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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

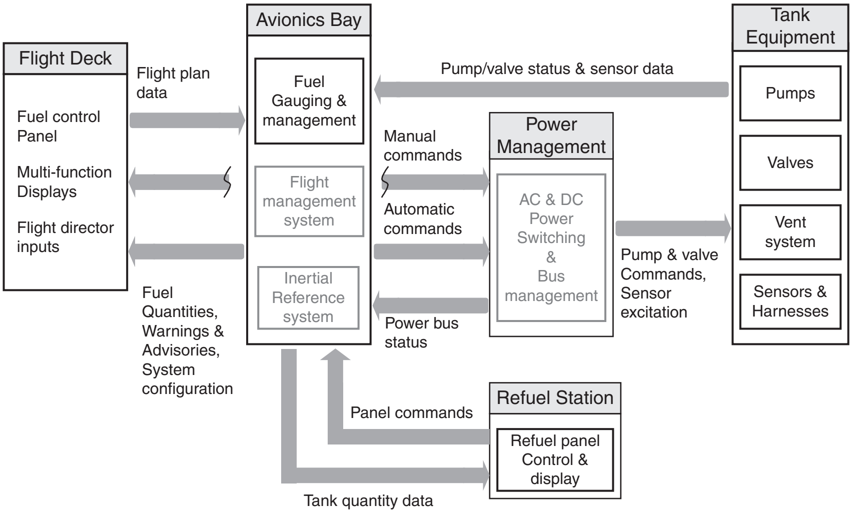

Figure 1.1 The fuel system from an aircraft perspective.

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

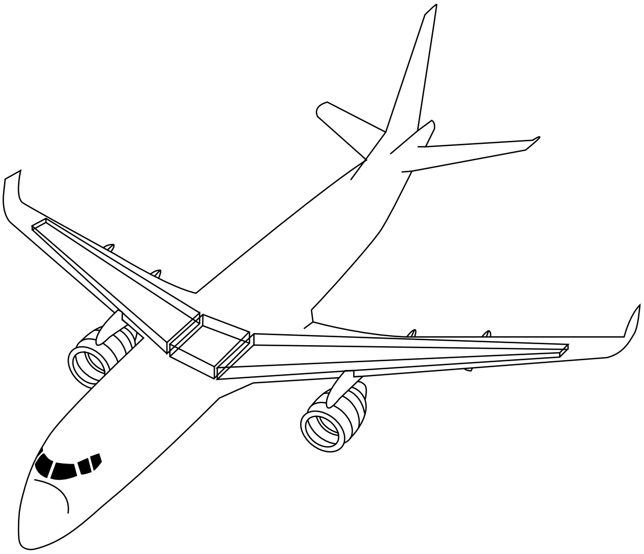

Figure 1.2 Typical transport aircraft fuel tank arrangement.

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.

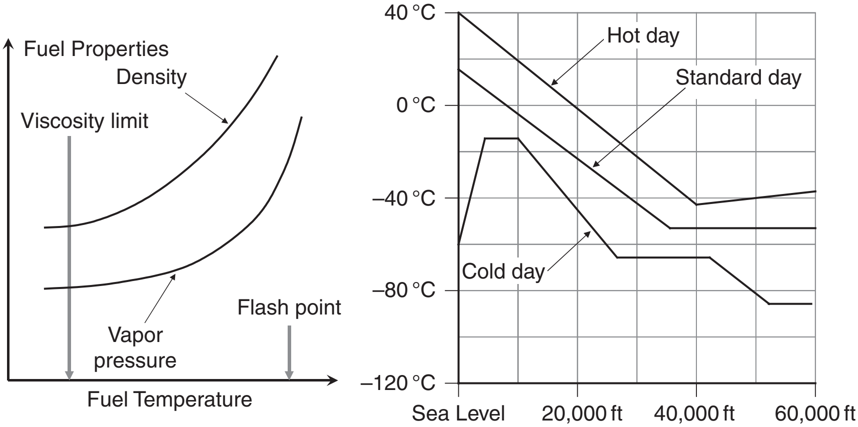

Figure 1.3 Fuel characteristics vs operating conditions.

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 mass rather than its volume. This characteristic creates problems for the fuel quantity gauging system that must accommodate this variable either by widening the accuracy tolerance of the measurement system or by inferring density from dielectric constant or, preferably, measuring density directly thus compensating for this parameter in tank quantity computations.

