



AEROSPACE INFORMATION REPORT

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Superseding AIR5691A

Guidance for the Design and Installation of Fuel Quantity Indicating Systems (FQIS)

RATIONALE

Errors have been identified with one of the equations within the document, and updates are needed to reflect latest regulatory changes and changes to approved additives (as part of Five-Year Review activity). Various typographical errors have also been corrected.

FOREWORD

Fuel gauging systems on modern aircraft are large, complex systems, consisting of multiple sensors located in the hostile environment of the fuel tanks. The measurement of those sensors is complicated due to strict regulations around the amounts of in-tank energy and current that can be applied, in order to maintain intrinsically safe systems.

Standards of acceptability of FQIS error, especially for large airplanes, have evolved to meet market expectations. 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. Measurement of these characteristics has also been made more important by 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). This need for reduced error magnitudes also increases the complexity of the fuel gauging system, driving up both the number and variety of sensors.

Despite the improvements in the systems, the majority of systems still use a variation of capacitance technology, which was first introduced in the late 1940s.

This document is intended to give an overview of all the factors which should be considered in the design of a modern fuel gauging system. It concentrates on system design for large commercial aircraft (Part 25 aircraft), but many of the items are equally applicable to small aircraft (Part 23) and rotorcraft (Part 27 and Part 29).

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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, much of the guidance is equally applicable to 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 190E jet compared to 11 fuel tanks on an Airbus A380, as well as aircraft with multiple body tanks/auxiliary cargo tanks. 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 requirements for center of gravity (CG) measurement/control that may 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 +1 724-776-4970 (outside USA), www.sae.org.

AIR1184	Capacitive Fuel Gauging System Accuracies
AIR4170	Reticulated Polyurethane Foam Explosion Suppression Material for Fuel Systems and Dry Bays
AIR4246	Contaminants for Aircraft Turbine Engine Fuel System Component Testing
AIR6325	Fuel Level Point Sensing
ARP1870	Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety
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 SAE ITC, ARINC Industry Activities, 16701 Melford Blvd, Suite 120, Bowie, MD 20715, Tel: +1 240-334-2578, <https://www.aviation-ia.com/>.

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 (NOTE: References are specifically to data contained within ARINC 611-1)
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 D910	Standard Specification for Leaded Aviation Gasolines
ASTM D1655	Standard Specification for Aviation Turbine Fuels
ASTM D7566-21	Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons

2.1.4 EASA Publications

Available from European Aviation Safety Agency, Ottoplatz, 1, D-50679 Cologne, Germany, Tel: +49 221 8999 000, www.easa.europa.eu

CS-25	Certification Specifications for Large Aeroplanes
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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
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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 23	Code of Federal Regulation, Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes
14 CFR Part 25	Code of Federal Regulation, Airworthiness Standards: Transport Category Airplanes
14 CFR Part 27	Code of Federal Regulation, Airworthiness Standards: Normal Category Rotorcraft
14 CFR Part 29	Code of Federal Regulation, Airworthiness Standards: Transport Category Rotorcraft
AC 25-981-1D	Fuel Tank Ignition Source Prevention Guidelines

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

Copies of these documents are available online at <https://quicksearch.dla.mil>.

MIL-DTL-5624	Turbine Fuel, Aviation, Grades JP-4 and JP-5
MIL-DTL-83133	Turbine Fuel, Aviation, Kerosene Type, JP-8 (NATO F-34), F-35, and JP-8+100 (NATO F-37)
MIL-STD-1472	Human Engineering Design Criteria Standard Department of Defense
MIL-STD-1553	Digital Time Division Command/Response Multiplex Data Bus

2.1.9 UL Publications

Available from UL, 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
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2.1.10 CRC Publications

Available from Coordinating Research Council, 5755 North Point Parkway, Suite 265, Alpharetta, GA 30022, Tel: 678-795-0506, www.crcao.com.

CRC Report No. 647	World Fuel Sampling Program
CRC Report No. 663	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.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE AE4L-78 Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware

2.2.2 IEC Publications

Available from IEC Central Office, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 02 11, www.iec.ch.

