A Systems Design Approach to Fuel Measurement in Hybrid-Electric Aircraft

Mark Connors
Director of Technology
Liquid Measurement Systems
Georgia, VT, USA

ABSTRACT

Aircraft development efforts are rapidly shifting toward the use of distributed electric propulsion. As the industry moves along a path to full electrification, hybrid propulsion systems will be increasingly employed where battery technology does not support a fully electric design. The fuel systems in new aircraft designs can be challenging, and the existing regulatory framework may not be capable of dealing with unique aircraft designs that do not neatly fit within existing categories. This presents a challenge to aircraft designers. Fuel remains essential to the propulsion system, and an optimal, yet simple fuel system will be necessary to leave room in the design trade space for more challenging and risky functions. Understanding the certification requirements and having a basic knowledge of the tradeoffs in fuel measurement accuracy are the key elements necessary to support a systems approach to optimizing a fuel measurement subsystem.

INTRODUCTION

The regulatory landscape is uncertain for many hybrid aircraft designs – are you a rotary wing aircraft, or a fixed wing aircraft, neither, both…? Defining a path to certification will require an examination of the underlying intent of the existing regulations in order to define what parts of each may apply to a given unique aircraft design and/or mission. Eventually this will likely lead to definitions beyond 14 CFR Part 23, 25, 27, 29 categorization. In the short term an aircraft designer will have to pick one, define how to comply with it, and explain any differences through a request for deviation. A comparison of those deviations relative to an existing requirement under another Part of 14 CFR is likely to be an easier path to certification than proposing a completely new requirement.

To facilitate that approach, this paper provides a roadmap through existing regulations specific to fuel measurement systems. A thorough examination of 14 CFR is provided to compare and contrast the requirements between Parts 23, 25, 27 and 29. Additional requirements, such as TSO-C55a and associated military regulations and industry design standards, are also discussed.

With that framework in place, examples are provided to help meld various approaches, by applying industry lessons learned, guidance in the FAA Advisory Circulars, and other sources. This will help systems engineers define the requirements and restrictions on the design. It also aims to help them navigate through the definition of realistic subsystem requirements, and shows how to meet them through an optimal fuel measurement system design. Further discussion includes a more in depth look at specific design considerations, such as functional independence, and where they begin to significantly drive design considerations [1]impacting cost, risk, and development timeline.

Efficiently designed hybrid systems will reduce the industry's reliance on fossils fuels. This places an emphasis on more efficient use of a reduced amount of fuel, and therefore a need to more accurately understand the fuel state. The second half of this paper looks at factors impacting accuracy in fuel measurement, and how a systems approach, focusing on a well-integrated subsystem, can improve accuracy.

Sources of fuel measurement error can broadly be categorized into those related to the aircraft installation, the fuel, and the measurement device. All three categories will be discussed briefly with a more in depth focus on identifying approaches airframers can take to control error sources. A notional subsystem error budget is presented, allowing for a discussion of the individual contributors and the magnitude of their impact on fuel quantity error.

Practical examples of factors that affect each error source will be discussed, with emphasis on the significant error sources that lie within the airframe (and specifically fuel tank) design, as well as those impacted through subsystem definition and

---

Presented at the Vertical Flight Society's 76th Annual Forum & Technology Display, Oct. 6-8, 2020, Virtual.

integration. These discussions aim to demonstrate that a thorough systems approach leads to an optimal solution. Error sources within the fuel measurement subsystem can best be controlled by the supplier when requirements are defined up front and early by the customer.

REQUIREMENTS AND REGULATIONS

The existing FAA aircraft certification system has evolved with the industry and reflects the technology, designs, and operations that have existed for decades. While it is certainly not a completely “black and white” world, it is fairly straightforward to lay out a path to certification along the lines of the airworthiness standards in Parts 23, 25, 27, and 29.

There have always been aircraft that don’t fit neatly, such as the Leonardo AW609 tilt rotor, but recent developments in distributed electric propulsion have resulted in more radical shifts in design and operation that are sure to continue. In determining a path to certification, what rules apply? Does an aircraft that takes off and lands vertically, but flies on wing in forward flight need to comply with crash resistance?

This, and other specific examples, will be discussed further below. The first hurdle to pass, more generally, is: what will the regulators accept, and how will they decide? The European Aviation Safety Agency (EASA) recently released a “special condition” for non-helicopter VTOL aircraft that is based on EASA’s CS-23 certification specification for light airplanes. The FAA has been slower to react, voicing more generally the use of “consensus standards” to fill the gaps where new designs don’t fit into existing airworthiness standards.

The processes would seem to start with determining the closest fit to an existing aircraft type for your design. Logically this would leave the least “gray area” and reduce the number of gaps. In any case, gaps will need to be identified, and closing them requires understanding the intent of an individual requirement within the airworthiness standards. A problem arises in that many functional requirements don’t appear in a consistent manner across the different airworthiness standards. This is true when looking at overall aircraft design and performance standards or requirements for specific aircraft subsystems.

Determining if a requirement applies to your design requires an exploration of the intent of the requirement. The “best fit” airworthiness standard may vary depending on what facets of the aircraft and subsystem design you are evaluating. This paper focuses solely on a comparison of the various regulations that apply to fuel measurement – including the FAA Airworthiness Standards and Technical Standard Order (TSO), as well as associated industry and military standards.

To aid in discussion, general categories have been labeled to compare a requirement, or group of requirements, that relate to one another across the various regulatory sources. Appendix A provides a matrix of the categories, citing the full requirement in many cases, or a shortened version that includes only the portions of the requirement that pertain directly to fuel measurement systems. Each category is broken out in sections below for discussion of applicability, intent, and potential means of compliance.

More general requirements for all types of avionics (such as those pertaining to wiring, cockpit displays, general design practices and safety guidance, etc.) are not covered. While they are important, and must be considered, they would unreasonably increase the scope of this work.

This paper likely asks more questions than it answers, and the sections below are not intended to be a definitive road map. The aim is to provide a framework, and guide discussion, hopefully easing the path to certification. And ultimately, some day, those discussions may support the development of requirements for new airworthiness standards.

General Fuel Measurement

There is a basic requirement for some method of fuel measurement in all four airworthiness standards. The only significant difference is that Part 23 requires only a means to determine total usable fuel available, while Parts 25, 27, and 29 require a fuel quantity indicator for each tank. The need for multiple displays can be a design driver for cockpit panel layout when using individual indicators, and also needs to be considered in terms of complexity of software in the fuel measurement electronics and any multi-function display units that may be used.

