.
Climb 1	a) Turbomatch not run. b) Fuel burn, distance and time increments interpolated from file. c) Emission indices are phase allowances read from a data table.
Climb 2	a) Turbomatch run to supply inlet combustor data to APPEM. b) Fuel burn, distance and time increments interpolated from file. c) Emission indices calculated by APPEM.
Climb 3	a) Turbomatch run to supply inlet combustor data to APPEM, and thrust & fuel flow to the flight route module. b) Fuel burn, distance and time increments based on Turbomatch thrust & fuel flow. c) Fuel burn, distance and time increments interpolated from file. d) User-specified EAS.
Climb 4	a) Turbomatch run to supply inlet combustor data to APPEM, and thrust & fuel flow to the flight route module. b) Fuel burn, distance and time increments based on Turbomatch thrust & fuel flow. c) Fuel burn, distance and time increments interpolated from file. d) EAS interpolated from aircraft mass after take-off.
Acceleration 1	a) Turbomatch not run. b) Fuel burn, distance and time increments interpolated from file. c) Emission indices are phase allowances read from a data table.
Acceleration 2	a) Turbomatch run to supply inlet combustor data to APPEM (thrust is indicative) b) Fuel burn, distance and time increments interpolated from file. c) Emission indices calculated by APPEM.
Acceleration 3	a) Turbomatch run to supply inlet combustor data to APPEM, and thrust & fuel flow to the flight route module. b) Fuel burn, distance and time increments based on Turbomatch thrust & fuel flow. c) Emission indices calculated by APPEM.

Cruise 1 (step cruise)	a) Turbomatch not run. b) Fuel burn interpolated from file. c) Emission indices are phase allowances read from a data table.
Cruise 2 (step cruise)	a) Turbomatch run to supply inlet combustor data to APPEM. b) Fuel burn interpolated from file. c) Emission indices calculated by APPEM.
Cruise 3 (climb cruise)	a) Turbomatch run to supply inlet combustor data to APPEM, and thrust & fuel flow to the flight route module. b) Fuel burn, distance and time increments based on Turbomatch thrust & fuel flow. c) Emission indices calculated by APPEM.
Step climb 1	a) Turbomatch not run. b) Fuel burn, time & distance increments interpolated from file. c) Emission indices are phase allowances read from a data table.
Step climb 2	a) Turbomatch run to supply inlet combustor data to APPEM. b) Fuel burn, time & distance increments interpolated from file. c) Emission indices calculated by APPEM.
Step climb 3	a) Turbomatch run to supply inlet combustor data to APPEM, and thrust & fuel flow to the flight route module. b) Fuel burn, distance and time increments based on Turbomatch thrust & fuel flow. c) Emission indices calculated by APPEM. d) Climb at constant cruise Mach number.
Holding 1	a) Turbomatch not run. b) Fuel flow & recommended Mach number interpolated from file. c) Emission indices are phase allowances read from a data table.
Holding 2	a) Turbomatch run to supply inlet combustor data to APPEM. b) Fuel flow & recommended Mach number interpolated from file. c) Emission indices calculated by APPEM.

Appendix D.6 Calculation Methods for SKY Major Parameters

The following table presents a classification of the major SKY parameters which are categorised with respect to calculation procedure and flight phase. The 8 parameters considered include fuel burn (dm), distance (dr), time (dt), fuel flow (ff), air speed (true air speed Vt, equivalent air speed Ve or Mach number Mn), the engine handle (h ; it can be fuel flow, TET, etc.), net thrust requirement (T) and emission indices (ei). The phase numbering convention is explained in Appendix D.5. Appendix D.2 explains how the flight parameters are calculated (dm, dr, dt, ff, speed, h, T) while the evaluation of emission indices (ei) is described further in Appendix D.9.

Phase	Parameter Calculation Procedures						
	Analysis	Interp'tion	Allow'ce	TMC	TMD	APPEM	No Calc.
Start, taxi-out & taxi-in	dm		dt, ff, ei				Vt, T, dr
Take-off 1	ff, Vt	dm, dr, dt	ei				T
Take-off 2	ff, Vt, h	dm, dr, dt			T	ei	
Climb* 1	dt, ff, h, T	dm, dr	Ve, ei				
Climb* 2	dt, ff, h, T	dm, dr	Ve			ei	
Climb* 3	dm, dr, dt	h	Ve	T, ff		ei	
Climb* 4	dm, dr, dt	h, Ve		T, ff		ei	
Acceleration 1	ff	dm, dr, dt, Vefin	ei, Veini				T
Acceleration 2	ff, h	dm, dr, dt, Vefin	Veini		T	ei	
Acceleration 3	dm, dr, dt	h	Veini, Vefin	T, ff		ei	
Cruise 1	dt, T, ff	dm	dr, Mn, ei				
Cruise 2	dt, T, ff (=h)	dm	dr, Mn			ei	
Cruise 3	dm, dt		dr, Mn	T, ff, h		ei	
Step Climb 1	ff, Vt, T	dm, dr, dt	ei				
Step Climb 2	ff (=h), Vt, T	dm, dr, dt				ei	
Step Climb 3	dm, dr, dt	h	Mn	T, ff		ei	
Descent	ff, T	dm, dr, dt, Mn	ei				
Holding 1	dm, dr, dt, T	ff, Mn	ei				
Holding 2	dm, dr, dt, T	ff, Mn				ei	
App. & Landing	dm, Vt		dt, ff, ei				T, dr

* applicable to both initial and en-route climb
TMC = Turbomatch coupled (to fuel burn prediction) ; TMD = Turbomatch decoupled i.e. Turbomatch is run with ambient conditions and fuel flow fed by the flight route module so that emission indices can be computed by the emission module. In this case, the thrust estimated by Turbomatch is not required by the flight route module.
Vt = TAS ; Ve = EAS ; ini = initial ; fin = final

Table 1 : Categorisation of SKY Major Parameters

Appendix D.7

SKY Flight Route Module - Computation of Atmospheric Conditions

The ambient pressure, temperature and density in International Standard Atmosphere and in off-standard atmospheres can be determined as a function of pressure altitude and ISA deviation using the terminology and relationships presented in Table 1 & 2 (ESDU, 1986). Off-standard atmospheric conditions can be calculated provided that a profile of ISA deviations along the flight path is made available to SKY by means of a dedicated input data file. Wind speeds are supplied to SKY in a similar manner allowing the performance effects of headwinds and tailwinds to be accounted for. ISA deviations and wind speeds are then interpolated by SKY's *Flight Route Module* with respect to range and altitude.

Density	ρ	Temperature	t
Relative density	σ	Relative temperature	θ
Pressure	p	Pressure altitude	h
Relative pressure	δ	ISA deviation	Δt
Denotes sea level	0	Denotes ISA figure	std

Table 1 : Parameters Involved in the Computation of Atmospheric Conditions by SKY's *Flight Route Module*

	Range of pressure heights, h (m)		up to 11000 m (36089 ft)	11000 to 20000 m
Quantity	Format of numerical expressions	Constants in numerical expressions		
Temperature in International Standard Atmosphere, t_{std} (K)	A + Bh	A = B =	288.15 -6.5×10^{-3}	216.65 0
Pressure in International Standard and off-standard atmospheres, p_{std} (Pa)	(i) $(C + Dh)^E$ (ii) $F \exp(Gh)$	C = D = E = F = G =	8.9619638 $-0.20216125 \times 10^{-3}$ 5.2558797	128244.5 $-0.15768852 \times 10^{-3}$
Density in International Standard Atmosphere, ρ_{std} (kg.m^{-3})	(i) $(I + Jh)^L$ (ii) $M \exp(Nh)$	I = J = L = M = N =	1.048840 $-23.659414 \times 10^{-6}$ 4.2558797	2.0621400 $-0.15768852 \times 10^{-3}$
Density in off-standard atmospheres, ρ (kg.m^{-3})	$\frac{\rho_{std}}{1 + \frac{\Delta t}{t_{std}}}$			

Table 2 : Equations Used by SKY's *Flight Route Module* to Compute Atmospheric Conditions

Appendix D.8

SKY Flight Route Module - Computation of Drag

The drag coefficient C_D of subsonic transport aircraft can be described as the sum of the nominal drag (i.e. the drag at the nominal Reynolds number with no account for aeroelastic effects) and a correction for Reynolds number and aeroelastic effects. The nominal drag is a function of the aircraft aerodynamic configuration (i.e. the position of the under-carriage and high-lift devices), lift coefficient C_L and Mach number. The effect of Reynolds number and aeroelasticity are usually described by means of a correction to the nominal drag as a function of altitude, ISA deviation and aircraft gross weight. To some extent, the altitude and weight effects can be described through the parameter C_L .

Because, in the case of the Boeing 747-400, these altitude and weight-dependent effects are small in comparison to the total drag (no more than 1% at typical cruise conditions), they are chosen not to be included at this stage in the computer system. The user should therefore bear in mind that the current version of SKY's *flight route module* does not offer the capability to account for such effects.

For a given configuration, the aircraft nominal drag coefficient can be related to the lift coefficient and Mach number in the following manner :-

$$(1) \quad C_D(Mn) = C_{D_0}(Mn) + k(Mn)C_L + k'(Mn)C_L^2$$

Based on this relationship, the drag characteristic is supplied to SKY's *flight route module* in the form of a tabulation of C_{D_0} , k and k' for a range of Mach numbers. The tabulated data corresponds to the "en-route" aerodynamic configuration where the flaps and undercarriages are retracted, a configuration selected before the end of take-off up to the beginning of approach/landing to the destination airport. The low speed take-off and approach/landing phases where the flaps and undercarriages are extended can not use this configuration. However, as aircraft performance look-up tables are employed to determine the fuel burn, time and distance for these two phases, there is no need for SKY to be supplied with additional low speed drag polars.

Appendix D.9

SKY Emission Module - Modelling Description

1. INTRODUCTION

SKY's *Emission Module* (previously known as APPEM in former publications) is a FORTRAN computer program designed to evaluate the performance and emissions of jet engine combustors burning Kerosene fuel $C_{12}H_{24}$. The combustor can be defined by means of 34 parameters characterising combustor dimensions, aerodynamics, injection system, fuel properties and primary zone flow conditions. The emissions are calculated using semi-empirical correlations. The constants of the emissions and primary zone efficiency correlations can be modified. The output consists of CO, UHC, NO_x , CO_2 and H_2O emission indices as well as miscellaneous combustion parameters such as ideal primary zone flame temperature, pressure loss and efficiency.

As a subroutine of the SKY aircraft engine emissions simulation system, the *Emission Module* is interfaced with the *Aero Engine Module* TURBOMATCH - Cranfield gas turbine simulation system - and provides a complete report of mission emissions upon completion of the flight route simulation. Using data available in the *combustor input data file* and combustor inlet thermodynamical conditions from the *Aero Engine Module* (stagnation pressure and temperature, air and fuel flow rate), it calculates combustor performance parameters (pressure loss and efficiency) which are fed back to the *Aero Engine Module*. It will take several iterations before the combustor performance parameters evaluated by the *Emission Module* and those employed by the *Aero Engine Module* are sufficiently close. When this is realised, at the final iteration, the CO, UHC, NO_x , CO_2 and H_2O indices corresponding to the flight step under simulation are recorded and output in the emission section of SKY's output data file.

The sub-modules incorporated in the *Emission Module* represent the physical phenomena that underpin combustor performance and emission modelling. This report describes the physics embodied in the sub-modules as well as their status regarding validation. The flow charts and subroutine trees are situated in Appendices D.10 and D.11 provide an overview of the program structure. An example of input data file is available in Appendix D.12 while Appendix D.13 shows a typical SKY output data file incorporating the flight emission section.

2. EMISSIONS MODELLING AND VALIDATION

2.1 Approach

The concentration levels of NO_x , CO and UHC pollutants can be related to the temperature, time and concentration histories of the gases within the combustor. These

histories vary from one combustor to another and for any given combustor, with changes in operating conditions. In this respect, the primary aim of this approach has been to develop a simple modular model, which has limited accuracy, but wide fields of utilisation for various engine cycles. The approach chosen is one of adopting semi-empirical correlations such as those established by Lefebvre (1987) for NO_x , CO and UHC as well as some of the several NO_x correlations employed by the Aeronox research project (Aeronox, 1995).

On the one hand, to be fully successful, a model must accommodate the complex flow behaviour and include a kinetic scheme of the important chemical reactions occurring within the combustor. The kinetics of some relevant combustion processes are, unfortunately, not well understood at the present time, particularly for the production of carbon, carbon monoxide, and the hydrocarbon species that are intermediaries in the fuel oxidation process. The adoption of a modelling technique using such correlations is therefore amply justified.

On the other hand, there is the necessity to reach a compromise between accuracy of representation, ease of use, and capability for calibration and further improvements. As the *Emission Module* is designed to run as a subroutine of an already large program, strong emphasis has been put on computation rapidity. Modularity has been also paramount since the combustor/emissions module must offer the possibility to change the emissions correlations easily.

2.2 Lefebvre's NO_x , CO and UHC Semi-Empirical Correlations

2.2.1 Introduction

Lefebvre's equations are selected because they embody the main variables of combustor size, pressure loss, flow proportions, and inlet operating conditions. The effect of variations in overall combustor fuel-air ratio is also included via its influence on primary zone temperature. As these correlations have not been validated for the high pressure conditions of high bypass ratio turbofan combustors, some of their constants had to be modified to match today's turbofan emissions (see Section 2.2.5).

