Aircraft Fuel Systems

Roy Langton

Retired Group VP Engineering, Parker Aerospace, USA

Chuck Clark

Retired Marketing Manager, Air & Fuel Division, Parker Aerospace, USA

Martin Hewitt

Retired Director of Marketing, Electronic Systems Division, Parker Aerospace, USA

Lonnie Richards

Senior Expert, Fuel Systems, Airbus UK, Filton, UK

WILEY

A John Wiley and Sons, Ltd, Publication

Aircraft Fuel Systems

Aerospace Series List

The Global Airline Industry	Belobaba	April 2009
Computational Modelling and Simulation of Aircraft and the Environment, Volume 1: Platform Kinematics and Synthetic Environment	Diston	April 2009
Aircraft Performance Theory and Practice for Pilots	Swatton	August 2008
Aircraft Systems, 3rd Edition	Moir & Seabridge	March 2008
Introduction to Aircraft Aeroelasticity and Loads	Wright & Cooper	December 2007
Stability and Control of Aircraft Systems	Langton	September 2006
Military Avionics Systems	Moir & Seabridge	February 2006
Design and Development of Aircraft Systems	Moir & Seabridge	June 2004
Aircraft Loading and Structural Layout	Howe	May 2004
Aircraft Display Systems	Jukes	December 2003
Civil Avionics Systems	Moir & Seabridge	December 2002

Aircraft Fuel Systems

Roy Langton

Retired Group VP Engineering, Parker Aerospace, USA

Chuck Clark

Retired Marketing Manager, Air & Fuel Division, Parker Aerospace, USA

Martin Hewitt

Retired Director of Marketing, Electronic Systems Division, Parker Aerospace, USA

Lonnie Richards

Senior Expert, Fuel Systems, Airbus UK, Filton, UK

WILEY

A John Wiley and Sons, Ltd, Publication

This edition first published 2009

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex,
PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

Aircraft fuel systems / Roy Langton . . . [et al.].
p. cm. — (Aerospace series)
Includes bibliographical references and index.
ISBN 978-0-470-05708-7 (cloth)
1. Airplanes—Fuel systems. I. Langton, Roy.
TL702.F8A35 2008b
629.134′351—dc22
2008036183

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 978-0-470-05708-7

Set in 10/12pt Times by Integra Software Services Pvt. Ltd. Pondicherry, India
Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire, UK

This book is dedicated to the memory of Richard Jorgensen

Contents

Acknowledgements

This book would not have been completed without the help and support of many colleagues and organizations who provided valuable information with enthusiasm. A large proportion of the design and equipment examples were provided by Parker Aerospace and Airbus by virtue of the fact that they are (or were) the employees of the authors for many years. Parker Aerospace has become a major source for fuel systems equipment to the industry and the Airbus fuel systems "Center-of-excellence" based in Filton UK has become one of Parker's major customers over the past decade.

The authors feel that it is appropriate to name specific individuals who gave much of their personal time in helping this project come to fruition:

Ron Bueter	Ray Bumpus
John Bunting	James Chu
Paul DiBella	Chris Horne
Alan Kocka	Joe Monaco
Mike Nolte	Candy Parker
David Sandy	Tim Pullen
John Passmore-Strong	Ira Rubel

In addition, the following organizations were an important source of information in support of the preparation of this book:

AMETEK, Inc
BAE SYSTEMS
Boeing
Bombardier
Embraer
GE Aviation

List of Acronyms

ACT	Additional Center Tank
ADCN	Air Data Communications Network
AFDX	Avionics Full DupleX
AGP	Alternate Gauging Processor
AIMS	Aircraft Information Management System
AIR	Aerospace Information Report
API	Armor Piercing Incendiary
APU	Auxiliary Power Unit
ARINC	Aeronautical Radio InCorporated
ARP	Aerospace Recommended Practice
ARSAG	Aerial Refueling Systems Advisory Group
ASCB	Avionics Standard Communications Bus
ASM	Air Separation Module
ASTM	American Society for Testing and Materials
AWG	American Wire Gauge
BDA	Boom-Drogue Adapter
BIT	Built In Test
BITE	Built In Test Equipment
CAD	Computer Aided Design
CCA	Common Cause Analysis
CDR	Critical Design Review
CDS	Central Display System
CENELEC	European Committee for Electrostandardisation
CG	Center of Gravity
CMCS	Central Maintenance Computer System
CMF	Central Maintenance Function
CPIOM	Central Processor Input/Output Module
CS	Certification Specification
DAC	Digital-to-Analog Converter
DEU	Data Entry Unit
DIN	Discrete INput