Compliance with this requirement can be achieved with a system that performs three basic functions: sensors in the tank to monitor fuel level, electronics to read and interpret the in tank sensors, and a means to display the information to the aircrew. This would normally consist of a fuel probe (typically a capacitive sensor), a signal conditioning unit, and either an individual flight deck indicator or integration into a multi-function display.

It is also important to note that the fuel quantity indicator is defined under the more general category of Powerplant Instruments. This results in the need for more general compliance to the entire Powerplant Instrument section, with additional requirements to understand and consider. This is covered in more detail in further discussion.

Another overarching point to acknowledge is the specific application of the term “Usable Fuel” which is further defined below. While this is actually a function determined by the overall fuel systems design, it must be established in order to fully define multiple requirements for fuel measurement.

The general requirement for fuel measurement creates the relationship to TSO C-55a which defines minimum performance standards for the system. Although not mandatory, the TSO does constitute a baseline set of requirements and associated means of compliance, and can generally be used as information to help understand the intent of a regulation.

Low Level Warning

There is a distinct difference in the airworthiness standards between fixed wing airplanes and rotorcraft on the requirements for low level warning. There is no requirement in Part 23 or 25, while both Part 27 and 29 share the exact same requirement for a low fuel warning device in each tank that feeds and engine. This device must:

1) Provide a warning to the flightcrew when approximately 10 minutes of usable fuel remain.
2) Be independent of the normal fuel quantity indicating system.

The general intent of this requirement seems straightforward: to provide an alert to a critical fuel level and provide time for the aircrew to respond. The distinction in the need for this type of alert between fixed wing aircraft and rotor craft is not completely clear. While no direct reference was found, it seems obvious that the impact of fuel starvation is felt almost immediately in a rotorcraft, as opposed to some period of time over which an airplane will glide, and the pilot can respond. Rotorcraft typically can use auto rotation with a high likelihood of a survivable crash landing, but the lower altitudes at which the typically fly create less time for decision making.

Compliance with this requirement adds to the complexity of the fuel measurement system. The degree of complexity is somewhat driven by the definition of independence. A complete discussion of independent systems is beyond the scope of this paper, but is in line with typical system design decisions driven by SAE ARP4754 and 4761. In general, the elimination of single point failure would require separate sensors (potentially with unique sensing methods - for common mode failure avoidance), separate processing and power circuits, and possibly mechanical separation through individual enclosures and electrical connectors, and possibly separate wiring harnesses.

It is also important to note that the requirement is for an alert to the aircrew. This typically is a visual indication, such as a warning lamp. The use of a continuous readout that must be monitored, and a critical level determined through interpretation of a range of values, is not generally acceptable.

Pressure Refueling (High Level Warning)

Specific requirements exist for all commercial aircraft (Part 25 and 29) when performing pressure refueling. The requirements for rotorcraft under Part 29 are less stringent than for fixed wing aircraft under Part 25.

The requirements under part 29.979 simply state that there must be a primary and secondary means to prevent damage to the tank by over pressurization. Guidance in FAA Advisory Circular AC 29.979 points to mechanical devices operating on differential pressure or fuel level sensing. Typically a mechanical device is the less complex and costly choice. In some cases, though, failure mode and effects analysis may identify a common mode failure, which could point to a backup solution through fuel level sensing.

In many fuel system designs tank venting eliminates the direct risk of over pressurization. A secondary risk is created, though, when overfilling of tanks results in fuel spillage through the vent. Part 25 requirements seem to acknowledge the impact of this risk, both in terms of safety and the environmental impact of spilled fuel. In 25.979 the requirement is to provide an automatic shutoff means to prevent exceeding the maximum quantity of the tank.

Additionally, there are requirements to allow for a “pre-check” of proper function of the shutoff prior to fueling, and having an indication at each fueling station if the shutoff fails. This drives a more complicated design, usually based on fuel level sensing. Depending on the need for independence, capacitive fuel gauges that are already in the system can be used to trigger an additional output signal that operates a shutoff valve at a predetermined maximum fuel level. The system may need to include a predictive methodology to account for the delay created in the physical closure of the valve(s). Or other sensors (optical, float, thermistor, for example) may be incorporated in the system. Sensors can also be incorporated in the fuel vent to detect the presence of fuel and trigger the shutoff.

The “pre-check” functionality must be considered in the system design, and can add complexity to the controller hardware and software. This creates the need for a human interface, with a “press to test” switch and some method to display functions and faults. Often this is incorporated into a refueling panel near the fueling point that has additional functionality, such as pre-setting a desired fuel level other than full. Displaying the failure indication at the refueling station(s) adds complexity, and in some aircraft can add significant wiring due to the relative locations of the fuel measurement system controller and the refueling stations.

Indication, Accuracy and Calibration

For the most part, the airworthiness standards are relatively consistent for requirements related to the indication of the fuel quantity and the required accuracy and calibration. Part 23 is general and vague, adding no specific requirements to the previously stated basic requirement to determine total useable fuel. The requirements for presentation of fuel quantity information to the flight crew are not specific, and apply only through those requirements common to all “Powerplant” instruments.

Part 25, 27 and 29 largely agree with one another, and provide additional specific guidance on the display of fuel quantity information:

1) The system must indicate useable fuel quantity in each tank. There are exceptions for treating interconnected tanks as one when they share outlet, airspace, venting, and cannot feed separately.
2) Each indicator must be calibrated to read zero when the tank has reached the unusable level.
3) For any system where unusable fuel exceeds one gallon or five percent of tank capacity (whichever is greater), a red arc must be marked on the indicator from the calibrated zero point to the lowest reading possible in level flight.

The unusable fuel supply is established as a fuel system design parameter, but has bearing on the fuel measurement system in this case. This is defined as the quantity where the first evidence of engine malfunction occurs. This determination must take into account the most adverse fuel feed condition that can occur during any intended operations and flight maneuvers. In practice, the unusable fuel can often more easily be defined as the point at which fuel boost pump outlet pressure starts to drop (i.e. the onset of fuel pump cavitation). The engine still has fuel at this point, but the pump cavitation is the first evidence of the coming engine malfunction.

The “red arc” requirement, as written, applies most directly to analog dial displays and is somewhat dated. It does not easily apply to modern digital displays in many cases, and is typically complied with through some means of color coding.

In some cases there may also be a quantity of fuel that is useable but not measurable, due to limitations of fuel gauge placement. Fuel system design methods typically minimize unusable fuel as good practice, and a coordinated design approach helps to match fuel gauge location and fuel feed points to optimize fuel measurement accuracy. The “red arc” requirement can be met (essentially eliminated) by ending the fuel gauge at the unusable fuel level. It therefore can’t read lower than zero useable because there is no sensing into the unusable fuel.