It is assumed that all NO_x , UHC and CO emissions are produced in the primary zone and that the reactions involved are inhibited by the low temperature conditions of both the secondary and dilution zones. For nitric oxide, carbon monoxide and unburned hydrocarbon, Lefebvre (1984) assumes that their exhaust concentration is proportional to the product of three terms which are selected to represent the following :-

- mean residence time in the combustion zone
- chemical reaction rates
- mixing rates

Expressions for these three parameters may be derived in simplified form :-

$$(1) \quad \text{Residence time} = \frac{L}{U} = \frac{L\rho A}{\dot{m}_A} = \frac{PV}{\dot{m}_A RT} \propto \frac{PV}{\dot{m}_A T}$$

(2) Assuming that reaction rates are a function of pressure and temperature only :-
Reaction rate $\propto P^m \exp(zT)$

(3) Assuming that mixing rates are a function of liner pressure drop :-

$$\text{Mixing rate} \propto \left(\frac{\Delta P}{P} \right)^x$$

Based on this approach, Lefebvre derived the correlations for NO_x, CO and UHC (see following sections) with factors and constants obtained from extensive experimental work. As will be detailed in the relevant paragraphs, excellent correlation of experimental data on NO_x and CO by Lefebvre expressions has been achieved on a large family of engines (see Table 1) throughout the operating conditions outlined on Figures 1, 2 and 3, and with up to 13 different fuels (JP-4 and JP-8 families).

Engine	OPR	BPR	W kg/s	Thrust kN	SFC mg/N/s	Combustor type	Remarks	Source of reference
J79-17A	13.5*	0		79(to) 53(mil) 12(cr)	56 (to+ab) 24(mil) 27(cr)	cannular, 10 cans, dual igniters in cans 4 & 5	GE turbojet	Jane's 68/69
J79-17C	13.5*	0		79(to) 53(mil) 12(cr)	56 (to+ab) 24(mil) 27(cr)	cannular, 10 cans	GE turbojet Smokeless	Jane's 68/69
F100** or PW- JTF92	25			67(to)		annular, large diam. duplex fuel nozzles	Pratt&Whitney	Jane's 78/79
F101	11		159	76(cold) 134(full)		annular, airblast	GE turbofan	Jane's 78/79
TF33	13- 14.3	≈1.5	≈230	93.4(to) TF33- PW- 100A	16(to)	tubo-annular, 8 cans, each with 6 fuel nozzles	Pratt&Withney turbofan derived from J57/JT3C turbojet	Jane's 78/79 Jane's 67/68
TF39	26	8	680	183(to)		Annular	GE turbofan	Jane's 73/74
TF41	20	0.77	117 67(hp)	67(to)	18(to)	tubo-annular, 10 tubes, duple spray atomising burner	Rolls-Royce /Allison turbofan	Jane's 78/79 Jane's 68/69
* J79-GE-10 OPR (similar to J79-GE-17) ; ** information classified								
OPR = overall pressure ratio ; BPR = bypass ratio ; W = engine inlet air flow SFC = specific fuel consumption ; t-o = take-off ; mil = military rating ; cr = cruise ; cold = cold rating full = full augmentation								

Table 1 : Engines Used to Validate Lefebvre's NO_x and CO Correlations

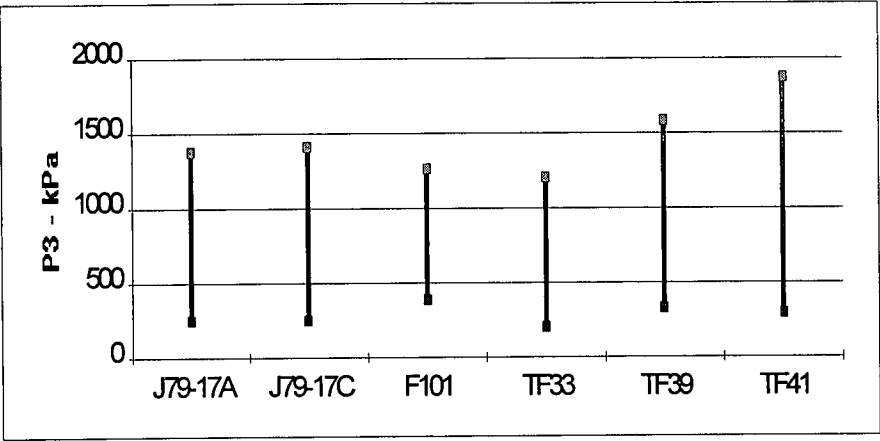
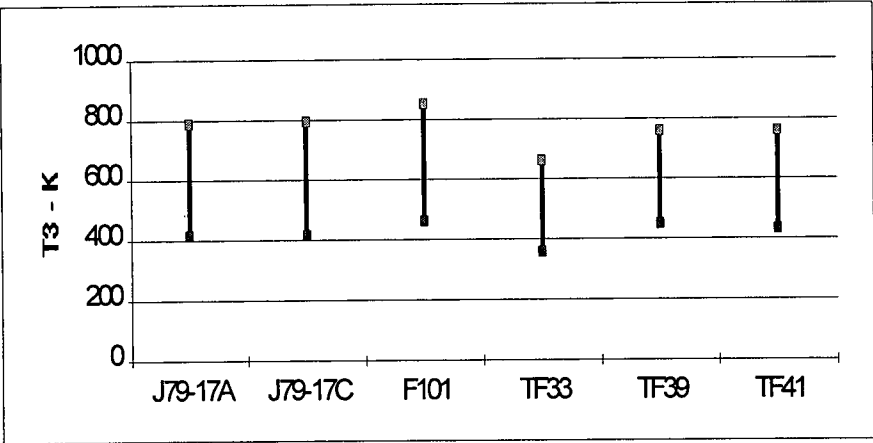
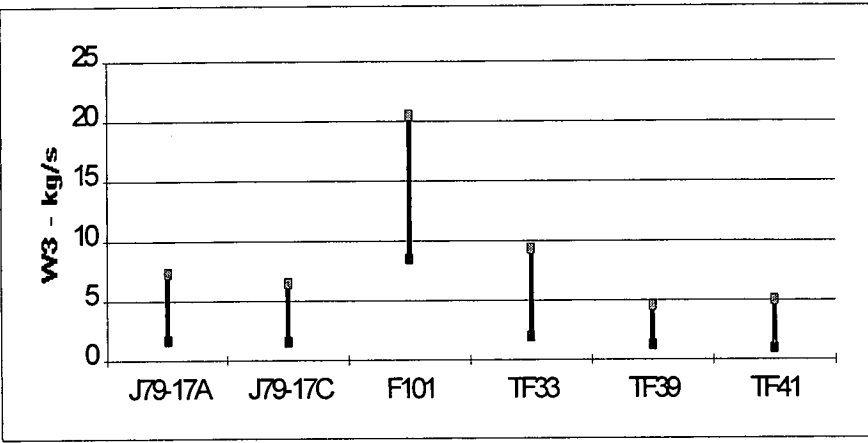


Figure 1, 2 and 3 : Variations of Operating Conditions for Engines Used in Lefebvre's Correlation Validation

2.2.2 Oxides of Nitrogen

According to the physical description provided in the introductory section :-

$$(4) \quad \text{NO}_x = f(\text{residence time}), (\text{reaction rate}), (\text{mixing rate})$$

$$(5) \quad \text{NO}_x = A \left(\frac{P V_c}{\dot{m}_A T} \right) \left(\frac{\Delta P}{P} \right)^x P^m \exp(zT)$$

$$= \frac{A V_c \left(\frac{\Delta P}{P} \right)^x P^y \exp(zT)}{\dot{m}_A T}$$

Where $y=1+m$ and A, x, m, z, y are constants.

Lefebvre's semi-empirical model for the prediction of NO_x emissions, based on considerations of mixing rates, chemical reaction rates, and combustor residence time, leads to the following expression :-

$$(6) \quad \text{NO}_x = \frac{9 \times 10^{-8} P_3^{1.25} V_c \exp(0.01 T_{st})}{\dot{m}_A T_{pz}} \text{ g / kg}$$

For NO_x , drop size is unimportant since, at the high pressure conditions where NO_x emissions are most prominent, the fraction of the total combustion volume employed in fuel evaporation is so small that wide variations in fuel drop size have a negligible effect on NO_x emissions.

T_{st} is the stoichiometric flame temperature corresponding to the inlet temperature, T_3 . The equation suggests that, in the combustion of heterogeneous fuel-air mixtures, it is the stoichiometric flame temperature T_{st} that determines the formation of NO_x . However, for the residence time in the combustion zone, which is also significant to NO_x formation, the appropriate temperature term is the bulk value T_{pz} , as indicated in the denominator.

This equation is suitable for conventional spray combustors only. For lean premix/prevaporize combustor in which the maximum attainable temperature is T_{pz} , it may be used, provided that T_{pz} is substituted for T_{st} . It should also be noted that predictions of NO_x based on this equation tend to be too high when the overall air/fuel ratio exceeds a value of around 100 (kerosene, $\phi < 0.2$). This is because with diminishing fuel/air ratio the flame shrinks back toward the fuel nozzle and no longer occupies the entire combustion volume. However, this is not considered a serious drawback since, in practice, interest is normally focused on conditions of high fuel/air ratio where NO_x formation rates attain their highest values.

Validation of these correlation on seven engines (J79-17A, J79-17C, F100, F101, TF33, TF39, and TF41) has been performed and yields the results shown on Table 2.

It is found that NO_x emissions are very dependent on combustor operating conditions, and also on the size of the combustion zone which governs the time available for NO_x formation. The key factor controlling NO_x is the stoichiometric flame temperature which, in turn, is almost solely dependent on combustor inlet temperature. As far as fuel type is concerned, physical properties are of little consequence, except at low power conditions where NO_x emissions are always quite small due to the corresponding low values of T_{st} . Fuel chemistry also has little influence on NO_x because it affects only slightly the values of bulk gas temperature (T_{st}).

Engine/Combustor	Approximated mean and maximum discrepancy (%) among the 13 tested fuels			
	<i>EI < 10 g/kg</i>		<i>EI > 10 g/kg</i>	
	<i>Mean</i>	<i>Max</i>	<i>Mean</i>	<i>Max</i>
J79-17A	30	100	5	25
J79-17C	25	100	5	25
F100	15	25	15	30
F101	15	40	10	25
TF33	15	30	10	15
TF39	15	-	5	-
TF41	20	50	10	25
<i>Average</i>	<i>20%</i>	<i>100%</i>	<i>10%</i>	<i>30%</i>

Table 2 : Comparison of Measured and Predicted NO_x Emission Indices for 7 Tested Combustors (Derived from Graphs Produced by Lefebvre, 1984)

2.2.3 Carbon Monoxide

According to the physical description provided in the introductory section :-

$$(7) \quad \text{CO} = f((\text{residence time})^{-1}, (\text{reaction rate}), (\text{mixing rate}))$$

$$(8) \quad \text{CO} = C \left(\frac{\dot{m}_A T}{P V_C} \right) \left(\frac{\Delta P}{P} \right)^a P^n \exp(-cT)$$

$$= C V_C^{-1} \dot{m}_A T \left(\frac{\Delta P}{P} \right)^a P^b \exp(-cT)$$

Lefebvre's semi-empirical model for the prediction of CO emissions leads to the following expression :-

$$(9) \quad \text{CO} = \frac{86 \dot{m}_A T_{pz} \exp(-0.00345 T_{pz})}{(V_C - V_E) \left(\frac{\Delta P_L}{P_3} \right)^{0.5} P_3^{1.5}} \text{ g / kg}$$

At low pressure operation where CO emissions attain their highest concentrations, a significant proportion of the primary zone volume is needed to evaporate the fuel. Under these conditions, any factor that influences fuel evaporation rates, such as evaporation constant or mean drop size, will have a direct effect on the volume available for chemical reaction and, therefore, on the emissions of CO (and UHC). Thus, for the CO correlation, the effects of fuel type cannot be ignored.

The formation of CO in the primary zone takes appreciably longer than the time required to produce NO_x . In consequence, the relevant temperature is not the local peak value adjacent to the evaporating fuel drops, but the average value throughout the primary zone, namely T_{pz} . Atomisation quality affects CO emissions through its influence on the rate of evaporation of the fuel spray. As CO emissions are most important at low pressure conditions, where evaporation rates are relatively low, it is necessary to reduce the combustion volume, V_C , by the volume occupied in fuel evaporation, V_E . This is evaluated as :-

$$(10) \quad V_E = 0.55 \times 10^{-6} \frac{f_{pz} \dot{m}_A D_0^2}{\rho_{pz} \lambda_{eff}}$$

It is of interest to note the inclusion of a pressure loss term in this correlation. This suggests that the higher turbulence created by an increase in liner pressure drop promotes better mixing in the combustion zone and helps to eliminate the rich and weak pockets of fuel-air mixture, both of which are conducive to high rates of CO formation.

Validation of these correlation on five engines (J79-17A, J79-17C, F100, F101, and TF41) has been performed and yields the results shown on Table 3. It is observed that combustor size and operating conditions play a prominent role in determining the level of CO emissions. Special importance is attached to inlet temperature and primary zone fuel/air ratio, due to their combined effect in resolving the primary zone temperature. As in the case of NO_x emissions, the influence of fuel chemistry is small and is manifested through slight variations in T_{pz} with changes in lower calorific value.

