SAE Aerospace
An SAE International Group

AEROSPACE INFORMATION REPORT

AIR5691

Issued 2013-01

Guidance for the Design and Installation of Fuel Quantity Indicating Systems

RATIONALE

This guidance document has been produced in an effort to record best practice in fuel gauging system design and indicate those things which should be considered in the design of a new fuel gauging system in order to achieve an accurate and reliable fuel quantity indicating system (FQIS). It is also intended to capture changes in design practice since ARINC 611-1 was issued in 1999.

FOREWORD

Airlines and aircraft operators continue to experience an assortment of in-service problems caused by fuel gauging systems. The complex nature of the system and its importance to the operation of the aircraft tends to produce faults that need to be repaired prior to further flight. This is especially true on older systems where the probes in a tank were treated as a single input. These faults typically are inconvenient to repair and often require an extensive amount of time to isolate and correct. With more advanced systems where each probe is connected individually to the processing electronics this can be less of an issue, and flights can continue with a single probe failure or even multiple probe failures in some cases, allowing failures to be addressed as a scheduled maintenance issue.

Older systems often exhibited a large number of in-flight faults that can be difficult or impossible to reproduce on the ground. This, combined with the limited BITE (Built-In Test Equipment) facilities on older systems has led to many abortive attempts at trouble-shooting and thousands of man-hours of unproductive effort spent in trying to determine the root cause of the fault. The primary problem with older FQIS systems has been associated with the electrical connections and connectors and the need to approach troubleshooting from a fundamental physics approach (i.e., what could impact shifts in capacitance value). The fuel tank wiring harnesses with associated connectors are often the cause of the problem due to the size (gauge of wire), shielding, system complexity, routing of wire and moisture ingress. Problems in this area are brought about by the systems susceptibility to grounding anomalies on shielded cables (particularly applicable to older systems based on 400 Hz AC capacitance measuring technology). The problem most often observed is due to the wire harness shields no longer being properly grounded, and thus the noise rejection of the system is degraded and the harness capacitance can cause large errors in FQI reading. The replacement of a wiring harness requires typically up to 1 day of actual replacement time, once the replacement wire harness(es) are received, which generally equates to 3 days of aircraft downtime. Often there is the necessity to replace the entire wiring harness, when frequently the fault is caused by just one faulty wire, as it is not always obvious where the intermittent failure is.

Other shortcomings of capacitance systems, based on widespread experience with capacitance technology, are problems associated with the presence of water in the fuel. Water can be present in solution when the fuel is loaded (uplifted). The water solubility in fuel increases with temperature, conversely, as the fuel temperature decreases the water precipitates out of the fuel, leading to more free water in the tank, which ultimately changes to ice. The water settles at the bottom of the tank and can build up to such a level that it starts to rise between the concentric tubes of capacitance probes and may cause erroneous measurements. Liquid water has a very high dielectric constant when compared to aviation fuels (nominal 40 to 1 ratio) that introduces significant changes in measured capacitance for fuel sensors that are immersed in water, even if that immersion affects only the lower few millimeters of the probe. It must be noted that frozen water is not conductive and has a dielectric constant not far from fuel (1.4 to 1 ratio) and so does not have the same effect as free water. Traditional fuel systems address water condensation by frequent sumping/water drain activities from the fuel tanks and placement of the fuel sensors sufficiently above the bottom of the tank to mitigate water accumulation effects. Fuel probes are designed to readily shed water from collecting on the inner surfaces of the capacitive sensor. These measures do not solve the problem entirely, but reduce it to a practical level.

Ultrasonic fuel quantity systems also have issues with water as there is a boundary layer between fuel and water, and reflection of the ultrasonic signal from this boundary can be read as fuel level.

Ultrasonic systems can have other issues such as temperature cycling extremes experienced by the fuel tanks putting thermal stress on the ultrasonic transducer, so the sensor quality is paramount. In addition, air bubbles in fuel will cause the sensor not to be able to read the fuel height, as the lower surface of the bubble will reflect the ultrasonic signal, leading to a lower height reading for sensors affected by bubbles, This is particular problem during climb, where the fuel will out-gas rapidly producing many bubbles.

A bigger problem area is the perceived poor accuracy of fuel quantity systems (no matter what the base technology) from the viewpoint of operating crews. Discrepancies between the FQIS and the bowser meter on dispensing trucks during refueling can lead to delays where the loaded quantity must be checked. Crews may uplift more fuel than required as a contingency factor to compensate for perceived inaccuracies. Declared system accuracy can have an effect on the required fuel load, with less accurate systems requiring extra fuel to be loaded. A more accurate system results in less fuel needed as a contingency factor. However, several surveys have shown that improved accuracy of better than 1% would not allow a more refined fuel loading, and is not of economic benefit to the airlines. Even where extra fuel is not uplifted, there will be a direct cost of carrying additional fuel when the gauges are under-reading. It should be noted that the perceived inaccuracies in older gauging systems is often due to undetected or unannunciated failures rather than design inaccuracy. When determining the desired fuel system accuracy, be it 1%, 2% or greater, the aircraft design and operational considerations need to be considered to meet the market requirements.

Standards of acceptability of FQIS error, especially for large airplanes, have changed. Error magnitudes which were considered satisfactory in the era of low fuel costs, when many systems were designed, are no longer acceptable. "Normal" variations in fuel characteristics such as permittivity/dielectric constant (K) and density (D) can cause unacceptable errors if these characteristics are not measured directly. The variations have been tolerable in the past when most systems did not make direct measurement of one or both these characteristics, but are no longer tolerable in higher accuracy systems. The problem is further aggravated with the introduction of new sources of crude oil in the past decade, and the recent introduction of alternate fuels ("bio-fuels" and "synthetic fuels": fuels created from non-petroleum sources). Finally, assignment of inexperienced personnel to a particular aircraft often results in "trial and error" or "shotgun" troubleshooting, partly as a result of the inherently ambiguous system BITE (Built-In Test Equipment). Frequently the most accessible components, which are not necessarily defective, are removed and replaced (normally the processor or indicator). Operating in this manner has several disadvantages. Maintenance costs are driven upwards because of testing unverifiable failures in the shop. Also, operators experience needless departure delays. Specialized test equipment addresses most of the troubleshooting concerns, but it requires costly equipment and personnel that have the necessary training/schooling to be able to utilize them to have an advantageous effect.

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1. SCOPE

This document is applicable to commercial and military aircraft fuel quantity indication systems. It is intended to give guidance for system design and installation. It describes key areas to be considered in the design of a modern fuel system, and builds upon experiences gained in the industry in the last 10 years.

1.1 Purpose

This document is intended to serve as guidance to airframe and equipment manufacturers for the design and installation of Fuel Quantity Indicating Systems (FQIS) used on commercial and military aircraft. Although it focuses on the type of systems traditionally used for larger aircraft, where applicable it also shows what is different about systems used for smaller aircraft and helicopters.

This document is not intended to be a fully definitive specification, but concentrates on areas where it is felt guidance is needed to fully understand the design intent.

It is difficult to completely define a set of characteristics which would fully cover a standard FQIS. The reasons are primarily:

1. New technologies, particularly in the sensor field will most likely be introduced
2. There are various configurations of fuel tanks in aircraft, - for example two fuel tanks on an Embraer 123 compared to nine fuel tanks on the 910K version of a Boeing 747-400 (747-KKK). This variation does not lend itself to a single FQIS solution
3. There are different safety criticality considerations depending on the application, for example, the effects of center of gravity (CG) that impact the architecture of FQIS
4. Migration from metal to composite airframe structure design.

However, it is possible to establish guidelines covering most areas of system architecture and installation that can be applied across most aircraft.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP1870	Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety
AIR4246	Contaminants for Aircraft Turbine Engine Fuel System Component Testing
ARP4754	Guidelines for Development of Civil Aircraft and Systems

ARP4761	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
ARP5412	Aircraft Lightning Environment and Related Test Waveforms
ARP5414	Aircraft Lightning Zoning
ARP5577	Aircraft Lightning Direct Effects Certification
ARP8615	Fuel System Components: General Specification For

2.1.2 ARINC Publications

Available from ARINC Incorporated, 2551 Riva Road, Annapolis, MD 21401, Tel: 800 633 6882, https://www.arinc.com/cf/store/index.cfm

ARINC 429	Mark 33 Digital Information Transfer System (DITS) Specification
ARINC Report 604	Guidance for the Design and Use of Built-In Test Equipment (BITE)
ARINC Report 607	Design Guidance for Avionics Equipment
ARINC Report 609	Design Guidance for Aircraft Electrical Power Systems
ARINC Report 611	Guidance for the Design and Installation of Fuel Quantity Systems
ARINC 664	Avionics Full-Duplex Switched Ethernet

2.1.3 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM D1655	Standard Specification for Aviation Turbine Fuels
ASTM D7566	Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons

2.1.4 EASA Publications

Available from European Aviation Safety Agency, Postfach 10 12 53, D-50452 Koeln, Germany, Tel: +49-221-8999-000, www.easa.eu.int.

CS-25	Certification Specifications for Large Aeroplanes

2.1.5 ESA Publications

Available from European Space Agency, European Space Agency, 8-10 rue Mario Nikis, 75738 Paris Cedex 15, France, tel: +33 1 5369 7654, http://esmat.esa.int/ecss-q-st-70-20c.pdf

Q-70-20A	Secretariat for European Cooperation for Space Standardization (ECSS) specification: Determination of The Susceptibility of Silver-Plated Copper Wire and Cable to Red-Plague Corrosion 19 December 2000

2.1.6 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

14 CFR Part 25 Code of Federal Regulation, Airworthiness Standards: Transport Category Airplanes

14 CFR Part 23 Code of Federal Regulation, Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes

14 CFR Part 29 Code of Federal Regulation, Airworthiness Standards: Transport Category Rotorcraft

2.1.7 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

DO-160 Environmental Conditions and Test Procedures for Airborne Equipment

DO-178 Software Considerations in Airborne Systems and Equipment Certification

DO-254 Design Assurance Guidelines for Airborne Electronic Hardware

2.1.8 U.S. Government Publications

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, https://assist.daps.dla.mil/quicksearch/.

MIL-STD-1742 Human Engineering Design Criteria Standard Department of Defense

MIL-STD-1553 Aircraft Internal Time Division Command/Response Multiplex Data Bus

2.1.9 UL Publications

Available from Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062-2096, Tel: 847-272-8800, www.ul.com.

UL 913 Intrinsically Safe Apparatus and Associated Apparatus for use in Class I, II, III, Division 1, Hazardous (Classified) Locations

2.1.10 CRC Publications

Available from Coordinating Research Council, 3650 Mansell Road, Suite 140, Alpharetta, GA 30022, Tel: 678-795-0506, www.crcao.com.

CRC Reprt No. 647 World Sampling Program

CRC Report No. 635 Handbook of Aviation Fuel Properties

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Aerospace Technical Report.

SAE AE4L	Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware
AC 20-53	Protection of Airplane Fuel Systems against Fuel Vapor Ignition due to Lightning
AC 25-981-1c	Fuel Tank Ignition Source Prevention Guidelines
SFAR 88	Special Federal Aviation Regulations No. 88: Transport Airplane FuelTank System Design Review, Flammability Reduction and Maintenance and Inspection Requirements, Final Rule
BS5501: Part 7:	Electrical Apparatus for Potentially Explosive Atmospheres 1977: EN50 014
IEC 600079	Electrical Apparatus for Explosive Gas Atmospheres: 3rd Edition
MIL-G-7940	Gauge, Liquid Quantity, Capacitor type, Installation and Calibration of
MIL-G-26988	Gauge, Liquid Quantity, Capacitor type Transistorized, General Specification for

2.3 Definitions, Symbols, and Terminology

The definitions, symbols and terminology given in this section are only intended to address key areas specific to this document. All other definitions are contained in referenced documents.

2.3.1 Definitions

FAULT: A failure of an in-tank or outside tank component, including wiring, which contributes to the possibility of creating an ignition source or impacts gauging accuracy (e.g., the shorting of a fuel probe by a contaminant).

GROUND: A conducting connection, whether intentional or accidental, between an electrical circuit or equipment and the earth or to some conducting body that serves in place of the earth. ARP1870 defines a ground as "A conducting connection, whether intentional or accidental, by which an electric current or equipment is connected to the earth, or to a conducting structure that serves a function similar to an earth ground (that is, a structure such as a frame of an air, space, or land vehicle that is not conductively connected to earth)."

QUALITATIVE: Those analytical processes that assess system and airplane safety in a subjective, or objective, but non-numerical manner.

QUANTITATIVE: Those analytical processes that apply mathematical methods to assess system and airplane safety.

SHIELD: Also known as a screen. A conductor which is grounded to an equipment case or aircraft structure at both ends and is routed in parallel with and bound within a cable bundle. The effect of the shield is to provide a low resistance path between equipment so connected.

2.3.2 Acronyms

AC	Advisory Circular
AC	Alternating Current
ACARS	Aircraft Communications Addressing and Reporting System
AIR	Aerospace Information Report
ARP	Aerospace Recommended Practice
ARINC	Aeronautical Radio Incorporated.
BITE	Built-in-Test Equipment
CAN	Controller Area Network
CG	Center of Gravity
D	Density
DC	Direct Current
DITS	Digital Information Transfer System
EASA	European Aviation Safety Agency
EM	Electromagnetic
EME	Electromagnetic Energy
EMI	Electromagnetic Interference
EWIS	Electrical Wiring In Systems
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FQIS	Fuel Quantity Indicating System
FQS	Fuel Quantity System
HEFA	Hydroprocessed Esters and Fatty Acids
HIRF	High Intensity Radiated Field
IMA	Integrated Modular Avionics
K	Permittivity/Dielectric Constant
LRU	Line Replaceable Unit
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
RSS	Root-sum-squared
SFAR	Special Federal Aviation Regulation
TSU	Transient Suppression Unit
UL	Underwriters Laboratories
VAC	Volts Alternating Current
VDC	Volts Direct Current
VOS	Velocity of Sound

2.3.3 Terminology

AUTO IGNITION TEMPERATURE: The minimum temperature at which an optimized flammable vapor and air mixture will spontaneously ignite.

ELECTRICAL BONDING: The joining of metallic parts to form an electrically conductive path which assures electrical continuity and the capacity to safely conduct any current imposed between the metallic parts.

ELECTROMAGNETIC INTERFERENCE (EMI): Any emitted, radiated, conducted or induced voltage which degrades, obstructs, or repeatedly interrupts the desired performance of electronic equipment.

ELECTROSTATIC DISSIPATION: Bleeding away of any charge build-up on structures or equipment. To ensure that there will be no internal static discharge, the fuel tank and all internal installations must have design features that address possible static buildup through dissipation paths.

EXPOSURE TIME: The period of time between when an item was last known to be operating properly and when it will be known to be operating properly again. This definition applies to latent failures.

FAIL-SAFE DESIGN: 14 CFR/CS §25.981 paragraph a(3) defines a fail-safe design as "Demonstrating that an ignition source could not result from each single failure, from each single failure in combination with each latent failure condition not shown to be extremely remote, and from all combinations of failures not shown to be extremely improbable." Within the context of 14 CFR/CS §25.1309, an extremely improbable event (catastrophic) is defined as having a probability of less than 10^{-9} per flight hour. Within the context of 14 CFR/CS §25.1309, an extremely remote event (severe major) is defined as having a probability of less than 10^{-7} per flight hour.

HIRF: High Intensity Radiated Field. Expected aircraft radiated field environment resulting from exposure to RF transmitters (e.g., RADAR) throughout the world.

IGNITION SOURCE: A source of sufficient energy to initiate combustion of the fuel vapor within the ullage space.

INTEGRITY: The integrity of a system is the probability of that system displaying data or performing an operation which may appear correct to the users of the system, but in actual fact is in error or inappropriate, without the system indicating that there is a fault (i.e., the error is caused by an undetected failure)

INTRINSICALLY SAFE: Any instrument, equipment, or wiring that is incapable of releasing sufficient electrical or thermal energy under normal operating or anticipated failure conditions to cause ignition of a specific hazardous atmosphere mixture in the most easily ignited concentration. Refer to AC25.981-1C for a comprehensive review of energy sources and acceptable energy magnitudes.