IEC 60079 Electrical Apparatus for Explosive Gas Atmospheres: 3rd Edition

2.2.3 FAA Publications

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

AC 20-53 Protection of Airplane Fuel Systems against Fuel Vapor Ignition due to Lightning

2.2.4 Other Publications

BS 5501-7 Electrical Apparatus for Potentially Explosive Atmospheres - Part 7: Intrinsic Safety "i"

BS EN 50014 Electrical Apparatus for Potentially Explosive Atmospheres - General Requirements

MIL-G-7940 Gauge, Liquid Quantity, Capacitor type, Installation and Calibration of

MIL-G-26988 Gauge, Liquid Quantity, Capacitor type Transistorized, General Specification for

SFAR 88 Special Federal Aviation Regulations No. 88: Transport Airplane Fuel Tank System Design Review, Flammability Reduction and Maintenance and Inspection Requirements, Final Rule

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: ARP1870 defines 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: The practice of surrounding conductors, cables, and electronics with conductive or magnetic materials to guard incoming or outgoing emissions of electromagnetic frequencies. In the case of a capacitance fuel gauging system harness, the HiZ conductor is enclosed in a shield and the harness to a sensor may be enclosed in a second shield depending on the electromagnetic environment. Also referred to as a **SCREEN**.

THREAT: An external effect, such as lightning or HIRF, or an induced signal environment which may cause the system to malfunction in some way, if not addressed in the design of the system. A threat can be a known, intentional environment (i.e., lightning) or induced from other co-located sub-systems.

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
DAL	Design Assurance Level
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
TDR	Time Domain Reflectometry
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 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.

FUEL SAMPLE: A small quantity of fuel taken from a larger batch fuel supply for purposes of establishing or determining the variation of fuel properties within a single fuel type (i.e., Jet A, JP-8, etc.). Specifically, this is different from fuel samples often taken from aircraft to determine fuel quality for safe operation purposes.

HIGH INTENSITY RADIATED FIELD (HIRF): Expected aircraft radiated field environment resulting from exposure to radio frequency (RF) energy of a strength sufficient to adversely affect either a living organism or the performance of a device subjected to it. An example is 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 inverse of numerical 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 AC 25.981-1D 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 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 resistive 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 or system in the absence of faults.

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

SIGNIFICANT LATENT FAILURE: An undetected 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

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

- a. Capacitance: In use on multiple platforms since the late 1940s.
- b. Ultrasonic: In use on a limited number of platforms since the mid-1990s.
- c. Time domain reflectometry (TDR): In use since the mid-2000s.

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, derived, or default value) gives a mass, which is displayed in the cockpit and/or at the fueling panel.

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 and improve accuracy, 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. These systems are not addressed in this document.

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 two electrodes are spatially separated and located with high quality fuel resistant polymer support pins. Probes are usually mounted on tank ribs using 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 elastomeric separator is not recommended, since the elastomer separator can fail and the probe may become shorted to ground.

For metallic probes, the outer electrode is usually manufactured from precision aluminum alloy tubing, corrosion protected by some means (for example, electroless nickel plate). The inner electrode is usually manufactured from precision parallel aluminum alloy tube, corrosion protected by some means (for example, chromate film).

For composite probes, the outer electrode is manufactured from precision fiberglass tube covered with a metallic inner layer or precision carbon fiber conductive tubes. The inner electrode is manufactured from precision fiberglass tube covered with metallic outer layer or precision carbon fiber conductive tubes. The metallic deposit of fiberglass probes can be shaped to build a specific capacitance versus height relationship. Redundant fiberglass probes with two segregated active surfaces within a single tube are currently in use on some aircraft.

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.

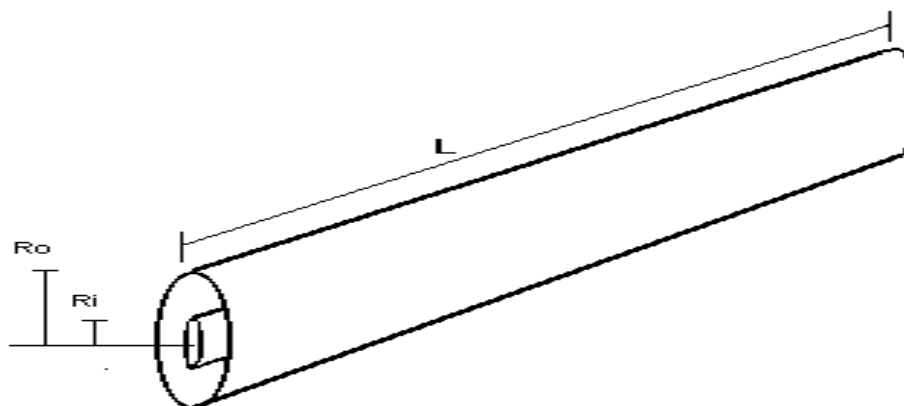


Figure 1 - Concentric tube capacitor in air

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

$$C_E = (2\pi \epsilon_o K L) / [\ln(R_o/R_i)] \quad (\text{Eq. 1})$$

where:

C_E = capacitance in Farads

ϵ_o = permittivity constant 8.85×10^{-12} Farad/meter

K = dielectric constant ($K_{\text{AIR}} = 1$)

L = length in meters

R_o = radius of outer tube in meters (inner radius)

R_i = radius of inner tube in meters (outer radius)

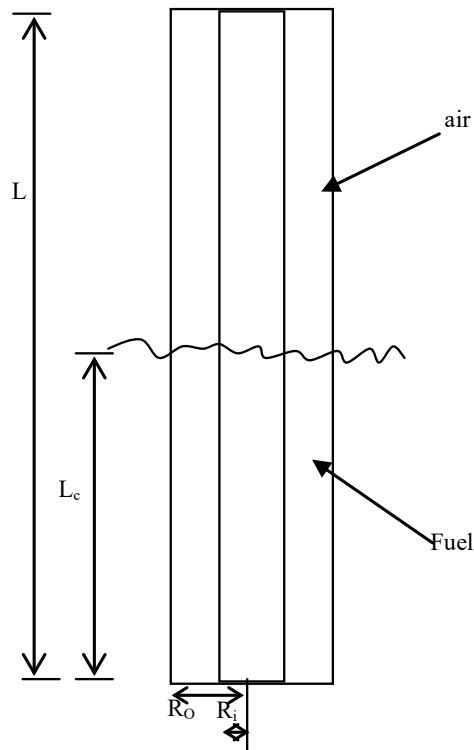


Figure 2 - Partially immersed probe

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

$$C_T = [(2\pi \epsilon_0)/\ln(R_o/R_i)] * (K_F - 1) L_C + C_E \quad (\text{Eq. 2})$$

where:

C_T = total sensor capacitance measured in Farads

L_C = length covered in meters

K_F = dielectric constant of fuel

C_E = sensor empty capacitance in Farads

ϵ_0 = 8.85×10^{-12} Farad/meter

R_o = radius of outer tube in meters (inner radius)

R_i = radius of inner tube in meters (outer radius)

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:

$$L_C = (C_T - C_E) / \{ (K_F - 1) * [(2\pi \epsilon_0)/\ln(R_o/R_i)] \} \quad (\text{Eq. 3})$$

3.1.1.2 Common Capacitance Measurement Techniques

There are two main methods for measuring the capacitance of the probe. These are called AC and DC acquisition systems. 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 “Lo-Z,” via an unscreened drive wire connected to the outer tube. A screened return, also called “high impedance” or “Hi-Z,” is connected to the inner tube making a three wire capacitance measurement. The screen is configured as a Faraday shield, and only grounded at one end. 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 the current quadrature signal, which allows the pure capacitive measurement to be disassociated from the fluid conductivity effects on the measurement. Older systems nominally run at around 400 Hz, whereas for newer systems that operate at higher excitation frequencies (typically up 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, older systems have only shown medium reliability due to wire harness problems. Most older AC capacitance systems performance issues can now be addressed with improved wire harness designs and 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 Hi-Z 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 wire harness.

DC capacitance systems have been in service for more than 35 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. Since the change in regulations following on from SFAR-88, the safety demonstration for the diodes within a flammable zone has become more problematic, and so newer systems have reverted to AC type systems.

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 measurement signal proportional to tank fuel volume.
- DC profiled: Inner tube profiled to provide a measurement signal proportional to tank fuel volume.
- 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, usually providing the output either in the form of a DC voltage or a pulse train where the DC voltage or time period or frequency of pulses is proportional to the capacitance. Recent smart probes can provide output in the form of a data bus (ARINC 4298, CAN, RS422/485, etc.). This type of probe is mostly used in helicopter tanks, where a single probe is used to gauge a tank. Safety barriers must be considered to ensure compliance with ignition source prevention inside the fuel tank.