Engine/Combustor	Approximated mean and maximum discrepancy (%) among the 13 tested fuels			
	<i>EI < 10 g/kg</i>		<i>EI > 10 g/kg</i>	
	<i>Mean</i>	<i>Max</i>	<i>Mean</i>	<i>Max</i>
J79-17A	100	300	5	15
J79-17C	50	100	5	15
F100	50	200	<5	10
F101	20	100	<5	15
TF41	40	90	<5	15
<i>Average</i>	<i>50%</i>	<i>300%</i>	<i>5%</i>	<i>15%</i>

**Table 3 : Comparison of Measured and Predicted CO Emission Indices
for 5 Tested Combustors (Derived from Graphs Produced by Lefebvre, 1984)**

2.2.4 Unburned Hydrocarbons

The prediction for UHC is achieved using the following expression (Lefebvre, 1987). The physical principles and explanations described earlier for CO emissions also apply to UHC.

$$(11) \quad \text{UHC} = \frac{86 \dot{m}_A T_{pz} \exp(-0.00345 T_{pz})}{(V_C - V_E) \left(\frac{\Delta P_L}{P_3} \right) P_3^{2.5}} \text{ g / kg}$$

$$(12) \quad \text{UHC} = \frac{\text{CO}}{\left(\frac{\Delta P_L}{P_3} \right)^{0.5} P_3} \text{ g / kg}$$

2.2.5 Adjustment of Lefebvre's Emissions Correlations

The emissions indices obtained from these correlations must be interpreted as levels that would be measured from a combustor of a similar design and technology level than that of the engines tested by Lefebvre. If we take two combustor designs having identical volumes, inlet conditions and primary zone stoichiometry. One of them has improved mixing prior to combustion through better fuel atomisation and placement, and higher pressure drops across the liner. As a result of its more homogeneous combustion, this combustor would yield lower or higher NO_x levels than the other combustor, depending on the average fuel/air ratio. The effect of the atomisation process on NO_x emissions cannot be reflected by Lefebvre's correlation. This shows that it is essential to use correlations tailored to the combustor type as well as to the injection system. It can be achieved by a different correlation or by an adequate modification of some of the

coefficients of Lefebvre's model. The modular structure of the *Emission Module* allows for such implementations.

At the operating conditions of the high bypass ratio turbofans powering the B747-400, and using combustor data, fuel properties, and a fuel atomisation model typical for such engines, these correlations yield emissions indices larger than the levels compiled by the ICAO for similar powerplants at take-off and climb-out conditions (Le Dilosquer, 1995a and 1995b). This could be due to the fact that the correlations were developed with combustors incorporating fuel atomisers less efficient than those employed by nowadays engines. Table 4 shows the typical levels that should be expected from such powerplants (data derived from ICAO Emissions Databank, 1993). Levels of UHC and CO are not provided at climb out since it is not possible to derive any typical change from take-off to climb-out due to the different injection systems employed.

Engine/Phase	NO _x EI	CO EI	UHC EI
Take off	30	0.5	0.1
Climb out	20	No consistent trend	

Table 4 : Typical Emissions Indices Measured at Take-off and Climb-out for Engines Powering the B747-400 (ICAO Emissions Databank, 1993)

As it is believed that the physical interpretations that led to building these correlations are valid, some of the correlation coefficients should be changed so that realistic levels can be achieved. It is reasonable to assume that reaction rates and mixing rates within the combustor will follow the same trends with pressure, temperature, and liner pressure loss. The only coefficients left for calibration are the correlation multipliers. It is proposed to modify them in order to obtain indices in the region of those presented in Table 4. The new coefficients are shown on Table 5. In SKY's *Emission Module*, Lefebvre's correlations use the new constants to compute more representative indices for high bypass ratio turbofans.

Correlated species	NO _x	CO	UHC
Original multiplier	$9 \cdot 10^{-8}$	86	11,764
T/O index	155	2.32	0.65
C/O index	121	3.88	1.25
New multiplier	$2 \cdot 10^{-8}$	19	1810
T/O index	34.5	0.51	0.10
C/O index	26.9	0.86	0.19

Table 5 : Modification of the "Multiplier" Coefficients in Lefebvre's Correlations (Le Dilosquer, 1995).

The NO_x correlation used with the new multiplier now provides indices sufficiently close to the levels attained at take-off and climb-out by the cycles to be evaluated by the next chapter. The new CO and UHC correlations also provide indices close to actual levels. However, some of the B747-400 powerplants show dissimilar trends from take-

off to climb-out conditions. As previously explained, this is due to the injection systems adopted which differ from one engine to another. Nevertheless, for the purpose of a general comparison of cycles, and with the emphasis put on NO_x, the model of airblast fuel injection incorporated in the *Emission Module* is considered to be sufficient to provide orders of magnitude for low power emissions.

2.3 Evaluation of Water Vapour and Carbon Dioxide Emission Indices

Water vapour and carbon dioxide emission indices can be derived from the reaction scheme describing the combustion of kerosene and air. As shown in Table 6, indices are dependent solely on overall combustion efficiency for lean mixtures, and on efficiency, equivalence ratio, and even fuel carbon number (carbon dioxide at $1.2 < \phi$) for rich mixtures. The effect of humidity is not included in the water vapour index.

Eq. Ratio	Emission Index formula in kg/kg of fuel (Partial calculation with fuel C ₁₂ H ₂₄ i.e. x=12 and y=24)	
	CO ₂	H ₂ O
$\phi \leq 1$	$\eta x \frac{M_1}{M_f} = 3.14 \eta$	$\eta \frac{y}{2} \frac{M_2}{M_f} = 1.28 \eta$
$1 < \phi \leq 1.2$	$\frac{(2\eta - \phi)x}{\phi} \frac{M_1}{M_f} = 3.14 \frac{(2\eta - \phi)}{\phi}$	$\frac{\eta \frac{y}{2} M_2}{\phi M_f} = 1.28 \frac{\eta}{\phi}$
$1.2 < \phi$	$\frac{\eta - (\phi - \eta)\left(\frac{x-1}{x}\right)}{\phi} x \frac{M_1}{M_f} = 3.14 \frac{\eta - (\phi - \eta)\left(\frac{x-1}{x}\right)}{\phi}$	$\frac{\eta \frac{y}{2} M_2}{\phi M_f} = 1.28 \frac{\eta}{\phi}$
Molecular weights : CO ₂ → M ₁ (44.0095 g/mol) H ₂ O → M ₂ (18.016 g/mol) ; C ₁₂ H ₂₄ fuel → M _f (168.323 g/mol)		

Table 6 : Emission Index Formula of Water and Carbon Dioxide for Various Equivalence Ratios

3. COMBUSTOR PERFORMANCE MODELLING

3.1 Pressure Loss

Overall pressure loss is calculated by means of the well established following expression. The pressure loss factor is an aerodynamic characteristic specific to the combustor and independent of operating conditions (see Table 7).

(13)

$$\frac{\Delta P_{3-4}}{P_3} = \frac{\Delta P_{3-4}}{q_{\text{ref}}} \frac{R}{2} \left(\frac{\dot{m}_3 \sqrt{T_3}}{A_{\text{ref}} P_3} \right)^2$$

It is also necessary to determine the liner pressure loss in order to evaluate CO and UHC emissions from Lefebvre's correlations. To achieve this, overall pressure loss factor is replaced by the liner pressure loss factor which can be considered as approximately half the overall parameter.

Combustor configuration	Overall pressure loss factor
Tubular	37.5
Tubo-annular	25
Annular	18

Table 7 : Typical Values of Overall Pressure Loss Factor

3.2 Combustion Efficiency

Overall combustion efficiency is required by the *Aero Engine Module* to determine the combustor outlet temperature. In general, combustion efficiency tends to be limited by reaction kinetics and/or evaporation rates at low pressure, and by mixing rates at high pressures when liner pressure losses are inadequate. Appropriate heat release criteria for the two extreme levels of pressure are presented in Table 8.

Pressure level	Performance parameter	Derivation	Heat-release criterion
Low (below 100kPa)	$\frac{P_3^2 A_{\text{ref}} D_{\text{ref}} \exp\left(\frac{T}{100}\right)}{\dot{m}_A}$	Burning-velocity and stirred-reactor models	W/(m ³ .Pa ²)
High (above 300 kPa)	$\left(\frac{P_3 A_{\text{ref}}}{\dot{m}_A T_3^{0.5}} \right) \left(\frac{\Delta P_L}{P_3} \right)^{0.5}$	Mixing-rate parameter	W/(m ² .Pa)

Table 8 : Heat Release Criteria for Gas Turbine Combustors (Lefebvre, 1983)

At low pressure conditions combustion efficiency can be expressed as the product of reaction rate efficiency η_{c0} and evaporation rate efficiency η_{ce} (Lefebvre, 1987). These two efficiency correlations are embodied in the *Emission Module*. At high pressure, the computed efficiency will be very close to 100% as the reaction and evaporation mechanisms are not limiting. In this case, adequate mixing will be assumed (including liner pressure losses kept at an appropriate level) resulting in 100% combustion efficiency.

$$(14) \quad \eta_{c_0} = 1 - \exp \left[\frac{-0.022 P_3^{1.3} V_c \exp \left(\frac{T_c}{400} \right)}{f_c \dot{m}_A} \right]$$

$$(15) \quad \eta_{c_e} = 1 - \exp \left[\frac{-36 \times 10^6 P_3 V_c \lambda_{eff}}{T_c D_0^2 f_c \dot{m}_A} \right]$$

Variables used in these correlations are in SI units apart from P_3 expressed in kPa, D_0 (sauter mean diameter) in μm and λ_{eff} (effective evaporation constant) in $\text{mm}^2 \cdot \text{s}^{-1}$.

4. INTERMEDIATE PHYSICAL MODELLING

4.1 Ideal flame Temperature

Lefebvre's semi-empirical emissions correlations require the evaluation of ideal flame temperature (Lefebvre, 1987 & 1995). Data from ideal temperature rise charts are employed to this effect (Rolls-Royce, 1964). The data has been read, tabulated and incorporated in the module to interpolate ideal flame temperature against air inlet temperature, fuel to air ratio, and combustion pressure. For the computation to be valid, the reactants must satisfy the following requirements :-

Air composition	N ₂ 0.75525 by weight
	O ₂ 0.23143 by weight
	A 0.01286 by weight
	CO ₂ 0.00046 by weight
Fuel composition	(CH ₂) _n
Fuel carbon/hydrogen ratio	5.958 by weight
Fuel calorific value	10308 Chu/lb = 43.17 MJ/kg
Fuel temperature	288 K
Fuel to air ratio	0 to 0.080 by weight
Air inlet temperature	250 to 1400 K
Combustion pressure	101 to 6205 kPa

Tables 9 and 10 present the magnitude of errors produced as a result of uncertainties in the plotting or reading of the charts, and the approximation of the charts by the computer program. Depending on operating conditions, the maximum errors on the ideal temperature rise range from 0.3% to 0.7%. In the extrapolated region defined by Figure 4, the errors can be higher.

Fuel/Air Ratio Range	Air Inlet Temp. Range (K)	Cumulated Maximum Error (% of Temp. Rise)		
		Chart	Program	Total
0 - 0.080	250 - 850	0.1	0.1	0.2
0 - 0.080	900 - 1400	0.2	0.1	0.3

Table 9 : Maximum Errors on Ideal Temperature Rise Prior to Pressure Correction

Fuel/Air Ratio	Pressure (kPa)	Air Inlet Temp at which max error will occur (K)	Maximum error (K)			Max error (% of overall temp. rise)
			Chart	Program	Total	
.0676	6205	450	4.4	2	6.4	0.35
.0676	3447	450	4.0	2	6.0	0.30
.0676	1724	450	0.9	2	2.9	0.10

Table 10 : Maximum Error on Pressure Addendum

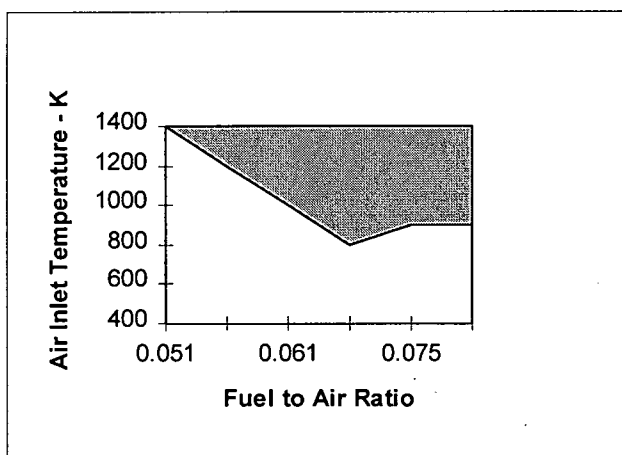


**Figure 4 :
Region of Extrapolation Where
Error is Uncertain (Shown in Grey)**

4.2 Sauter Mean Diameter

The fuel droplet size is required to calculate combustion efficiency. The *Emission Module* can evaluate the initial mean drop size D_0 for two types of fuel injectors (pressure swirl and airblast atomisers) but other atomiser types or other correlations could be easily included to provide more coverage and/or increased applicability.