LATENT FAILURE: A failure whose presence may not be readily apparent to the flight crew or maintenance personnel.

LIGHTNING DIRECT EFFECTS: Any physical damage to the aircraft and/or equipment due to direct attachment of the lightning channel and/or conduction of lightning current. This includes dielectric puncture, blasting, bending, melting, burning and vaporization of aircraft or equipment surfaces and structures. It is also includes directly injected voltages, currents and EM fields in the structure and associated wiring and plumbing. Refer to ARP5577

LIGHTNING INDIRECT EFFECTS: Electrical transients in aircraft electrical circuitry which occurs when energy from a direct strike to the aircraft is coupled into equipment wiring or other structure and plumbing. These transients are coupled through electromagnetic field penetration into the aircraft interior, or through structural IR voltage rises due to the lightning current flow on the aircraft.

LIGHTNING STRIKE ZONES: Aircraft surface areas and structures classified according to the possibility of lightning attachment, dwell time and current conduction. Refer to ARP5414.

NORMAL OPERATION: The operating condition of a component in the absence of faults and threats.

OUTGASSING: Release of dissolved air from fuel, during climb. This causes spontaneous generation of air bubbles within the fuel.

SIGNIFICANT LATENT FAILURE: Failure that would, in combination with one or more specific failures or events, result in a hazardous or catastrophic failure condition.

ULLAGE: Space above the fuel surface within an aircraft fuel tank (i.e., space between the fuel surface and upper tank surface), filled with a mixture of air and fuel vapor

UNSAFE SYSTEM OPERATING CONDITION: Operating condition in which the airplane is operating one failure away from a catastrophic fuel tank ignition that is greater than extremely remote.

3. OVERVIEW OF GAUGING TECHNOLOGIES AND FUEL CHARACTERISTIC MEASUREMENTS

3.1 General

Fuel gauging systems typically use one of two technologies to measure the height of fuel within the fuel tanks. These are:

a. Capacitance

b. Ultrasonic

Each of these sensing technologies is described below. In principle the gauging system downstream of the sensor interface will be largely the same, since both sensor technologies are used to derive a fuel height. Downstream algorithms then use the fuel heights to calculate a volume of fuel in each tank. Combining this with a density (measured or default value) gives a mass, which is displayed in the cockpit.

For each of these technologies variations in fuel characteristics caused by fuel types, temperature, stratification and various other factors can influence the calculated mass. In order to compensate for these it is necessary to provide some measurement of permittivity/dielectric constant for a capacitance system, and Velocity of Sound for an ultrasonic system.

For aircraft where high accuracy is not required, it is not necessary to measure density and it may not be necessary to measure temperature or permittivity, depending on what the accuracy requirements are.

Smaller aircraft may use other systems, such as floats. This technology is used in some piston-engine aircraft. For piston-engine aircraft it is more common to display a volume in the cockpit, rather than the mass display used in turbine engine aircraft.

3.1.1 Capacitance Gauging

A capacitance gauging system utilizes a number of concentric tube capacitors to measure the fuel height within each tank at multiple points within the tank. These height measurements are then used to determine a fuel volume and fuel mass in each tank.

3.1.1.1 Probe Construction and Principles

A capacitance probe consists of two concentric conductive tubes forming the electrodes of the capacitor. The tubes can be metallic or composite (carbon fiber or epoxy). The probe outer electrode is usually manufactured from precision aluminum alloy tubing, corrosion protected by some means (for example electroless nickel plate), although this can be composite with a conductive inner layer. The inner electrode is usually manufactured from precision parallel aluminum alloy tube, corrosion protected by some means (for example chromate film), although this can be composite with a conductive outer layer. The two electrodes are spatially separated and located with high quality fuel resistant polymer support pins. Probes are usually mounted using either two or more brackets attached to the tube, or by fitting the probe with an integral metallic flange for attachment to the tank wall at one end, with the other end supported by a self-draining elastomeric cup (chimney). In modern systems, the use of a metallic flange with an elastometric separator is not recommended, since the elastomer separator can fail and the probe may become shorted to ground, which reduces the protective gap.

Typically in modern systems the tubes forming the inner and outer tubes are of uniform diameter, giving a linear capacitance per unit length. In older systems, and in systems today fitted to smaller aircraft, the inner tube may be "profiled" (consist of different diameters for metallic tubes or variation of conductive layer surface for composite tubes), with the capacitance per unit length reflecting roughly the different shape of the tank at different heights to give an approximation of volume/unit length.

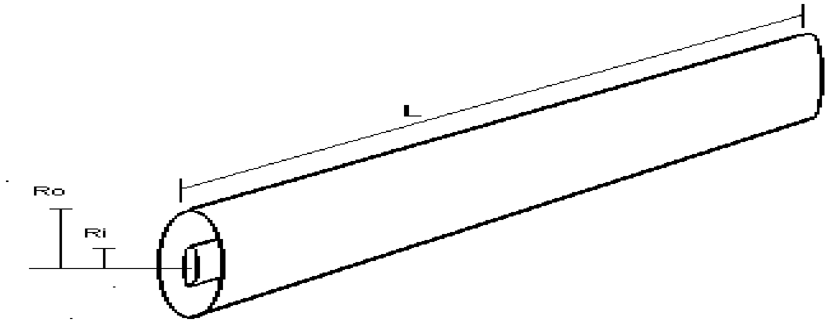

FIGURE 1 - CONCENTRIC TUBE CAPACITOR IN AIR

From first principles the capacitance of the probe in air is given by:

$$C = (2\pi\ \varepsilon_o\ K\ L) / [\ \ln(R_O/R_i)] \quad \text{(Eq. 1)}$$

where:

C = capacitance in pF

ε_o = 8.85

K = Dielectric Constant (K_{AIR} = 1)

L = Length meters

R_O = Radius of outer tube

Ri = Radius of inner tube

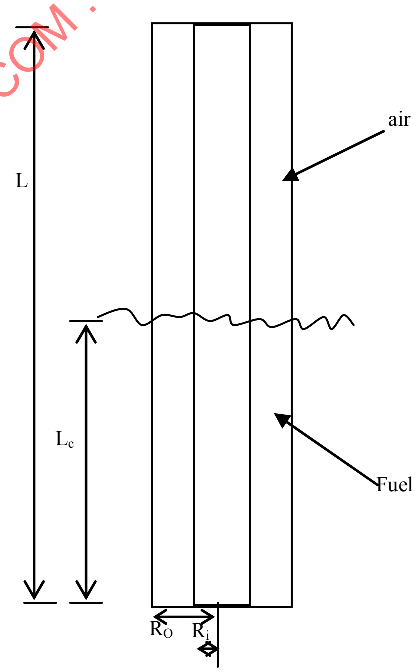

FIGURE 2 - PARTIALLY IMMERSED PROBE

As the probe becomes immersed in fuel the capacitance can be calculated by:

$$C = [(2\pi\ \varepsilon_o)/\ln(R_O/R_i)\ ]*(\ K_F - 1)\ L_C + C_E \qquad \text{(Eq. 2)}$$

where:

C = total sensor capacitance

L_C = Length covered

K_F = Dielectric constant of fuel

C_E = Sensor empty capacitance

ε_o = 8.85

R_O = Radius of outer tube

R_i = Radius of inner tube

The dielectric constant of fuel is approximately 2.1 times that of air, hence as the fuel fills the area between the two tubes displacing the air, the capacitance increases until it is approximately double that of the empty value when fully immersed. Height can be calculated as:

$$LC = [(Cmeasured - CE)\ /\ (KF - 1)]\ *\ [(2\pi\ \varepsilon o)/\ln(RO/Ri)] \qquad \text{(Eq. 3)}$$

3.1.1.2 Common Capacitance Measurement Techniques

There are two main methods for measuring the capacitance of the probe. These are AC and DC. These are described in summary below.

In addition some aircraft, especially smaller business jets, some military fighters and some helicopters use "smart" or "active" capacitance where the electronics for measuring the capacitance is embedded within the terminal block of the capacitor, and time domain or data bus signal is returned to the interface unit.

a. AC Capacitance Measurement Principle

The probe is energized by an AC signal, also called ‘low impedance’ or ‘LoZ’, via an unscreened drive wire connected to the outer tube. A screened return, also called ‘High impedance’ or ‘HiZ’, is connected to the inner tube making a 3 wire capacitance measurement. This arrangement ensures that only the capacitance between the two electrodes is measured and minimizes the effects of cable and other stray capacitances. Any breaks in the Hi-Z screening leads to a much higher capacitance reading, and this has caused problems with AC capacitance measurement systems. The return signal is fed into a virtual earth amplifier where the gain is set by the inverse ratio of probe capacitance to feedback capacitance. The resultant signal is fed into a demodulator to extract current quadrature signal. Older systems nominally run at around 400 Hz, whereas for systems that operate at higher excitation frequencies (typically to 18 kHz), a higher return signal is obtained, improving the EMI/EMC performance. By combining the capacitance measurement with knowledge of fuel permittivity the fuel height may be calculated.

AC capacitance measurement systems have been in service for more than 60 years. The sensors have high reliability, but historically systems have only shown medium reliability due to wire harness problems. Most older AC performance issues can now be addressed with extensive BITE capability of the computerized signal acquisition system to assist the aircraft operator with fault determination.

Attention to conductor and screen materials/alloys will also improve reliability.

b. DC Capacitance Measurement Principle

Each sensor is constructed in a similar manner to that of an AC probe depicted in Figure 1. A small terminal block containing two diodes is mounted on the probe. These diodes provide half-wave rectification of the signal on the probe.

The probe is energized by an AC signal via a drive wire connected to the outer tube. The resultant return signal is half wave rectified and the resultant current is directly proportional to the capacitance between the two electrodes. The diode voltage drop has an effect on the measurement and can be taken into account either by direct measurement or by using a dual voltage technique to eliminate the effects. On less accurate systems the diode voltage drop is not measured, but is assumed to be a constant value. The return signal is fed into a virtual earth amplifier and the resultant voltage scaled by the feedback resistor. By combining the capacitance measurement with knowledge of fuel permittivity the fuel height may be calculated.

No screened cable is required for operation, but in order to meet EMC requirements it may be necessary to screen the drive cables.

DC capacitance systems have been in service for more than 30 years. The sensor reliability is slightly lower than AC sensors, due to the addition of the diodes. But the overall system reliability is comparable to that of an AC system.

3.1.1.3 Other Capacitance Measurement Techniques

Due to the period that fuel capacitance measurement systems have been in service, variations on AC and DC measurement techniques have been implemented to address explicit system and performance issues. It is beyond the scope of the report to address all of these, but so that the reader is aware to consider the possibility, some are noted below.

- AC Profiled: Inner tube profiled to provide a linear measurement signal proportional to fuel height
- DC Profiled: Inner tube profiled to provide a linear measurement signal proportional to fuel height
- Full Height Compensated: Bias capacitor added to set the zero fuel level to zero output signal
- Ratio-metric: Ratio between a fixed capacitor and the fuel height
- "Smart"/"active" probes: the signal conditioning electronics is located on the probe, and locally generates the waveform to drive the probe.

3.1.2 Ultrasonic Gauging

The ultrasonic sensor consists of a ceramic transducer which resonates in fuel at a high frequency (of the order of 1 MHz). Directly above the transducer is a single tube (known as the ‘stillwell’) within which the height of a column of fuel is measured. The tube is topped off with a ventilated end cap. The body of the sensor itself is electrically inactive and, due to electrostatic requirements should be bonded directly to the tank structure.

The basic principle of ultrasonic gauging technology is to generate an ultrasonic sound wave and measure the time taken for it to travel from the source, reflect off the fuel surface and return to the source. This is shown in Figure 3.

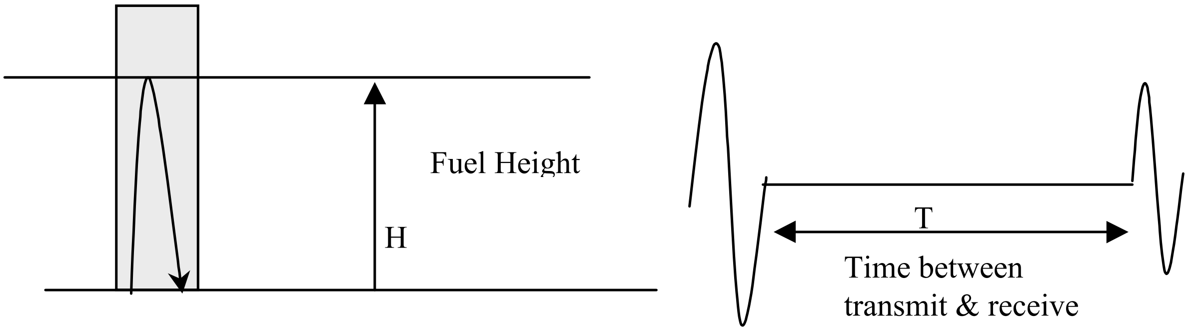

FIGURE 3 - ULTRASONIC PROBE OPERATION

From first principles, the height of fuel is given by:

$$H = T * VOS / 2 \quad \text{(Eq. 4)}$$

where:

H = height of fuel

T = time between transmission and receipt of reflection

VOS = velocity of sound through the fuel

To date ultrasonic measurement systems have had very limited application - they are currently in use on the Boeing 777, the F-22 and the NH90. There are issues with sensitivity to bubbles in the fuel during outgassing, and angle of tilt of the probe, although these can be overcome with the development of suitable software algorithms.

3.1.3 Comparison of Capacitance and Ultrasonic Measurement Techniques

Table 1 gives a comparison between AC Capacitance, DC Capacitance and ultrasonics for various parameters of interest in a gauging system.

TABLE 1 - COMPARISON OF GAUGING TECHNIQUES

Parameter	AC Capacitance	DC Capacitance	Ultrasonics
Physical Measurement	Fuel rising in tube changes capacitance	Fuel rising in tube changes capacitance	Fuel rising above transducer changes time of signal to reach surface and reflect back to transducer
Other measurements needed for accuracy of height determination	Permittivity	Permittivity	Velocity of Sound
Measured Parameter	Phase angle from AC voltage waveform, or AC voltage or change in voltage and current (i.e., or i = C*dv/dt)	Pseudo-rectified DC current	Time using voltage pulse
System Accuracy	Nominal 1% system at full	Nominal 1% system at full	Nominal 1% system at full
Accuracy Limitations	Manufacturing tolerances, processing electronics, number of sensors	Manufacturing tolerances, processing electronics, diode characteristics if not measured, number of sensors	Positioning of mechanical elements used for VOS measurement, manufacturing tolerances on placement of transducer, number of sensors
Fuel Temperature Effects	Output for given height varies with temperature. Stratification can cause errors, but these are negligible for existing systems	Output for given height varies with temperature. Stratification can cause errors. Diode characteristics change with temperature (but can be measured)	Time for given height changes with temperature. System implementation can take account of stratification easily (measurement of VOS at different heights in tank)
Long Term Stability	Sensors can become contaminated, affecting accuracy. Harness degradation affects accuracy	Sensors can become contaminated, affecting accuracy. Harness degradation may affect accuracy slightly	Transducers can fail due to thermal stress. Wiring connectivity and crosstalk.
Water Effects	Can cause large inaccuracies or loss of function	Can cause large inaccuracies or loss of function	Sensors at low levels will read the water/fuel boundary as the fuel height. which will result in loss of function
Other Contamination	Depends on frequency of operation - higher frequencies cause less error due to contamination	Depends on frequency of operation - higher frequencies cause less error due to contamination	Unknown
Bubble Effects	Small inaccuracies	Small inaccuracies	Can cause large inaccuracies - complex S/W algorithms needed to eliminate effects
Debris	Can short circuit probe - potential for spark/heating effects	Can short circuit probe - potential for spark/heating effects	Probe electrically inert => no effect. Mechanical arrangement can prevent access into wavepath

TABLE 1 - COMPARISON OF GAUGING TECHNIQUES (CONTINUED)