The requirement to read zero at the unusable fuel level is the only direct requirement on accuracy in the airworthiness standards. In general a fuel measurement system should be designed to minimize over reporting of fuel, particularly in system failure or degraded accuracy situations. This represents a “fail safe” condition. As the fuel quantity approaches zero this is more critical. Meeting the requirement to always read zero at the unusable quantity often requires designing in a negative bias (driving the tolerance single sided) to not ever over report available fuel. Depending on the accuracy of the system, though, this can create a significant amount of fuel that is virtually unusable, at least for flight planning purposes, and limits the operational envelope of the aircraft.

For commercial aircraft the additional requirements for landing with the regulated fuel reserve also drives a desire for accuracy. This also creates a negative bias, requiring the reserves to account for any measurement error, and effectively increasing the reserve quantity. A more accurate system can reduce this added fuel weight, which can be a significant economic advantage in larger aircraft.

It is important to note that there are no explicit accuracy requirements in the airworthiness standards, other than the zero reading at unusable stated above. If TSO-C55a authorization is required, there are Minimum Performance Standards (MPS) defined that refer to SAE AS405C and SAE AS8029. These standards (as well as MIL-G-26988) define tolerance classes, which are all generally similar to one another. Three classes are typically defined, roughly forming low (4 - 6%), medium (2 - 4%), ad high (0.5 - 2%) accuracy ranges. The total tolerance bands typically combine two separate bands, one relating to the total fuel quantity and another related to the fuel quantity at any given point. The total fuel quantity band is narrower, which results is an overall tightening of the tolerance band as the tank empties.

There are no strict requirements for applying a certain class to a certain type of aircraft. It is generally accepted, though, that the accuracy required is defined relative to the criticality of fuel measurement functions derived from the system safety hazard analysis. This would obviously drive higher accuracies on Part 25 aircraft due to the increased severity of the consequences of fuel starvation on a commercial aircraft. Other functions may need to be considered as well, such as the use of fuel quantity data by a fuel management system that is designed to automatically maintain center of gravity, potentially impacting controllability of the aircraft.

There is guidance in FAA Advisory Circulars AC 27.1337 and AC 29.1337 that system accuracy is acceptable when it meets a tolerance of ±2 percent of the total useable fuel plus ±4 percent of the remaining usable fuel at any gauge reading. The AC also defines a method for determining an aircraft attitude to be used for the calibration point at which accuracy is determined.

The defined accuracy classes are not directly related to system level requirement flow down categories, but have been historically segmented into groups based around the capability of existing measurement technologies and the acceptable level of complexity of the fuel measurement system. System design vs accuracy will be discussed in further detail below, but in general a highly accurate system requires the addition of some combination of temperature, density and dielectric measurement to the basic capacitive fuel gauges. As seen in the previous discussion, the addition of equipment to a system to increase accuracy must be balanced against gains in safety and reliability as well as potential economic gains based on the planned operation of the aircraft.

Safety and Survivability

Many of the general requirements related to safety and survivability of aircraft apply to fuel measurement systems. A complete discussion of all potential requirements is beyond the scope of this paper, and should be considered in the aircraft design and definition of requirements for any subsystem. There are three particular areas that relate more directly to fuel measurement that will be discussed:

1) Crash Resistance
2) Explosion Prevention
3) Lightning Protection

The requirements for crash resistance apply only to rotorcraft, in both Part 27 and Part 29. As applied to fuel measurement system components, the requirements are generally the same. The overall intent of the requirement is to reduce the risk of post-crash fire due to ignition of fuel or fuel vapors, by designing the fuel system to maintain structural integrity under survivable crash loads.

The tank design typically incorporates a sealed bladder that prevents fuel from spilling if the aircraft crashes. Any components mounted in the tank must be designed to structurally fail in a manner that does not compromise the integrity of the bladder. Capacitive sensor design typically consists of two concentric tubes which, if not carefully designed, can create a risk of puncture to the bladder under crash loads. Any components that mount through the tank wall, such as electrical connectors or flange mounted fuel probes, must also be designed to maintain their seal integrity under survivable crash loads.

The topic of fuel tank explosion prevention is covered in far more detail under Part 25 than in Parts 23, 27, and 29. There are no direct requirements in Part 23 that seem to relate directly to fuel tank explosion, although general design guidelines obviously provide some level of protection. Part 27 and 29 have requirements under the overall fuel system design section that limit the maximum exposed surface temperature of any component in the fuel tank to a level less than the auto ignition temperature of the fuel or fuel vapor. There are also general guidelines for limiting sparks and electrical arcs in proximity to the fuel tanks. Compliance is less stringent, but is in line with methods described in detail for Part 25 below.

The requirements under 25.981 are extremely detailed and cover multiple aspects of fuel system design. The requirements that apply most directly to fuel measurement systems control or eliminate ignition sources related to high temperature and spark/arc danger. In practical terms, FAA Advisory Circular AC 25.981-1D breaks this down into four design criteria:

1) Electrical Sparks and Arcs less than 200 microjoules have been demonstrated to not ignite hydrocarbon fuels. Systems designed with safety factor to account for reliability and maintenance intervals must limit energy introduced into the fuel tank to 50 microjoules.
2) Risk of ignition by filament heating can be addressed by designing systems with a maximum steady state current of 25 milliamps RMS, a failure condition to 50 mili-amps, and a max transient of 125 milliamps.
3) The danger of friction sparks is generally low in fuel measurement systems, but should be considered for any moving parts.
4) Autoignition risk has a safe margin when systems are designed with maximum temperatures below 400 degrees Fahrenheit.
5) Risks of static electricity build up in the fuel must also be considered, to comply with the 50 microjoules spark limit. Static build up through friction created by fuel flow must have redundant paths for dissipation.

Fuel measurement system components must be designed to meet these requirements, and the aircraft designer should ensure that by properly defined subsystem requirements. Compliance also requires coordination with the fuel measurement systems provider to define system interfaces, wire harness routing, and maintenance and inspection procedures.

Requirements for protecting the overall fuel system from lightning exists in all four relevant airworthiness standards. As with explosion prevention, Part 23 is very general, Parts 27 & 29 are similar to one another, and Part 25 is the most detailed. The requirements all state that the fuel system must be designed to prevent the ignition of fuel due to direct and swept lightning, with these differences:

1) Part 27 mentions fuel only, while Parts 25, 27, and 29 state fuel and fuel vapors.
2) Parts 23, 27 and 29 take into account the risk of corona and streamering at the fuel vent outlets.
3) Part 25 further defines a critical lightning strike as a strike that when combined with a design or structural failure causes a risk of ignition.
4) Part 25 describes the fuel system to include components that penetrate or connect to the tank.
5) Part 25 specifically requires the prevention of Catastrophic fuel vapor ignition

Much of the guidance for compliance with these requirements is related to the overall fuel system, particularly tank design, as well as the overall aircraft design. This requires methods to conduct and dissipate the electrical energy from a lightning strike. The design factors for fuel measurement systems relate mostly to electrical bonding of components and shielding of wiring harnesses. This prevents the buildup of static charges and eliminates conductive paths into the tank. These design decisions rest with the fuel measurement system supplier, but should be confirmed by the airframer. Decisions at the aircraft design level can impact compliance, though.