In the case of the pressure swirl atomiser, Lefebvre's analysis of the flow processes in the final orifice of a simplex nozzle (Lefebvre, 1983) together with Jasuja's data (A. K. Jasuja, 1979) lead to the following equation for SMD adopted in the module :-

$$(16) \quad \text{SMD} = 2.25 \left(\frac{\sigma \mu_F}{\rho_A} \right)^{0.25} \Delta P_F^{-0.5} \quad (\text{Pressure swirl atomiser})$$

Jasuja examined the airblast atomisation characteristics of kerosene (A. K. Jasuja, 1979). The experimental data is stated to correlate well with the equation :-

$$(17) \quad \text{SMD} = 10^{-3} \left[1 + \frac{1}{\text{AFR}} \right]^{0.5} \left[\frac{(\sigma \rho_F)^{0.5}}{\rho_A U_A} + 0.06 \left(\frac{\mu_F^2}{\sigma \rho_A} \right)^{0.425} \right] \quad (\text{Airblast atomiser})$$

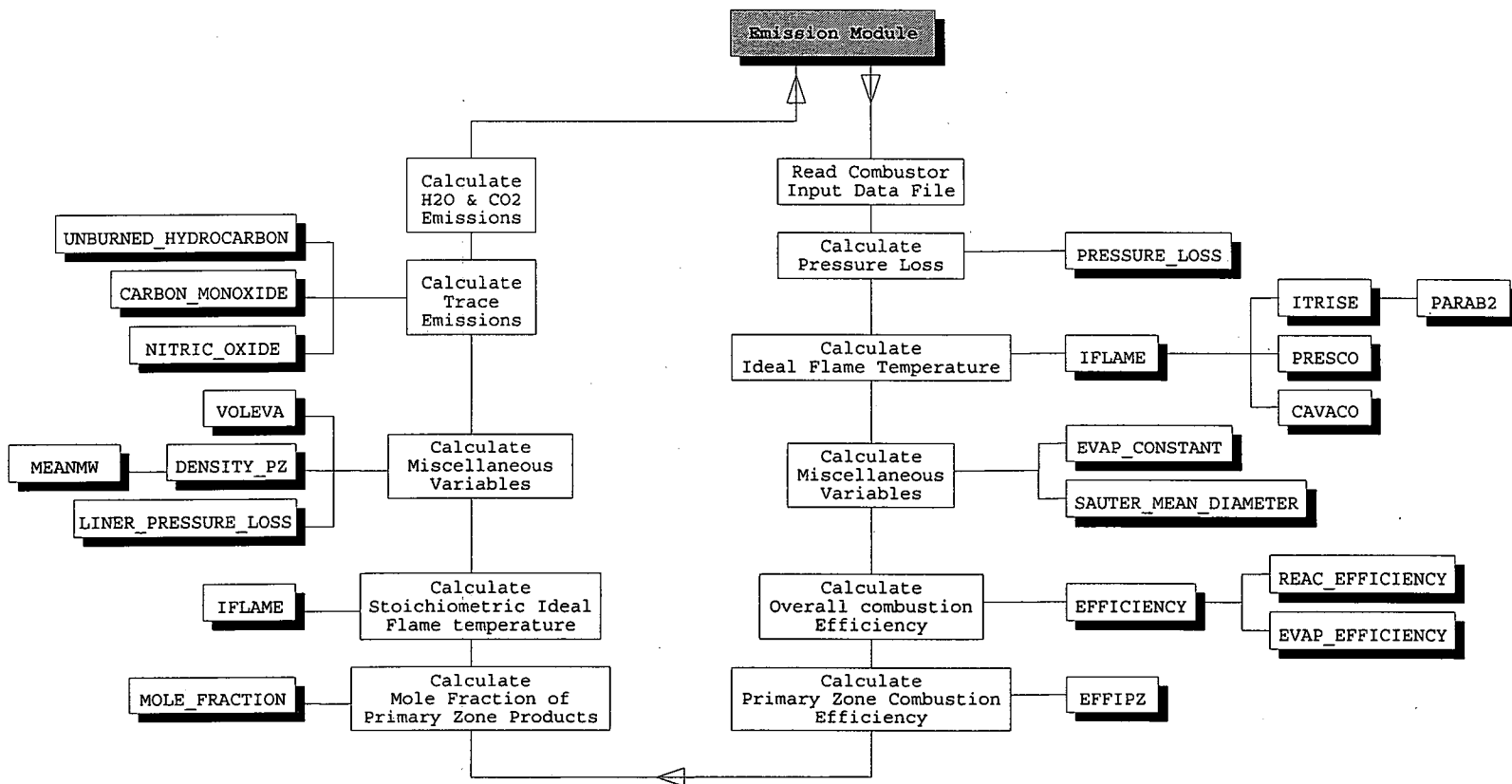
Although this expression does not embody the atomiser dimensions, it is considered to be sufficient for the purpose of estimating combustion efficiency.

4.3 Evaporation Constant

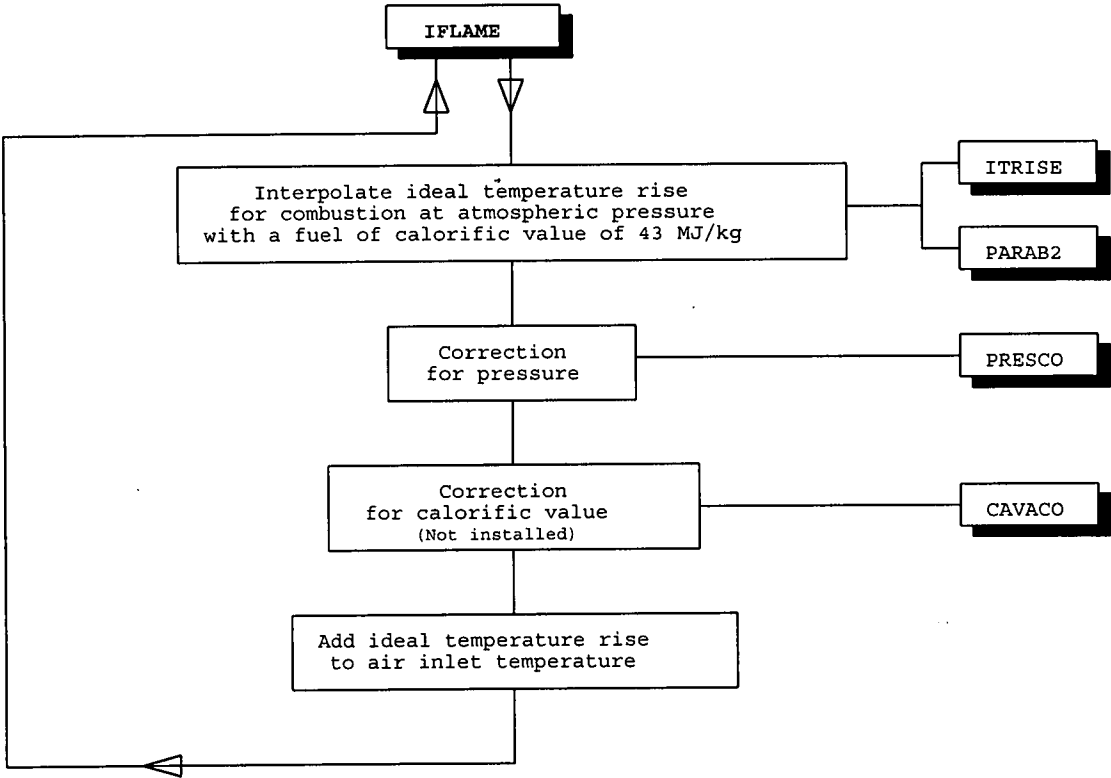
The effective evaporation constant is required to evaluate the evaporation-rate-limited combustion efficiency. It is computed by means of an embedded look-up table. This table has been generated using the variation of effective evaporation constant with normal boiling point at several pressures, from curves established by J. S. Chin and A. H. Lefebvre (1982). This parameter is a function of pressure, temperature, UD_0 which is the product of fuel velocity relative to the mainstream gas velocity and SMD, and the fuel boiling point (taken as 500K for kerosene).

Appendix D.10 SKY Emission Module - Flow Charts

1. EMISSION MODULE FLOW CHART



2. IDEAL FLAME TEMPERATURE COMPUTATION FLOW CHART



Appendix D.11

SKY Emission Module - Subroutine Tree

Emission Module	PRESSURE_LOSS		
	IFLAME	ITRISE	PARAB2
	SAUTER_MEAN_DIAMETER	PRESCO	
	EVAP_CONSTANT	CAVACO	
	EFFICIENCY	REAC_EFFICIENCY	
	EFFIPZ	EVAP_EFFICIENCY	
	MOLE_FRACTION		
	DENSITY_PZ	MEANMW	
	LINER_PRESSURE_LOSS		
	VOLEVA		
	UNBURNED_HYDROCARBON		
	CARBON_MONOXIDE		
	NITRIC_OXIDE		

Appendix D.12

SKY Input Data Files - Examples

The appendix presents a selection of input data files required for a typical run. They are those which are most likely to require updating. The remaining files are of the format of "Dragpo01.dat" presented further.

Typical "Input.dat"

```
lontok01.dat
4.
engine01.dat
-
snglann1.dat
engine01.dat
-
snglann1.dat
engine01.dat
-
snglann1.dat
engine01.dat
-
snglann1.dat
engine01.dat
-
snglann1.dat
isadev01.dat
wind01.dat
dragpo01.dat
takoff01.dat
climbi01.dat
clspdi01.dat
accel01.dat
climbe01.dat
clspde01.dat
cruise01.dat
clallo01.dat
altcap01.dat
descen01.dat
desspd01.dat
hold01.dat
misapp01.dat
eindex01.dat
icao02.dat
sky01.dat
sky01s.dat
```

Typical Aircraft/Mission Input Data File ("r5538i01.dat")

```
Comments
*****
496.      ! Mission / Passengers
5537.9    ! Mission / Range -nm
64863.    ! Mission / PW fixed or payload weight -kg
165107.   ! Mission / OEW1 Empty weight no engines -kg
```

0. ! Mission / EF embarked fuel weight for next trip -kg
 394625. ! Weight limit / MTOW maximum take-off weight -kg
 285763. ! Weight limit / MLW maximum landing weight -kg
 247208. ! Weight limit / MZFW maximum zero fuel weight -kg
 165107. ! Weight limit / OEW op'al empty weight (no engines) -kg
 395986. ! Weight limit / MRW maximum ramp weight -kg
 174093. ! Weight limit / MFC maximum fuel capacity -kg
 5.00 ! Time / Start -min
 12.00 ! Time / Taxi-out -min
 0.00 ! Time / Air manoeuvre or holding -min
 6.00 ! Time / Approach & landing -min
 5.00 ! Time / Missed approach -min
 6.00 ! Time / Taxi-in -min
 0. ! Altitude / Departure airport (hdep) -ft
 1500. ! Altitude / Start initial climb (ref : hdep) -ft
 10000. ! Altitude / Start en-route climb (ref : sl) -ft
 3. ! Altitude / Flight levels (step cr.) or 1 & supply ini cr alt
 31000. ! ref SL
 35000. ! "
 39000. ! "
 5000. ! Altitude / Holding (ref : sl) -ft
 1500. ! Altitude / End of descent (ref : harr) -ft
 0. ! Altitude / Destination airport (harr) -ft
 5. ! A/C fuel flow / Start -kg/min
 46.27 ! A/C fuel flow / Taxi-out -kg/mn
 92.08 ! A/C fuel flow / Approach & landing -kg/mn
 46.27 ! A/C fuel flow / Taxi-in -kg/mn
 7.63 ! A/C geometry / Wing aspect ratio
 510.97 ! A/C geometry / Wing area (aerodynamic ref.) -m2
 250. ! Speed / Initial climb KEAS (proc 3) -kts
 340. ! Speed / En-route climb KEAS (proc 3) -kts
 0.85 ! Speed / Cruise mach number
 0.025 ! Descent angle relative to ground (proc 2 & 3) -rad
 1. ! Reserves / proc (0=no account ; 1=account)
 0. ! Reserves / Fixed reserve or contingency -kg
 0.05 ! Reserves / Ratio of final reserve to block fuel
 200. ! Reserves / Diversion distance -nm
 29000. ! Reserves / Diversion initial cruise altitude -ft
 0.85 ! Reserves / Diversion cruise Mn
 30.00 ! Reserves / Holding time at end of descent -min
 1. ! Proc / start weight estimation
 395203. ! Initial estimate / start weight (if req) -kg
 0. ! Proc / ISA deviations (0=no 1=account for ISA dev)
 0. ! Proc / Wind components (0=no 1=account for wind)
 1. ! Proc / take-off
 1. ! Proc / initial climb
 1. ! Proc / acceleration
 1. ! Proc / en-route climb
 1. ! Proc / cruise
 1. ! Proc / climb allowance for step cruise
 1. ! Proc / descent
 0. ! Proc / holding location
 0. ! Proc / account for holding in fuel weight prediction
 1. ! Proc / holding
 1. ! Proc / diversion initial climb
 1. ! Proc / diversion acceleration
 1. ! Proc / diversion en-route climb
 1. ! Proc / diversion cruise
 1. ! Proc / diversion descent
 1. ! Proc / diversion holding
 5. ! Steps / initial climb
 1. ! Steps / acc to en-route climb speed

```

5.      ! Steps / en-route climb
1.      ! Steps / acc to cruise Mn
1.      ! Steps / climb allowance for step cruise
5.      ! Steps / descent
500.    ! Step / cruise distance relative to wind -nm
0.000002 ! Tolerance 1 / start weight convergence
0.000005 ! Tolerance 2 / cruise range estimation
0.000005 ! Tolerance 3 / descent aircraft mass

```

Typical Engine Model Input Data File ("engine01.dat")

Comments

```
*****
```

```

256000. ! Rated output -N
4309.   ! Engine weight -kg

```

The remaining lines may incorporate a typical Turbomatch input data file.