DMC	Display Management Computer
DPUP	Display Primary Micro-Processor
DSP	Digital Signal Processor
DRUP	Display Redundant Micro-Processor
EAP	Experimental Aircraft Program
EASA	European Aviation Safety Agency
ECAM	Electronic Centralised Monitor
EICAS	Engine Indication, Cautions and Advisories System
EIS	Entry Into Service
ELMS	Electrical Load Management System
EMI	Electro Magnetic Interference
EMC	Electro Magnetic Compatibility
ETOPS	ExTended long range OPerationS
FAA	Federal Aviation Authority
FAR	Federal Airworthiness Regulation
FCU	Fuel Conditioning Unit
FHA	Functional Hazard Analysis
FMC	Fuel Management Computer
FMECA	Failure Modes Effects and Criticality Analysis
FMQGS	Fuel Management and Quantity Gauging System
FMMS	Fuel Measurement and Management System
FMS	Flight Management System
FOD	Foreign Object Damage
FPMU	Fuel Properties Measurement Unit
FQDC	Fuel Quantity Data Concentrator
FQGS	Fuel Quantity Gauging System
FQIS	Fuel Quantity Indication System
FQPU	Fuel Quantity Processing Unit
FSAS	Fuel Savings Advisory System
FWC	Flight Warning Computer
HDU	Hose-Drum Unit
HEI	High Energy Incendiary
HEXFET	Hexagonal Field Effect Transistor
HIRF	High Incidence Radiated Frequencies
IDG	Integrated Drive Generation
IFR	Instrument Flight Rules
IFMCGS	Integrated Fuel Measurement & Center-of-Gravity System
IFMP	Integrated Fuel Management Panel
IGBT	Insulated Gate Bi-Polar Transistor
IMA	Integrated Modular Avionics
IML	Inner Mold Line
INCOSE	InterNational Council on Systems Engineering

INS	Inertial Navigation System
IRP	Integrated Refuel Panel
JAA	Joint Aviation Agency
JFGW	Jettison Fuel to Gross Weight
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LP	Low Pressure
LROPS	Long Range OPerationS
LRU	Line Replaceable Unit
MAU	Modular Avionics Unit
MCU	Modular Concept Unit
MFD	Multi Function Display
MLI	Magnetic Level Indicator
MLW	Maximum Landing Weight
MMEL	Master Minimum Equipment List
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MTBF	Mean Time Between Failures
MTBUR	Mean Time Between Unscheduled Removals
MTOW	Maximum Take-Off Weight
NACA	National Advisory Committee for Aeronautics
NEA	Nitrogen Enriched Air
NPSH	Net Positive Suction Head
NPSHa	Net Positive Suction Head available
NPSHr	Net Positive Suction Head required
NTSB	National Transportation Safety Board
OBIGGS	On-Board Inert Gas Generation System
OEM	Original Equipment Manufacturer
OHP	OverHead Panel
O-O	Object-Oriented
PDR	Preliminary Design Review
PF	Power Factor
PSSA	Preliminary System Safety Analysis
PTFE	PolyTetreFluoroEthylene
PUP	Primary MicroProcessor
PWM	Pulse Width Modulation
RF	Radio Frequency
RTD	Resistance-Temperature Device
RTCA	Radio Technical Commission for Aeronautics
RUP	Redundant MicroProcessor