The routing of wiring harnesses is one example. Harnesses that enter the tank are often constructed with a complete over braid shield to prevent direct lighting attachment on conductors. If these harnesses are routed only through areas already protected from lightning, and/or kept to a minimal length, the over braid is likely not required.

ACHIEVING ACCURACY

The accuracy of the fuel measurement system is a design parameter that goes beyond safety considerations and compliance. Increased accuracy supports optimizing the use of available fuel, which directly increases the range and endurance of the aircraft. Specifically for hybrid electric systems, more accurate determination of the fuel state provides better input for algorithms that are determining the optimal use of the overall available energy.

A complete discussion of fuel measurement system design is beyond the scope of this paper. What follows is a discussion of the most prevalent error sources, and methods to minimize them or compensate for them. For purposes of discussion, these errors are grouped into three general categories related fuel measurement system error, aircraft design/installation error, and fuel variation. Some errors impact more than one category. Fuel variation will not be discussed in detail, as these errors are not driven by design choices, but it is worthy of further research when defining a fuel measurement system. The generic system used for discussion is limited to a basic fuel measurement system without a compensator (to measure dielectric value) or densitometer.

Errors can also be categorized as a bias error or random error. Bias errors can be defined through analysis and "wet test" calibration, and then controlled. Random errors must be accounted for in the system accuracy estimation due to variation in fuel system components and aircraft fuel tanks, as well as fuel characteristics. Random errors can typically be bounded by determination of their probability distribution, through analysis and tolerance control, and maintained through the use of Statistical Process Control by the manufacturer.

The error budget presented in Appendix B is for a capacitive gauging system, as this is the most widely used. Errors specific to the fuel measurement gauges apply only to that type of system. While the error source may be different, the magnitude of errors for any fuel measurement system should be within the same range, if overall accuracy is to be achieved. Other sources of error apply, in most cases, regardless of the type of fuel gauge used.

Nearly all fuel measurement systems use some method to determine the height of the fuel level relative to the tank. Errors from that point on are geometrical errors (impacting the relationship between height and volume) and errors related to variation in fuel characteristics. The calculation of fuel mass from volume relies on accurate determination of the density of the fuel. Those geometrical and fuel errors are common to all fuel measurement systems.

One caveat here: the inherent operation of capacitive gauges is subject to the Clausius –Mossotti relationship, which defines an opposing relationship between the dielectric constant and density of fuel. This makes capacitive gauges "self-compensating" to some degree, and determination of system error therefore cannot treat these parameters separately. This makes the calculated mass output of a capacitive gauging system largely independent of variations in fuel dielectric and fuel density. The error analysis should take this factor into account and not treat fuel dielectric and density as independent error sources.

Evaluating Error Sources

An example error budget is presented in Appendix B. The example uses an arbitrary system of five tank units (fuel measurement probes) to measure a nominal total fuel volume of 750 gallons. For purposes of evaluating the magnitude of individual error sources, the probes vary in length but are assigned a consistent value of "probe rate" (2 picoFarads per inch) and "probe resolution" (5 gallons per inch and 2.5 gallons per picoFarad) for each probe.

To understand the magnitude of individual error sources, each error must be evaluated in terms of its impact on the calculated fuel quantity in terms of mass. Individual errors are defined by different parameters, as shown in Appendix B "Error Parameter" column. Then each error is introduced into the fuel quantity calculation by manipulating the specific tank unit parameter or fuel property accordingly. The fuel quantity is calculated using a series of equations.

The measured capacitance (C_m) of each probe is calculated using the equation:

$$C_m = (\alpha * (K-1) * Ca) + Ce$$

Where:

C_m = Measured Capacitance (Probe Reading)

α = the fraction of the probe that is filled with fuel

K = the dielectric constant of the fuel

C_e = Empty ("Dry") Capacitance (Sensor capacitance with only air as a dielectric)

C_a = Active Capacitance (Sensor capacitance that changes when a dielectric other than air occupies some or all of the sensor)

In a perfect sensor, $C_a = C_e$. However, there are generally small areas of the sensor that prevent entrance of the active dielectric (fuel). The capacitance of these areas is called Dead

Capacitance (C_d) since the capacitance doesn't change when the fuel level changes.

Therefore: $C_a = C_e - C_d$

A measured volume (V_m) for each probe is calculated using the equation:

$$V_m = ((C_{m} - C_e) / ((K-1) * C_a)) * \text{Full Volume}$$

The total volume is a summation of all probe measured volumes. Total fuel Mass is then determined by multiplying Volume by Density.

Throughout this series of equations, error sources can be introduced parametrically, and the impact on fuel mass can then be seen. Examples of the most significant error sources are presented below.

Probe Build Variation

Errors relative to variation from a nominal probe response typically appear most directly in the probe dry capacitance value. This is controlled (and verified) during probe production within a defined tolerance band, expressed either directly in terms of capacitance (i.e. +/- XX picoFarads) or as a percentage of the probe's actual dry capacitance value.

These errors directly affect the probe height calculation as a variation in empty capacitance and active capacitance. The impact on quantity error is larger in a full probe than an empty probe, and also increases with probe length. Although these are random errors, they are bounded by acceptance testing during production. This limits the errors within a tolerance range which can be incorporated into the error budget.

Signal Conditioner Variation

The electronics that excite the fuel measurement probes and monitor the return signal will vary from unit to unit in a production environment. This error is very similar in nature to the probe error described in the previous section. It is represented in the fuel calculation as an error in the probe capacitance, and will have the same relative impact on the total fuel quantity error. It is also a random error, but is bounded through tolerance controls that are verified during acceptance testing.