3.1.2 Ultrasonic Gauging

An 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, if metallic materials are used.

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](#).

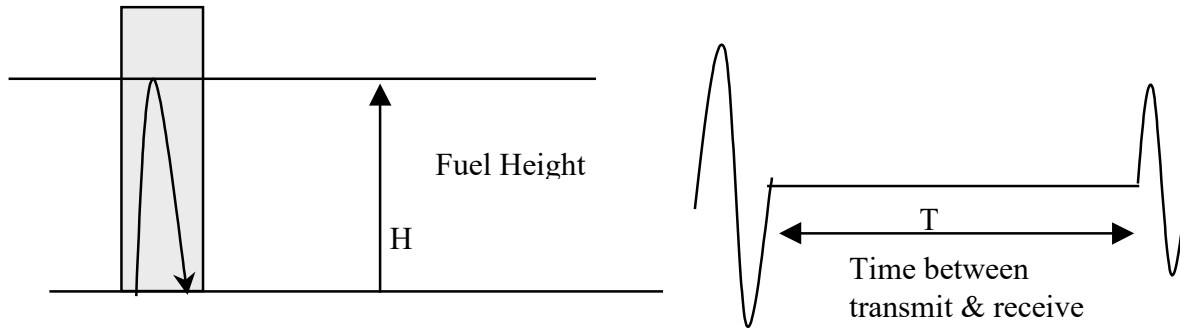


Figure 3 - Ultrasonic probe operation

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 Lockheed Martin F-22, and the NH Industries 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 $I(t) = C \cdot dv/dt$).	Pseudo-rectified DC current.	Time using voltage pulse.
System accuracy	Nominal 1% system at full	Nominal 1% system at full. ⁽¹⁾	Nominal 1% system at full. ⁽¹⁾
Accuracy limitations	Manufacturing tolerances, processing electronics, number of sensors, fuel properties.	Manufacturing tolerances, processing electronics, diode characteristics if not measured, number of sensors, fuel properties.	Positioning of mechanical elements used for VOS measurement, manufacturing tolerances on placement of transducer, number of sensors, fuel properties.
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 (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.	Transducers can fail due to thermal stress. Wiring connectivity and crosstalk can affect functionality.
Water effects	Can cause inaccuracies or loss of function.	Can cause 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 wave path.
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

Parameter	AC Capacitance	DC Capacitance	Ultrasonics
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 and operating voltage can mitigate most of these problems.	Can be susceptible to noise and interference—common rejection worse than AC systems. Use of harness shielding can mitigate most of these problems.	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% more.	Baseline, ~40% more.
Ease of connection to multiple processors	Difficult—can introduce errors. Has been implemented successfully for newer systems	Difficult—can introduce errors.	Moderation, but needs SW arbitration.
Bonding/in tank safety	For metallic construction, outer tube electrically active so cannot be bonded.	For metallic construction, outer tube electrically active so cannot be bonded.	For metallic construction, outer tube electrically inactive so has to be bonded to structure.

⁽¹⁾ Assuming permittivity or velocity of sound and density is measured and used for mass calculations.

3.1.4 Time Domain Reflectometry

TDR is widely used to accurately locate discontinuities in transmission lines. TDR uses a fundamental characteristic of transmission line theory whereby an interface with different characteristic impedance will cause some of the incident signal energy to be reflected back to the sending source. The amplitude and phase of the reflected signal is a function of the relationship between the transmission line characteristic impedance and the characteristic impedance at the interface. This property can be used to measure the height of fuel by determining where the surface of the fuel is, as the interface between air and fuel represents a discontinuity.

TDR is similar to a pulsed radar system used to measure distance by measuring the time delay between the transmitted and received pulses where distance is proportional to the velocity of propagation of the signal in the medium. While a radar system propagates its signal through the air, a TDR system may propagate its signal through different media which have a propagation velocity less than the speed of light. The transmission line characteristic impedance, Z_c , is also a function of the substances' electric permittivity and is related to the characteristic impedance in air, Z_0 , by $Z_c = Z_0/\sqrt{\epsilon_r}$.

The relative permittivity (dielectric constant) for several pertinent materials is given in [Table 2](#).