Parameter	AC Capacitance	DC Capacitance	Ultrasonics
Mounting position options	Any angle, or through top or bottom of tank on flange. Cranked probes possible	Any angle, or through top or bottom of tank on flange. Cranked probes possible	Angle should be as near vertical as possible. Cannot be mounted through top of tank (transducer must be submerged)
Angle of operation	Any angle	Any angle	Depends on design, may be limited
Probe connection	Probes can be daisy chained or individually addressed	Probes can be daisy chained or individually addressed	Probes individually addressed
Harness and Wire Screening	Accurate operation depends on maintaining screening in-tank and out-tank	Out-tank screening of drive required for EMC protection and to address emissions from drive signal	Screening only required in high EMI environment, and to address emissions from drive signal
EMC Susceptibility	Can be susceptible to noise and interference - careful selection of operating frequency can mitigate most of these problems	Can be susceptible to noise and interference - common rejection worse than AC systems	Less susceptible than cap systems because of time-domain signal
Weight (excluding harnesses)	Lightest	Slightly heavier than AC	Slightly heavier than AC
Electronic Processing Complexity	Least complex, analogue electronics	Slightly more complex than AC systems, but fairly simple analogue electronics	Fairly complex - timing circuits required
Hardware scaling	Long and short probes require different scaling to maintain resolution	Long and short probes require different scaling to maintain resolution	No hardware scaling required to maintain resolution
Software complexity for height calculations	Simple conversion calculations - can also be done with no software to drive moving coil indicator	Simple conversion calculations - can also be done with no software to drive moving coil indicator	Always requires software conversion - more complex than capacitive systems
Power Consumption	Baseline	Baseline - ~20%	Baseline - ~40%
Ease of Connection to multiple Processors	Difficult - can introduce errors	Difficult - can introduce errors	Moderation, but needs SW arbitration
Bonding / In tank Safety	Outer tube electrically active so cannot be bonded	Outer tube electrically active so cannot be bonded	Outer tube electrically inactive so has to be bonded to structure

3.2 Other In-Tank Sensors

To achieve a highly accurate fuel quantity it is also necessary to measure fuel characteristics. Depending on the design of the system in may be necessary to measure:

a. Permittivity (for capacitance based systems)

b. Velocity of Sound (for ultrasonic based systems)

c. Density

d. Temperature (depending on the algorithm used, not used on all aircraft)

Different sensors are used for the measurement of each of these, although they may be combined into one unit. Typically permittivity or velocity of sound, temperature and density should be measured throughout the flight, but with certain densitometer technology, density can only be measured during refuel operations on the ground. The measurement of density and permittivity or velocity of sound during refuel can be used to establish the relationship between the three fuel characteristics, and this relationship can be used in conjunction with permittivity/velocity of sound measurements during the flight to calculate a density. In addition, on some aircraft the measured density and permittivity or velocity of sound is calculated for tanks with no density/permittivity measuring devices, based on measured parameters in a tank with such measuring devices and an established relationship between the parameter and temperature (needs temperature to be measured in both tanks).

Other measurements within the tank may include the use of point level sensors (wet/dry determination at pre-set locations within the tank). These may be based on a short capacitance probe, but may be based on other technologies such as thermistors, optics or ultrasonics. These are not discussed further at this revision of this document, but may be included in a later revision.

3.3 Dielectric Constant (Permittivity) Measurement

Dielectric constant, also called permittivity, can vary from fuel sample to fuel sample, and is also influenced by temperature, pressure, contamination of the fuel, fuel additives, etc.

Permittivity of a substance is the characteristic that describes how it affects any electric field within the substance. A high permittivity reduces the presence of an electric field. For example, the capacitance of a capacitor can be increased by increasing the permittivity of the dielectric material.

The permittivity of air is described by the constant ε_o which comes from Coulomb's Law, and is basically an empirically derived value relating the force between two point charges, where it is defined as:

$$\text{Force} \propto \frac{1}{4\pi\varepsilon_o dist^2} Q_1 Q_2 \qquad \text{(Eq. 5)}$$

where:

Q_1, Q_2 are the two point charges, and dist is the distance between them

Since capacitance is a measure of storage of this charge, the relationship

$$\text{Cwith material between plates} = \varepsilon r \text{ x Cair} \qquad \text{(Eq. 6)}$$

where:

C = capacitance and ε_r is the permittivity of the material

Relative permittivity, ε_r, (often referred to as just permittivity or dielectric or K), is the ratio between this force in vacuum (approx the same as air), and this force in the material.

ε_r for water is typically 80 at 20 °C
ε_r for aviation fuel (Jet A) is typically about 2.1 at 30 °C
ε_r for air is typically about 1.00005364
ε_r for ice is typically 2.85 at -5 °C

$$K = \varepsilon r = \varepsilon s / \varepsilon o, \text{ where } \varepsilon s \text{ is the static permittivity of the material} \quad \text{(Eq. 7)}$$

This can also be defined as $\varepsilon_r = C_x / C_o$, where these are capacitance measurements with an air dielectric (C_o) and then with the material in question (C_x).

The dielectric constant, K, is a measure of the extent to which a substance concentrates the electrostatic flux lines, (also determines how much energy is stored). For time-varying electromagnetic fields, the dielectric constant of the material becomes frequency dependent and is generally referred to as permittivity. It is a physical property of any material which is caused by the polarization of the material when placed between two electrodes. This is due to the material becoming charged in the opposite sense to the electrodes, in the layers adjacent to the electrodes, and resisting the field.

For example the permittivity of fuel (Jet A) is nominally 2.1 at 30 °C, therefore the capacitance measured when the probe is full is approximately 2.1 times that measured when the probe is empty. This is derived based on the following graph shown in Figure 4.

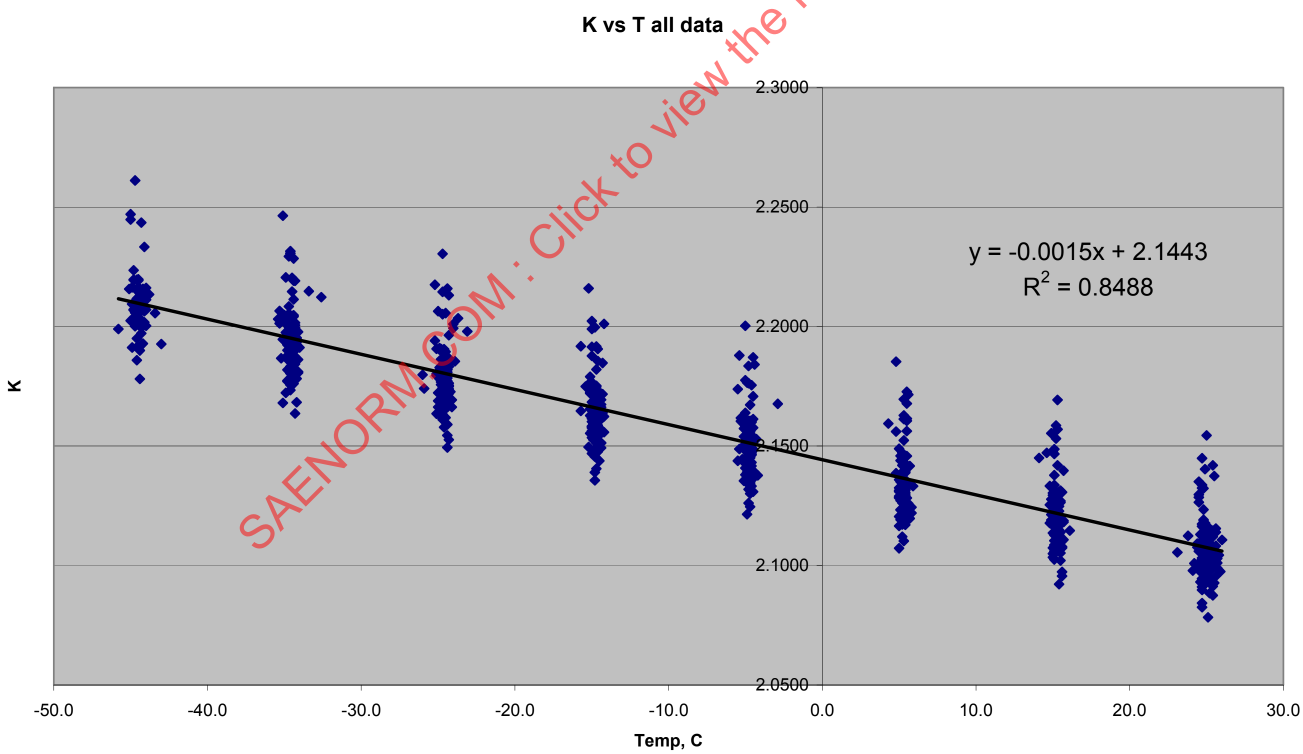

FIGURE 4 - LINE OF BEST FIT FOR JET A FUEL SAMPLES FROM ARINC 611

The range of variation in permittivity for fuel is usually considered to be approximately 1.99 to 2.3. The chart below is based on the 114 fuel samples quoted in ARINC 611-1 (data from 1991). Note: Further information on the range of values for typical jet fuels is available in the CRC Handbook of Aviation Properties and the CRC Word Sampling Programme Report.

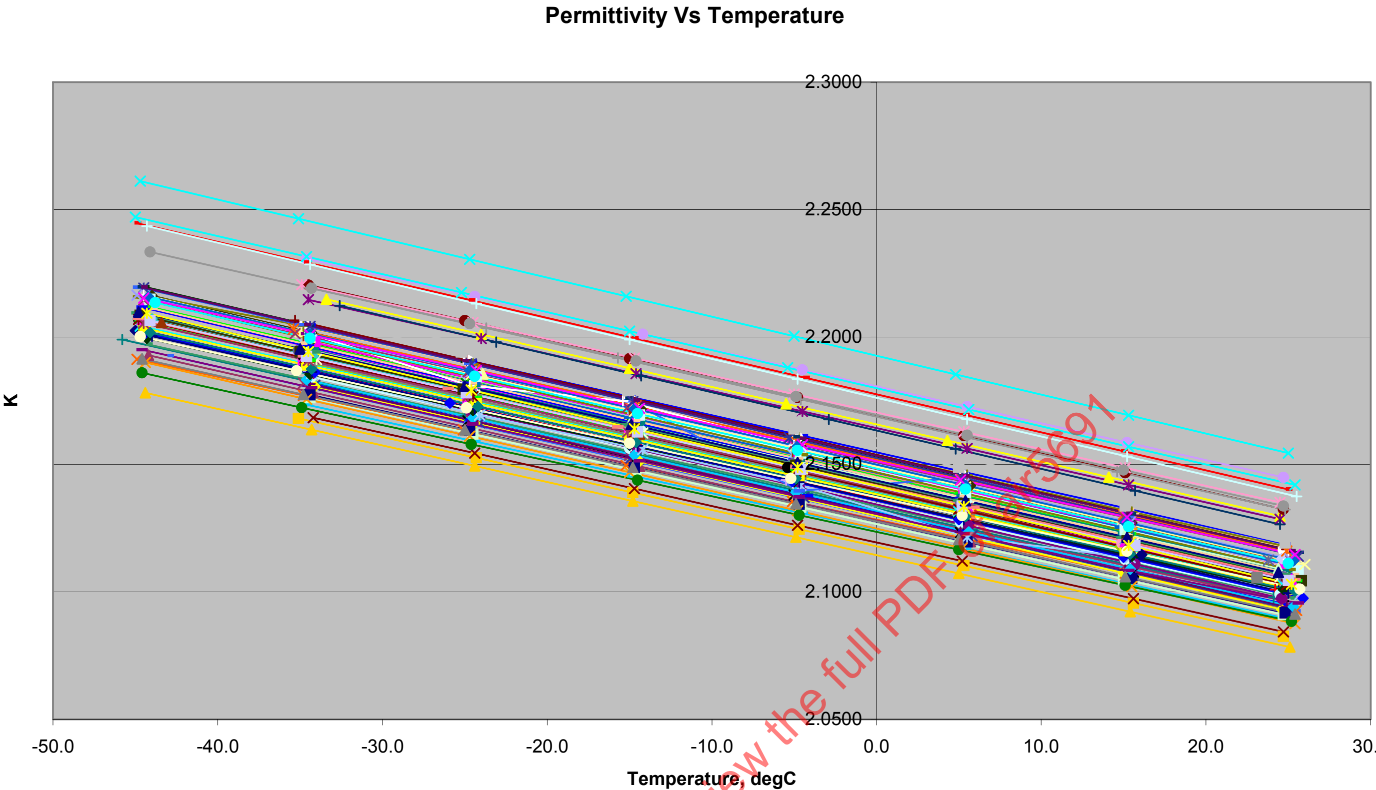

FIGURE 5 - JET A PERMITTIVITY SPREAD FOR FUEL SAMPLES

In order to achieve a highly accurate fuel quantity measurement it is necessary to measure the permittivity of the particular fuel in the aircraft. This can be achieved either by the use of a dedicated "k-cell" or "compensator" which is effectively a capacitor of known, highly accurate dry value. Measurement of the fully immersed, wetted capacitance value can then be used to calculate the permittivity of the surrounding fuel using the equation:

For a concentric tube construction:

$$K_F - 1 = \frac{C_F - C_E}{L_F} \times const \quad \text{(Eq. 8)}$$

where:

$$const = \frac{\ln\left(R_O / R_I \right)}{2\pi\varepsilon_0} \quad \text{(Eq. 9)}$$

where:

C_F = Full capacitance (i.e., when compensator is fully immersed)

C_E = Empty capacitance

L_F = Length of compensator

A similar equation applies to a parallel plate arrangement within a k-cell. The preferred option is to use a capacitor with multiple parallel or concentric electrodes in order to have an empty capacitance of the order of 40 to 100 pf, thus providing good resolution and accuracy in determination of the permittivity value. If a short probe is used, the capacitance value is typically too small to give good resolution, but can be used if no other source is available. The k-cell must be mounted low in the tank, near the sump, and have a low profile to ensure that it is totally immersed for as long as possible. It should be noted that this possibly causes problems with stratification, where the fuel close to the wing skin may be much colder than the bulk of the fuel in the tank and hence may induce errors in the permittivity measurement.

If permittivity is not measured, and a default (usually 2.1, which the data shows is the extrapolated value at 30 °C - see Figure 5) is used, errors of up to 3.3% (2 sigma level) of permittivity can occur. This error can be reduced to 1.3% (2 sigma level) if temperature is measured and default permittivity corrected by -0.00149/°C for each °C that the measured temperature varies from 30 °C. (i.e., actual permittivity = 2.1 * (measured temperature - 30) * -0.00149). Note that default permittivity is usually only used under multiple failure conditions in modern large commercial aircraft, but in smaller aircraft, and older aircraft with less accurate gauging systems then this is very often used as permittivity is not measured.

3.3.1 Impact of Inerting

For aircraft with inerting systems, the ullage space is no longer filled with air, but is filled with a nitrogen enriched atmosphere. This has minimal impact on the discussion of permittivity, since the permittivity of pure nitrogen is very similar to that of air - the relative permittivity for air is 1.0005364, whereas nitrogen is 1.00005474. Potentially this would lead to a 0.001% difference in capacitance readings for empty probes.

3.4 Velocity of Sound Determination

Velocity of Sound through a medium varies as a function of temperature and density of the medium and the exact chemical structure of the medium. This means that the velocity of sound can vary from fuel sample to fuel sample, as shown in Figure 6. Note: Further information on the range of values for typical jet fuels is available in the CRC Handbook. of Aviation Properties and the CRC Word Sampling Programme Report.