Vapor pressure is a key factor in determining the limiting operational altitude for a given fuel (assuming an open vent system) since fuel vaporization (high evaporation rates and ultimately boiling) can occur at high altitudes, particularly with wide-cut fuels. For this reason, one critical certification test involves a maximum rate of climb with hot fuel in the tanks to identify or quantify any such limitations. In military aircraft with very high altitude ceilings a closed vent system is employed in order to maintain an adequate margin between tank ullage pressure and the fuel vapor pressure during operation at very high altitudes.

Freeze point is an important characteristic during long-range high altitude operations. Towards the end of a long flight when fuel quantities are lower, the fuel bulk temperature can approach the freeze point of commonly used jet fuels causing wax to precipitate out of solution. This wax can create obstructions and block filters and can as a result lead to engine shut-down. For this reason, the fuel bulk temperature is continuously monitored and safe operating margins maintained. If safe operating fuel temperature limits are approached the crew is required to take action (descend and/or increase Mach number) to alleviate the situation. This can be a serious problem when operating in Polar Regions if operating Mach number margins are small since descending may not necessarily locate any warmer air.

Each of these characteristics will be covered in detail in the ensuing chapters; however, they are presented here to illustrate some of the issues that must be addressed by the aircraft fuel system designer in the process of integrating the fuel system into the total aircraft design from a functional perspective.

As fuel is supplied to the engine it is pumped to high pressure and metered into the combustion chamber. The high pressures are necessary because combustion chamber pressure can be as high as 1000 psig (68 bars). Along the way, the fuel is used to cool the engine lubrication oil via a heat exchanger. The concern now becomes high temperature limitations for the fuel which, if fuel temperatures exceed 350 deg F (177 deg C), can lead to coking of the fuel nozzles with attendant loss of performance.

The engine thermal problem is largely due to the fact that the high pressure fuel pump is usually sized by the engine starting requirement when cranking speeds are low. Therefore during operation above idle speed there is typically an excess of high pressure pump capacity and this is spilled back to the pump inlet by the fuel metering control system (see Figure 1.4).

The thermal problem is exacerbated further when operating at high altitude cruise conditions where engine rotational speed (and hence pump speed) is high but fuel consumption is low resulting in a lot of undesirable heat generation. In some aircraft designs hot fuel from the engines is fed back to the aircraft fuel tanks as a cooling measure. There are issues related to this arrangement and these are covered in detail in Chapter 4 under ‘Ancillary Systems’.

The most important functional requirement of the aircraft fuel system is to provide fuel to the propulsion engines (and to the Auxiliary Power Unit (APU) when fitted) within a predetermined range of acceptable pressures and temperatures as and when required throughout the specified operational envelope of the aircraft.

Providing an appropriate and reliable source of fuel to the propulsion system is fundamental to the need to keep the aircraft airborne by allowing the engine(s) to convert the fuel’s chemical

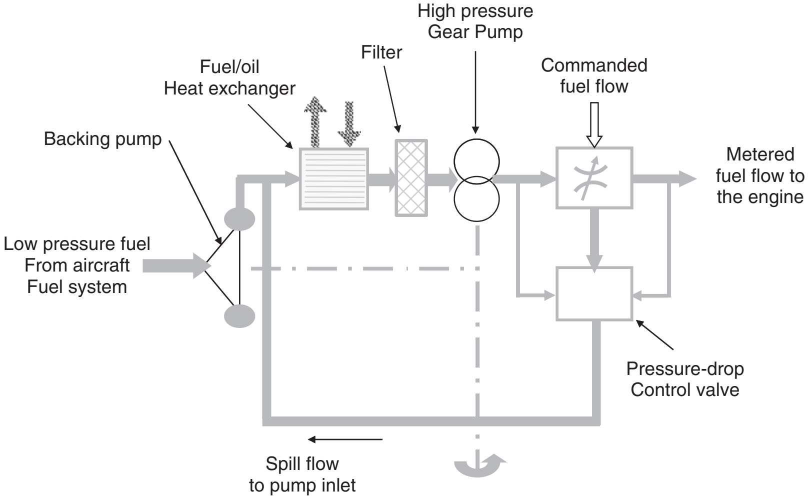

Figure 1.4 Simplified engine fuel metering control schematic.

energy into thrust continuously in accordance with aircraft's control system requirements. The criticality of this requirement therefore demands that the integrity of the fuel system from a functional perspective be equivalent to that of any of the flight critical systems on board since failure to provide this function would result in a catastrophic event, i.e. loss of aircraft.