Typical Combustor Model Input Data File ("snglann1.dat")

Comments

```
*****
```

```

12.      ! FUEL CARBON NUMBER
24.      ! FUEL HYDROGEN NUMBER
0.43165036E+08 ! FUEL CALORIFIC VALUE - J/kg
300.     ! FUEL TEMPERATURE AT INJECTION - K
0.022    ! FUEL SURFACE TENSION - kg/s2
0.0013   ! FUEL VISCOSITY AT INJECTION - kg/m/s
800.     ! FUEL DENSITY AT INJECTION - kg/m3
18.      ! OVERALL PRESSURE LOSS FACTOR (TUB=37.5 TUBO-ANN=25 ANN=18-20)
9.       ! LINER PRESSURE LOSS FACTOR
0.088    ! COMBUSTOR VOLUME - m3
0.24     ! CASING CROSS SECTIONAL AREA - m2
0.43     ! COMBUSTION AIR FRACTION
15.      ! PRIMARY ZONE GAS VELOCITY - m/s
0.4      ! PRIMARY ZONE TURBULENCE LEVEL
0.1      ! LINER REFERENCE WIDTH - m
3.       ! INJECTOR TYPE (1=VAP 2=PRESS SW ATOM 3=AIRBL ATOM)
0.85     ! INJECTOR COEFF (PRESS=1.0 AIRBL=0.85 AIR ASSIST=0.9 VAP=0.8)
0.       ! ATOM'TION PRESSURE DIFFERENTIAL ACROSS THE PR. ATOMISER - Pa
0.72     ! PRIM. ZONE EFFICIENCY COEFFICIENT 1 (originally 0.72)
0.29     ! PRIM. ZONE EFFICIENCY COEFFICIENT 2 (originally 0.29)
0.15475E-02 ! PRIM. ZONE EFFICIENCY COEFFICIENT 3 (originally 0.15475e-02)
108.     ! PRIM. ZONE EFFICIENCY COEFFICIENT 4 (originally 108.)
1863.    ! PRIM. ZONE EFFICIENCY COEFFICIENT 5 (originally 1863.)
19.      ! CO SCALING CONSTANT (originally 86.)
-0.5     ! CO PRESSURE LOSS CONSTANT (originally -0.5)
-1.5     ! CO PRESSURE CONSTANT (originally -1.5)
-0.00345 ! CO PZ TEMPERATURE CONSTANT (originally -0.00345)
1810.    ! UHC SCALING CONSTANT (originally 11764.)
-1.      ! UHC PRESSURE LOSS CONSTANT (originally -1.)
-2.5     ! UHC PRESSURE CONSTANT (originally -2.5)
-0.00345 ! UHC PZ TEMPERATURE CONSTANT (originally -0.00345)
2.0E-08  ! NOX SCALING CONSTANT (originally 9.0E-08)
1.25     ! NOX PRESSURE CONSTANT (originally 1.25)
0.01     ! NOX ST TEMPERATURE CONSTANT (originally 0.01)

```

Typical Drag Polar Input Data File ("dragpo01.dat")

Comments

2.
4.
1.
12.
1.
3.
1.
1.
1.
1.
2.
3.
4.
.25
.35
.45
.55
.65
.75
.80
.82
.84
.85
.86
.88
.024071
.021695
.020422
.019514
.019582
etc.
.019577
.089867
.101489
.113733
.155563
.202050

Appendix D.13

SKY Output Data File - Example

```
*****
*
* SKY v1.0
*
* Simulation of medium and long range flight routes of civil
* subsonic transport aircraft, including the detailed performance
* of the gas turbine engines and the prediction of flight emissions.
*
* Marc Le Dilosquer, 1997
* School of Mechanical Engineering
* Cranfield University
*
*****
```

```
-----
1) CASE STUDY
-----
```

```
File : skyres02.dat
Date : 24- 5-1997
Time : 16:20:35
```

```
-----
2) DATA FILES
-----
```

```
File names ..... input.dat

Aircraft/mission ..... r5538i01.dat
Propulsion unit(s) ..... 4

Propulsion unit 1,2,3,4
Engine ..... engine01.dat
Combustor ..... -
Climb rating ..... -
Thrust contribution ..... .250

Atmosphere
ISA deviations ..... isadev01.dat
Wind speeds ..... wind01.dat

Aircraft performance
Drag polar ..... dragpo01.dat
Take-off ..... takoff01.dat
Initial climb ..... climbi01.dat
Ini climb speed schedule .... clspdi01.dat
Acceleration ..... accel01.dat
En-route climb ..... climbe01.dat
E-r climb speed schedule .... clspde01.dat
Cruise ..... cruise01.dat
Step climb allowance ..... clallo01.dat
Altitude capability ..... altcap01.dat
Descent ..... descen01.dat
Descent speed schedule ..... desspd01.dat
Holding ..... hold01.dat
```

Missed Approach misapp01.dat

Emission simulation

Emission indices eindex01.dat

ICAO recommendations icao02.dat

Output

Standard skyres02.dat

Arranged for SKYVision skysgc02.dat

Arranged for Excel 5.0 skyres02.xls

Messages

SKY high level messages skymsg01.txt

SKY low level messages skymsg02.txt

Turbomatch messages skymsg03.txt

3) COMPUTATION STATUS

Running time 0/ 0/ 6

Warnings 0

Iterations 8

Tolerance sought0000020

Iteration	Start mass -kg	Variation
1	395203.0	-.0034454
2	393841.4	-.0011800
3	393376.6	-.0004001
4	393219.3	-.0001354
5	393166.0	-.0000457
6	393148.0	-.0000153
7	393142.0	-.0000052
8	393140.0	-.0000019

Simulation procedures

No	Phase	ID	Fuel burn	Fuel flow	Thrust	Em. Indices
Mission						
1	Start	1	Analysis	Allowance	Nil	Allowance
2	Taxi-out	1	Analysis	Allowance	Nil	Allowance
3	Take-off	1	Interpol	Analysis	Nil	Allowance
4	Initial Climb	1	Interpol	Analysis	Analysis	Allowance
5	Acceleration	1	Interpol	Analysis	Nil	Allowance
6	En-route climb	1	Interpol	Analysis	Analysis	Allowance
7	Cruise	1	Interpol	Analysis	Analysis	Allowance
8	Step climb	1	Interpol	Analysis	Analysis	Allowance
9	Descent	1	Interpol	Analysis	Analysis	Allowance
10	Holding	1	Analysis	Interpol	Analysis	Allowance
11	Approach	1	Analysis	Allowance	Nil	Allowance
12	Landing	1	Analysis	Allowance	Nil	Allowance
13	Taxi-in	1	Analysis	Allowance	Nil	Allowance
Diversion						
14	Missed approach	1	Interpol	Analysis	Nil	Allowance
15	Initial Climb	1	Interpol	Analysis	Analysis	Allowance
16	Acceleration	1	Interpol	Analysis	Nil	Allowance
17	En-route climb	1	Interpol	Analysis	Analysis	Allowance
18	Cruise	1	Interpol	Analysis	Analysis	Allowance
19	Step climb	1	Interpol	Analysis	Analysis	Allowance
20	Descent	1	Interpol	Analysis	Analysis	Allowance

21	Holding	1	Analysis	Interpol	Analysis	Allowance
22	Approach	1	Analysis	Allowance	Nil	Allowance
23	Landing	1	Analysis	Allowance	Nil	Allowance

4) AIRCRAFT/MISSION

Flight analysis

Aircraft weights

Payload	64863. kg	PW
Engines	17236. kg	EW
Empty	165107. kg	OEW1
Empty + engines	182343. kg	OEW2=OEW1+EW
Zero fuel	247206. kg	ZFW=OEW2+PW
Landing	264159. kg	LW=ZFW+TRF
Take-off	392560. kg	TOW=LW+MF
Ramp	393115. kg	RW=TOW+TOF
Start	393140. kg	SW=RW+SF+SW

Fuel analysis

Diversion	10489. kg	DF
Fixed reserve	0. kg	FXF
Final reserve	6463. kg	FNF
Total reserve	16952. kg	TRF=DF+FXF+FNF
Taxi-in	278. kg	TIF
Mission	128401. kg	MF
Taxi-out	555. kg	TOF
Start	25. kg	SF
Embarked	0. kg	EF
Carried	145933. kg	CF=SF+TOF+MF+TRF+EF
Block	129259. kg	BF=SF+TOF+MF+TIF

Flight performance

Passengers	496 -
Range	5537.9 nm
Range specific	42.844 nm/t
Time mission	11.46 hrs
Time block	11.84 hrs
RPM performed	2746799. nm
RPM specific	21250. nm/t
TNM performed	359205. t.nm
TNM specific	2779.0 nm

Flight analysis - Phase breakdown

Phase	Height -ft	Mass -kg	Fuel -kg	-%	Time -hr	-%	Distance -nm	-%
Start	0.	393140.	25.	.0	.083	.7	.0	.0
Taxi-out	0.	393115.	555.	.4	.200	1.7	.0	.0
Take-off	0.	392560.	1687.	1.3	.047	.4	8.7	.2
Initial climb	1500.	390873.	1542.	1.2	.051	.4	15.5	.3
Acceleration	10000.	389330.	531.	.4	.010	.1	7.7	.1
En-route climb	10000.	388800.	5039.	3.9	.250	2.1	117.8	2.1
Cruise 1	31000.	383761.	13024.	10.1	1.002	8.5	500.0	9.0
Cruise 2	31000.	370737.	12558.	9.7	1.002	8.5	500.0	9.0
Cruise 3	31000.	358179.	12173.	9.4	1.002	8.5	500.0	9.0
Cruise 4	31000.	346006.	11847.	9.2	1.002	8.5	500.0	9.0
Cruise 5	31000.	334159.	11536.	8.9	1.002	8.5	500.0	9.0

Cruise 6	31000.	322623.	1043.	.8	.067	.6	33.0	.6
Cruise 7	35000.	321580.	11029.	8.5	1.020	8.6	500.0	9.0
Cruise 8	35000.	310551.	10598.	8.2	1.020	8.6	500.0	9.0
Cruise 9	35000.	299952.	10279.	8.0	1.020	8.6	500.0	9.0
Cruise 10	35000.	289674.	9992.	7.7	1.020	8.6	500.0	9.0
Cruise 11	35000.	279682.	9740.	7.5	1.020	8.6	500.0	9.0
Cruise 12	35000.	269942.	4536.	3.5	.486	4.1	238.1	4.3
Cruise totals	31000.	383761.	118355.	91.6	10.664	90.1	5271.1	95.2
Descent/holding	35000.	265406.	695.	.5	.334	2.8	117.3	2.1
Holding only	0.	0.	0.	.0	.000	.0	.0	.0
Approach/landing	1500.	264711.	552.	.4	.100	.8	.0	.0
Taxi-in	0.	264159.	278.	.2	.100	.8	.0	.0
Mission totals	0.	0.	128401.	99.3	11.455	96.8	5537.9	100.0
Block totals	0.	0.	129259.	100.0	11.838	100.0	5537.9	100.0

Flight analysis - Step breakdown (1/2)

Step	Height	Mass	Fuel		Time	Distance			
-	-ft	-ft	-kg	-kg	-kg/s	-min	-min	-nm	-nm
Start									
1	0.	0.	393140.	145933.	25.0	.08	.0	5.00	.0
Taxi-out									
2	0.	0.	393115.	145908.	555.2	.77	5.0	12.00	.0
Take-off									
3	0.	1500.	392560.	145353.	1687.1	10.05	17.0	2.80	.0
Initial climb									
4	1500.	1700.	390873.	143666.	308.5	11.45	19.8	.45	8.7
5	3200.	1700.	390564.	143357.	308.4	11.74	20.2	.44	10.8
6	4900.	1700.	390256.	143049.	308.4	7.06	20.7	.73	12.9
7	6600.	1700.	389947.	142741.	308.4	7.06	21.4	.73	16.6
8	8300.	1700.	389639.	142432.	308.4	7.25	22.1	.71	20.3
Acceleration									
9	10000.	0.	389330.	142124.	530.8	14.66	22.9	.60	24.1
En-route climb									
10	10000.	4200.	388800.	141593.	762.0	6.77	23.5	1.88	31.8
11	14200.	4200.	388038.	140831.	795.4	5.46	25.3	2.43	44.4
12	18400.	4200.	387242.	140035.	1013.6	5.58	27.8	3.03	61.8
13	22600.	4200.	386229.	139022.	1197.5	5.54	30.8	3.60	85.2
14	26800.	4200.	385031.	137824.	1270.0	5.18	34.4	4.09	115.0
Cruise									
15	31000.	0.	383761.	136554.	13023.9	3.61	38.5	60.13	149.6
16	31000.	0.	370737.	123530.	12558.0	3.48	98.6	60.13	649.6
17	31000.	0.	358179.	110972.	12173.0	3.37	158.7	60.13	1149.6
18	31000.	0.	346006.	98799.	11847.0	3.28	218.9	60.13	1649.6
19	31000.	0.	334159.	86952.	11536.5	3.20	279.0	60.13	2149.6
20	31000.	4000.	322623.	75416.	1043.3	4.33	339.1	4.02	2649.6
21	35000.	0.	321580.	74373.	11028.8	3.00	343.1	61.21	2682.6
22	35000.	0.	310551.	63344.	10598.5	2.89	404.3	61.21	3182.6
23	35000.	0.	299952.	52745.	10278.7	2.80	465.5	61.21	3682.6
24	35000.	0.	289674.	42467.	9991.6	2.72	526.7	61.21	4182.6
25	35000.	0.	279682.	32475.	9739.9	2.65	587.9	61.21	4682.6
26	35000.	0.	269942.	22735.	4535.8	2.59	649.2	29.14	5182.6
Descent/holding									
27	35000.	-6700.	265406.	18199.	107.6	.53	678.3	3.36	5420.6
28	28300.	-6700.	265299.	18092.	109.6	.52	681.7	3.50	5446.0
29	21600.	-6700.	265189.	17982.	119.8	.51	685.2	3.92	5469.7
30	14900.	-6700.	265069.	17862.	180.4	.62	689.1	4.87	5492.3
31	8200.	-6700.	264889.	17682.	177.5	.68	694.0	4.36	5518.2
Approach/landing									
32	1500.	-1500.	264711.	17505.	552.5	1.53	698.3	6.00	5537.9
Taxi-in									

33 0. 0. 264159. 16952. 277.6 .77 704.3 6.00 5537.9 .0

Flight analysis - Step breakdown (2/2)

Step	Height -ft	Mach	TAS -kt	EAS -kt	ROC -ft/s	Gamma -deg	Tnet -kN	Drag -kN	SEP -ft/s	L/D	L/Dm	Cl