Table 2 - Dielectric constant of common materials

Material	Dielectric Constant (ϵ_r)
Air	1.000588
Water	80
Teflon	2.1
Jet A - 1	2.12

For example, given its geometry, the characteristic impedance of an empty TDR sensor (air dielectric) is 80 Ω , but when Jet A ingresses into the tube, the impedance of the portion of the tube occupied by the fluid is now closer to 55 Ω ($80/\sqrt{2.12}$) yielding an interface reflection that is readily detectable. Together with characterization of the "time of flight" to the location of the impedance change, the position and type of medium can be ascertained to a high degree of accuracy.

3.1.4.1 Theory of Operation

TDR is a proven technology adapted for use in measuring fluid levels in aircraft tanks. In its simplest form, TDR in fuel tank would result in three dominant reflections: (1) from the top of the sensor, (2) from the fuel level surface, and (3) from the end of the sensor as depicted in [Figure 4](#). Inside the sensor, the TDR pulse would initially travel through air (tank ullage), then through the fuel and then through any other fluid, such as water, before encountering the end of the probe. At each interface, a signal reflection is detected and the system uses the signal strength and velocity of propagation through the media to calculate the type of interface (fuel, hydraulic fluid, water, etc.) and the height of the individual layers inside the sensor.

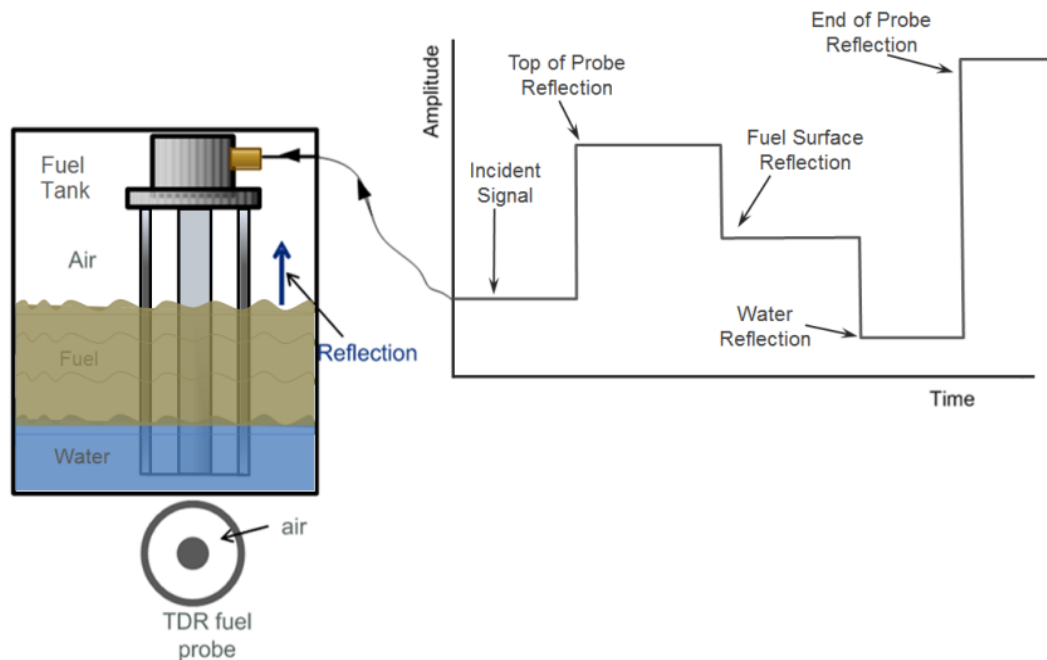


Figure 4 - TDR principles

Figure 4 shows a conceptual representation of a probe and the waveform resulting from a high speed pulse transmitted down the waveguide. As the pulse encounters the first impedance change at the top of the probe and then at the surface of the fluid, a portion of the pulse is then reflected back up the waveguide adding to the incident pulse. The signal continues down the waveguide and encounters the open ended (open termination) portion of the probe. These signal reflections result in the waveform of Figure 4.

The sensor itself is simply a center conductor rod and an outer tube concentrically arranged as to form a coaxial transmission line with air as the dielectric. Fluid is allowed to ingress and occupies the space between the center conductor and the outer tube resulting in different impedances that cause TDR signal reflections. The TDR algorithm calculates the distance between the top of the probe and the fuel surface by using the time of flight through air, 30 cm/nano-second—essentially, the speed of light.