Probe Position Error

The potential for errors associated with probe position is a consideration for both the fuel measurement system supplier and the airframer or tank supplier. Variation in the location of the mounting provisions on the probe or the of mating hardware and/or hole locations in the fuel tank have the same potential for introducing error in the fuel quantity calculation. The effect is basically a direct shift in the height to volume relationship, with a direct impact on fuel quantity. The error is greatest in a full probe and approaches zero error at empty. The magnitude of the error varies with probe resolution. A probe with a higher ratio of gallons per inch (lower resolution) will have higher percentage of impact on fuel quantity error for a given error in probe position. This is a random error, but is bounded by mechanical tolerances on the mounting features of the probe and fuel tank, which can be controlled through drawing definition, manufacturing practices and inspection. A reasonable limit for this error, when developing an error budget, can be determined through tolerance stack up analysis.

Wiring Harness Variation

This error occurs due to variation in the inherent capacitance of the wiring harness and external influences (so called "stray capacitance") that create noise on the signal line. Generally speaking, this is any capacitance not associated with the fuel probe.

In modeling the impact of this error, the actual value of the assumed stray cap is added directly to C_m (Measured Capacitance) of the probe. This will change the probe response, even at empty. The error magnitude is independent of probe length or fuel level, since it is essentially "dead" capacitance and is not changing with the "active" response of the probe. The magnitude of the error varies with probe resolution. A probe with a higher ratio of gallons per pF (lower resolution) will have higher percentage of impact on fuel quantity error for a given value of stray capacitance.

A wiring harness of a given length will have a fixed inherent capacitance so this error can be treated largely as a bias error, which can be eliminated by subtracting the known nominal stray capacitance from the measured capacitance value. There will be variation in the actual harness length, so some random error must still be considered. During production, the stray capacitance of the harness can be measured as part of the Acceptance Test Procedure (ATP) to verify strays have been controlled to within the desired limits. Shielding of signal lines, including proper termination at all connection points, reduces the level of stray capacitance. Installation of wiring harnesses in the aircraft can affect stray capacitance, so an additional ATP may further identify and control errors.

Tank Capacity Variation

This error is the result of variations in the geometry of individual fuel tanks from the nominal design due to manufacturing tolerances, mechanical stresses, and environmental effects. This results in a direct impact on the height to volume ratio in the fuel quantity calculation, and is modeled in the error budget as a multiplier effect on the calculated fuel quantity. So, on a percentage basis, an error in tank capacity results in the same percentage of error in fuel quantity.

Also on a percentage basis, the error is the same for any tank size and any fill level. The actual impact of the error, in terms of gallons of fuel, will vary directly with tank size and fill level, and goes to zero as the tank empties.

This is a random error, and can be controlled by drawing tolerances, manufacturing methods, and inspection of tanks in production. The control of this error is the responsibility or the airframer and/or tank supplier.

Tank Study Error

This error is introduced through errors in the tank study, where the height to volume relationships are established. Errors are introduced due to inconsistencies in the modeling of the tank geometry and internal components, as well as the overall resolution of the model. Errors are also introduced due to changes in aircraft attitude, which changes the relationship between the fuel plane (the top surface of the fuel volume) and the fuel probes.

Like tank capacity variation, this results in a direct impact on the height to volume relationship in the fuel quantity calculation. In this case, though, it is modeled in the error budget as an additive effect on the calculated fuel quantity. This represents, mathematically, a combination of random errors that cannot be measured directly but are estimated to be within a given range and incorporated as single bias error.

Since this error results from the aircraft's ability to change attitude and geometry on the ground and in flight, it is expressed as a probability. Generally accepted is that the error will be within the stated value during flight and ground operations 95.45% of the time (a 2σ probability distribution). This error can be reduced by using two different tank tables, one for ground operations and one for flight. This requires an input from the aircraft, usually weight on wheels, to allow selection of the correct tank table.

Tank study errors are basically sampling errors. The more sensors we have, the more accurately we can sense where each increment of fuel is located. Practically, there is a limit to how many sensors we can use and where we can locate them. The result is an array of errors based on fuel height, sensor location, tank shape, etc. Generally these errors get smaller as the fuel level decreases and larger as it increases, but there is a lower limit near empty and an upper limit near full. The specific errors are determined by mathematical analysis of the tank geometry, sensor placement, and fuel plane orientation. This analysis can be refined through testing on a representative aircraft.

As previously stated, this error is a represented as a bias error and combines many potential variables of the tank study. System validation should include a wet test, which fills and drains the tank in prescribed (and measured) increments of mass or volume, and compares to the calculated fuel quantity. This provides data to adjust the height to volume relationship, reducing the errors associated with the tank study. Remaining differences between the actual quantity and calculated quantity represent the bias error in the tank study.

OVERALL DESIGN GUIDANCE

The coordinated definition of requirements for aircraft design, fuel system design, and fuel measurement system design allows tradeoffs to be made among requirements at all levels. This drives reduced system complexity and cost. In many cases a decision to add functionality at a higher level can eliminate the need for redundant functionality in multiple lower level systems.

For a hybrid aircraft, when looking specifically at compliance with FAA airworthiness standards, the requirements definition process must account for the "harmonization" of the airworthiness standards described in this paper. In regard to the requirements for fuel measurement systems, the optimal choice may be just to comply with both fixed wing and rotary wing standards – defaulting to the higher standard where they differ.

The added cost and complexity is typically not that great, when requirements are defined up front and the system can be optimized for the given application. The added functionality also may have ancillary benefits. For example: redundancy for reasons of safety also results in higher reliability and less aircraft downtime.

In looking at the comparison of airworthiness standards, there are a few examples for different types of aircraft that can provide insight.

An aircraft that takes off and lands vertically and accomplishes forward flight on wing is potentially subject to both Part 23/25 and 27/29 airworthiness standards. Among the distinctions between rotary wing and fixed wing, the most significant requirement is the addition of an independent low level sensor for rotary wing aircraft. The marginal benefit of this system is an advantage for a fixed wing aircraft, even if not required by regulation. With proper design, the added complexity can be minimized. Separate sensors are required for independence, but control electronics can often be combined within the same unit that controls the fuel measurement probes. Consideration must be given in maintaining independence through separate power input, separate control boards, individual connectors, and other factors.

Fuel system crash resistance is also a differentiator between rotary and fixed wing aircraft. This can be a high driver of complexity in the overall fuel system design - for fuel tanks, bladders, break away valves, and other components. The burden on the fuel measurement system comes down to the design of in-tank hardware, by ensuring that these units do not damage the tank or create leaks under crash loads. Careful design of the fuel probes, and particularly the use of materials such as carbon fiber composite, allows for a structural failure mode that does not create any debris with high enough mass and sharp edges to puncture the tank or bladder. This can be accomplished with minimal added cost and complexity.

Compliance with 14 CFR 25.981 (for eliminating sources of ignition of fuel vapors) should also be considered, even in cases where Part 25 may not directly apply. Compliance with the basic guidance can be accomplished with minimal added cost and complexity in most cases. Full compliance requires a baseline probability of fuel tank explosion to be less than 1E-9. Meeting this requirement can require added levels of redundancy in critical areas of the system design. The added redundancy will obviously also add to the system complexity and cost.