SAC	Strategic Air Command
SAE	Society of Automotive Engineers
SFAR	Special Federal Aviation Regulation
SSA	System Safety Analysis
STE	Special Test Equipment
TIU	Tank Interface Unit
TPU	Tank Processing Unit
TSP	Tank Signal Processor
TSU	Transient Suppression Unit
UAV	Uninhabited Air Vehicle
UARRSI	Universal Aerial Refueling Receptacle Slipway Installation
UML	Unified Modeling Language
USGPM	US Gallons Per Minute
VF	Variable Frequency
VOS	Velocity Of Sound
VSCF	Variable Speed Constant Frequency
WOW	Weight On Wheels

Series Preface

The field of aerospace is wide ranging and covers a variety of products, disciplines and domains, not merely in engineering but in many supporting activities. These combine to enable the aerospace industry to produce exciting and technologically challenging products. A wealth of knowledge is contained by practitioners and professionals in the industry in the aerospace fields that is of benefit to other practitioners in the industry, and to those entering the industry from university or other fields.

The Aerospace Series aims to be a practical and topical series of books for engineering professionals, operators and users and allied professions such as commercial and legal executives in the aerospace industry. The range of topics spans design and development, manufacture, operation and support of the aircraft as well as infrastructure operations, and developments in research and technology. The intention is to provide a source of relevant information that will be of interest and benefit to all those people working in aerospace.

This book co-authored by Roy Langton, Chuck Clark, Martin Hewitt and Lonnie Richards is a unique treatise on aircraft fuel systems, dealing with the design considerations for both commercial and military aircraft systems. As well as describing the system and its components in detail, *Aircraft Fuel Systems* also deals with the design process and examines the key systems drivers that a fuel system designer must take into account. This promises to be a standard work of reference for aircraft fuel systems designers.

Ian Moir, Allan Seabridge and Roy Langton

1

Introduction

While aircraft fuel systems are not generally regarded as the most glamorous feature of aircraft functionality they are an essential feature of all aircraft. Their implementation and functional characteristics play a critical role in the design, certification and operational aspects of both military and commercial (civil) aircraft. In fact the impact of fuel system design on aircraft operational capability encompasses a range of technologies that are much more significant than the nonspecialist would at first realize, particularly when considering the complexities of large transport and high speed military aircraft applications.

To illustrate this point, Figure 1.1 shows the power and intersystem information flow for a typical fuel system in a modern transport aircraft application. This 'aircraft perspective' demonstrates the interconnectivity of the fuel system with the overall aircraft and provides an indication of the role of the aircraft fuel system in the functionality of the aircraft as a whole.

This book brings together all of the issues associated with fuel systems design, development and operation from both an intersystem and intrasystem perspective covering the design, functional and environmental issues associated with the various technologies, subsystems and components.

The range of aircraft applications covered herein focuses on gas turbine powered aircraft from the small business jet to the largest transport aircraft including military applications such as fighter aircraft and helicopters.

The fuel systems associated with small internal combustion engine-powered aircraft used by the General Aviation community are not discussed in this publication since the system-level challenges in this case are minimized by the flight envelope which is confined to low altitudes and speeds and therefore the fuel system issues for these aircraft applications are relatively straightforward.

The scope of the material presented herein is focused on all areas of aircraft fuel systems from the refuel source to the delivery of fuel to the engine or engines of the aircraft. The engine fuel control system is only covered here at a high level since it is a separate and complex subject in its own right and will therefore be addressed in depth in a separate Aerospace Series publication addressing aircraft propulsion systems.