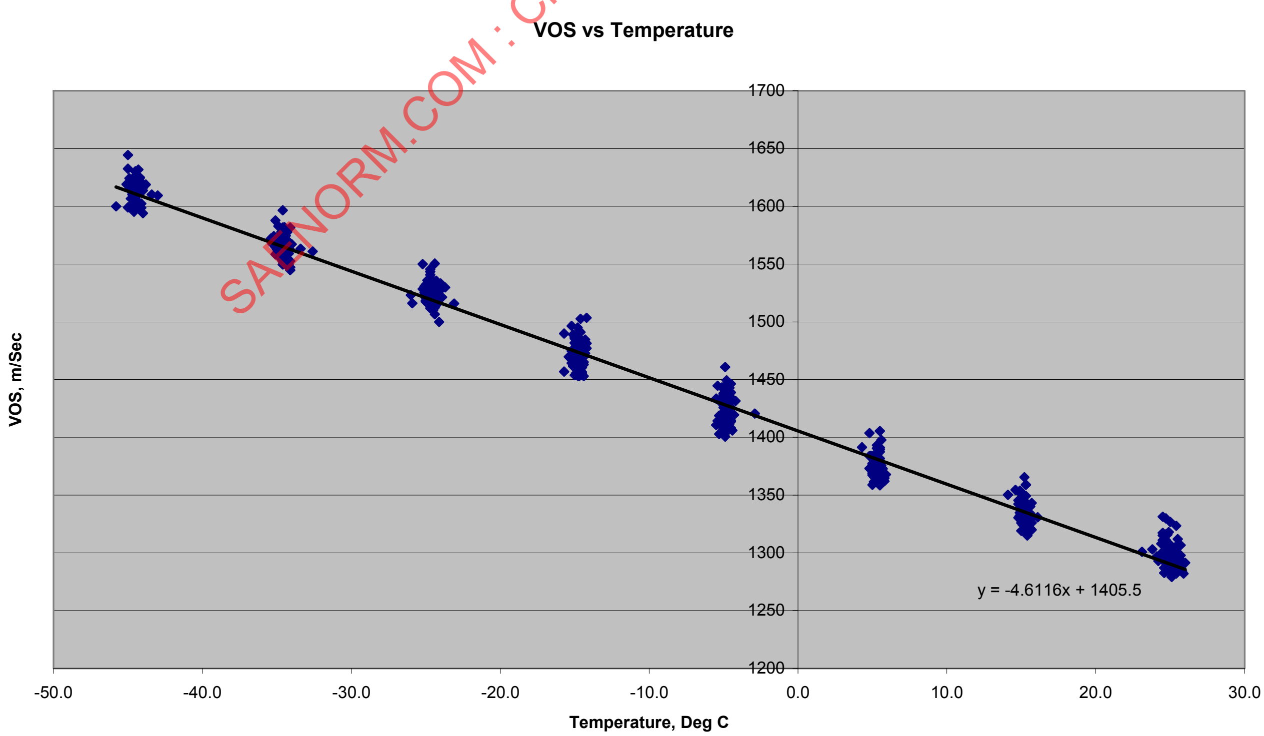

FIGURE 6 - VELOCITY OF SOUND VARIATION FROM ARINC 611 DATA

In order to accurately determine height of fuel from the time measured, velocity of sound must be measured. The easiest way to measure this is to have an intrusion at a known height above the transducer and measure the time of flight for a transmitted signal to be reflected back to the transducer from this intrusion. This is shown in Figure 7.

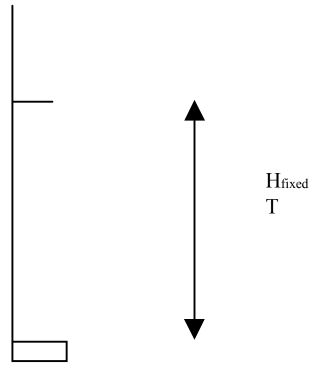

FIGURE 7 - VELOCITY OF SOUND MEASUREMENT

From first principles:

$$VOS = 2 * H/T \quad \text{(Eq. 10)}$$

where:

VOS = Velocity of Sound

H = Height of intrusion

T = Time between transmission and received reflection

If a default velocity of sound is used instead of a measured value, an error of up to 15.9% (2 sigma level) in velocity of sound can occur over the temperature range -54 to +55 °C, leading to a similar error in probe heights and hence volume. This is based on assuming a default speed of sound of 1267.1 m/s (value at 30 °C), and the information from ARINC 611-1. In a similar way to permittivity, this error can be reduced if the default value has temperature correction applied for measured temperature of the fuel. Using a factor of -4.6116 m/s/°C, would give errors of up to 1.7% (2 sigma level). Note that default velocity of sound would only be used under multiple failure conditions.

3.5 Density Measurement

In order to determine final mass of fuel accurately it is necessary to determine the density of the fuel. This can be done in one of several ways (or combinations of these):

a. Use a default value

b. Derive a value from permittivity

c. Derive a value from Velocity of Sound

d. Direct Measurement

3.5.1 Default Value

A value of 810 kg/m^3 (6.76 lb/gal) is recommended for Jet A and Jet A-1, and a normal range of 775 kg/m^3 (6.47 lb/gal) to 840 kg/m^3 (7.01 lb/gal).

NOTE: 1 lb/gal = 119.82642681 kg/m^3

Using default density with no temperature correction, variation in density due to temperature can lead to up to a 4.6% error (2 sigma level) in density and hence mass, based on the information from ARINC 611-1. It should be noted that this error is offset by an opposing error in permittivity, and hence probe capacitance and, therefore, the overall mass error would be in the order of 3%.

If the temperature of the fuel is measured the default density can be corrected for actual fuel temperature.

Note that for modern large commercial aircraft default density would only be used under multiple failure conditions, but for smaller aircraft, or older aircraft, with less accurate gauging systems a default density is commonly used as these aircraft do not include a means for measuring density.

Again this error is offset by the permittivity error, giving an overall mass error of around 2%.

3.5.2 Density Calculated From Permittivity

Once permittivity has been determined by measurement using a K-cell or compensator, this can be used to calculate density using the following Clausius-Mosatti equation:

$$D = \frac{K-1}{a+b(K-1)} \qquad \text{(Eq. 11)}$$

where:

K is the measured permittivity value

a and b are values which can be fixed or measured depending on system implementation

The values of a and b vary considerably between different fuel samples, as can be seen in Figure 8. Note: Further information on the range of values for typical jet fuels is available in the CRC Handbook. Of Aviation properties and the CRC Word Sampling Programme report.

This method can give errors of up to 1.07% at the 2-sigma level using line of best fit from graph, using a default a and b.

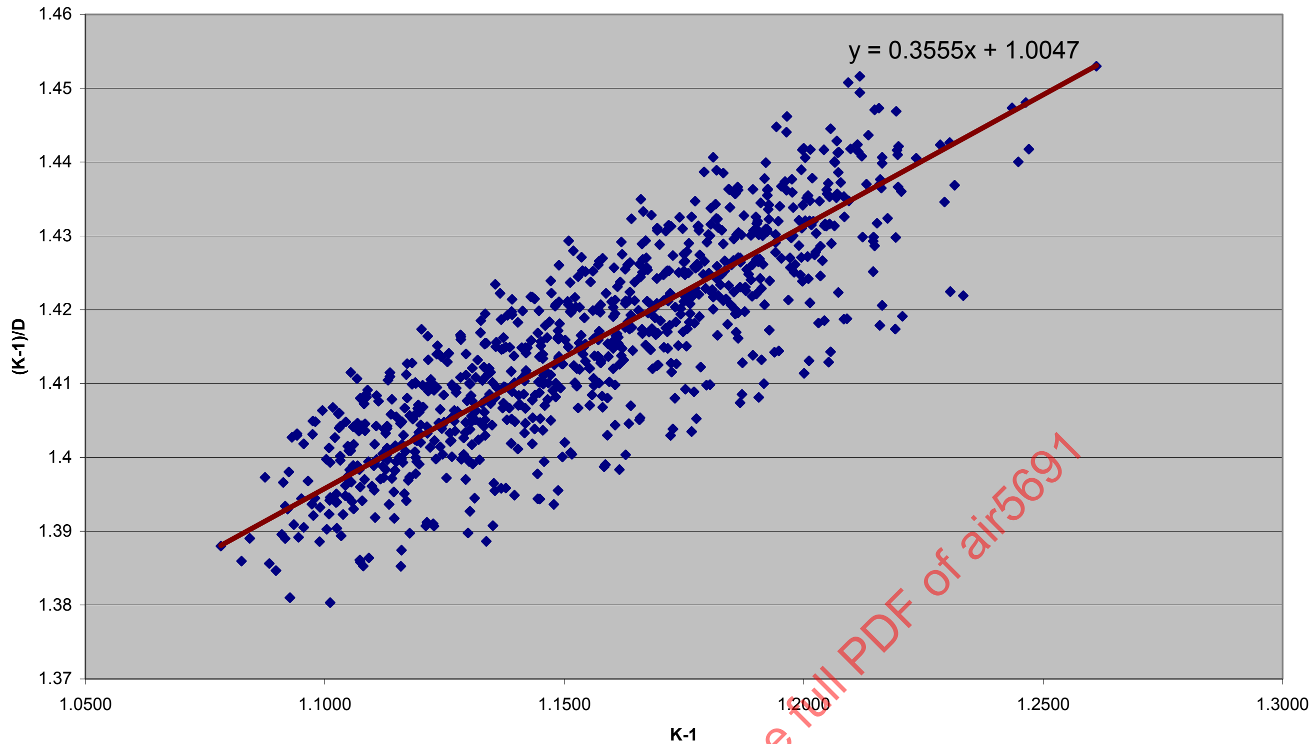

FIGURE 8 - DENSITY VERSUS PERMITTIVITY BASED ON ARINC 611 DATA

Accuracy can be improved by measuring both permittivity and density and using this information to derive either the a or b value (defining the other as a constant). The permittivity should be measured as close as possible to the densitometer, and in the same fuel layer where possible, in order to ensure the temperature of the fuel is consistent between that measured by the densitometer and that in which the permittivity is measured. The permittivity sensor and densitometer can be combined into one unit, and placed in/near the refuel gallery such that the new fuel being loaded fills the device. This ensures that the characteristics of the new fuel are always measured, even if there is not homogeneous mixing of old and new fuel. An algorithm can then be used to calculate the correct permittivity and density for the mixture of old and new fuels.

This method assumes that the a-value is temperature invariant and will remain the same for a particular sample. The data given in ARINC 611 shows that is not always the case, so errors of up to 0.09% can be seen, due to variation in fuel samples which are not linear. This is minimal when compared with the overall system accuracy of 1%, and has negligible effect on fuel quantity measurement.

3.5.3 Density Calculated From Velocity of Sound

Once velocity of sound has been determined this can be used to calculate density, using either a simple linear equation given below, or a more accurate equation also involving a temperature correction:

$$D = c * \text{velocity of sound} + f \qquad \text{(Eq. 12)}$$

Where from Figure 9, based on the ARINC 611-1 data c could be 0.1644 $kg/m^2/s$ and f could be 579.31 kg/m^3.

Similar to the values for a and b in the relationship between permittivity and density, the values of c and f vary considerably between different fuel samples, as can be seen in Figure 9. In order to ensure an accurate value for density it is preferable to measure density during refueling using a densitometer (see 3.5.4) and use this value and the measured value of velocity of sound to fix a value for f or c (making the other a pre-defined constant).

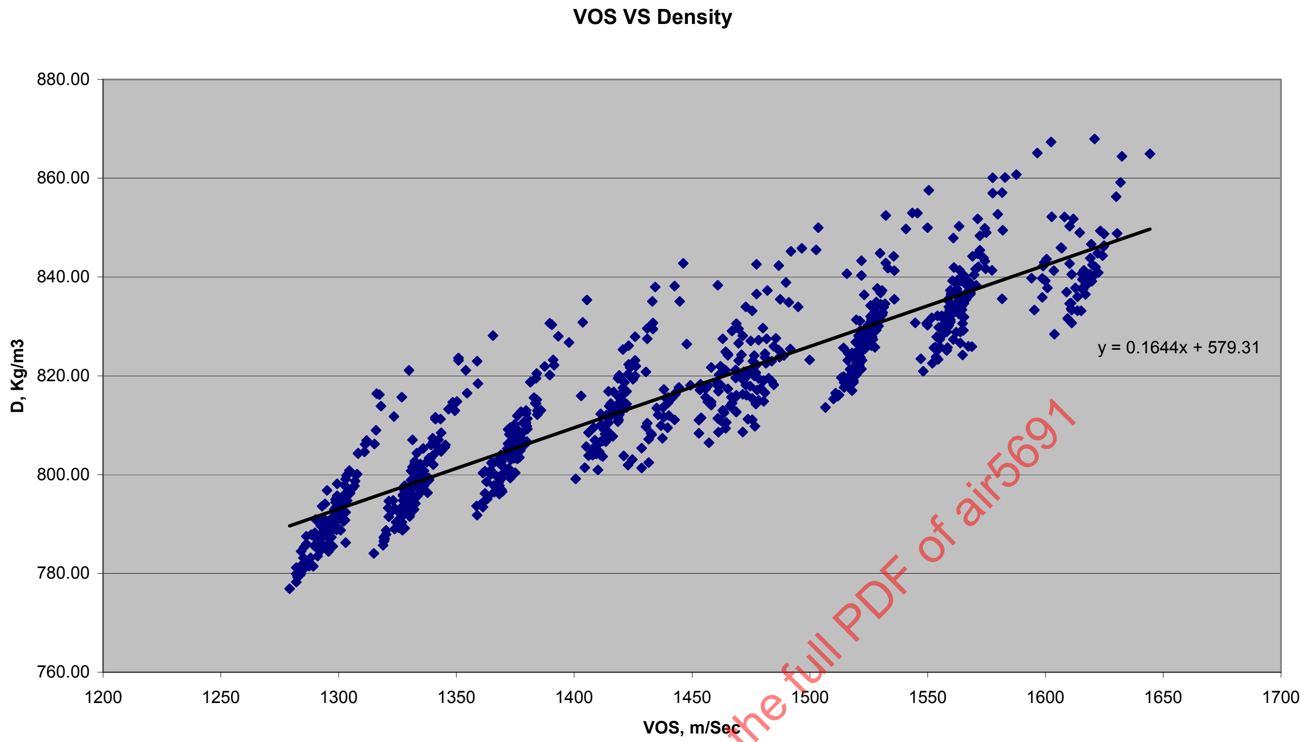

FIGURE 9 - FUEL DENSITY VERSUS VELOCITY OF SOUND BASED ON ARINC 611 DATA

The velocity of sound should be measured using fixed calibration points as close as possible to the densitometer, and in the same fuel layer where possible, in order to ensure the temperature of the fuel is consistent between that measured by the densitometer and that in which the sound velocity is measured.

If the fuel type is not fixed, this method can give density errors of up to 1.94% (2 sigma level), assuming nominal c and fuel type values from above.

With the fuel type measured at refuel, the errors drop to around 0.37% (2 sigma level).

3.5.4 Densitometer Density

There are several methods of measuring density directly. Many devices use a magneto-strictive method, where a plate or cylinder is vibrated via a signal from a "maintaining amplifier". As the density changes, the resonant frequency of the vibration changes, and this can be used to determine density. These devices work well on the ground, but can stop vibrating, or give misleading readings during take-off and climb as bubbles generated during out-gassing can cling to the vibrating element and cause the vibration to slow or stop. For this reason it is preferable to use this device to only measure density on the ground, and, as discussed in previous sections, derive the relationship between density and permittivity or velocity of sound in order to calculate density during flight. Note that the relationship between temperature and density can also be established, and this is another option for deriving density during flight.

Most vibrating element densitometers give a density measurement with 0.3 to 0.4% accuracy.

Other commonly used devices are using float type measurement principle (Archimedes principle), they are simple and reliable. This type of sensor can be used during all phases of the flight as it is not affected by bubbles. The accuracy of the float type density sensor is in the range of 0.2%.

3.5.5 Temperature Measurement

Temperature is usually measured by means of a "Platinum Resistance Thermometer" or PRT, either within the fuel tank or held within a sleeve penetrating the spar. These devices are available in standard resistance versus temperature relationships. Two wire, three wire, or four wire measurement techniques can be used depending on the accuracy required. Two wire measurement is the least accurate, since the harness resistance will impact the measurement. Three wire techniques partly eliminate the harness resistance, and four wire techniques totally eliminate effects of harness resistance and maximize the accuracy of the measurement.

Temperature measurement is not used in the determination of fuel quantity on all aircraft, but, as noted in the preceding paragraphs, on some aircraft it is used in the calculation of permittivity and density.