The technologies required to comply exist, and fuel measurement system providers likely have most of the components for compliance built into their basic designs. As with crash resistance, this is largely a matter of good design practice. Decisions regarding selection of components, circuit card design, shielding and grounding techniques, and material choices need to be considered. These choices can result in added cost and complexity, with more expensive and/or redundant components. This impact can be minimized, and the advantages in increased reliability of the system should also be factored in.

CONCLUSIONS

A systems design approach, taking into account regulatory requirements and focusing on controlling factors that drive measurement error, will result in the optimal sub system design for fuel measurement. Lessons learned from previous development programs show that this results in reduced development timelines, lower development costs, lower recurring costs, and reduced risk.

Author contact: Mark Connors
mark.connors@liquidmeasurement.com

APPENDIX

Appendix A – FAA Certification Requirements Comparison

Appendix B – Sample Error Study

ACKNOWLEDGMENTS

The author would like to thank Larry Maier of Ambrosius Engineering for his insights and contributions to the content of this paper.

REFERENCES

1. 14 CFR Part 23, Code of Federal Regulation, Airworthiness Standards: Normal Category Airplanes, Federal Aviation Administration, Washington DC
2. 14 CFR Part 25, Code of Federal Regulation, Airworthiness Standards: Transport Category Airplanes, Federal Aviation Administration, Washington DC
3. 14 CFR Part 27, Code of Federal Regulation, Airworthiness Standards: Normal Category Rotorcraft, Federal Aviation Administration, Washington DC
4. 14 CFR Part 29, Code of Federal Regulation, Airworthiness Standards: Transport Category Rotorcraft, Federal Aviation Administration, Washington DC
5. EASA SPECIAL CONDITION Vertical Take-Off and Landing (VTOL) Aircraft, SC-VTOL-01, European Union Aviation Safety Agency, Cologne, Germany
6. TSO-C55a, Fuel and Oil Quantity Instruments, Federal Aviation Administration, Washington DC, 2007
7. Guidelines for Development of Civil Aircraft and Systems ARP4754A, Rev. 21 Dec 2010, Society of Automotive Engineers, Warrendale, PA
8. Guidelines And Methods For Conducting The Safety Assessment Process On Civil Airborne Systems And Equipment ARP4761, Rev. 01 Dec 1996, Society of Automotive Engineers, Warrendale, PA
9. FAA Advisory Circular AC 29-2C, Certification of Normal Category Rotorcraft, Federal Aviation Administration, Washington DC, 2018
10. Fuel and Oil Quantity Instruments AS405D, Rev. 22 Aug 2012, Society of Automotive Engineers, Warrendale, PA
11. Minimum Performance Standard for Fuel and Oil Quantity Indicating System Components AS8029, Rev. 16 Feb 2008, Society of Automotive Engineers, Warrendale, PA
12. MIL-G-26988, Military Specification: Gauge, Liquid Quantity, Capacitor Type Transistorized, General Specification For, US Government Printing Office, 1971
13. FAA Advisory Circular AC 27-1B, Certification of Normal Category Rotorcraft, Federal Aviation Administration, Washington DC, 2018
14. FAA Advisory Circular AC 25.981-1D, Fuel Tank Ignition Source Prevention Guidelines, Federal Aviation Administration, Washington DC, 2018