Start												
1	0.	.000	.0	.0	.0	.00	0.	0.	0.	.00	.00	.000
Taxi-out												
2	0.	.000	.0	.0	.0	.00	0.	0.	0.	.00	.00	.000
Take-off												
3	0.	.281	185.6	185.6	8.9	1.63	0.	313.	0.	12.29	17.31	1.348
Initial climb												
4	1500.	.437	287.7	281.4	63.1	7.47	763.	209.	689.	18.35	18.38	.585
5	3200.	.451	295.0	281.4	64.7	7.47	766.	208.	711.	18.37	18.41	.584
6	4900.	.465	302.7	281.4	38.9	4.37	540.	212.	430.	18.09	18.13	.584
7	6600.	.480	310.6	281.4	38.9	4.26	537.	215.	434.	17.80	17.84	.583
8	8300.	.496	318.9	281.4	39.9	4.26	543.	218.	449.	17.51	17.55	.583
Acceleration												
9	10000.	.513	327.4	281.4	.0	.00	0.	222.	0.	17.21	17.26	.582
En-route climb												
10	10000.	.632	403.5	346.7	37.3	3.14	485.	223.	459.	17.09	18.27	.383
11	14200.	.686	431.4	346.7	28.8	2.27	414.	218.	368.	17.47	18.54	.382
12	18400.	.748	462.4	346.7	23.1	1.70	371.	218.	308.	17.45	18.34	.381
13	22600.	.817	496.6	346.7	19.4	1.33	317.	219.	214.	17.32	17.96	.380
14	26800.	.850	508.0	346.7	17.1	1.14	286.	218.	152.	17.36	17.44	.420
Cruise												
15	31000.	.850	499.0	299.6	.0	.00	218.	218.	0.	17.23	17.44	.506
16	31000.	.850	499.0	299.6	.0	.00	210.	210.	0.	17.34	17.44	.489
17	31000.	.850	499.0	299.6	.0	.00	202.	202.	0.	17.40	17.44	.473
18	31000.	.850	499.0	299.6	.0	.00	195.	195.	0.	17.44	17.44	.456
19	31000.	.850	499.0	299.6	.0	.00	188.	188.	0.	17.43	17.44	.441
20	31000.	.839	492.6	295.8	16.6	1.14	236.	179.	147.	17.67	17.75	.437
21	35000.	.850	490.2	272.9	.0	.00	183.	183.	0.	17.20	17.44	.511
22	35000.	.850	490.2	272.9	.0	.00	176.	176.	0.	17.31	17.44	.494
23	35000.	.850	490.2	272.9	.0	.00	169.	169.	0.	17.39	17.44	.477
24	35000.	.850	490.2	272.9	.0	.00	163.	163.	0.	17.43	17.44	.461
25	35000.	.850	490.2	272.9	.0	.00	157.	157.	0.	17.43	17.44	.445
26	35000.	.850	490.2	272.9	.0	.00	152.	152.	0.	17.40	17.44	.429
Descent/holding												
27	35000.	.872	503.0	280.0	-33.2	-2.24	0.	159.	0.	16.31	16.31	.401
28	28300.	.747	443.7	280.0	-31.9	-2.44	0.	147.	0.	17.74	18.34	.400
29	21600.	.646	394.2	280.0	-28.5	-2.45	0.	147.	0.	17.69	18.57	.400
30	14900.	.562	352.4	280.0	-22.9	-2.21	0.	163.	0.	15.97	16.85	.400
31	8200.	.440	282.8	250.0	-25.6	-3.08	0.	142.	0.	18.26	18.39	.501
Approach/landing												
32	1500.	.440	289.7	283.3	-4.2	-.49	0.	153.	0.	16.94	18.39	.390
Taxi-in												
33	0.	.000	.0	.0	.0	.00	0.	0.	0.	.00	.00	.000

5) AERO ENGINE PERFORMANCE

Main engine parameters - Propulsion unit 1,2,3,4

Step	Height -ft	Mach	Tnet -N	Fuel -kg/s	s.f.c. -kg/MN/s

Start					
1	0.	.000	0.	.021	.000

Taxi-out					
2	0.	.000	0.	.193	.000
Take-off					
3	0.	.281	0.	2.513	.000
Initial climb					
4	1500.	.437	190833.	2.862	14.997
5	3200.	.451	191531.	2.935	15.323
6	4900.	.465	135093.	1.764	13.059
7	6600.	.480	134375.	1.765	13.132
8	8300.	.496	135819.	1.812	13.338
Acceleration					
9	10000.	.513	0.	3.664	.000
En-route climb					
10	10000.	.632	121269.	1.692	13.952
11	14200.	.686	103496.	1.366	13.197
12	18400.	.748	92648.	1.396	15.064
13	22600.	.817	79302.	1.385	17.464
14	26800.	.850	71430.	1.295	18.124
Cruise					
15	31000.	.850	54597.	.903	16.531
16	31000.	.850	52428.	.870	16.599
17	31000.	.850	50454.	.844	16.719
18	31000.	.850	48652.	.821	16.874
19	31000.	.850	47003.	.799	17.009
20	31000.	.839	59073.	1.081	18.305
21	35000.	.850	45850.	.751	16.375
22	35000.	.850	43982.	.722	16.405
23	35000.	.850	42289.	.700	16.546
24	35000.	.850	40742.	.680	16.695
25	35000.	.850	39328.	.663	16.860
26	35000.	.850	38035.	.648	17.050
Descent/holding					
27	35000.	.872	0.	.133	.000
28	28300.	.747	0.	.130	.000
29	21600.	.646	0.	.127	.000
30	14900.	.562	0.	.154	.000
31	8200.	.440	0.	.170	.000
Approach/landing					
32	1500.	.440	0.	.384	.000
Taxi-in					
33	0.	.000	0.	.193	.000

6) COMBUSTION & EMISSIONS

NOx, CO & UHC emissions - Phase breakdown - Propulsion unit 1,2,3,4

	NOx			CO			UHC		
	-kg	-%	-g/kg	-kg	-%	-g/kg	-kg	-%	-g/kg

Start	.0	.0	4.6	.09	.5	13.74	.01	.1	.89
Taxi-out	.6	.0	4.6	1.91	11.2	13.74	.12	1.4	.89
Take-off	24.8	1.9	58.7	.25	1.5	.59	.16	1.8	.39
Initial climb	15.6	1.2	40.5	.17	1.0	.43	.10	1.2	.27
Acceleration	5.4	.4	40.5	.06	.3	.43	.04	.4	.27
En-route climb	51.1	3.9	40.5	.54	3.2	.43	.34	3.8	.27
Cruise 1	132.0	10.2	40.5	1.40	8.2	.43	.88	9.8	.27
Cruise 2	127.3	9.8	40.5	1.35	7.9	.43	.85	9.5	.27
Cruise 3	123.4	9.5	40.5	1.31	7.7	.43	.82	9.2	.27
Cruise 4	120.1	9.2	40.5	1.27	7.5	.43	.80	8.9	.27
Cruise 5	116.9	9.0	40.5	1.24	7.3	.43	.78	8.7	.27

Cruise 6	10.6	.8	40.5	.11	.7	.43	.07	.8	.27
Cruise 7	111.8	8.6	40.5	1.19	7.0	.43	.74	8.3	.27
Cruise 8	107.4	8.3	40.5	1.14	6.7	.43	.72	8.0	.27
Cruise 9	104.2	8.0	40.5	1.10	6.5	.43	.69	7.8	.27
Cruise 10	101.3	7.8	40.5	1.07	6.3	.43	.67	7.5	.27
Cruise 11	98.7	7.6	40.5	1.05	6.2	.43	.66	7.4	.27
Cruise 12	46.0	3.5	40.5	.49	2.9	.43	.31	3.4	.27
Cruise totals	1199.5	92.2	40.5	12.72	74.9	.43	7.99	89.4	.27
Descent/holding	1.7	.1	9.6	.18	1.0	1.01	.06	.7	.37
Holding only	.0	.0	.0	.00	.0	.00	.00	.0	.00
Approach/landing	1.3	.1	9.6	.14	.8	1.01	.05	.6	.37
Taxi-in	.3	.0	4.6	.95	5.6	13.74	.06	.7	.89
Mission totals	1300.0	100.0	40.3	15.96	93.9	.50	8.87	99.2	.28
Block totals	1300.3	100.0	40.2	17.00	100.0	.53	8.94	100.0	.28

H2O & CO2 emissions - Phase breakdown - Propulsion unit 1,2,3,4

	H2O			CO2					
	-kg	-%	-g/kg	-kg	-%	-g/kg			
Start	8.	.0	1284.	20.	.0	3138.			
Taxi-out	178.	.4	1284.	436.	.4	3138.			
Take-off	542.	1.3	1284.	1324.	1.3	3138.			
Initial climb	495.	1.2	1284.	1210.	1.2	3138.			
Acceleration	170.	.4	1284.	416.	.4	3138.			
En-route climb	1617.	3.9	1284.	3953.	3.9	3138.			
Cruise 1	4181.	10.1	1284.	10217.	10.1	3138.			
Cruise 2	4031.	9.7	1284.	9852.	9.7	3138.			
Cruise 3	3908.	9.4	1284.	9550.	9.4	3138.			
Cruise 4	3803.	9.2	1284.	9294.	9.2	3138.			
Cruise 5	3703.	8.9	1284.	9050.	8.9	3138.			
Cruise 6	335.	.8	1284.	818.	.8	3138.			
Cruise 7	3540.	8.5	1284.	8652.	8.5	3138.			
Cruise 8	3402.	8.2	1284.	8315.	8.2	3138.			
Cruise 9	3299.	8.0	1284.	8064.	8.0	3138.			
Cruise 10	3207.	7.7	1284.	7838.	7.7	3138.			
Cruise 11	3127.	7.5	1284.	7641.	7.5	3138.			
Cruise 12	1456.	3.5	1284.	3558.	3.5	3138.			
Cruise totals	37992.	91.6	1284.	92849.	91.6	3138.			
Descent/holding	223.	.5	1284.	545.	.5	3138.			
Holding only	0.	.0	0.	0.	.0	0.			
Approach/landing	177.	.4	1284.	433.	.4	3138.			
Taxi-in	89.	.2	1284.	218.	.2	3138.			
Mission totals	41395.	99.8	1284.	101166.	99.8	3138.			
Block totals	41492.	100.0	1284.	101403.	100.0	3138.			

Emissions - Step breakdown - Propulsion unit 1,2,3,4

Step	Height	NOx		CO		UHC		H2O		CO2	
-	-ft	-g/kg	-kg	-g/kg	-kg	-g/kg	-kg	-g/kg	-kg	-g/kg	-kg
Start											
1	0.	4.6	.0	13.74	.09	.89	.01	1284.	8.	3138.	20.
Taxi-out											
2	0.	4.6	.6	13.74	1.91	.89	.12	1284.	178.	3138.	436.
Take-off											
3	0.	58.7	24.8	.59	.25	.39	.16	1284.	542.	3138.	1324.
Initial climb											
4	1500.	40.5	3.1	.43	.03	.27	.02	1284.	99.	3138.	242.
5	3200.	40.5	3.1	.43	.03	.27	.02	1284.	99.	3138.	242.
6	4900.	40.5	3.1	.43	.03	.27	.02	1284.	99.	3138.	242.
7	6600.	40.5	3.1	.43	.03	.27	.02	1284.	99.	3138.	242.

8	8300.	40.5	3.1	.43	.03	.27	.02 1284.	99. 3138.	242.
Acceleration									
9	10000.	40.5	5.4	.43	.06	.27	.04 1284.	170. 3138.	416.
En-route climb									
10	10000.	40.5	7.7	.43	.08	.27	.05 1284.	245. 3138.	598.
11	14200.	40.5	8.1	.43	.09	.27	.05 1284.	255. 3138.	624.
12	18400.	40.5	10.3	.43	.11	.27	.07 1284.	325. 3138.	795.
13	22600.	40.5	12.1	.43	.13	.27	.08 1284.	384. 3138.	939.
14	26800.	40.5	12.9	.43	.14	.27	.09 1284.	408. 3138.	996.
Cruise									
15	31000.	40.5	132.0	.43	1.40	.27	.88 1284.	4181. 3138.	10217.
16	31000.	40.5	127.3	.43	1.35	.27	.85 1284.	4031. 3138.	9852.
17	31000.	40.5	123.4	.43	1.31	.27	.82 1284.	3908. 3138.	9550.
18	31000.	40.5	120.1	.43	1.27	.27	.80 1284.	3803. 3138.	9294.
19	31000.	40.5	116.9	.43	1.24	.27	.78 1284.	3703. 3138.	9050.
20	31000.	40.5	10.6	.43	.11	.27	.07 1284.	335. 3138.	818.
21	35000.	40.5	111.8	.43	1.19	.27	.74 1284.	3540. 3138.	8652.
22	35000.	40.5	107.4	.43	1.14	.27	.72 1284.	3402. 3138.	8314.
23	35000.	40.5	104.2	.43	1.10	.27	.69 1284.	3299. 3138.	8064.
24	35000.	40.5	101.3	.43	1.07	.27	.67 1284.	3207. 3138.	7838.
25	35000.	40.5	98.7	.43	1.05	.27	.66 1284.	3127. 3138.	7641.
26	35000.	40.5	46.0	.43	.49	.27	.31 1284.	1456. 3138.	3558.
Descent/holding									
27	35000.	9.6	.3	1.01	.03	.37	.01 1284.	35. 3138.	84.
28	28300.	9.6	.3	1.01	.03	.37	.01 1284.	35. 3138.	86.
29	21600.	9.6	.3	1.01	.03	.37	.01 1284.	38. 3138.	94.
30	14900.	9.6	.4	1.01	.05	.37	.02 1284.	58. 3138.	141.
31	8200.	9.6	.4	1.01	.04	.37	.02 1284.	57. 3138.	139.
Approach/landing									
32	1500.	9.6	1.3	1.01	.14	.37	.05 1284.	177. 3138.	433.
Taxi-in									
33	0.	4.6	.3	13.74	.95	.89	.06 1284.	89. 3138.	218.