3.5.6 Effect of Synthetic Fuels on Permittivity and Density

Synthetic fuels such as HEFA, approved under ASTM D7566, exhibit a slightly different relationship between K and D (and velocity of sound and D). These fuels are used in a 50/50 blend with standard petroleum Jet-A or Jet-A1, thus ensuring both permittivity and density are within the normal range for Jet-A/Jet-A1 per ASTM D1655, but consideration needs to be given to the effects on a-value if the system is to make use of a-value in density calculation, or in fault diagnosis.

4. SYSTEM DESIGN CONSIDERATIONS

4.1 General

The Fuel Quantity Measurement system must provide a measure of fuel quantity, and must make any measurements needed in a manner which will not impact tank safety. The contribution of the FQIS to tank safety is discussed later in this document. This initial discussion will consider measurement of fuel quantity.

Ideally the FQIS should present an accurate and reliable indication of the useable fuel mass remaining for the approved fuel types, within the approved aircraft operating envelope, and at all times. The FQIS must indicate the quantity of usable fuel in each tank and it must read ‘zero’ during level flight when the fuel quantity reaches the unusable fuel determined by 14 CFR/CS 25.959. As a minimum the FQIS should present an accurate and reliable indication of useable fuel mass remaining for any fuel, under any conditions at the critical phase in the flight - the point at which a diversion decision would need to be made.

The intent of 4.2 is to identify the significant influences and to provide guidance as to their magnitude and how these may be dealt with. The accuracies stated within this section are considered to be achievable in the presence of expected contaminants and those additives deliberately introduced to alleviate problems arising from microbial growth activity, to prevent the build-up of electrostatic charge, or to provide anti-icing protection, etc. In assessing the accuracy of a given system, consideration should also be given to temperature gradients of the fuel in the tank, and temperature gradients due to loading of fuel at significantly higher temperatures than the fuel remaining in the tank.

The FQIS should operate without anomalies or faults for long periods of time. System reliability and integrity should provide a high degree of confidence. To this end, 4.3, 4.4, and 4.5 discuss various system architectures and techniques which can be employed to provide fault detection and functional redundancy and high integrity. Reliability goals are also discussed.

It is intended that BITE (Built-In-Test Equipment) provides a clear, unambiguous presentation of faults to the ground crew, as much as possible, and appropriate advisories to the flight crew. BITE should clearly indicate system anomalies and recommend the proper corrective action when necessary. Although ambiguity cannot be completely designed out, the intent is to make fault detection an important part of the initial design, and not just an add-on.

It should be noted that the requirements for improved accuracy and/or improved integrity and the requirements for reliability may cause a direct conflict in implementation, in that additional components may be required for improved accuracy and integrity, leading to a lower overall system reliability.

4.2 Accuracy Requirements

4.2.1 General

Generally there are at least two and often three or four accuracy regions of interest to the operator. Typically these represent ground refueling and normal flight at which relatively high accuracy (e.g., 1% of total fuel quantity or better) is desired and one or more "extended" flight attitude regions over which some reduction in accuracy is acceptable.

In cases where the FQIS provides data to other flight critical systems it is necessary to have high integrity data. In these situations high integrity data takes precedence over highly accurate data. In other situations a lower integrity signal may be preferable to no indication. The level of integrity required must be derived from an aircraft level hazard analysis. The technologies described in Section 3 all give a configuration of a system that uses many types of sensors (density, permittivity, temperature, etc.) to achieve the accuracy desired by the OEM and airlines while also providing the most economical solution (minimized equipment within the FQIS to reduce system weight, minimized additional fuel uplifted).

NOTE: Systems should provide basic backup gauging at reduced accuracy in order to accommodate a variety of failures, especially for large commercial aircraft.

4.2.2 Operational Accuracy Goals

The accuracy required will depend on the type and size of aircraft. For modern large commercial aircraft, or military transport aircraft it is common to require the ARINC 611-1 specified accuracies shown in Figure 10. It is possible to achieve better accuracy, but this would require additional sensors - this becomes a trade for weight/cost of the system against any benefits of improved accuracy.

For smaller aircraft this level of accuracy may not be required, and it is common for 737 sized and smaller aircraft for the accuracy on ground and in cruise to be 2.75% or 3% at full (and may be 1.75% at empty).

For some biz-jets and piston engine aircraft (Part 23 aircraft) the accuracy requirements may be as low as 5% at full.

For helicopters (Part 29 Aircraft), the gauging system accuracy is acceptable when it meets a tolerance of ±2% of the total useable fuel plus ±4% of the remaining usable fuel at any gauge reading, provided that the gauge indicates zero fuel with unusable fuel in accordance with § 29.959 in the tank. (For a 100-gal tank this formula would allow a ±6-gal error at the full level, ±4-gal error at 50-gal level, converging to a ±2-gal error at low fuel with the further provision that the zero mark accurately reflects unusable fuel.)

In no circumstances should the FQIS over-read when a tank is near empty. In addition, 14 CFR/CS 25.1337 states that unusable fuel must not be indicated on the gauges. One method of achieving this is to have a slight negative bias in the fuel quantity calculation at near zero usable fuel quantity, although exact implementation must be considered carefully to ensure no sudden jumps in displayed fuel quantity as the fuel increases or decreases past the point at which the bias starts to operate.

Some airlines believe that the ARINC 611-1 figures are not stringent enough for large aircraft and would like even better accuracy, although justification for increased accuracy is vague.

Increased accuracy is perceived as giving benefits in terms of reduced reserve fuel, but this may not justified by airline fuel needed calculations. Feedback from various airlines has suggested that the desire for increased accuracy is driven by the perception that increased accuracy equates to a more reliable fuel quantity system. This discussion has more merit on a large transport category aircraft than a small aircraft as the needed reserve fuel is significantly higher quantity. Error for large tanks translates into a much higher uplift of fuel to compensate for the error. For example 1% error on an Airbus A320/Boeing 737 sized aircraft might only equate to around 200 kg of fuel, but 1% on an Airbus A380 sized aircraft might equate to around 2.5 tons.

It should be noted that accuracy of the FQIS in usage with airlines is judged by comparison with the fuel used meters (flight manuals require the crew to cross-check fuel used with FQI at periodic intervals on large commercial aircraft for example) and the bowser metering at refuel. Each of these systems also has inaccuracies and the tolerance on the comparison should allow for the combined error of the systems being compared. Today most bowsers use a volumetric fuel measurement system, and rely on manual measurement of density (usually only once/day) in order to calculate fuel mass for comparison with the FQIS produced values of fuel mass. A recent paper from IATA has proposed that the use of Coriolis meters, or slipstream densitometers to remove errors associated with manual measurement of density.

The more accuracy a system is required to be, the more probes are required to measure the height of fuel (to ensure no discontinuities at different attitudes). More probes then means that a system may be less available at its standard accuracy.

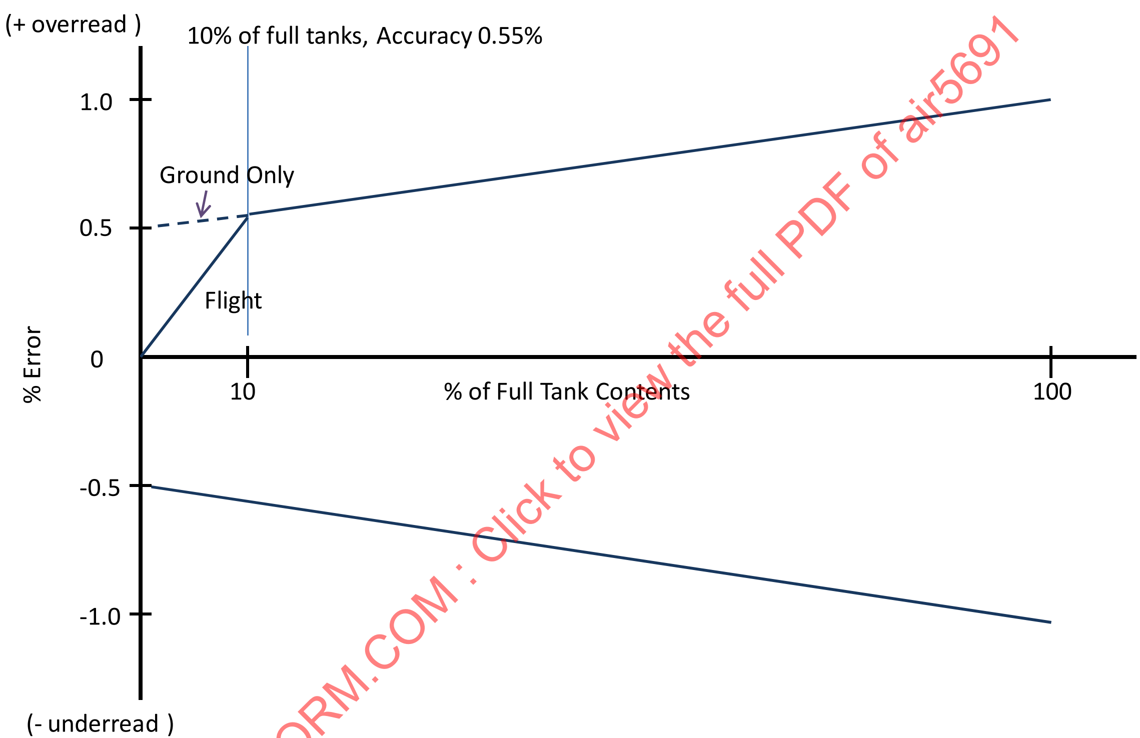

FIGURE 10 - FUEL QUANTITY ACCURACY

4.2.2.1 Reduced Accuracy

Based on ARINC 611, if a single probable fault results in the reduced accuracy of all tank indications, then the resulting accuracy should not be worse than twice the operational accuracy goal. Under these conditions no fault indication should be displayed to the flight crew. Note that the impact of a single fault may depend on the architecture of the system - if each tank is gauged separately, then a single fault will only affect one tank, if multiple tanks are processed through the same signal conditioning circuitry, then a single failure may cause a reduction in accuracy of all tanks.

4.2.2.2 Degraded Accuracy

Based on ARINC 611, when a fault condition is detected whereby the accuracy of the total fuel quantity is greater than two and less than four times the operational accuracy goal, then the system should provide an indication of system degraded accuracy to the flight deck (usually a "-" masking the lower digits of the display).

4.2.2.3 Unknown or "Failed" Accuracy

Based on ARINC 611, when the accuracy degrades beyond four times the operational accuracy goal, then the system should provide a warning of this unknown accuracy to the flight deck which is different than the indication used in the degraded mode (e.g., blank displays).

4.3 Accuracy Analysis and Error Sources

4.3.1 Scope of Accuracy Analysis

The goal of this section is to provide a uniform standardized method for analysis of all error sources.

Accuracy analysis should be performed for all areas of interest and for all operational modes. The analysis should include the error sources described in Section 3 as a minimum. All error sources should be properly expressed in terms of the effect they have on overall system accuracy.

4.3.2 System Errors

System errors can be split into bias errors (those always potentially present under certain conditions, such as discontinuities in gauging caused by ungaugable level of fuel between the top of one probe and the bottom of another at certain attitudes) and random errors (those which are independent of each other and of the system state, such as component/installation tolerances). Errors which are deterministic functions of predictable environmental conditions should be treated as bias errors.

A standard method of combining the errors identified should be used. The accuracy analysis should be performed with the fuel distributed in accordance with the normal fuel management schedule. For each error source, the analysis should take into account both the bias component (if any) and the random component (if any).

The accuracy specification is normally applied to individual tank contents, but may be applied to all fuel on board dependent on the desired performance of the system.

NOTE: All accuracy data is normally expressed as a percentage of full tank.

4.3.3 Random and Bias Errors

There are two possible types or error - Random Error and Bias Error. These are defined as:

Random Error: An error which cannot be controlled by the measurement process and is random in nature, but is assumed to follow a particular probability distribution which is used to describe its aggregate behavior. For example this can be things like component and installation tolerances. These will typically vary from aircraft to aircraft, and even minute to minute due to component tolerances, etc. The errors can be assumed to be within a normal distribution.

Bias Error: An error which can be controlled by the measurement process and is quantified by its mean value of deviation from the ‘true’ value of the subject parameter. A typical example is discontinuities in fuel quantity measurement when the fuel surface lies between the upper sensing point of one probe, and the lower sensing point of another at a specific attitude and fill point within the tank. These, given certain conditions, will always be present. For example if the tank modeling includes discontinuities, at the fuel height/pitch/roll at which that discontinuity occurs, the error associated with that discontinuity will always be present.

4.3.4 Methods of Accuracy Analysis

Three methods for overall system performance analysis are described below. The second two methods (from ARINC 611) provide a very comprehensive analysis, and each has its advantages and disadvantages. The first method is a very simplistic arithmetic error combination method, and whilst this is often used, it is much less comprehensive than the more analytical methods.

Analysis of the performance of FQIS, which uses numerous correlation techniques to combine the information derived from a relatively large number of sensors, can only be done economically by computer modeling and simulation, so the second two methods are much more appropriate than the first simplistic method.

4.3.4.1 Method 1 - Arithmetic Combination of Errors

Random errors should be evaluated individually at the two sigma (i.e., two standard deviations) level. All the identified random errors should then be combined using root sum squaring (RSS).

The bias errors should be combined using a simple algebraic sum of the identified errors.

The RSS value and the sum of the bias errors should then be combined (summed) to determine probability of compliance with the accuracy goals stated in 3.2.2.

For example if the following errors have been identified:

a. Sensor tolerance = 0.02% of max tank contents

b. Signal conditioning = 0.01% of max tank contents

c. Tank modeling = 0.3% of max tank contents

d. Tank deflection = 0.2% of max tank contents

Then a and b can be treated as random errors, giving an RSS value of square root ($0.02^2 + 0.01^2$) i.e., a value of 0.0224% and d) would be treated as bias errors, giving a sum of bias errors of 0.5%.

This would give an overall probable system error of 0.5224%.

In reality modern systems have far more than one sensor, so errors from each sensor, and the signal conditioning associated with that sensor would have to be analyzed to determine its effects on the overall tank quantity measurement, which is much better done using the following two methods than this simplistic approach.

4.3.4.2 Method 2 - Partial Derivative Method

(Based on ARINC 611)

This method first derives the partial derivative of the total fuel output with respect to each error source. The entire system should be simulated. At each test case the nominal values of all sensor inputs are re-established and the result (total fuel indication) is noted. Then each sensor input is varied - one at a time - by a small amount, and the change in output is noted. This establishes the sensitivity of the output signal to each error source. These sensitivities are then used to translate the individual mean and random errors into values that represent percent of total fuel. The errors are then combined by adding the bias errors and root sum squaring (RSS) the random errors.

4.3.4.3 Method 3 - Monte Carlo Method

(Based on ARINC 611)

In this case and as in Method 2 the entire system should be simulated. The mean and standard deviations for each random error source are then entered, and random number generators are used to establish random values for each error source. These randomly chosen errors are imposed on their sensor signals simultaneously, rather than one at a time. A large number of sets of randomly chosen error values are used, and the resulting total fuel errors are accumulated in statistical "buckets". The final system accuracy is then obtained by statistical analysis of the accumulated error data, including the bias errors.

4.3.4.4 Comparison of Method 2 and Method 3

Method 2 requires considerable less processing time, which is its primary advantage. Method 3 requires a large number of sets of randomly selected error values in order to achieve good statistical confidence. The advantage of Method 3 is that all errors are imposed simultaneously and any FQIS features that serve to amplify or attenuate individual error sources are faithfully evaluated. Method 3 is the most commonly used method.

4.3.5 Error Sources

Table 2 highlights the main error sources to be considered when doing an accuracy analysis. The table indicates the nature of the random and bias components of the error, and the source (airframer or FQIS vendor) from which the magnitude of the error should be supplied.

Table 3 indicates possible error sources which are not necessarily considered directly in any numerical accuracy analysis, but which should be considered and addressed during the design of the system.

4.3.6 Error Sources in Accuracy Analysis

The following subsections provide a detailed discussion of error sources which should be included in FQIS accuracy analysis.

4.3.6.1 Tank Manufacturing Tolerances

Fuel tank manufacturing tolerances result in a slight variation in the size and shape of each manufactured fuel tank as compared to the nominal design documentation used to develop the FQIS. Some errors may be completely random on a tank by tank basis due to the machining and fabrication variables. Some errors may be repeatable (i.e., a bias) on a tank by tank basis due to imperfect tooling dimensions or design modifications that were not included in the FQIS design.