It is also critical to the aircraft operation that the pilot and crew know how much fuel is on board and where it is located. The fuel measurement and fuel management system provides this function which must have extremely high integrity.

In summary, the primary aircraft fuel systems functions are as follows:

- The fuel system must make sure that the feed tanks associated with each engine are maintained full as long as possible by transferring fuel from the other (auxiliary) tanks into the feed tanks in accordance with a predetermined fuel burn schedule taking care to ensure that the balance of the aircraft laterally is maintained. Lateral imbalance can result from differences in fuel consumption between engines or inter-system failures that result in inadvertent fuel transfer. Fuel leakage overboard can also be a serious hazard resulting in imbalance and, more seriously a reduction in range. Detection and location of leaks is a major issue that has to be addressed by the fuel system designer.
- The system must also accommodate the effect of an engine failure by providing the ability to crossfeed between feed tanks so that the remaining engine(s) have access to the failed engine's fuel and that the aircraft does not become significantly unbalanced laterally
- In the event of an engine failure during or shortly after take-off the pilot may decide to return to the airfield. This situation can be problematic for the landing gear since maximum take-off weight can be significantly higher than the maximum landing weight. The fuel jettison system provides a means to quickly dump fuel overboard to achieve a safe landing weight before attempting a landing.

The above commentary is intended to set the scene for the more detailed discussions that are addressed in detail in the later chapters.

1.2 The Fuel System Design and Development Process

In many cases the fuel system function can be classified as a complex integrated process that involves major interactions between many aircraft systems. The process of designing, developing and certifying a modern aircraft fuel system is therefore a major undertaking and the demand for mature functionality at entry into service is, as with any major operational system, critical to both the aircraft manufacturer and the aircraft operator. Also the importance of addressing lessons learned from previous systems cannot be over-emphasized.

For this reason Chapter 11 provides an important insight into the technical and program management issues that must be addressed in the fuel system design and development process in order to maximize the potential for high system maturity at entry into service. The downside of this situation, where operational issues remain to be discovered in service by the airlines or the military operators, can be an enormous cost in both monitory and reputation terms to the aircraft manufacturer and to the equipment supplier.

Therefore the supplier/airframer combination that can develop a design and development process that guarantees a maximum probability of achieving maturity at entry into service offers an enormous operational benefit to both the aircraft manufacturer, the equipment supplier and to the user communities.

The design and development process can be best expressed by the well known ‘V’ Diagram (see Figure 1.5).

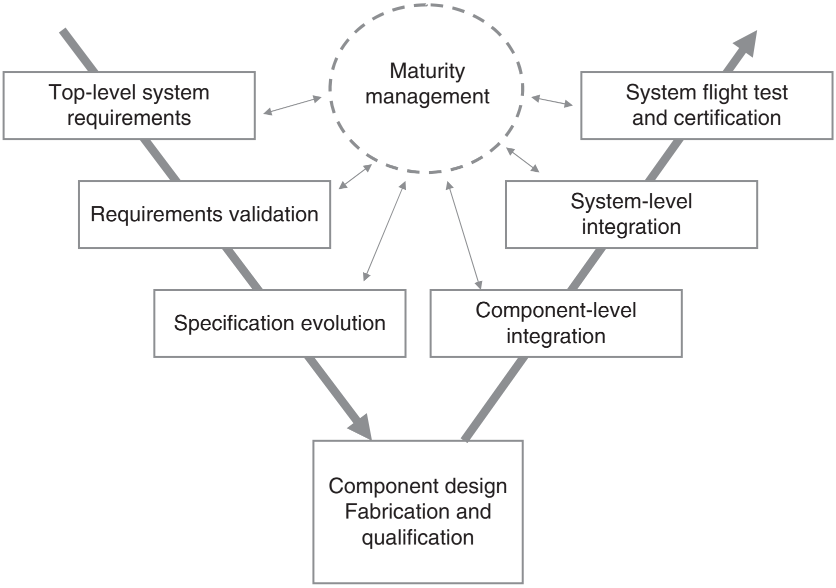

Figure 1.5 The ‘V’ diagram concept.

The process begins at the top left with top level system requirements. As the process moves down the left side of the ‘V’ the level of detail increases until the requirements of the major components of the system are defined. At each level, the applicable requirements are validated for completeness and correctness.