Combustion parameters (1/2) - Propulsion unit 1,2,3,4

Step	Height	W3	P3	T3	Fuel	Phi	Phipz	Tflid	Tstid	Dpz
-	-ft	-kg/s	-Atm	-K	-kg/s	-	-	-K	-K	-kg/m3
Start										
1	0.	.00	.000	0.	.02	.000	.000	0.	0.	.000
Taxi-out										
2	0.	.00	.000	0.	.19	.000	.000	0.	0.	.000
Take-off										
3	0.	.00	.000	0.	2.51	.000	.000	0.	0.	.000
Initial climb										
4	1500.	.00	.000	0.	2.86	.000	.000	0.	0.	.000
5	3200.	.00	.000	0.	2.93	.000	.000	0.	0.	.000
6	4900.	.00	.000	0.	1.76	.000	.000	0.	0.	.000
7	6600.	.00	.000	0.	1.76	.000	.000	0.	0.	.000
8	8300.	.00	.000	0.	1.81	.000	.000	0.	0.	.000
Acceleration										
9	10000.	.00	.000	0.	3.66	.000	.000	0.	0.	.000
En-route climb										
10	10000.	.00	.000	0.	1.69	.000	.000	0.	0.	.000
11	14200.	.00	.000	0.	1.37	.000	.000	0.	0.	.000
12	18400.	.00	.000	0.	1.40	.000	.000	0.	0.	.000
13	22600.	.00	.000	0.	1.38	.000	.000	0.	0.	.000
14	26800.	.00	.000	0.	1.29	.000	.000	0.	0.	.000
Cruise										
15	31000.	.00	.000	0.	.90	.000	.000	0.	0.	.000
16	31000.	.00	.000	0.	.87	.000	.000	0.	0.	.000
17	31000.	.00	.000	0.	.84	.000	.000	0.	0.	.000

18	31000.	.00	.000	0.	.82	.000	.000	0.	0.	.000
19	31000.	.00	.000	0.	.80	.000	.000	0.	0.	.000
20	31000.	.00	.000	0.	1.08	.000	.000	0.	0.	.000
21	35000.	.00	.000	0.	.75	.000	.000	0.	0.	.000
22	35000.	.00	.000	0.	.72	.000	.000	0.	0.	.000
23	35000.	.00	.000	0.	.70	.000	.000	0.	0.	.000
24	35000.	.00	.000	0.	.68	.000	.000	0.	0.	.000
25	35000.	.00	.000	0.	.66	.000	.000	0.	0.	.000
26	35000.	.00	.000	0.	.65	.000	.000	0.	0.	.000
Descent/holding										
27	35000.	.00	.000	0.	.13	.000	.000	0.	0.	.000
28	28300.	.00	.000	0.	.13	.000	.000	0.	0.	.000
29	21600.	.00	.000	0.	.13	.000	.000	0.	0.	.000
30	14900.	.00	.000	0.	.15	.000	.000	0.	0.	.000
31	8200.	.00	.000	0.	.17	.000	.000	0.	0.	.000
Approach/landing										
32	1500.	.00	.000	0.	.38	.000	.000	0.	0.	.000
Taxi-in										
33	0.	.00	.000	0.	.19	.000	.000	0.	0.	.000

Combustion parameters (2/2) - Propulsion unit 1,2,3,4

Step	Height	PLov	PLlin	Effre	Effev	Effov	Effpz	SMD	EvaCt
-	-ft	-%	-%	-%	-%	-	-	-mc.m	-mm2/s

Start									
1	0.	.00	.00	.0	.0	.0	.0	.00	.000
Taxi-out									
2	0.	.00	.00	.0	.0	.0	.0	.00	.000
Take-off									
3	0.	.00	.00	.0	.0	.0	.0	.00	.000
Initial climb									
4	1500.	.00	.00	.0	.0	.0	.0	.00	.000
5	3200.	.00	.00	.0	.0	.0	.0	.00	.000
6	4900.	.00	.00	.0	.0	.0	.0	.00	.000
7	6600.	.00	.00	.0	.0	.0	.0	.00	.000
8	8300.	.00	.00	.0	.0	.0	.0	.00	.000
Acceleration									
9	10000.	.00	.00	.0	.0	.0	.0	.00	.000
En-route climb									
10	10000.	.00	.00	.0	.0	.0	.0	.00	.000
11	14200.	.00	.00	.0	.0	.0	.0	.00	.000
12	18400.	.00	.00	.0	.0	.0	.0	.00	.000
13	22600.	.00	.00	.0	.0	.0	.0	.00	.000
14	26800.	.00	.00	.0	.0	.0	.0	.00	.000
Cruise									
15	31000.	.00	.00	.0	.0	.0	.0	.00	.000
16	31000.	.00	.00	.0	.0	.0	.0	.00	.000
17	31000.	.00	.00	.0	.0	.0	.0	.00	.000
18	31000.	.00	.00	.0	.0	.0	.0	.00	.000
19	31000.	.00	.00	.0	.0	.0	.0	.00	.000
20	31000.	.00	.00	.0	.0	.0	.0	.00	.000
21	35000.	.00	.00	.0	.0	.0	.0	.00	.000
22	35000.	.00	.00	.0	.0	.0	.0	.00	.000
23	35000.	.00	.00	.0	.0	.0	.0	.00	.000
24	35000.	.00	.00	.0	.0	.0	.0	.00	.000
25	35000.	.00	.00	.0	.0	.0	.0	.00	.000
26	35000.	.00	.00	.0	.0	.0	.0	.00	.000
Descent/holding									
27	35000.	.00	.00	.0	.0	.0	.0	.00	.000
28	28300.	.00	.00	.0	.0	.0	.0	.00	.000
29	21600.	.00	.00	.0	.0	.0	.0	.00	.000

30	14900.	.00	.00	.0	.0	.0	.0	.00	.000
31	8200.	.00	.00	.0	.0	.0	.0	.00	.000
Approach/landing									
32	1500.	.00	.00	.0	.0	.0	.0	.00	.000
Taxi-in									
33	0.	.00	.00	.0	.0	.0	.0	.00	.000

NOx, CO & UHC emissions - Phase breakdown - All propulsion units

	NOx			CO			UHC		
	-kg	-%	-g/kg	-kg	-%	-g/kg	-kg	-%	-g/kg
Start	.1	.0	4.6	.34	.5	13.74	.02	.1	.89
Taxi-out	2.6	.0	4.6	7.63	11.2	13.74	.49	1.4	.89
Take-off	99.1	1.9	58.7	1.00	1.5	.59	.66	1.8	.39
Initial climb	62.5	1.2	40.5	.66	1.0	.43	.42	1.2	.27
Acceleration	21.5	.4	40.5	.23	.3	.43	.14	.4	.27
En-route climb	204.3	3.9	40.5	2.17	3.2	.43	1.36	3.8	.27
Cruise 1	528.0	10.2	40.5	5.60	8.2	.43	3.52	9.8	.27
Cruise 2	509.1	9.8	40.5	5.40	7.9	.43	3.39	9.5	.27
Cruise 3	493.5	9.5	40.5	5.23	7.7	.43	3.29	9.2	.27
Cruise 4	480.3	9.2	40.5	5.09	7.5	.43	3.20	8.9	.27
Cruise 5	467.7	9.0	40.5	4.96	7.3	.43	3.11	8.7	.27
Cruise 6	42.3	.8	40.5	.45	.7	.43	.28	.8	.27
Cruise 7	447.1	8.6	40.5	4.74	7.0	.43	2.98	8.3	.27
Cruise 8	429.7	8.3	40.5	4.56	6.7	.43	2.86	8.0	.27
Cruise 9	416.7	8.0	40.5	4.42	6.5	.43	2.78	7.8	.27
Cruise 10	405.1	7.8	40.5	4.30	6.3	.43	2.70	7.5	.27
Cruise 11	394.9	7.6	40.5	4.19	6.2	.43	2.63	7.4	.27
Cruise 12	183.9	3.5	40.5	1.95	2.9	.43	1.22	3.4	.27
Cruise totals	4798.1	92.2	40.5	50.89	74.9	.43	31.96	89.4	.27
Descent/holding	6.6	.1	9.6	.70	1.0	1.01	.26	.7	.37
Holding only	.0	.0	.0	.00	.0	.00	.00	.0	.00
Approach/landing	5.3	.1	9.6	.56	.8	1.01	.20	.6	.37
Taxi-in	1.3	.0	4.6	3.81	5.6	13.74	.25	.7	.89
Mission totals	5200.0	100.0	40.3	63.83	93.9	.50	35.49	99.2	.28
Block totals	5201.4	100.0	40.2	67.99	100.0	.53	35.76	100.0	.28

H2O & CO2 emissions - Phase breakdown - All propulsion units

	H2O			CO2		
	-kg	-%	-g/kg	-kg	-%	-g/kg
Start	32.	.0	1284.	78.	.0	3138.
Taxi-out	713.	.4	1284.	1742.	.4	3138.
Take-off	2166.	1.3	1284.	5294.	1.3	3138.
Initial climb	1980.	1.2	1284.	4839.	1.2	3138.
Acceleration	682.	.4	1284.	1666.	.4	3138.
En-route climb	6469.	3.9	1284.	15811.	3.9	3138.
Cruise 1	16723.	10.1	1284.	40869.	10.1	3138.
Cruise 2	16124.	9.7	1284.	39407.	9.7	3138.
Cruise 3	15630.	9.4	1284.	38199.	9.4	3138.
Cruise 4	15212.	9.2	1284.	37176.	9.2	3138.
Cruise 5	14813.	8.9	1284.	36201.	8.9	3138.
Cruise 6	1340.	.8	1284.	3274.	.8	3138.
Cruise 7	14161.	8.5	1284.	34609.	8.5	3138.
Cruise 8	13608.	8.2	1284.	33258.	8.2	3138.
Cruise 9	13198.	8.0	1284.	32254.	8.0	3138.
Cruise 10	12829.	7.7	1284.	31354.	7.7	3138.
Cruise 11	12506.	7.5	1284.	30564.	7.5	3138.
Cruise 12	5824.	3.5	1284.	14233.	3.5	3138.
Cruise totals	151968.	91.6	1284.	371398.	91.6	3138.

Descent/holding	892.	.5	1284.	2180.	.5	3138.
Holding only	0.	.0	0.	0.	.0	0.
Approach/landing	709.	.4	1284.	1734.	.4	3138.
Taxi-in	356.	.2	1284.	871.	.2	3138.
Mission totals	165580.	99.8	1284.	404664.	99.8	3138.
Block totals	165968.	100.0	1284.	405614.	100.0	3138.

Flight emission analysis

Parameter	NOx	CO	UHC	H2O	CO2
kg/flight	5201.4	67.99	35.76	165968.	405614.
Flight index g/kg	40.24	.526	.277	1284.00	3138.00
kg/cruise	4798.1	50.89	31.96	151968.	371398.
Cruise index g/kg	40.54	.430	.270	1284.00	3138.00
kg/RPM	1.894	.0248	.0130	60.42	147.67
kg/TNM	14.480	.1893	.0996	462.04	1129.20
kg/LTO 1,2,3,4	.00	.00	.00	-	-
kg/LTO limit 1,2,3,4	.00	.00	.00	-	-
Compliance 1,2,3,4	.0	.0	.0	-	-

7) ATMOSPHERIC CONDITIONS

Step	Height -ft	Patm -atm	Tatm -K	Tisa -K	Trel -K	Datm -kg/m3	Drel -	Vwind -m/s	Vsound -m/s
Start									
1	0.	1.000	288.2	.0	1.000	1.2248	1.000	.0	661.7
Taxi-out									
2	0.	1.000	288.2	.0	1.000	1.2248	1.000	.0	661.7
Take-off									
3	0.	1.000	288.2	.0	1.000	1.2248	1.000	.0	661.7
Initial climb									
4	1500.	.947	285.2	.0	.990	1.1720	.957	.0	658.3
5	3200.	.890	281.8	.0	.978	1.1142	.910	.0	654.4
6	4900.	.835	278.5	.0	.966	1.0586	.864	.0	650.5
7	6600.	.783	275.1	.0	.955	1.0052	.821	.0	646.6
8	8300.	.734	271.7	.0	.943	.9538	.779	.0	642.6
Acceleration									
9	10000.	.688	268.3	.0	.931	.9045	.738	.0	638.6
En-route climb									
10	10000.	.688	268.3	.0	.931	.9045	.738	.0	638.6
11	14200.	.583	260.0	.0	.902	.7910	.646	.0	628.6
12	18400.	.491	251.7	.0	.873	.6888	.562	.0	618.5
13	22600.	.412	243.4	.0	.845	.5969	.487	.0	608.2
14	26800.	.343	235.1	.0	.816	.5148	.420	.0	597.7
Cruise									
15	31000.	.284	226.7	.0	.787	.4416	.361	.0	587.0
16	31000.	.284	226.7	.0	.787	.4416	.361	.0	587.0
17	31000.	.284	226.7	.0	.787	.4416	.361	.0	587.0
18	31000.	.284	226.7	.0	.787	.4416	.361	.0	587.0
19	31000.	.284	226.7	.0	.787	.4416	.361	.0	587.0
20	31000.	.284	226.7	.0	.787	.4416	.361	.0	587.0
21	35000.	.235	218.8	.0	.759	.3795	.310	.0	576.7
22	35000.	.235	218.8	.0	.759	.3795	.310	.0	576.7
23	35000.	.235	218.8	.0	.759	.3795	.310	.0	576.7
24	35000.	.235	218.8	.0	.759	.3795	.310	.0	576.7
25	35000.	.235	218.8	.0	.759	.3795	.310	.0	576.7
26	35000.	.235	218.8	.0	.759	.3795	.310	.0	576.7

Descent/holding										
27	35000.	.235	218.8	.0	.759	.3795	.310	.0	576.7	
28	28300.	.321	232.1	.0	.805	.4877	.398	.0	593.9	
29	21600.	.430	245.4	.0	.851	.6179	.504	.0	610.6	
30	14900.	.567	258.6	.0	.898	.7732	.631	.0	626.9	
31	8200.	.737	271.9	.0	.944	.9568	.781	.0	642.8	
Approach/landing										
32	1500.	.947	285.2	.0	.990	1.1720	.957	.0	658.3	
Taxi-in										
33	0.	1.000	288.2	.0	1.000	1.2248	1.000	.0	661.7	

Appendix E.1

Key Technology Limiters Affecting Engine Cycle Design

The appendix presents a list of the major design considerations and limitations with their implications on cycle performance parameters. The cycle parameters presented in the right-hand column are either inputs required by SKY Aero Engine and Emission Modules (e.g. pressure ratios, temperatures, etc.) or lead indirectly to such parameters (e.g. cooling efficiency level leading to a maximum operating temperature such as TET).