It is important that the calculation of the nominal shape of the tank under various load conditions be extremely accurate. The analysis should properly reflect the mean shape of the tank and all parts of the tank structure that displace fuel. Fuel tank manufacturing tolerances are to be considered. If the net volume tolerance in the manufacturing process is too large to support the desired systems accuracy than it may be appropriate to include a trimmer to calibrate the system once installed. For example, a single point trimmer may be used to provide a fixed input to the processor to calibrate the system to the actual full tank volume. A second trimmer can be included to provide a fixed input to the processor to calibrate the system to zero at empty. If a trimmer is used, the accuracy analysis should continue to take into account the effects of manufacturing tolerances on the shape of the height-volume curves. On modern systems, trimmers should be used only as a last resort to meet the accuracy goals contained herein - they are not preferred because they give additional maintenance burdens for the airlines. Trimmers are standard on older aircraft systems.

TABLE 2 - ERROR SOURCES AND CONSIDERATIONS - ERRORS DIRECTLY ACCOUNTED FOR IN ACCURACY ANALYSIS

Error Source	Description	Airframer (A) / Supplier (S) Contribution	Bias	Random
DESIGN CONTRIBUTION				
Tank manufacturing process	Fuel tank manufacturing tolerance resulting in a slight variation in the size and shape of each manufactured fuel tank as compared to nominal.	A - Specify tank shape and manufacturing tolerances. S - Digitize tank design for datum.	If there is a constant jig problem.	Global versus local coordinate systems, relative dimensions, tolerance build ups, non-linear shapes.
Tank Modeling	Tank study fidelity and accuracy of height versus volume curve(s).	A - specify tank shape S - Analyze tank study errors	At a particular quantity and attitude where there is a discontinuity	None.
Implementation of tank datum model in flight software	For FQI datum volume calculation use stored data, interpolation may be necessary.	A - Specify bulk volumes. S - Define tank datum model, then perform empirical tests on datum shape and validate against bulk volumes.	At a particular point where the data is not stored but evaluated. May be due to lack of stored data, i.e., requires use of interpolation.	Pseudo random due to mathematical processes, e.g., interpolation, non-linear shapes, etc.
Tank internal structure modeling	Fidelity of tank studies caused by errors such as internal structure, tubing, etc.	A - Specify internal structures, e.g., pipe work, spars, etc. Specify net volumes. S - Define and model internal structures and the flooding of them, perform empirical tests on datum model and validate against net volumes.	Caused by irregular distribution of internal structure components within tank, e.g., pipes on floor of tank, etc.	Dependent on fidelity of modeling of flooding of internal structures.
Sensor mounting tolerances	The tolerances associated with the location of mounting brackets, flanges plates or mounting holes, fringing affects.	A - Specify sensor mounting tolerances. S - Perform empirical tests on datum model.	If a probe has been relocated during manufacturing and software is not updated.	Tolerances on sensor mounting points

TABLE 2 - ERROR SOURCES AND CONSIDERATIONS - ERRORS DIRECTLY ACCOUNTED FOR IN ACCURACY ANALYSIS (CONTINUED)

Error Source	Description	Airframer (A) / Supplier (S) Contribution	Bias	Random
Tank deflection, expansion, twist, deformation	Errors due to distortion of the fuel tank from the normal datum shape, to be taken into account when designing the fuel measurement system.	A - Specify wing expansion, twist and deflection for various flight conditions and fuel loads. Specify typical aircraft flight profiles. S - Define tank deformation model from datum driven by flight conditions and fuel loads, then perform empirical tests.	The bias error is caused by error of deformation model during predominant flight conditions e.g., ground refuel, cruise, etc. It should be noted that different considerations may need to be given to bladder tanks where there may be up to a 70% increase in bladder material volume when fuel saturated. Also if the bladder changes shape during emptying, it may hold fuel around any gauging probes causing an offset in readings at near empty conditions.	The random error is caused by error of deformation model during exceptional flight conditions, e.g., turbulence, maneuvering, etc.
Calculation algorithms	Any errors due to software computation and methodology.	A - None. S - Perform empirical tests.	Any truncation.	Any rounding.
Technology Dependent Effects and Errors				
Sensor manufacturing, mechanical	Sensor mechanical manufacturing tolerances.	A - Nothing required. S - Define effects, if any on gauging accuracy, perform empirical tests.	A constant manufacturing problem or a change for which software is not updated.	Length, tube spacing, target positions, non-linearity of section, etc.
Measurement linearity	The ability for the sensors to measure over the entire range.	A - Nothing required. S - Not normally relevant with software based systems due to software characterization possibilities, can apply to small analogue systems.	Constant error at points of non-linearity.	None: Covered by manufacturing tolerance.
Sensor mounted electronic circuit and components	Electronic errors of sensor mounted components.	A - Specify specialized environmental requirements, e.g., energy storage limit in tank, etc. S - Define design features incorporated to meet above requirements, effects on gauging accuracy.	An error not taken into account in algorithms (e.g., diode voltage).	Diode error or on probe circuit errors due to component tolerance and the environment.

TABLE 2 - ERROR SOURCES AND CONSIDERATIONS - ERRORS DIRECTLY ACCOUNTED FOR IN ACCURACY ANALYSIS (CONTINUED)

Error Source	Description	Airframer (A) / Supplier (S) Contribution	Bias	Random
Sensor environment	Errors due to the environment changes on the sensor.	A - Nothing required, already specified by sample flight profiles. S - Define expected long term effects and any operational procedures to counter these.	None: Even though the effect of a particular set of environmental conditions will cause a quantifiable error, because there are an infinite number of cases, it is more appropriate to account for the whole set of possibilities by considering them as random errors.	Expansion of the metals and plastics.
Probe Implementation	Errors due to the way the probe has been implemented.	A - Nothing required. S - Define design features incorporated to achieve gauging, effects on gauging accuracy.	e.g., in ultrasonics: the use of thresholds for signal detection and the effects of amplitude, in capacitance: the effects of "fringing" , parasitic capacitances, dewetting effects, etc.	Similar effects to Bias but non-linearities caused by overlapping limited range effects.
Signal conditioning	e.g., analogue and digital (AD) off sensor electronics used for capacitive measurement, threshold effects for ultrasonics, PSU tolerance effects, etc.	A - Nothing required. S - Perform empirical tests.	An error not taken into account in algorithms.	Half the resolution of the D to A, component tolerance, temperature effects and PSU effects.
Errors Caused By System Specification				
Effects of display resolution and rounding	Display resolution and rounding.	A - Specify display resolution and format. S - Define effects.	Display truncation (i.e., loss of LS digit).	Effects of communication buses i.e., ARINC 429 resolution/rounding.

TABLE 3 - ERROR SOURCES AND CONSIDERATIONS - ERRORS SOURCES TO BE CONSIDERED DURING DESIGN

Error Source	Description	Airframer (A) / Supplier (S) Contribution	Bias	Random
DESIGN CONTRIBUTION				
Fuel surface shape and formation	The effects of aircraft acceleration, attitude, and time on fuel surface shape. Separate transient and steady state effects.	A - Specify typical aircraft flight profiles. S - Model transient and steady state effects, then perform empirical tests.	Caused by computed height and orientation of eventual flat fuel plane, e.g., accelerometer errors, attitude measurement errors during steady flight.	Caused by transient effects e.g., turbulence, maneuvering, etc. which generate transient and non-flat fuel planes.
Anomalous fuel distribution	The effects of different fuel heights in cell (e.g., due to proximity to flow restrictions and flow near those restrictions).	A - Specify ungaugable/ scavenged fuel quantities and flow restrictions. Specify typical fuel movement and transfer regimes within typical flight profiles. S - Model flow (e.g., using fluids dynamic software, e.g., Phoenix) or empirical methods, then perform empirical tests.	Effects are only produced when fuel is moved by pumping or change in attitude, this effect may be seen in variations in the "Fuel On Board" quantity when fuel is moved from tank to tank. Air pockets above sensors may also cause anomalies if not properly vented	Caused by tank geometry differences from aircraft to aircraft and between different variants of same aircraft.
Fuel temperature stratification and temperature variation with time	The effects of both horizontal and vertical temperature stratification both in flight and during refuel over time.	A - Specify operating temperatures and flight profiles. Specify refuel schedules, fuel characteristic variations from different sources. S - Model temperature stratification (e.g., using fluid dynamics software, e.g., Phoenix) and variation with time (using typical flight profiles), define a model, and then perform empirical tests.	Center and partially filled wing tanks colder at bottom than top. Refuel is performed on ground at fuel storage temperatures; while most of the flight is in the cold of the stratosphere (typically at -50C) with large thermal time constants (fuel can take longer than the flight to cool to stratospheric temperatures). This can be a significant issue on long extended flights, especially over polar regions.	Fuel temperature mixing as a result of transient events (e.g., maneuvering, etc.). Impact on fuel quantity measurement (in particular for ultrasonic technology).
Fuel type variation	Variation across a range of fuels of the same type which can cause variation in permittivity and/or density and the relation between permittivity, density and temperature	A - Specify mixing of fuels during refueling V- Define measurement/inference scheme for permittivity and density, then perform empirical tests		Caused by variation within a specified range of fuels.

TABLE 3 - ERROR SOURCES AND CONSIDERATIONS - ERRORS SOURCES TO BE CONSIDERED DURING DESIGN (CONTINUED)

Error Source	Description	Airframer (A) / Supplier (S) Contribution	Bias	Random
Density characteristic variations	Variation of the fuel density over the operating range.	A - Define any stratification or lack of mixing which may occur S - Define density inference scheme, then perform empirical tests.	Caused by positioning of densitometer or dielectric compensators asymmetrically within temperature stratification (i.e., usually at bottom of probe/tank for maximum height coverage).	Density variation with temperature and dielectric constant source data is usually scattered. Dielectric compensators use dielectric constant to infer density or assume empty K of air when probes are in air/vapor mix. Ultrasonics use VOS/temperature relationship. Air entrainment in the sensors may also give rise to density errors.
Fault mode analysis	Effects of detected faults in probes, harness, interfaces, etc.	A - None. S - Perform empirical tests.	Biased faults, e.g., under-reading, spatial concentrations of faults, etc.	Unbiased faults, irregular spatial distribution of faults, etc.
Effects of fuel additives and contaminants	Effects of common fuel additives and contaminants.	A - Specify peak concentrates of any additives in the fuel S - Define impact on gauging accuracy	None: Would require same quantity and same concentrate of same additive(s) in all aircraft.	As defined in Appendix B; various concentrates and volumes.
Water Contamination	Contamination of water above 200ppm, separation and pooling of water at low points.	A - Specify the maximum water contamination levels and collection areas and expected max separated water quantities. S -Define effects, if any, on gauging accuracy.	The fuel system design can lead to a bias error if the water separates and collects at base of a capacitance probe and/or densitometer.	Error if water separates and collects within a capacitance probe. Uniform concentration can affect dielectric constant/density.
Effects of aircraft wiring	Errors due to environment effects on sensor wiring.	A - Specify errors for relevant parameters for any harness sections not produced by the vendor (depends on specific solution and gauging technology and therefore not expected for RFP; Vendors to make relevant assumptions). S - Define effects, if any, on gauging accuracy.	Effects of wire property variation in manufacture. This can include wire length, stray capacitance, shielded wire capacitance, etc. Effects of rework without software compensation.	Variation as a function of time or environment and installation. Insulation effects over time.

TABLE 3 - ERROR SOURCES AND CONSIDERATIONS - ERRORS SOURCES TO BE CONSIDERED DURING DESIGN (CONTINUED)

Error Source	Description	Airframer (A) / Supplier (S) Contribution	Bias	Random
Microbial growth	Effects of thin film of biological growth coating sensors.	A - Specify amount of microbial growth to be allowed for. S - Define effects, if any, on gauging accuracy.	None:	Refer to 4.3.7.10
Fuel variation across aircraft tanks	The fuel characteristics may vary from tank to tank.	A - Specify different fuel sources possible, e.g., multi refueling trucks, etc. S - Define inference scheme or multiple instrumentation.	None with multiple densitometers or dielectric compensators, ideally one per tank.	The fuel is different between tanks (applies only if any fuel characteristic is inferred for one tank from measurement in another tank), e.g., fuelled from different refueling trucks.
Accuracy verification	The error associated with verifying the fuel system accuracy	A - Nothing required. S - Define accuracy of TE used and any identified error in process.	Method of test causing offset (e.g., fuel already on board not accounted for, overwing fuelling resulting in different distribution).	Tolerance of Test Equipment used.

4.3.6.2 Tank Modeling Error

In the typical capacitance systems and ultrasonic systems, the sensors serve to locate the fuel surface at a discrete number of points in the fuel tank. Digital processing interprets the fuel surface measurement and calculates fuel volume. Future gauging techniques (e.g., pressure sensing, sensors based on optical technology) may use other methods to determine fuel surface, but will still need to relate measurement to amount of fuel in the tank. This involves the solution of a solid geometry problem using stored numerical data that approximates the true geometrical shapes. The solution can be affected by anything that alters the shape or orientation of the fuel surface.

Aircraft fuel tanks have complex shapes and a considerable amount of internal structure, tubing, and other equipment that displace fuel. The FQIS design process requires the development of height versus volume relationships. The accuracy of these height-volume curves depends on the rigor with which all the shape data is described in the "tank study" computer programs.

A standardized treatment is needed for the deterministic portion of the modeling errors. The worst observed error spike, leading to a fluctuation in gauging occurring at some unique (and hopefully unlikely) combination of pitch, roll, deflection and fuel load should not be used as the bias component of the modeling error. Rather, the entire population of modeling errors corresponding to the whole set of combinations of pitch, roll, deflection and fuel load should be determined. The mean and standard deviation of the population should then be determined and used as bias and random errors, respectively.

There is a concern of this approach is that the odd error spike could occur at a unique combination of pitch, roll, etc., such as the normal pitch attitude at zero roll, with a wing deflection corresponding to the normal payload of fuel where a decision is made to continue the flight or divert. One way of addressing this concern is to apply weighting factors to the modeling errors, with the more likely situations heavily weighted. Another possibility is to be very specific in stating the conditions at which the "normal cruise accuracy" is desired.

FQIS manufacturers have indicated that there would be a large penalty in cost, weight and reliability if the worst case modeling error were used as a bias error. This is because additional probes and higher specification components would be needed to achieve the elimination/reduction of more error sources.

In practice, modern, advanced FQIS provide fuel quantity information to a high degree of accuracy for both steady state ground and flight conditions, with increased errors for transient and more extreme attitude conditions.

4.3.6.3 Implementation of Tank Datum Model in Flight Software

There are many different approaches which can be used to derive the fuel volume from the sensor data. Virtually all methods used in highly accurate (1% or better) systems use algorithms which rely on stored tables of numeric data to describe the tank shape or give height volume curves at different attitudes. For look-up tables, there is a tradeoff between accuracy of analysis and the amount of memory space allocated for storing such tables (i.e., the fidelity/granularity of the tables). Typically tables are stored for a number of pitch and roll angles and number of height steps, with extrapolations made for situations not fitting exactly in to the tables. If tables of numeric data describing the tank shape are used, then polynomial equations must be used to determine the intersection between the plane of the fuel surface and the tank walls. This can use significant processor time, and the error will depend on how precisely the tank shape is represented by the data stored and the equations.

4.3.6.4 Tank Internal Structure Modeling Error

Manufacturing tolerances may result in variation in the size, shape and position of each item which displaces fuel within the tank (e.g., pipes, pumps, spars, etc.). This can cause discrepancies (non-linearities) in the gauging of the tank. Some errors may be completely random on a tank by tank basis due to the machining and fabrication variables. In addition they may be repeatable (i.e., a bias error) on a tank by tank basis due to imperfect tooling dimensions or design modifications that were not taken into account in the FQIS design.

It is important that the calculation of all parts of the tank structure and components that displace fuel be extremely accurate. Allowances must be made for any structure or equipment which intrudes into the tank. This allowance ideally should be applied only when the item or structure actually impacts on the fuel measurement, but in practice it is often applied as a general reduction on fuel quantity across the volume of the tank.