It should be noted that because a capacitance sensor reacts to the bulk dielectric of the fluid being measured, it is greatly affected by changes in the fluid temperature, its composition, density and conductivity. Likewise, a float probe reacts to density which is also affected by temperature and fluid type. The TDR system measures the signal propagation to the fluid surface through air which is stable and invariant to these effects. This is a significant benefit of TDR based sensors over those of traditional float or capacitance sensors.

3.1.4.2 Advantages of TDR

TDR-based fluid sensors provide a number of advantages over the traditional capacitance probe used in fuel sensing systems today. These include:

- TDR accuracy is independent of the dielectric of the fluid and therefore will not vary based upon the range of fluid properties, making an accurate level measurement without the need for additional sensors to measure permittivity.
- The fluid's conductivity will not affect the performance of a TDR sensor. This differs from a capacitive sensor, which degrades rapidly if trying to characterize increasingly conductive fluids. This means that full accuracy can be maintained even in the presence of water that would render capacitance probes inoperable (typically the primary in-field failure mode).
- The TDR can concurrently measure the fuel level, and detect and measure the water level or ice without affecting its primary function of fuel level detection.

- The measurement technique allows for enhanced internal BIT, which allows identification of sensor faults, significantly reducing the change of giving an erroneous normal measurement. BIT can locate faults very accurately and thus can isolate failures to in-tank or out-of-tank components with high precision allowing for fast troubleshooting—faults can theoretically be isolated to a wire or a connection inside or outside the tank.
- TDR sensors are unaffected by external grounding or proximity to conductive tank walls. The probe can be bonded to the structure.
- TDR is unaffected by variations in wiring or the wiring harnesses used throughout the measuring system.

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, it may be necessary to measure:

- a. Fuel dielectric constant, also referred to as permittivity (for capacitance-based systems).
- b. Velocity of Sound in fuel (for ultrasonic based systems).
- c. Fuel density, also referred to as specific gravity.
- d. Fuel temperature (depending on the algorithm used, not used on all aircraft).
- e. Fuel conductivity.

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, temperature, 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 temperature and/or 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. Usually, the common thread of this relationship is temperature; thus, temperature needs to be measured in all 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 further discussed in AIR6325.

3.3 Dielectric Constant (Permittivity) Measurement

The dielectric constant, K , of a substance is the characteristic that describes how it affects any electric field within the substance and is a measure of the extent to which a substance concentrates the electrostatic flux lines (also determines how much energy is stored). A high permittivity reduces the presence of an electric field. 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. The capacitance of a capacitor can be increased by increasing the permittivity of the dielectric material between the capacitive plates.

The permittivity of air is described by the constant ϵ_0 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:

$$\text{Force} \propto \frac{1}{4\pi\epsilon_0 \text{dist}^2} Q_1 Q_2 \quad (\text{Eq. 5})$$

where:

Q_1, Q_2 = the two point charges

dist = the distance between them

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

$$C \text{ (with material between plates)} = \epsilon_r \epsilon_0 \times (A/d) \quad (\text{Eq. 6})$$

where:

C = capacitance

ϵ_r = the permittivity of the material

A = the area of overlap between the plates

d = the separation distance

Relative permittivity, ϵ_r (often referred to as just permittivity or dielectric or K), is the ratio between this force in vacuum (approximately 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.

$$K = \epsilon_r = \epsilon_s/\epsilon_0, \text{ where } \epsilon_s \text{ is the static permittivity of the material} \quad (\text{Eq. 7})$$

This can also be defined as $\epsilon_r = C_x/C_0$, where these are capacitance measurements with an air dielectric (C_0) and then with the material in question (C_x).

For fuel systems, the dielectric constant, also referred to interchangeably as permittivity, can vary from fuel sample to fuel sample, and is also influenced by temperature, pressure, contamination of the fuel, fuel additives, etc.

The permittivity of fuel (Jet A) is approximately 2.1 at 30 °C; therefore, the capacitance measured when the probe is fully immersed in fuel is approximately 2.1 times that measured when the probe is uncovered in air. This is derived based on the following graph shown in [Figure 5](#). Note: The data in this graph is derived from fuel data in ARINC 611 and CRC 647. The equation shown represents an Excel calculated trendline; for industry standard equations relating permittivity to temperature, refer to CRC 663.