Aircraft Fuel Systems R. Langton, C. Clark, M. Hewitt, L. Richards

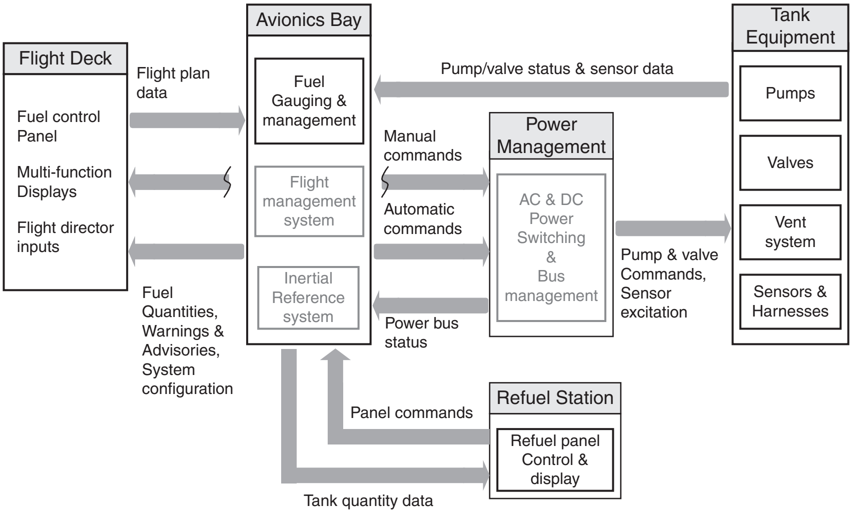

Figure 1.1 The fuel system from an aircraft perspective.

1.1 Review of Fuel Systems Issues

To introduce the subject of aircraft fuel systems the following paragraphs provide an overview of a number of the fundamental issues in an attempt to provide the reader with a feel for many of the key system and operational features that must be addressed routinely by the system design team. The comments offered in this introductory chapter are maintained at a fairly high level since a much more detailed treatment of every aspect of aircraft fuel systems is covered in the ensuing chapters.

1.1.1 Basic Fuel System Characteristics and Functions

To begin it must be appreciated that very large quantities of fuel (in terms of the fuel volume to aircraft volume ratio) must be stored aboard in order that the aircraft can meet its operating range requirements. This in turn demands a high refueling rate capability particularly in commercial transport applications where turnaround-time is a critical operational factor. While the introduction of pressure refueling goes a long way to solving this problem it does bring with it other related challenges such as the control of surge pressure following valve closure as the required tank quantities are reached. See Chapter 4 for more detail on this subject. Another pressure refueling-related issue concerns the prevention of electrostatic charge build-up resulting from fuel movement through piping at high velocities (see Chapter 9). Fuel spillage or structural damage must also be prevented through careful tank venting system design and rigorous control of the refueling process. This is addressed in Chapter 3 which discusses fuel storage and venting issues in detail.

Pressure refueling has become the standard used by all commercial and military aircraft where significant fuel quantities are involved (say 1000 gallons or more) although provision for gravity refueling is typically available on all but the largest transport aircraft where such a capability becomes impractical. The system must also make provision for defueling the aircraft for maintenance purposes and also in the, hopefully, rare event of an accident where it becomes necessary to remove the fuel from the aircraft before the aircraft can be safely moved. This process utilizes an external suction source. Frequently the on-board fuel pumps can be used to defuel the aircraft or to transfer fuel between tanks in support of ground maintenance needs.

An issue related to the refuel and defuel function is fuel jettison in flight. This function becomes an important procedure for large transport aircraft where take-off weight with a full fuel load can be substantially higher than the maximum landing weight. Therefore a major failure that takes place during or shortly after take-off can require jettison of fuel to reduce the weight of the aircraft to an acceptable level before an emergency landing can be made without exceeding the undercarriage/landing gear equipment design limits. The jettison system is required to move large quantities of fuel overboard as quickly as possible and to stop jettison before safe minimum fuel quantities are reached. This recognizes that in such emergency situations the crew will be very busy flying the airplane and would prefer not to have to spend valuable time monitoring the jettison process. Today's modern transports therefore have sophisticated jettison systems that must be prevented from uncommanded activation and be able to stop jettison automatically when some predetermined minimum fuel load or aircraft gross weight has been achieved.

Figure 1.2 shows a typical fuel tank layout for a commercial aircraft. Wing structure is a common location for fuel storage and in many commercial transports additional tanks are located in the area between the wings. Longer range aircraft and business jets may have tail tanks and/or additional fuselage tanks; however, in most cases the fuselage is primarily the place for passengers, cargo, flight deck (cockpit) and avionics equipment.