Modern engineering tools such as CAD systems allow detailed modeling of the tank and thus reduce the likelihood of errors associated with tank structure modeling; although tank studies analysis often do not have the fidelity to account for all structure.

4.3.6.5 Sensor Mounting Tolerances

The tolerances associated with the location of mounting brackets or flange plates (for internal or external mounting respectively) should be taken into account. The installation practices and procedures should also be considered. The key aspect is usually the height of the sensor about the bottom of the tank, but it’s location in the X-Y plane, and its angle of placement from the vertical can also have an effect on accuracy, depending on the algorithm used, although these aspects usually have a lesser effect.

4.3.6.6 Tank Deflection, Expansion, Twist, Deformation

As the aircraft uses fuel throughout the flight or as the aircraft is refueled on the ground the wing deflection will change, causing a change in the shape of the fuel tank. This will lead to discrepancies with the nominal deflection conditions under which the tank model was analyzed. Similarly during the flight wing twist will vary from the nominal causing changes in the tank shape. In addition as the wing heats and cools the tanks will expand and contract as the metal forming the tank walls expands and contracts, again causing a change in tank shape. All of these effects will contribute to errors in measured fuel quantity.

It is the responsibility of the airframe manufacturer to supply the FQIS designer with data concerning wing deflection. Where the amount of deflection is a deterministic function of parameters that are known to the FQIS processor (e.g., tank contents or weight-on-wheels) the processor algorithm should provide full or partial compensation for deflection. In this case, however, there may be an error due to the deflection of the actual wing being different than that of the nominal wing.

In addition, deflection may be dependent on some parameters that are not known to the FQIS processor (E.G., zero fuel weight). In this case there would be an error as a result of the unknown amount of deflection.

The magnitude of the errors may or may not be normally distributed, depending on the FQIS algorithm. Over the full range of combinations of attitude, tank fill levels and wing deflections, there are usually some combinations with relatively high error peaks. Because these combinations usually represent a very small portion of the total number of permutations it is generally accepted that FQIS will experience these errors infrequently and for rather short durations. Common practice in the past has been to either ignore the infrequent peak errors or treat them statistically, as if they were random in nature.

4.3.6.7 Calculation Algorithms

During the various stages of calculation from initial scaling of the input data to final calculation of the fuel mass, errors due to rounding and truncation of the data may occur. There will be a tradeoff between data resolution and storage/processing resources. Any rounding or truncation should be compatible with the overall accuracy requirements.

4.3.6.8 Sensor Manufacturing, Mechanical

Sensor hardware tolerances should be accounted for. In capacitance systems this includes errors in empty capacitance and active capacitance and effects of thermal expansion/contraction of the tubing. In ultrasonic systems this may include variation in positioning of intrusions for velocity of sound measurement and variations in length of stillwell (end cap variation). The tolerances used in the analysis should include any effects of time and/or prolonged immersion in the fuel tank environment.

4.3.6.9 Measurement Linearity

This addresses any errors introduced by non-linearities in the measurement sensor not compensated for by the software/signal processing. For example with a capacitance sensor, non-linearities may occur where there are supporting crosspieces, or around the terminal block.

4.3.6.10 Sensor Mounted Electronic Circuits and Components

Where components are used (i.e., Diodes in DC systems) all appropriate parameters should be taken into account, if these are not compensated for in the software or signal processing.

4.3.6.11 Sensor Environment

Any errors introduced by variation of the environment around the sensor. This is mainly changes in temperature and pressure, but any other effects not accounted for in other specific error contribution should be considered.

4.3.6.12 Probe Implementation

Errors caused by the way the probe has been implemented. For example with an ultrasonic system the use of threshold detection on the returning signal will cause an error of one or more wavelengths. For a capacitance system there will be errors due to fringing effects at the top and bottom of the probes. Attention to design will minimize these sources of error, so that they can be considered negligible when compared to the larger error sources in the system.

4.3.6.13 Signal Conditioning

All errors caused by electronic circuitry should be accounted for. In capacitance systems this includes the effects of distortion and frequency shift of the excitation voltage. It also includes the shift in gains and offsets in all circuit modules, generally to the points where the sensor data is converted to digital format in ultrasonic systems it includes the effects of timing errors and variations in drive frequency.

4.3.6.14 Effects of Display Resolution and Rounding

Any digital display or any encoding of the data onto a digital data bus such as ARINC 429 may cause an error in the displayed value due to either rounding or truncation of the data.

4.3.7 Error Sources in System Design

The following subsections provide a detailed discussion of potential error sources to be considered in design of FQIS.

4.3.7.1 Fuel Surface Shape and Formation

Both capacitance and ultrasonic fuel measurement techniques use sensors to measure the height of the fuel surface at various points throughout the tank. From these measurements a volume is computed assuming a flat, steady fuel surface. Under various maneuvering and acceleration conditions the fuel surface may not be flat, or may not be steady. If sensors are measured in sequence, the fuel surface may move between measurement of one sensor and the next. All of these effects may contribute to the error in fuel quantity

Generally, the most common source of error in fuel surface location is caused by variation in aircraft attitude. Aircraft attitude varies on the ground due to the slope of the tarmac and variations in tire and oleo pressure. In flight the attitude is commonly referred to as "effective attitude" as it reflects the acceleration vectors as well as the orientation of the aircraft. FQIS algorithms are usually designed to produce high accuracy at the normal cruise attitudes with some allowable degradation at extreme attitudes.

4.3.7.2 Anomalous Fuel Distribution

This is a temporary condition, caused by pumping fuel from one tank to another, or by sudden maneuvers.

The "normal fuel management schedule" should be treated as a single range of possible fuel distributions to allow for the fact that temperature and density effects may result in some variation to the relative tank volumetric distributions. Studies at each fuel load should include the range of volumetric contents for each tank that can realistically occur at that total load.

It should be noted that large, sharp modeling error peaks can occur under certain conditions of attitude and deflection of narrow regions of tank fill level. The analysis should not dismiss the possibility that several such peaks could occur simultaneously.

For example, assume the fuel management schedule is such that all four tanks of a four engine aircraft were normally utilized evenly. At 50% fuel capacity the normal fuel management schedule should model each tank as 50% full. Suppose the outboard tanks experienced a sharp peak positive modeling error in the 48 to 50% fill region and the inboard tanks experience a peak positive modeling error in the 50 to 52% region. The analysis should not rule out the possibility that these errors can occur simultaneously. Nor should the analysis assume that the two simultaneous but opposite sign peaks will cancel.

4.3.7.3 Fuel Temperature Stratification

All known fuel gauging technologies suffer errors when the fuel in the tank is not a homogenous mix. Stratification occurs typically on the ground as new fuel is introduced into the tank (particularly when baffles restrict mixing) and in flight due to heat transfer to the wing skins. Both horizontal and vertical stratification patterns should be considered.

The FQIS accuracy analysis should show the effect of specific amounts and patterns of stratification. The specific amounts of stratification should be determined by analysis of the fuel system, taking into account any features that serve to mix or circulate the fuel.

4.3.7.4 Fuel Type Variation

The accuracy analysis should take into account the approved fuel types and properties. As discussed in earlier paragraphs, the relationship between density and permittivity (and, in some cases, temperature) for a particular fuel type can vary from fuel sample to fuel sample. If all characteristics are not measured simultaneously, and within close physical proximity to each other (i.e., so that the same fuel is measured by all sensors), then some level of error will be introduced after each refuel, unless these characteristics are measured throughout the flight.

4.3.7.5 Fuel Density Characteristic Variations

Errors can be caused both by the positioning of the densitometer within the tank and by inference of density from another characteristic.

Any densitometer in a tank is usually positioned near the bottom of the tank to ensure immersion for the maximum period of time. Due to stratification effects, this often means that the fuel surrounding the densitometer is much colder than the bulk of the fuel in the tank, leading to errors due to this temperature variation.

In addition many systems derive a density value from another fuel characteristic such as permittivity or velocity of sound. The relationship between these characteristics can vary from fuel sample to fuel sample, and changes with temperature. If this variation is not accounted for, this is a further source of error.

4.3.7.6 Effects of Fuel Additives and Contaminants

The accuracy analysis should take into account the approved fuel additives and common contaminants. The analysis should consider combinations of additives at the approved concentrations for the aircraft approved fuel types. Refer to the common fuel contaminants listed in ARP8615 or ARP4246.

4.3.7.7 Fault Mode Analysis for Accuracy Impacts

The FQIS should be designed based on the certification considerations outlined in ARP4754 and the safety assessment criteria of ARP4761. Failure of sensors, or signal conditioning should be considered for their impacts on accuracy, and this should be taken in to account in the identification of degraded or unknown accuracy. If the effects are dependent on the combination of failure and fuel level within the tank, then accuracy mode should be designated by the most pessimistic circumstance - for example if a combination of probe failure means that the accuracy is worse than 2x specification when the fuel tank is less than 50% full, then consideration should be given to indicating degraded accuracy continuously.

4.3.7.8 Water Contamination

Water can cause errors both when in suspension and when it separates from the fuel and pools around equipment within the tank. The in-tank equipment should be designed to maximize water shedding capabilities and the design of the fuel tank and gauging system installation should ensure that water does not become trapped at the base of probes or within other equipment such as densitometers and compensators. Water collecting at the base of probes in capacitance systems can cause probes to fail range checks, and can cause large large positive errors (over-reads).

In operation a number of aircraft use scavenge system to recover the last remnants of fuel in the tank, or to remove free water from the bottom of the tank. This means that locally there can be fluctuations in water concentration and this should be considered when locating tank hardware.

4.3.7.9 Effects of Aircraft Wiring

Any errors due to cabling must be accounted for. These could be caused by variations in capacitive loading, wiring/connector resistance or other factors.

4.3.7.10 Microbial Growth

Error analysis should consider the possibility that a thin film of biological growth may coat the entire tank, including all exposed surfaces of sensors. Contamination can cause high conductivity paths between the electrodes of the sensors. It can change the permittivity of the medium between the electrodes, thus causing potential over-reads or probe failures.

4.3.7.11 Fuel Variation Across Aircraft Tanks

The error analysis should take into account that the fuel in every tank may not have exactly the same characteristics. In practice, at least tanks feeding an engine will have their own complete set of sensors on most aircraft.

Variation of fuel between tanks will depend on fuel usage and refueling philosophy. Some tanks may end up being refueled completely with fresh fuel, whereas others may contain a mixture of old and new fuel, thus there will be variation in characteristics. If density and permittivity/velocity of sound sensors are provided in every tank then this will not cause an error. If density is measured in some tanks, or in the refuel gallery as the aircraft is refueled, then some error will be introduced unless the effects of mixing old and new fuel are taken into account.

4.3.7.12 Accuracy Verification

Testing the FQIS accuracy may cause the tester to identify errors in fuel measurement which are actually due to the method of test and/or tolerance of the test equipment. Test results should be analyzed carefully to ensure that errors due to method of test do not cause the FQIS to be modified, or accuracy problems to be identified. In general, the test equipment must have much less error than the system being measured. In practice flow meters are used to check fuel quantity during verification testing.

4.4 System Architectures

4.4.1 General Architecture Considerations

Three main system requirements, availability (reliability), safety and integrity normally drive system architecture design. System architecture design can contribute to the amount a specific failure condition impacts the systems' ability to perform its function.

It is important as part of the requirements definition and analysis task to consider the most appropriate architecture for the system and for the aircraft. This should be a balance between the level of integrity required and the cost of the system. Often a simplex system is adequate, especially if high integrity is not required to address safety issues. This should be considered in conjunction with the hazards identified as part of the aircraft level hazard analysis and a preliminary system safety assessment.

Where high integrity or dispatchability is not of paramount importance, a simplex design can be used. In such cases, the reliability of the system becomes a key characteristic. Therefore to increase the availability of this system, the reliability will need to be improved. The Simplex System in Figure 11 represents the simplest FQIS architecture. Each component of the system is singular by design.

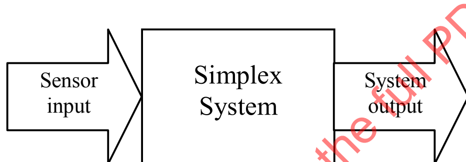

FIGURE 11 - SIMPLEX SYSTEM

As there is only a finite amount that reliability can be improved, a technique called redundancy can be used to provide multiple implementation of a function. A redundant Simplex System is depicted in Figure 12.

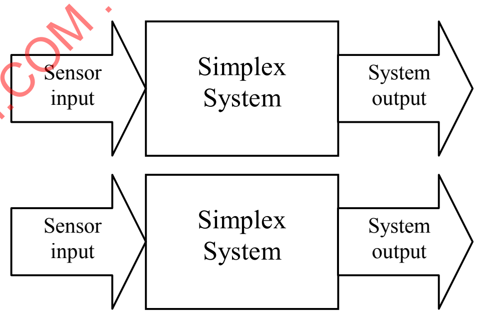

FIGURE 12 - REDUNDANT SIMPLEX SYSTEM

It is a design technique based on the assumption that a given set of faults with the same system effect will not occur simultaneously in two or more independent elements.

More typically the two simplex systems are integrated into one system giving redundancy only in the areas where the reliability cannot be improved. This system is known as a backup parallel design, that is, channel B is only required to operate after channel A fails is shown in Figure 13.

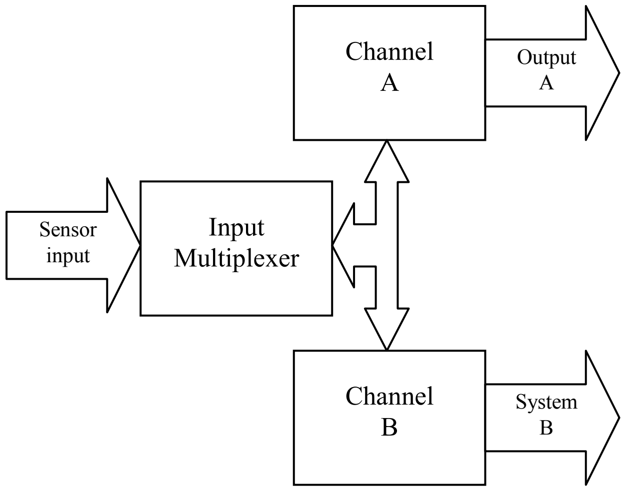

FIGURE 13 - PARALLEL SYSTEM

Redundancy may also be required to provide a fail-safe design protection from catastrophic failure conditions and meet the requirements associated with "Essential" or "Critical" classification. This classification is normally given to a system function, which could cause the complete loss of the aircraft if it fails. A typical example of this is in an aircraft where the fuel system, under failure conditions, could cause the inability to provide fuel to more than two engines. Fuel gauging could contribute to this aircraft level hazard by having a failure such that there was a large positive error, leading to unexpected fuel exhaustion. One solution to this situation will be to use a redundant system, where the primary transfer system is automatic and the secondary backup is manual. These methods of redundancy do not improve the availability of the automatic system but provide a manual backup to meet the safety requirements. An alternative to the manual backup would be to provide a redundant automatic system, improving automatic availability as well. One of the advantages the manual system provides is dissimilarity as shown in Figure 14.

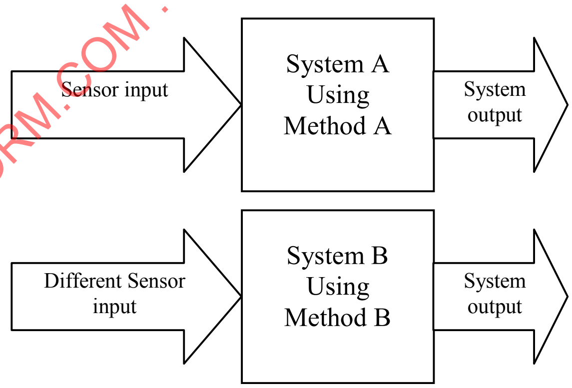

FIGURE 14 - DISSIMILAR FQIS SYSTEM

Architecture strategy incorporating dissimilarity can be a powerful means of reducing the potential for errors in requirements or in design implementation to cause serious effects. However a dissimilar design implementation of the same function cannot provide containment coverage for functional requirement errors unless adequate independence can be shown. Therefore using an independent parallel dissimilar, multiple channel architecture may provide protection from both random physical failures and anomalies due to design errors. In practice, this is not done fully since the cost would be excessive for very little gain, but may be partially implemented - for example using a subset of sensors to calculate fuel quantity through a dissimilar algorithm and separate processor to cross-check the primary gauging calculation.