Appendix A - FAA Certification Requirements Comparison

	Part 23	**Part 25**	**Part 27**	**Part 29**	**TSO-C55a (and SAE AS405C)**
General Fuel Measuremnt	23.2430 Fuel systems. (a) Each fuel system must— (4) Provide the flightcrew with a means to **determine the total useable fuel available** and provide uninterrupted supply of that fuel when the system is correctly operated, accounting for likely fuel fluctuations;	25.1305 Powerplant instruments. The following are **required powerplant instruments**: (a) **For all airplane**s. (2) A **fuel quantity indicator for each fuel tank.**	27.1305 Powerplant instruments. The following are the **required powerplant instruments**: (d) A **fuel quantity indicator, for each fuel tank**.	29.1305 Powerplant instruments. The following are the **required powerplant instruments**: (a) For each rotorcraft— (3) A **fuel quantity indicator, for each fuel tank**.	TSO-C55a, 3a. Functionality. This TSO's standards **apply to any instrument intended to provide cockpit indication of the quantity of fue**l or oil in a tank.
Low Level Warning			27.1305 Powerplant instruments. The following are the **required powerplant instruments**: (l) A **low fuel warning device for each fuel tank which feeds an engine**. This device must— (1) Provide a **warning** to the flightcrew when **approximately 10 minutes of usable fuel remains** in the tank; and (2) **Be independent** of the normal fuel quantity indicating system.	29.1305 Powerplant instruments. The following are the **required powerplant instruments**: (a) For each rotorcraft— (4) **A low fuel warning device for each fuel tank which feeds an engine.** This device must— (i) Provide a **warning** to the flightcrew when **approximately 10 minutes of usable fuel remains** in the tank; and (ii) **Be independent** of the normal fuel quantity indicating system.	
Pressure Refueling (High Level Warning		25.979 Pressure fueling system. **For pressure fueling systems**, the following apply: (b) An **automatic shutoff** means must be provided **to prevent** the quantity of fuel in each tank from **exceeding the maximum** quantity approved for that tank. This means must— (1) Allow **checking for proper shutoff operation before each fueling** of the tank; and (2) **Provide indication at each fueling station of failure** of the shutoff means to stop the fuel flow at the maximum quantity approved for that tank.		29.979 Pressure refueling and fueling provisions below fuel level (b) **For systems intended for pressure refueling**, a means in addition to the normal means for limiting the tank content must be installed to **prevent damage to the tank** in case of failure of the normal means. **** Note: The procedures outlined in the AC focus on overpressure, and there is **no mention of level sensors** as there is in 25.979. It would seem that this requirement likely does not apply to fuel measurement.	
Power Plant Instruments (Indication Accuracy, and Calibration)	23.2615 Flight, navigation, and powerplant instruments. (a) Installed systems must **provide the flightcrew member who sets or monitors parameters for the** flight, navigation, and **powerplant, the information necessary to do so during each phase of flight**.	25.1337 Powerplant instruments. (b) Fuel quantity indicator. There must be means to **indicate** to the flight crewmembers, the quantity, in gallons or equivalent units, of **usable fuel in each tank during flight**. In addition— (1) Each fuel quantity indicator must be **calibrated to read "zero"** during level flight when the quantity of fuel remaining in the tank is equal to the unusable fuel supply determined under 25.959; (2) **Tanks with interconnected outlets and airspaces** may be treated as one tank and need not have separate indicators; and (3) Each exposed sight gauge, used as a fuel quantity indicator, must be protected against damage.	27.1337 Powerplant instruments. (b) Fuel quantity indicator. Each fuel quantity indicator must be installed to clearly **indicate** to the flight crew the q**uantity of fuel in each tank in flight**. In addition— (1) Each fuel quantity indicator must be **calibrated to read "zero"** during level flight when the quantity of fuel remaining in the tank is equal to the unusable fuel supply determined under 27.959; (2) **When two or more tanks are closely interconnected by a gravity feed system and vented**, and when it is impossible to feed from each tank separately, at least one fuel quantity indicator must be installed; and (3) Each exposed sight gauge used as a fuel quantity indicator must be protected against damage.	29.1337 Powerplant instruments. (b) Fuel quantity indicator. There must be means to **indicate** to the flight crew members the quantity, in gallons or equivalent units, of **usable fuel in each tank during flight**. In addition— (1) Each fuel quantity indicator must be **calibrated to read "zero"** during level flight when the quantity of fuel remaining in the tank is equal to the unusable fuel supply determined under 29.959; (2) **When two or more tanks are closely interconnected by a gravity feed system and vented**, and when it is impossible to feed from each tank separately, at least one fuel quantity indicator must be installed; (3) **Tanks with interconnected outlets and airspaces** may be treated as one tank and need not have separate indicators; and (4) Each exposed sight gauge used as a fuel quantity indicator must be protected against damage.	TSO-C55a, Appendix 1, Figure 1 Defines Minimum Perfromance Standards (MPS) via amendments to SAE AS405C Class Accuracy Tolerance 1 +/- 0.75% full scale 2 +/- 2% of full scale 3 +/- 3% of full scale *** Also refers to SAE AS8029, but that document does not agree with Figure 1 in TSO-C55a, since it includdes accuracy tolerances for indicated value and full scale.
Fuel Quantity Indicator Markings		25.1553 Fuel quantity indicator. If the **unusable fuel supply** for any tank exceeds one gallon, or five percent of the tank capacity, whichever is greater, a red arc must be marked on its indicator extending from the calibrated zero reading to the lowest reading obtainable in level flight.	27.1553 Fuel quantity indicator. If the **unusable fuel supply** for any tank exceeds one gallon, or five percent of the tank capacity, whichever is greater, a red arc must be marked on its indicator extending from the calibrated zero reading to the lowest reading obtainable in level flight.	29.1553 Fuel quantity indicator. If the **unusable fuel supply** for any tank exceeds one gallon, or five percent of the tank capacity, whichever is greater, a red arc must be marked on its indicator extending from the calibrated zero reading to the lowest reading obtainable in level flight.	
Unusable Fuel		25.959 Unusable fuel supply. The unusable fuel quantity for each fuel tank and its fuel system components must be established at not less than the quantity at which the first evidence of engine malfunction occurs under the most adverse fuel feed condition for all intended operations and flight maneuvers involving fuel feeding from that tank. Fuel system component failures need not be considered.	27.959 Unusable fuel supply. The unusable fuel supply for each tank must be established as not less than the quantity at which the first evidence of malfunction occurs under the most adverse fuel feed condition occurring under any intended operations and flight maneuvers involving that tank.	29.959 Unusable fuel supply. The unusable fuel supply for each tank must be established as not less than the quantity at which the first evidence of malfunction occurs under the most adverse fuel feed condition occurring under any intended operations and flight maneuvers involving that tank.	

	Part 23	Part 25	Part 27	Part 29	TSO-C55a (and SAE AS405C)
Crash Resistance			27.952 Fuel system crash resistance. Unless other means acceptable to the Administrator are employed to minimize the hazard of fuel fires to occupants following an otherwise survivable impact (crash landing), the fuel systems must incorporate the design features of this section. These systems must be shown to be **capable of sustaining the static and dynamic deceleration loads** of this section, considered as ultimate loads acting alone, measured at the system component's center of gravity, **without structural damage to system components**, fuel tanks, or their attachments **that would leak fuel to an ignition source**. (f) Other basic mechanical design criteria. Fuel tanks, fuel lines, electrical wires, and **electrical devices** must be designed, constructed, and installed, as far as practicable, to be **crash resistant**.	29.952 Fuel system crash resistance. Unless other means acceptable to the Administrator are employed to minimize the hazard of fuel fires to occupants following an otherwise survivable impact (crash landing), the fuel systems must incorporate the design features of this section. These systems must be shown to be **capable of sustaining the static and dynamic deceleration loads** of this section, considered as ultimate loads acting alone, measured at the system component's center of gravity, **without structural damage to system components**, fuel tanks, or their attachments **that would leak fuel to an ignition source**. (f) Other basic mechanical design criteria. Fuel tanks, fuel lines, electrical wires, and **electrical devices** must be designed, constructed, and installed, as far as practicable, to be **crash resistant**.	
Fuel Tank Explosion Prevention		25.981 Fuel tank explosion prevention. (a) **No ignition source** may be present at each point in the fuel tank or fuel tank system **where catastrophic failure could occur due to ignition of fuel or vapors.** This must be shown by: (1) Determining the highest temperature allowing a safe margin below the lowest expected autoignition temperature of the fuel in the fuel tanks. (2) Demonstrating that no temperature at each place inside each fuel tank where fuel ignition is possible will exceed the temperature determined under paragraph (a)(1) of this section. This must be verified under all probable operating, failure, and malfunction conditions of each component whose operation, failure, or malfunction could increase the temperature inside the tank. (3) Except for ignition sources due to lightning addressed by §25.954, 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, taking into account the effects of manufacturing variability, aging, wear, corrosion, and likely damage. *Requirements in (b) and (c) are a tank system deisgn issues. *Requirements in (d) generally apply to CCDLs for any fuel measurement system component under 25.1529. *See 25.1705 Electrical Wiring Interconnection System (EWIS) and Appendix H Instructions for Continued Airworthiness)	27.963 Fuel tanks: general. (e) The **maximum exposed surface temperature** of any component in the fuel tank **must be less,** by a safe margin as determined by the Administrator, **than the lowest expected autoignition temperature of the fuel or fuel vapor in the tank.** Compliance with this requirement must be shown under all operating conditions and under all failure or malfunction conditions of all components inside the tank.	29.963 Fuel tanks: general. (e) The **maximum exposed surface temperature** of any component in the fuel tank **must be less,** by a safe margin as determined by the Administrator, **than the lowest expected autoignition temperature of the fuel or fuel vapor in the tank.** Compliance with this requirement must be shown under all operating conditions and under all failure or malfunction conditions of all components inside the tank.	
Fuel System Lightning Protection	23.2430 Fuel systems. (a) Each fuel system must— (2) Be designed and arranged to **prevent ignition** of the fuel within the system by **direct lightning strikes or swept lightning strokes** to areas where such occurrences are highly probable, or by **corona or streamering** at fuel vent outlets;	25.954 Fuel system lightning protection. (a) For purposes of this section— (1) A **critical lightning strike** is a lightning strike that attaches to the airplane in a location that, when combined with the failure of any design feature or structure, could create an ignition source. (2) A fuel system includes any component within either the fuel tank structure or the fuel tank systems, and any airplane structure or system **components that penetrate, connect to, or are located within a fuel tank**. (b) The design and installation of a fuel system **must prevent catastrophic fuel vapor ignition due to lightning and its effects, including**: (1) **Direct lightning** strikes to areas having a high probability of stroke attachment; (2) **Swept lightning** strokes to areas where swept strokes are highly probable; and (3) **Lightning-induced or conducted electrical transients**. (c) To comply with paragraph (b) of this section, **catastrophic fuel vapor ignition must be extremely improbable, taking into account flammability, critical lightning strikes, and failures within the fuel system.** *Requirements in (d) generally apply to CCDLs for any fuel measurement system component under 25.1529.	27.954 Fuel system lightning protection. **The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system by—** (a) **Direct lightning** strikes to areas having a high probability of stroke attachment; (b) **Swept lightning** strokes to areas where swept strokes are highly probable; or (c) **Corona and streamering** at fuel vent outlets.	29.954 Fuel system lightning protection. **The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system by—** (a) **Direct lightning** strikes to areas having a high probability of stroke attachment; (b) **Swept lightning** strokes to areas where swept strokes are highly probable; or (c) **Corona and streamering** at fuel vent outlets.	