Military fighters are a special case and while the wing space is used for fuel storage in these applications, almost any available space in the fuselage is fair game for fuel since range

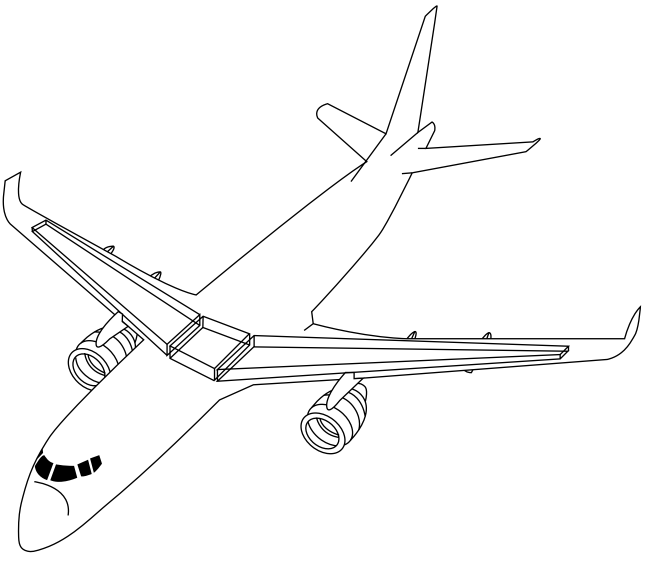

Figure 1.2 Typical transport aircraft fuel tank arrangement.

limitations are a perennial challenge for the military aircraft designer. Often the result is a number of fuselage tanks with complex shapes and a challenging fluid network design.

Fuel tank design for such large quantities of fuel on board an aircraft is a challenge for the aircraft structural designer who must also take into account the potential impact of an uncontained engine rotor burst. Such an event can generate high energy debris that can result in penetration of fuel tanks that are located in the path of the debris with subsequent loss of fuel. Consideration has to be made with regard to the ability of the aircraft to survive such an engine failure when establishing certification of the aircraft. This important issue is dealt with in more detail in Chapters 2 from an aircraft design and equipment location perspective.

In military applications battle damage with fuel tank penetration can result in loss of fuel and possible fuel tank explosion with an almost certain loss of the aircraft. For this reason, fuel tank inerting systems are commonly used to render the space above the fuel (ullage) safe from potential explosion. From a survivability perspective it is the overpressure resulting from a fuel tank explosion that can destroy an aircraft. Many different inerting techniques have been used by the military community over the past forty years including halon, stored liquid nitrogen, and reticulated foam installed in the tanks. More recently the On-Board Inert Gas Generation System (or OBIGGS) has become the standard approach to tank inerting because of the significant improvements in air-separation technology that have taken place in the past ten years. This system uses special-purpose fiber bundles to strip and dispose of a large percentage of the oxygen molecules from incoming air resulting in the generation of a source of nitrogen-enriched air (NEA). Engine bleed air is typically used as a source of air for separation. NEA output from the fiber bundles contains only a small percentage of oxygen and much less than what is required to sustain a fire or an explosion and therefore replacement of the ullage air with NEA will render a fuel tank inert and safe from potential explosion. A secondary but important issue concerns the air in solution within the fuel itself. Kerosene fuel can contain up to 14 % of air by volume at standard sea level conditions. Therefore as the aircraft climbs, this air, and more importantly the oxygen in the air, comes out of solution and can serve as a potential ignition source that must be dealt with in any effective inerting system solution.

Since the loss of TWA Flight 800 over Long Island in July 1996, the OBIGGS type of system, hitherto only used by the military, is becoming a commonly used subsystem in today's commercial aircraft.

This and other fuel tank safety issues are covered in detail in Chapter 10.

In many large transport aircraft the ratio of maximum fuel weight to total aircraft gross weight can be as much as much as 50 %. This can be compared to about 5 % for the typical automobile. This feature can in turn result in substantial variations in aircraft handling characteristics between the initial and final phases of flight.

Also, since fuel tanks are located in the wings, the effect of wing sweep is to change the longitudinal center of gravity (CG) of the aircraft as fuel is consumed causing a change in aircraft static stability and hence handling characteristics. In some aircraft the longitudinal CG is actively controlled by the fuel management system through the movement of fuel between fore and aft tanks automatically during the cruise phase.