Another architecture, which is used to provide segregation, is a "brickwall" design. This is used if the safety requirements need segregation between channels. Such a system requires each tank fuel quantity measurement to be segregated. This can be achieved by physically segregating the gauging systems for each tank, guaranteeing that any failure cannot impact the performance of any other tank quantity. This was traditionally achieved with separate gauges and now with integrated systems by separation of the circuits associated with each tank as shown in Figure 15.

In these integrated designs normally the main gauging elements are brickwalled but the totalization is not; therefore, with a failure in the left tank, the system would stop outputting the total and the failed tank, but still maintain the right tank output.

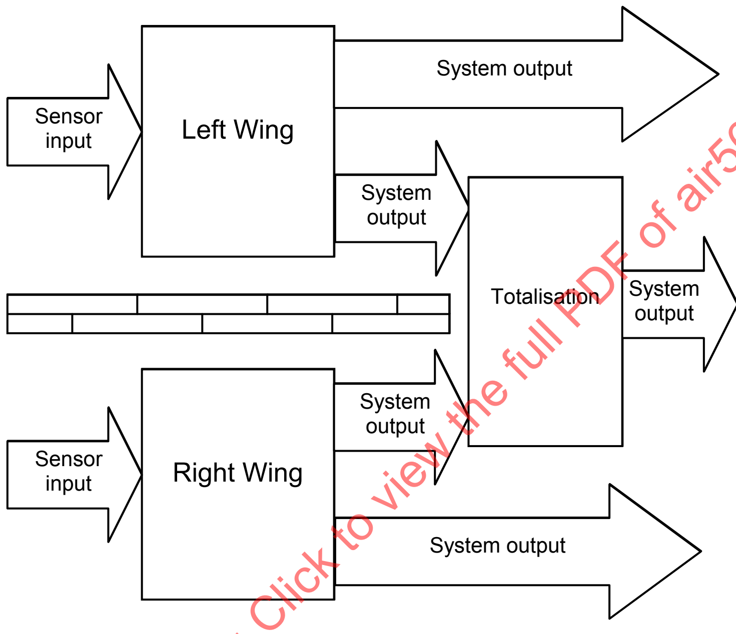

FIGURE 15 - "BRICKWALL" FQIS

With more integration of systems and the use of open Integrated Modular Avionics (IMA) platforms, systems are using common processors with software partitions. Partitioning, refer to Figure 16, is a design technique used for providing isolation to contain or isolate faults and to potentially reduce the efforts necessary for the system verification processes.

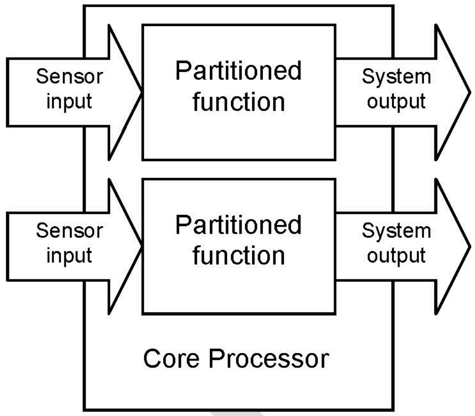

FIGURE 16 - PARTITIONED SYSTEM

The integrity of a system is all about how believable the output of the system is. To achieve a believable output an active-monitor parallel design (command - monitor) is used. This design used a command processor to compute the fuel mass, which is then checked, against the monitor processors computed mass.

If the processors disagree by a certain amount over a defined period of time, the output would be declared as invalid and the system output shutdown.

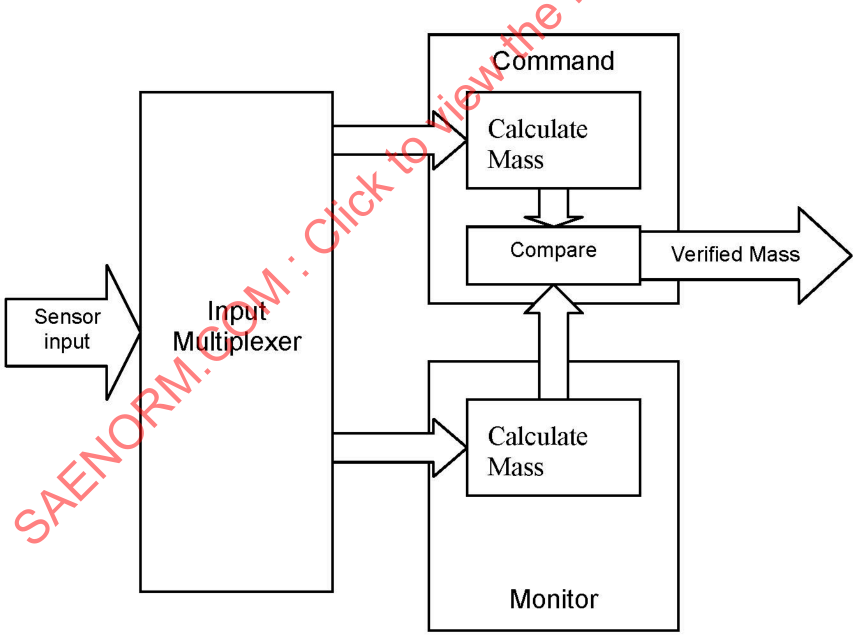

FIGURE 17 - MONITORED ARCHITECTURE

This architecture provides detection of random physical failures and with sufficient independence may detect anomalies due to design error.

The architecture used in any system will depend on which of the system requirements are the key requirements and most architectures are a combination of the above basic designs.

4.4.2 Influence of AC25.981-1C and Composite Aircraft on FQIS Architecture

The new requirements on energy levels and currents which are allowed within the fuel tank (see 4.7) have driven a change in architecture for fuel systems. This has been also seen as a way to mitigate the impacts of the use of composite material for commercial airframes, which provide less screening than metallic aircraft. In order to address potential lightning induced currents and the potential for shorts from other systems and power cables on the aircraft, a solution is to provide either a "transient suppression unit" (TSU) or a data concentrator with the sensor interface circuitry at the tank wall. Either of these units ensures that only intrinsically safe signals enter the fuel tank, by providing current and energy limitation directly at the tank wall against any defined threats.

A TSU provides basic protection to intrinsically safety signals being generated by a central FQIS located in an avionics rack elsewhere on the aircraft. The basic system architecture is:

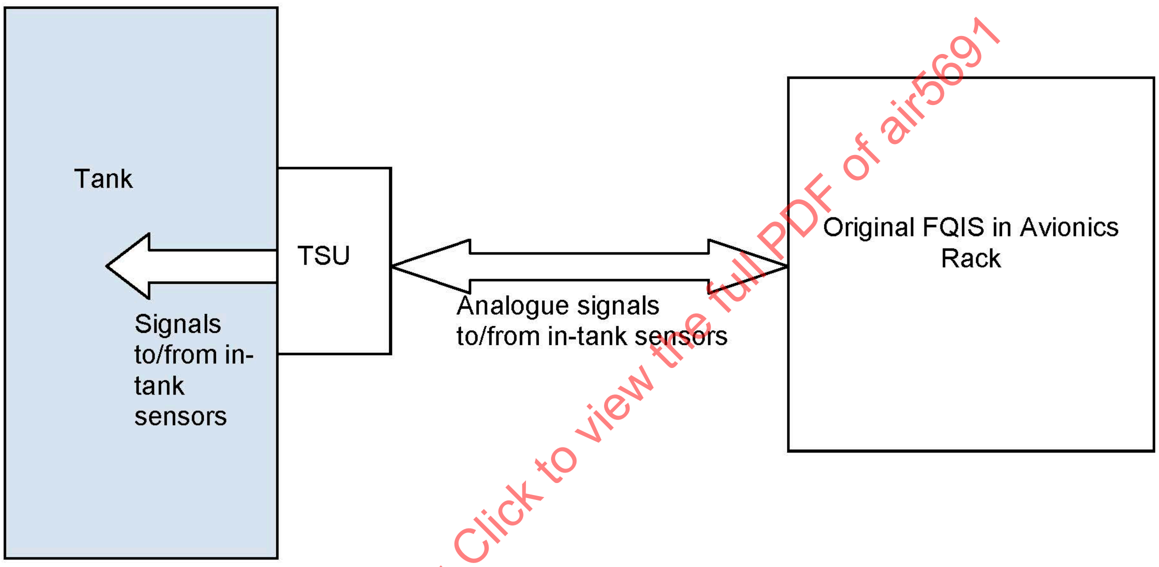

FIGURE 18 - ARCHITECTURE INCLUDING TSUS

This type of architecture is very often used when additional protection is needed within already existing systems.

A tank wall data concentrator provides the drive and signal conditioning for all in-tank sensors. It then transmits this data, usually in a digital form to a fuel gauging or fuel management computer located elsewhere. This computer could be part of an IMA system. The basic architecture is like this:

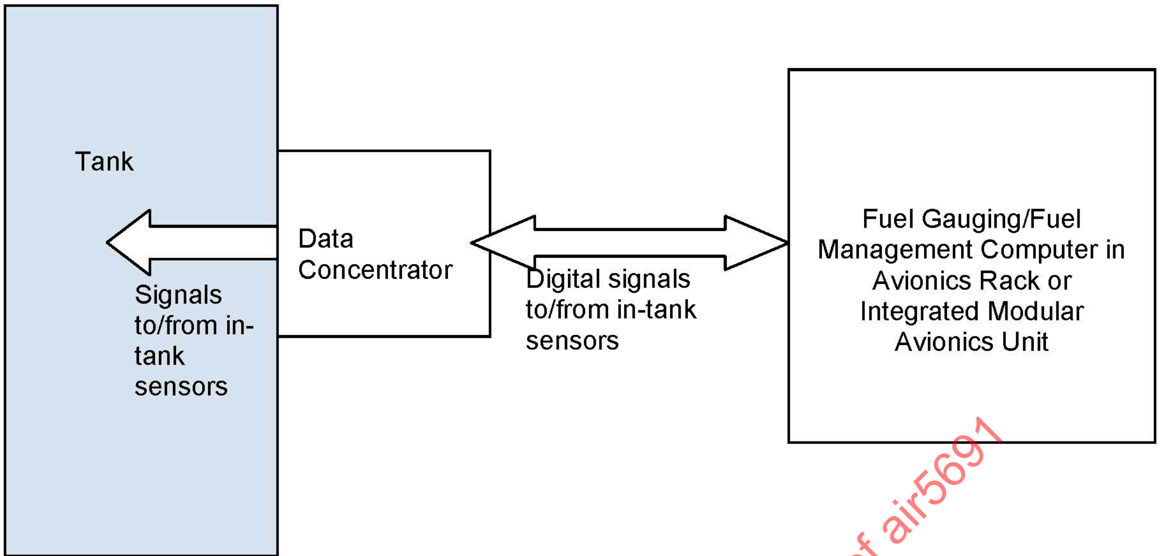

FIGURE 19 - ARCHITECTURE INCLUDING DATA CONCENTRATORS

4.4.3 System Power Supply

Within the system design, provisions should be made to refuel an aircraft on battery power alone. Under these conditions degraded accuracy would be acceptable, although not desirable. It is recommended that the FQI system be designed to operate from the aircraft DC power bus, so that it can be directly powered on the aircraft battery. Under normal operation the FQI system will be powered from ground power, or from the main aircraft power system.

It should be noted that during operation on battery power equipment cooling air will not be available.

4.4.4 Sensor Isolation

For larger systems, sensors should be individually addressable. This promotes maintainability so that it is possible to isolate faulty sensors readily. It also benefits accuracy, as individual sensor coverage can be accounted for. With a failed sensor, fuel quantity can be derived from the remaining sensors.

An exception to this is for low-end, low accuracy systems where the trade-off between cost and complexity and benefits of comprehensive BITE must be made. If the system has only simple analogue electronics, it is not worth having each probe addressed separately since the system cannot perform any more than a very basic BITE test. In these cases, probes should be bussed at the tank wall connector, allowing access to individual probes via ground based test equipment connected at the tank wall connector.

4.4.5 Use of Shielded Cable

AC capacitance systems require the use of shielded cable as an integral part of their operation. This is used to ensure that the stray capacitances within the harness are well defined and can be minimized. For DC systems and ultrasonic systems, shielded cable is not required for operation of the system, but should be used for lightning strike and EMI protection.

Airline consensus is that shielding anomalies in fuel tanks is the major problem in present day AC systems, and therefore recommends against the use of shielded cable, if possible. Conductor materials should be selected carefully - for example the use of tin plated wires may result in discontinuities.

With increased lightning and EMI requirements, and increased use of composite in the fabric of an aircraft it may be necessary to use shielded cable to protect from EMI.

4.4.6 In-tank Electronics

The use of electronic components inside the tank should be avoided unless it can be shown that there is benefit to the end user in terms of cost of ownership. Consideration should be given to safety, environmental factors, and the cost of servicing electronic components in the fuel tank.

4.4.7 LRU Adjustments

All LRU adjustments should be internal to the equipment and for shop use only. There should be no external adjustments to any LRU. It should not be necessary to recalibrate any FQS component upon replacement on the aircraft.

4.4.8 Reliability and Redundancy:

Some current technology gauging systems are perceived by the airlines as both unreliable and inaccurate. Often the user is confused whether poor accuracy is a function of the basic design, the system, or the type of fuel gauged. Accuracy of the system is often determined by cross-comparison of the measured quantity from the FQIS to other systems such as "Fuel Used" meters, the bowser meter following refuel or the quantity calculated from dipsticks. This can lead to apparent discrepancies due to the tolerances of the different systems. What the user requires is a more dependable system (i.e., repeatable readings that are "right" every time), but this is often mistakenly interpreted as a more accurate system. This does not alleviate the user from understanding that each measurement system has its own error, and so when comparing them, the user must be aware of the error in each system. The fuel bowser uses fuel flow and density, FQIS uses mass calculated from volume, etc., and the fuel sticks measure volume.

4.4.9 Effect of Faults

Systems should be designed so that a single probe failure does not cause the gauging to be lost. This is usually accomplished by each tank having its own independent array of sensors.

For larger systems, a degree of redundancy is usually required, such that any single failure within the system does not cause the display of FQI to become degraded or failed.

Where redundancy is used to satisfy a reliability goal, suitable partitioning or separation should be employed. A fault in any one channel should not propagate into another channel and prevent that channel from performing its intended functions.

If the sensors are multiplexed between redundant channels, no single fault, or probably double fault of the multiplexing system should prevent operation of more than one channel of the system.

4.5 Fault Diagnosis and Maintainability

4.5.1 Built-In Test Equipment (BITE)

The FQIS BITE should be designed so that it is possible to detect failure of all system LRUs. If a fault occurs in the FQIS, it should not be recorded in fault memory or set as a confirmed failure unless it persists for a time consistent with a hard failure (nominally 30 s). In addition BITE limits should be set at levels compatible with equipment design so as to prevent nuisance failures. Only those failures which require crew action should be reported to the flight crew. The real time annunciation to the flight crew where appropriate should be cancelled if the BITE subsequently detects that the system is serviceable. During refueling, where faster dynamic conditions prevail, BITE response times should be reduced. This is to try to prevent nuisance failures due to too tight a tolerance, or too rapid a confirm time. For example with ultrasonic probes the confirm time should be of sufficient duration that erroneous readings due to bubbles do not cause failures. For the safety aspect of the system, the intent is to ensure that some faults/failures are detectable, which means a balance between recording a fault versus not recording the fault. The detection time should be compatible with the functional aspects, but the fault may reduce the safety of the design so the preference would be to indicate the fault, rather than inhibit it.

The BITE facility should be designed in accordance with ARINC Report 604, "Guidance for the Design and Use of Built-In Test Equipment."