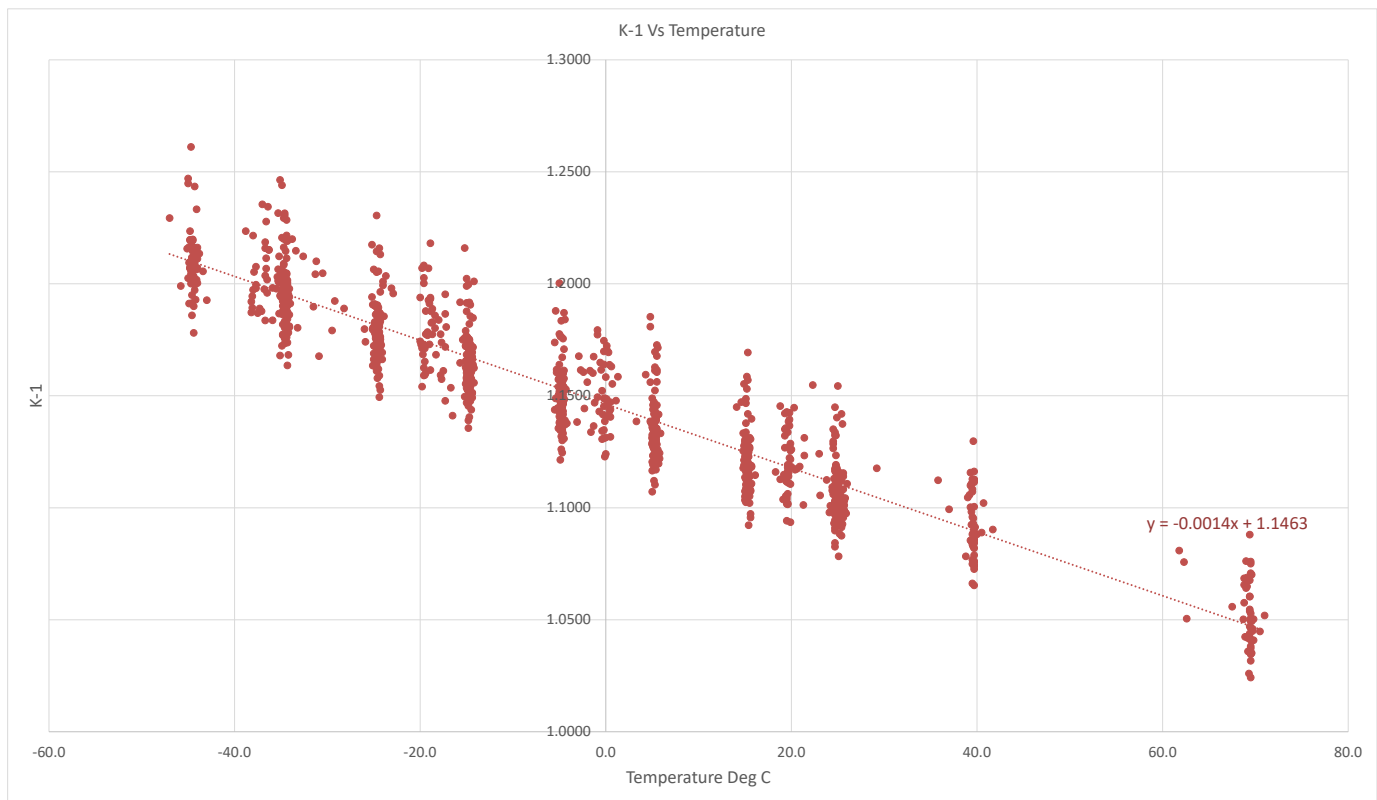


Figure 5 - Line of best fit for Jet A/Jet A1/JP-8 fuel samples from ARINC 611 and CRC 647

The range of variation in permittivity for fuel is usually considered to be approximately 1.99 to 2.3.

NOTE: Further information on the range of values for typical jet fuels is available in the CRC Handbook of Aviation Properties (CRC 663) and the CRC Word Fuel Sampling Program Report (CRC 647).

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 following equations.

For a concentric tube construction:

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

where:

$$const = \frac{\ln\left(\frac{R_O}{R_I}\right)}{2\pi\epsilon_0} \quad (\text{Eq. 9})$$

where:

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

C_E = empty capacitance

L_F = length of compensator