The subject of CG control and other fuel management issues are described in depth in Chapters 4 and 5.

For commercial aircraft, optimizing the aircraft longitudinal CG during cruise minimizes profile drag which, in turn, maximizes the operating range of the aircraft.

In the case of the Concorde supersonic transport, the fuel system was used to keep the aircraft stable over the wide range of speeds involved by moving fuel aft during supersonic flight and pumping it forward as the aircraft decelerated at the end of the cruise phase. Thus the fuel system became a critical part of the aircraft's flight control system and its failure mode criticality played an important role in the fuel system design solution. A description of the Concorde fuel system is presented in Chapter 12 of this book. Even though this aircraft is no longer in service the fuel system design issues outlined would remain applicable to any future supersonic transport aircraft application.

Another frequent use of the fuel contained in the wings of larger aircraft is to provide wing load alleviation to minimize wing bending moment and thereby reduce long-term wing fatigue effects. This benefit is achieved by using inner wing tank fuel before outer tank fuel. This is discussed further in Chapters 3 and 4.

In military applications the CG variation issue can be further aggravated by the use of variable geometry (variable sweep) wings and by the use of afterburners (reheat) where very large fuel flow rates can cause fast changes in aircraft balance. The United States F-111, B-1 and F-14 and the Panavia Tornado are examples of the use of variable wing sweep technology. In these cases the fuel system must compensate for the aircraft CG variation that occurs during changes in wing sweep so that pilot workload and variations in aircraft handling characteristics are kept to a minimum.

A major fuel system issue regarding military aircraft applications is the ability to provide aerial (or in-flight) refueling. This critical need has become an essential function in modern military aircraft applications. For strike aircraft, take-off with a full weapons load followed by a climb to altitude can consume a large percentage of the fuel on board. The ability to top-off the fuel tanks after reaching operational altitude provides an essential extension of the aircraft's mission capability and is considered a key force multiplier. The aerial refueling function further complicates the fuel system design by having to provide an in-flight hook-up system with fluid-tight connections and appropriate safe disconnect capability in case of unforeseen emergencies.

Over the past 50 years standard aerial refueling equipment and procedures have been established by NATO countries ensure full interoperability between coalition forces. The US Air Force has developed a flying boom standard that provides a much higher flow rate capability than the probe and drogue standard adopted by the US Navy and NATO. A detailed description of all aerial refueling standards used by the United States and NATO is covered in Chapter 5.

A major requirement that presents a number of key operational issues to the fuel system designer is the need to provide venting of the ullage space in the fuel tanks. Wing tanks while large in volume remain relatively thin particularly at the more outboard sections. During flight these tanks bend and twist with aerodynamic loads as well as being subject to wide variations in both pitch and roll attitude. The challenge for the vent system designer is to ensure that air pockets cannot be trapped during any combination of tank quantity and aircraft attitude throughout the complete flight envelope of the aircraft. It is also critical that there is sufficient vent capacity to maintain a small differential pressure between the tank ullage and the outside ambient during maximum descent rate since only a small pressure differential between the outside ambient and the fuel ullage space can induce very large loads on the aircraft structure because of the large surface areas involved.

A challenging vent system related issue concerns the management of water as a fuel contaminant. This is most significant in large transport, long-range applications where substantial quantities of water can condense into the fuel tanks during a descent into a hot and humid destination following an extended cruise at high altitude. The high utilization rates of modern commercial transports often make the practice of routine water drainage impractical since there is seldom enough time between missions for the water in the fuel to separate out so that it can be drained from the fuel tank sump.

Water management, therefore, is a major operational issue facing today's transport aircraft and the designers of the next generation of long-range aircraft need solutions to this problem that can be effectively applied. A more in-depth discussion of this problem is presented in Chapter 3.