At the bottom of the 'V' the components are designed to meet the newly validated requirements followed by fabrication, testing and qualification at the component level.

The right side of the 'V' represents the integration, verification and certification phases of the program beginning with component integration, then system integration and finally integration with the aircraft for flight test and certification.

This is only a brief overview of this methodology which is developed in more detail in Chapter 11.

1.2.1 Program Management

Program management is a critical skill that can make an immense difference between success or failure of a project to meet the operational expectations of the system provider and end user. People who can demonstrate this capability remain in high demand within the industry because their potential economic benefit, in the long run, can prove to be substantial to both the manufacturing and operating communities.

In the past decade or so the industry has seen a major shift in the responsibility and role played by the typical equipment supplier who is today expected to be 'Systems smart' with the ability to contribute to the functional requirements definition of its products from an aircraft system perspective. In fuel system applications this issue is particularly important because of the complexities of many modern applications where there are a large number of significant functional interactions with other aircraft systems including:

- ground refuel station
- flight management system
- power management system
- flight warning and advisory system
- display management system
- central maintenance computer
- propulsion system
- tank inerting system
- on-board maintenance system.

Historically the equipment supplier was typically isolated from the operational problems seen by the operator community who had to pay the price (via the purchase of expensive spare parts) of functional immaturity. In this scenario there was no incentive to the supplier community to change its way of doing business. More problems in the field meant more sales of spare parts which were priced to provide good margins.

Today this situation is no longer viable and applies not only to complex fuel systems but to aircraft systems design and development in general. Today the equipment supplier is typically required to take responsibility for meeting direct maintenance guarantees and equipment removal rates that are part of the contract. The equipment supplier community is now required to participate in the system design, development and certification process and to take an active involvement in the performance of their components as an integrated entity within the aircraft itself.

The design and development process aspect of this book, presented in Chapter 11 describes some of the essential tools that are necessary in the successful certification of today's complex fuel systems. The importance of 'Joint working' between the supplier and aircraft manufacturer's design team is emphasized as a major contributor to a successful program.

Specific methodologies for system design and development are described in detail including the SAE standards ARP 4754 reference [1] and 4761 reference [2]. These advisory documents instill a discipline into design and development process that emphasizes the importance of safety from the earliest conceptual phase through final definition of the requirements both at the system and component levels. Examples include the System Safety Analysis (SSA) and the Functional Hazard Analyses (FHA) which is a relative of the Failure Modes Criticality and Effects Analysis (FMECA) used throughout the industry.

An important issue with the design of aircraft fuel systems is to ensure that there are no common failure modes that can eliminate the effectiveness of functional redundancy. For example, since fuel properties are a common factor in fuel system operation, consistency in fuel quality standards may become a critical factor since any single event that could impact this situation would be considered a common mode failure. Potential causes include excessive fuel contamination; say with water or ice or freezing (waxing) of fuel due to operation for extended periods at flight conditions with recovery temperatures below the fuel freeze point.

Risk management is also a key discipline that is designed to identify all potential risks to the program and to develop and manage mitigation plans in order of criticality. This aspect of program management is crucial in minimizing the possibility of late developing crises with the attendant schedule and development cost penalties.

1.2.2 Design and Development Support Tools

There are many powerful support tools that are typically utilized to support the design and development activities. These are general purpose and in some cases proprietary software tools that allow the design team to validate requirements and verify the functional behavior of the system at various levels of integration through to the flight test phase.

Requirements traceability is important in complex integrated systems such as a modern aircraft fuel system. Requirements management tools are available that can ensure that all requirements are traceable from a top level system requirement to an expanding number of requirements at each level down to the component level.

Modeling and simulation tools are used to analyze fluid network performance during the various modes of operation providing information on pipe sizing, pressure losses and surge pressures. Models are also necessary to facilitate early testing of the system functionality by providing a pseudo aircraft to exercise the equipment against well before the real system/aircraft becomes available.

Fuel tank geometry analysis tools are essential to the fuel system designer particularly when tank shapes are complex and aircraft attitudes and g force variations are considerable. The system designer needs to be able to define the quantity and location of fuel probes that are necessary to meet accuracy requirements at an early stage. Similarly the location of pumps to minimize unusable fuel must be established early so that structural penetrations and installation provisions can be made.

An important activity that must occur in parallel with the design and development of the fuel system components is the provision of the Special Test Equipment (STE) necessary to both verify the performance and achieve the hardware and/or software qualification of those components.