DESIGN CONSIDERATIONS AND REQUIREMENTS	IMPACT ON CYCLE PERFORMANCE PARAMETERS
1) High reliability & long overhaul life This is achieved by maximising creep life and minimising thermal fatigue and oxidation. This will clearly depend on the component stresses (i.e. geometry and rotational speeds) and operating temperatures. The critical components include :- <ul style="list-style-type: none"> • HP compressor disc and blades • HP turbine disc, blades and NGVs • IP turbine discs and blades The shortest lives are usually allowed for turbine blades with 10000 to 20000 hours being required for civil engines. The combustor outlet temperature distribution strongly affect turbine life and is quantified through RTDF and OTDF (radial and overall temperature distribution factors). RTDF (typically 7 to 15%) is the relevant factor for the rotor blades, because the rotation creates automatic circumferential averaging. Typically, OTDF is set higher to between 20 to 35%, because it is expected that some airfoils will experience the hottest streaks.	<u>Compressor disc & blades :</u> T_3 (depending on OPR) $\eta_{HPC/poly}$ <u>HP turbine disc :</u> T_3 (depending on OPR) $\eta_{HPC/poly}$ T_4 <u>HP turbine blades & NGVs :</u> T_4 Cooling flow Cooling technology efficiency RTDF (combustor design) T_{bm} (blade metal temperature) η_{c*} (app. convection cooling efficiency) <u>IP turbine disc & blades :</u> T_4 Cooling flow Cooling technology efficiency
2) Combustor pressure differential An adequate level is required to drive the turbine cooling flows and avoid turbine overheating, typically at least 4%	Combustor overall pressure loss
3) Combustion mixing-rate controlled efficiency	Overall combustion efficiency
4) Effect of bleed-in flows on turbine aerodynamics They include cooling flow disturbance and boundary layer thickening. These effects can be estimated using a mix of CFD and empirical methods. Typically in-engine aerodynamic turbine efficiencies are some 2% lower than might be measured on a cold turbine rig, with no simulation of the cooling flows.	$\eta_{HPT/isen}$ $\eta_{IPT/isen}$
5) Fan and compressor surge margin Sufficient working surge margin (Z) is required across the intended flight envelope and under all likely transient	$Z_{Fan}, Z_{IPC}, Z_{HPC}$ $\eta_{Fan/poly}, \eta_{IPC/poly}, \eta_{HPC/poly}$ BPR

<p>conditions. The required surge margin is built up empirically from a consideration of the various sources of instability. The main factors contributing roughly equally are 1) allowance for build tolerances and in-service deterioration, 2) allowance for intake flow distortions due to cross-wind and/or severe pitch/yaw aircraft manoeuvres and 3) allowance for running line shift during engine transients. Typically, Z should lie between 15 and 25%. With high BPR turbofans, the surge margin requirement at SLS can impose BPR limitations if no variability in the bypass duct is incorporated to ensure stable operation.</p>	
<p>6) Fan and compressor stage loading The need to minimise fuel burn for civil applications leads to modest core compressor stage loadings (high component efficiencies). Fan stage pressure ratios (FPR) can be considerably higher (1.8 to 1.85), because high blade speed transonic designs are habitually used. HP compressors require lower stage pressure rises due to the combinations of rear stage stresses and temperatures and narrow flow annuli. On mechanical, noise and fan efficiency ground, fan pressure ratios beyond 1.8 are not acceptable.</p>	<p>FPR $\eta_{\text{Fan/poly}}$, $\eta_{\text{IPC/poly}}$, $\eta_{\text{HPC/poly}}$ Engine length Engine weight</p>
<p>7) Reynolds number effects From sea level to altitude cruise, Reynolds number can change by a factor of around 2.5, giving a compressor efficiency loss of some 1.5%. This reduction forces the engine to rematch to a slightly higher running line and must be included in the surge margin assessment.</p>	<p>Z_{Fan}, Z_{IPC}, Z_{HPC} $\eta_{\text{Fan/poly}}$, $\eta_{\text{IPC/poly}}$, $\eta_{\text{HPC/poly}}$</p>
<p>8) Combustor liner material and wall cooling requirements Until this day, combustor walls have not outpaced the turbines as cycle temperature limiters.</p>	<p>T_4</p>
<p>9) Fan tip speeds limitations due to mechanical considerations As diameter goes up LP spool speed must be reduced, with a growing mismatch between the operating requirements of the fan and the LP turbine, the speed of which must be kept high in order to retain acceptable stage loadings. Ultimately, fan tip speed cannot exceed 450 m/s imposing a limit on fan diameter. This problem can be met by increasing turbine stage numbers, but there are practical limits and 6 or 7 stages are about the most that might be accepted (engines with BPR of 5 have 3 or 4 LP turbine stages). Alternatives to increasing the number of LP turbine stages include using contra-rotating turbines or coupling the fan to the turbine via a step-up gearbox.</p>	<p>Nacelle diameter $\eta_{\text{HPT/isen}}$ Engine length (due to No of LP stages) Engine weight</p>
<p>10) Use of a gearbox to overcome LP shaft torque limitations and worsening efficiency levels for BPR beyond 9-10 High levels of LP turbine efficiency can be maintained at any BPR without the need for additional stages. The gearbox imposes a weight and cost penalty and internal mechanical losses. The mechanical efficiency is approximately 1.5% at cruise and 1% at take-off.</p>	<p>$\eta_{\text{HPT/isen}}$ Engine length (lower No of LP stages) Engine weight $\eta_{\text{LP/mech}}$</p>
<p>11) Low fan noise level Low fan tip speed reduces fan shock losses at the expense</p>	<p>$\eta_{\text{Fan/isen}}$</p>

of a slightly deteriorated fan efficiency	
12) Intake tolerance to fan inlet flow distortion Careful design of the nacelle is necessary to ensure that the cowl and intake aerodynamics are satisfactory at all operating conditions. Thin lipped intakes of low contraction ratio can minimise drag but could give rise to fan inlet flow distortion problems if crosswinds are present during take-off. The viability of ultra high bypass turbofans is critically dependent upon the successful development of advanced, lightweight, low drag nacelles.	Nacelle diameter Engine weight
13) Noise minimisation The noise components to be minimised include jet noise (requiring low exhaust jet velocities and as a result high BPR), fan noise (requiring low BPR at low thrust settings) and turbomachinery noise (requiring acoustic shielding). The magnitude of noise varies roughly as $Q_j V_j^8$. In high bypass engines, the far field noise comes in fairly equal measure from the fan and compression system, the LP turbine and the jets. It has been found that the use of mixed exhausts brings some noise benefits. Turbomachinery noise is largely dependent on the internal configurations of the compressor and turbine systems (blade numbers, spacings, etc.) although tip speeds are also important. The relationship between the noise and the engine cycle is indirect. Increasing BPR will raise the contribution from the fan. A major means of control is the use of acoustic linings in the duct both upstream and downstream of the fan. These are likely to become less effective with increasing BPR, particularly as the need to minimise cowl length and diameter for external drag reasons will restrict the space available for the linings. The low FPR required will alleviate the noise to some extent because fan tip speed can be reduced. Nevertheless, although difficult to quantify, it is possible that the noise problem can introduce an additional upper constraint on the choice of BPR.	BPR FPR Nacelle length and diameter Engine weight
13) nozzle variability mechanisms	BPR Nacelle length and diameter
14) Thrust reversal	Nacelle length and diameter Engine weight
15) Use of laminar flow control over nacelles Laminar flow control could provide significant benefits in terms of drag reduction over more conventional designs if practical systems capable of withstanding the commercial aircraft operating environment can be developed.	Engine weight
16) Engine core geometric constraints Limitations on LP shaft diameter as well as shaft torque.	Engine length (No of LP turbine stages) $\eta_{LPT/poly}$ BPR
17) Underwing ground clearance To achieve sufficient ground clearance, the nacelle must be closely & carefully coupled to the wing (nacelle/wing interference must be avoided) and be as slim-line as possible (requiring a sharp lip to the intake, which will make the engine more sensitive to cross-winds at low aircraft speeds (e.g. during ground handling). NB : the fan diameter can be estimated assuming a fan inlet	Nacelle diameter

Mach number of 0.68 at typical ADP conditions.	
18) Low fuel burn With a separate exhausts turbofans and for a given BPR, FPR can be selected so as to minimise s.f.c.	FPR

Appendix E.2

The CAPE Performance and Emission Simulation Management System

In order to carry out a large number of aero gas turbine performance points, there is a need to build a computer program that can read, modify and run Turbomatch input data files in accordance with a number of requirements including :-

- Adjustment of compressor isentropic efficiency for constant polytropic efficiency
- Adjustment of turbine isentropic efficiency for constant polytropic efficiency
- Adjustment of cooling air flow for constant turbine inlet temperature
- Fan pressure ratio optimisation for best s.f.c. (in the case of separate exhausts)
- Adjustment of TET for constant NO_x index
- Adjustment of HPC pressure ratio or IPC pressure ratio for constant OPR

The CAPE computer system has been designed to this effect and makes possible the comparison of cycles incorporating identical levels of compressor, turbine or blade cooling technologies. It is based on SKY *Aero Engine* and *Emission modules*. CAPE has been designed as a tool for the analysis of performance, fuel economy and low emissions, in the preliminary design of aero gas turbines (see Figure 1).

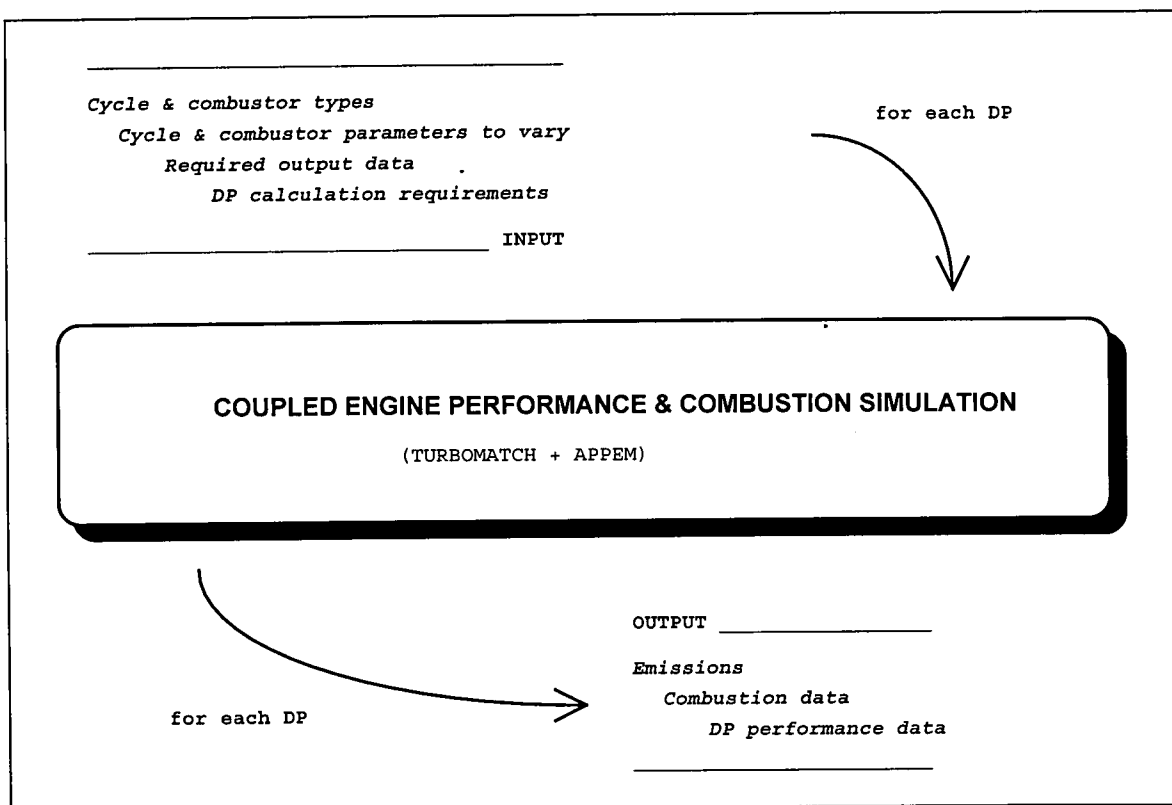


Figure 1 : CAPE Performance and Emissions Simulation Management System