Military aircraft that operate at very high altitudes use 'Closed vent' systems to ensure that the ullage pressure in the fuel in the tanks remains above the fuel vapor pressure under all operational flight conditions. This adds considerable complexity to the vent system since the pressure in the ullage relative to the outside ambient conditions must be kept within safe limits by controlling the airflow in and out of this space as the aircraft climbs and descends.

During flight the fuel system must make sure that all of the fuel on board remains available to the engines through timely transfer of fuel from the auxiliary tanks (where applicable) to the engine feed tanks as the mission progresses. This process has flight-critical implications and therefore flight deck (or cockpit) displays typically provide a continuously updated display of the total fuel on board and its specific location. In order to ensure high integrity of the fuel transfer process the crew will usually have the ability to manually intervene if necessary, by selecting various pumps and valves, to provide continued safe flight in the event of a transfer system malfunction. The good news is that fuel system faults do not have an immediate impact on aircraft safety in the same way that a flight control system fault would have, because the effects on the aircraft performance of fuel system-related failures tend to develop slowly. If the fuel system develops a fault that results in a fuel transfer problem, it may be many minutes or even hours before the fault has any significant impact on the aircraft. In most cases warnings to the crew of fuel system functional faults do not have to be acted upon urgently (except perhaps a low level fuel warning which requires the crew to act or land immediately). While this situation is comforting it can also be a reason for overlooking potentially serious issues.

This was the case with Air Transat flight TS 236 from Toronto to Lisbon in August 2001 that ended in an emergency landing in the Azores after loss of both engines as a result of a fuel leak in the Starboard engine. The automatic fuel management system continued to compensate for the fuel leak on the right-hand side of the aircraft by transferring fuel from the good side of the aircraft to the leaky side of the aircraft so that fuel was eventually lost overboard to the point where first one and than then both engines lost power. With more vigilance during the early part of the flight instead of being overly dependent upon the automatic systems that had the effect of masking an ongoing problem, this event could probably been avoided. Fortunately the aircraft landed safely and no lives were lost.

1.1.2 Fuel Quantity Measurement

The challenge for the fuel quantity measurement system is to provide accurate information over a wide range of aircraft attitudes and variations in fuel properties that occur, even for a common fuel type, as a result of refueling from different locations around the world. A 1 % error in fuel quantity measurement for a commercial transport aircraft with a 100 tonnes fuel capacity is 1 tonne which is equivalent to some 10 passengers and their baggage. Also, as a result of the tank geometry, tank sumps and fuel transfer galleries on board, a small portion of the total fuel stored on board may be classified as either unusable or ungaugable. In either case this represents an operating burden for the aircraft.

Measurement of fuel quantity is accomplished by an array of in-tank sensors that are designed to detect the fuel surface at a number of locations within the tank from which volumetric information, and hence mass, can be calculated.

The most commonly used sensing technology in aircraft fuel quantity gauging systems today is that utilizing capacitance sensors, commonly referred to as probes or tank units. A capacitance probe typically comprises a pair of concentric tubes designed for near vertical mounting at a specific location within a fuel tank to act as an electronic 'dip stick'. The capacitance between each of the two concentric tubes varies with the wetted length due to the permittivity difference between fuel and air.

The number of probes required is determined by the accuracy requirements and a number of separate arrays may be required to provide adequate functionality in the presence of equipment failures.

Capacitance gauging has been the mainstay of aircraft fuel quantity measurement technology for decades. A key factor for reluctance within the industry to make changes in the fuel gauging technology is the cost of in-tank maintenance. The expectation of the airline operator is to never have to go inside a fuel tank to perform unscheduled maintenance and that in-tank hardware must continue to operate safely and without the need for maintenance for 20 years or so.

Nevertheless, alternative technologies have been tried and are continually being studied. Some of the new gauging technologies currently being evaluated are discussed in Chapter 13.

The Boeing 777 gauging system is a particularly good example of this point. Boeing made a decision on the 777 program to change from traditional capacitance gauging technology to ultrasonic gauging in an attempt to improve in-tank maintenance costs.