Finally as the program enters the flight test and certification phase, there is a critical need for the specialist systems engineering groups to access, review and analyze enormous amounts of test data from both ground and flight test situations. Special tools for data recording, classification and analysis are essential to the efficient synthesis and evaluation on a continuous basis as the certification process proceeds.

These are just a few examples of the importance and benefits of design support tools that are available and necessary for the successful execution of a fuel system development program.

1.2.3 Functional Maturity

Functional maturity at entry into service is the Holy Grail of successful program management because the benefits of such an accomplishment are so overwhelmingly powerful from an operational perspective.

The challenge to the program manager is to establish an effective process that can measure and react to the prevailing maturity status in an effective and program-beneficial manner.

Maturity management must be applied to all of the various phases of a design and development program at the system requirements level. Lessons learned form previous programs can be used to establish derived requirements and associated verification processes.

One of the most challenging areas for maturity management is in the area of software design and verification. Software maturity typically improves with exposure to the operating environment. The maturity manager must therefore strive to maximize software operating time on test rigs and flight test aircraft while providing a software design that can incorporate changes quickly and with minimal disruption to the program operating structure.

The prospects for the successful implementation of a maturity management system and the downside of paying lip service to this critical issue are discussed in Chapter 11.

1.2.4 Testing and Certification

The testing, integration and certification activities involve the right side of the ‘V’ Diagram. For the first time real hardware and flight operational software are tested in integrated test rigs with varying degrees of fidelity. The equipment suppliers are primarily interested in the sub-system and component level integration issues while the aircraft manufacturer is focused more on the aircraft level functionality of the system.

The aircraft fuel system is one of the most interactive systems in modern aircraft today.

It is critical, therefore, that the development phase provide the maximum possible exposure of the fuel system components and operational software to detect, isolate and correct system-level functional issues well before the system is exposed to the actual aircraft.

Testing and certification issues are also covered in detail in Chapter 11.

1.3 Fuel System Examples and Future Technologies

The penultimate chapter contains several real world examples of aircraft fuel systems all of which are concerning commercial (civil) aircraft applications because of the security constraints imposed by the military aircraft community. Included are several modern aircraft fuel systems including large transport aircraft such as the Boeing 777, the new Airbus super jumbo A380 and the Concorde which contains many unique functions related to the extensive operational flight envelope of this aircraft. Smaller regional aircraft fuel system examples are also included in order to provide a perspective of the difference between the system technologies and the component solutions.

These applications attempt to put into perspective the content of the book from the design, development, certification and operational aspects of aircraft fuel systems.

The final chapter provides a view of the future regarding aircraft fuel systems technology and where this may take us from a systems and component design and development perspective.

The need to develop a revolutionary gauging technology has occupied the engineering community for many years. Capacitance gauging in either its AC or DC form has been the accepted standard of the industry for the past fifty years or more notwithstanding the recent ventures into ultrasonic gauging technology adopted by Boeing for their 777 aircraft. Suggestions regarding the most likely prospective new gauging technologies currently being considered are presented and discussed in this chapter.

While fuel pumping and management products and methods represent well established and mature technologies, the increasing power of electronics and sensing capabilities over the past twenty years or so has led to the consideration of new integrated concepts to improve fuel system functionality particularly during the refuel process. These and other new ideas are described and discussed in this chapter.

1.4 Terminology

The fuel systems engineering community has established, over many years, a terminology associated with the system, functional and product aspects of aircraft fuel systems that is worth explaining here as an aid in the understanding of the principles and examples presented throughout this book.

The following therefore is a definition of some of the terms and expressions commonly used in the industry today that appear within the chapters that follow in an attempt to assist the reader in obtaining a more in-depth understanding of fuel systems, their functions and the equipment involved. It is recommended that the following definitions be used as a reference to support the discussion that follows in the ensuing chapters:

Brick wall architecture: This architecture, used extensively by Boeing, requires that the gauging of each tank is independent of the other tanks. Thus no failure in one tank can propagate into the gauging of the remaining tanks.

Closed vent: As the term implies a closed vent system connects the ullage to the outside air via a control valve or valves (often referred to as ‘Climb and dive’ valves) in order to control ullage pressure. This is necessary to prevent high levels of fuel evaporation or even boiling in aircraft fuel tanks where flight at very high altitudes is involved.

Compensator: The compensator is a capacitor mounted low down in the fuel tank to provide a standard measure of fuel permittivity that allows the capacitance fuel probes to provide a fuel immersion coefficient that is ratiometric and independent of the prevailing fuel permittivity. A fully immersed tank probe can also serve as a compensator.

Crossfeed: This applies to multi engined aircraft and is the supply of fuel to an engine from the opposite side of the aircraft fuel system typically during operation with one engine shut down.

Defueling: The process of off-loading fuel from the aircraft via suction or by the use of on-board pumps.

Densitometer: The densitometer is typically an in-tank fuel density measurement sensor. The most common implementation uses the spring-mass resonance concept where the mass term is represented by the fuel. These sensors provide a frequency output that is proportional to fuel density; however, some sensor characterization is usually required (temperature compensation for example) to achieve the best accuracy performance.

Dual channel: Fuel quantity gauging and management systems typically require some level of redundancy to deliver the integrity requirements dictated by the airworthiness authorities. The dual channel approach is in common use. Here there are two independent channels, one declared as the ‘Master’ and the other as the ‘Slave’ or ‘Hot spare’. During normal operation the Master Channel is in control while the Slave executes identical software. If a fault should develop in the Master Channel, the Spare Channel takes over.

Dual-dual channel: The Dual-Dual architecture is essentially the same as the Dual Channel; however, here each channel has two computers; one as a command computer and the other as a monitor. This arrangement significantly improves achievable fault coverage.

Engine feed pressure: This is the pressure in the feed line to the engine which must be maintained above fuel vapor pressure with some margin. The term boost pressure is synonymous with feed pressure, as are boost pump and feed pump.

Fuel gauging and management: The Fuel Quantity Gauging System (FQGS) calculates the fuel quantities in each fuel tank for display to the flight crew and to the refueling station. In some applications this system is referred to as the Fuel Quantity Indication Systems (FQIS) or, when implemented as an integral part of the fuel management system, it may be referred to as the Fuel Measurement and Management System (FMMS) or the Fuel Management and Quantity and Gauging System (FMQGS). Other similar acronyms are also in use today.

Fuel-no air valve: A fuel no-air valve is normally located at the bottom of a fuel tank and is designed to close (stop transfer) when air enters the valve.

Fuel stratification: Fuel stratification can occur when an aircraft is turned around after a long flight. Any residual fuel may be very cold (say –30 degrees C). If the uplifted fuel for the continuing flight leg is relatively warm (say 10 degrees C) this fuel can lie on top of the colder, denser fuel causing gauging system errors.

Fuel transfer: Moving fuel from one location to another in the aircraft.

Non-modulating level control valve: A level control valve that provides a discrete deadband between the shut-off level and the re-opening level.

Open vent: Here the ullage is continually open to the outside air via the vent system piping and is typically of most commercial aircraft.

Pilot valve: A float operated valve that controls the state of a separately located valve. The float may be positioned to sense a high or low fuel level condition

Pre-check: This is the process of verifying the integrity of the refuel shut-off system by simulating a full tank condition via fluidic or electrical means prior to actually reaching the full tank condition.

Pressure refueling: The use of a high pressure source to facilitate fast refueling of aircraft

Scavenge: This involves moving the last vestiges of fuel from a fuel tank to a more accessible location (e.g. a feed tank or collector tank). Scavenged fuel would otherwise be trapped and/or unusable.

Sensing level: The level at which the pilot valve is set to operate by closing the pilot valve.

Suction feed: This is the supply of fuel to the engine created by suction from the engine. To accomplish suction feed the pressure at the engine must be above the fuel vapor pressure for the prevailing operating condition.

Surge pressure: This is the pressure rise in the refuel system upstream of the shut-off valve caused by the closure of the valve and is related to the phenomenon known as 'Water hammer'.

Tank pressurization: This is the provision of air pressure to the fuel tank ullage (usually from engine bleed air) to assist with high altitude and/or high temperature performance. Typically this is provided in conjunction with a closed vent system.

Tank probe/tank unit: Tank units or tank probes typically refer to fuel gauging probes that measure the wetted length or depth of immersion. Capacitance probes use the difference in permittivity between air and fuel.

Ullage: This is the space above the fuel surface within a fuel tank.

Valve overshoot: The volume of fuel that passes through a shutoff valve after the instant the valve is selected closed either by a pilot valve or other means.

The above list is just a snapshot of the many terms used within the industry and while they are mostly covered within each chapter to some extent, it may be useful for the reader to refer back to this section if confusion of terms occurs.