Ultrasonic gauging locates the fuel surface using a 'Sonar-like' technique wherein an ultrasonic wave is emitted and its echo from the surface detected. By knowledge of the speed of sound through the fuel, the fuel surface position can therefore be identified and, using a number of emitters, a surface plane can be defined and the fuel quantity computed. A detailed treatment of gauging system sensor technologies is presented in Chapter 7 and a description of the Boeing 777 fuel system and particularly the ultrasonic gauging system is described in Chapter 12.

It is interesting to note that the latest Boeing commercial transport aircraft program, the Boeing 787 Dreamliner reverted back to capacitance gauging technology for its fuel quantity measurement system.

The in-tank sensor arrays are excited electronically and the 'Fuel height' signals from the various probes are converted, using proprietary software algorithms, into tank quantity information for display to the flight crew.

Fuel quantity gauging systems are mass measuring rather than volumetric systems and they provide for continuous measurement over the full range of fuel quantity. Mass measurement is the most important parameter as it is a measure of stored energy related to fuel calorific content and, therefore, engine thrust. Nevertheless, discrete volumetric fuel measurement is also important and may be catered for by fuel level sensors which can either be integral to the gauging system or a separate system, depending on the requirements.

Examples of level sensing functions include high level sensing to ensure adequate fuel expansion space in a specific fuel tank by initiating fuel shut-off during refuel and transfer operations and low level sensing to provide warning to the flight crew of a low fuel tank quantity state.

In addition to the primary fuel gauging function a second measurement system called 'Secondary gauging' is required to ensure the integrity of this critical function and to permit safe aircraft dispatch in the presence of gauging system failures. The secondary gauge must use dissimilar technology to guard against common mode failures. A common type of secondary gauge is the Magnetic Level Indicator (MLI) where the position of the floating magnet can be read by the ground crew on a stick protruding from the base of the fuel tank. Several MLIs are usually provided. While this secondary measurement technique is significantly less accurate than the primary system it does serve to support the gauging system integrity requirement.

A detailed treatment fuel quantity measurement can be found in Chapters 4 and 7 from a system and equipment perspective respectively.

1.1.3 Fuel Properties and Environmental Issues

Perhaps the most significant issues to be recognized and dealt with regarding aircraft fuel systems are the wide variations in environmental conditions imposed by the flight envelope and the associated variations in local pressure and temperature that must be tolerated by the fuel and the equipment involved in its management. This is illustrated in qualitative terms in Figure 1.3.

A detailed treatment of fuel properties as they affect aircraft fuel systems can be found in Chapter 8.

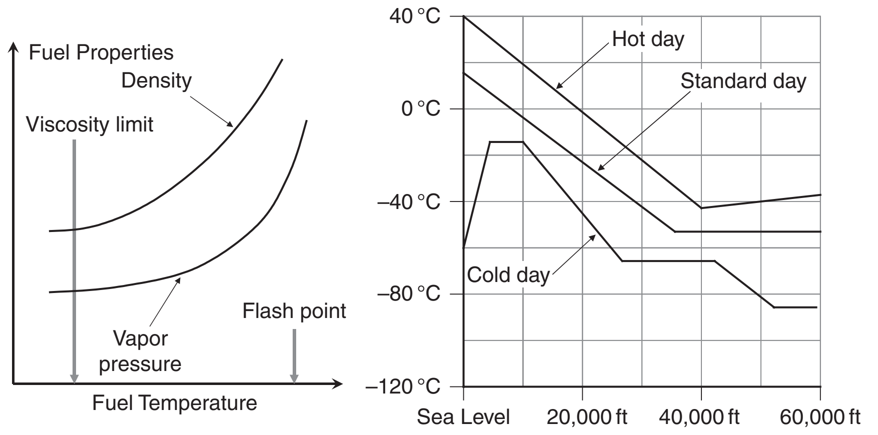

Figure 1.3 Fuel characteristics vs operating conditions.

Three highly significant characteristics of today's fuels are density (as it varies with temperature), vapor pressure and freeze point. The density variation means that an aircraft with full tanks at high temperature will have a significantly lower range (and gross weight) than an aircraft with full tanks at low temperature because the energy stored in the fuel is a function of its