Appendix B – Sample Error Study

Tank Unit Parameters						Fuel Properties				
Tank Unit Number	**Length** (inches)	**Ce** (pf)	**Ca** (pf)	**Cd** (pf)	**Volume** Gallons	**K-1**	**D** (lb/gal)	**Rate** (pF/in)	**Resolution** (gal/in)	**Resolution** (gal/pF)
TU1	10.000	20.000	19.750	0.250	50	1.1365	6.7260	2	5	2.5
TU2	20.000	40.000	39.750	0.250	100			2	5	2.5
TU3	30.000	60.000	59.750	0.250	150			2	5	2.5
TU4	40.000	80.000	79.750	0.250	200			2	5	2.5
TU5	50.000	100.000	99.750	0.250	250			2	5	2.5
					750					

% Cover	Cm TU1	Cm TU2	Cm TU3	Cm TU4	Cm TU5	Volume	K-1	D	Mass	Error Parameter	Quantity Error %	
Fuel Quantity - No System Errors											Empty Error	Full Error
1	42.446	85.176	127.906	170.636	213.366	750.000	1.1365	6.7260	5044.5			
0	20.000	40.000	60.000	80.000	100.000	0.000	1.1365	6.7260	0.0			
Probe Dry Capacitance Tolerance - Assume Ce and Ca change the same percentage										Percentage		
1	42.658	85.176	127.906	170.636	213.366	750.473	1.1365	6.7260	5047.7	0.5		0.06
0	20.100	40.000	60.000	80.000	100.000	0.223	1.1365	6.7260	1.5		0.03	
1	42.446	85.602	127.906	170.636	213.366	750.943	1.1365	6.7260	5050.8			0.13
0	20.000	40.200	60.000	80.000	100.000	0.443	1.1365	6.7260	3.0		0.06	
1	42.446	85.176	128.545	170.636	213.366	751.413	1.1365	6.7260	5054.0			0.19
0	20.000	40.000	60.300	80.000	100.000	0.663	1.1365	6.7260	4.5		0.09	
1	42.446	85.176	127.906	171.489	213.366	751.883	1.1365	6.7260	5057.2			0.25
0	20.000	40.000	60.000	80.400	100.000	0.883	1.1365	6.7260	5.9		0.12	
1	42.446	85.176	127.906	170.636	214.433	752.353	1.1365	6.7260	5060.3			0.31
0	20.000	40.000	60.000	80.000	100.500	1.103	1.1365	6.7260	7.4		0.15	
Signal Conditioner Error - Difference between actual capacitance and measured capacitance										Percentage		
1	42.594	85.176	127.906	170.636	213.366	750.331	1.1365	6.7260	5046.7	0.35		0.04
0	20.070	40.000	60.000	80.000	100.000	0.156	1.1365	6.7260	1.0		0.02	
1	42.446	85.474	127.906	170.636	213.366	750.660	1.1365	6.7260	5048.9			0.09
0	20.000	40.140	60.000	80.000	100.000	0.310	1.1365	6.7260	2.1		0.04	
1	42.446	85.176	128.354	170.636	213.366	750.989	1.1365	6.7260	5051.2			0.13
0	20.000	40.000	60.210	80.000	100.000	0.464	1.1365	6.7260	3.1		0.06	
1	42.446	85.176	127.906	171.233	213.366	751.318	1.1365	6.7260	5053.4			0.18
0	20.000	40.000	60.000	80.280	100.000	0.618	1.1365	6.7260	4.2		0.08	

1	42.446	85.176	127.906	170.636	214.113	751.647	1.1365	6.7260	5055.6			0.22
0	20.000	40.000	60.000	80.000	100.350	0.772	1.1365	6.7260	5.2		0.10	
Probe Vertical Position - Sensor end points do not match the tank study data										Inches		
1	42.446	85.176	127.906	170.636	213.366	750.500	1.1365	6.7260	5047.9	0.1		0.07
0	20.000	40.000	60.000	80.000	100.000	0.000	1.1365	6.7260	0.0		0.00	
1	42.446	85.176	127.906	170.636	213.366	750.500	1.1365	6.7260	5047.9			0.07
0	20.000	40.000	60.000	80.000	100.000	0.000	1.1365	6.7260	0.0		0.00	
1	42.446	85.176	127.906	170.636	213.366	750.500	1.1365	6.7260	5047.9			0.07
0	20.000	40.000	60.000	80.000	100.000	0.000	1.1365	6.7260	0.0		0.00	
1	42.446	85.176	127.906	170.636	213.366	750.500	1.1365	6.7260	5047.9			0.07
0	20.000	40.000	60.000	80.000	100.000	0.000	1.1365	6.7260	0.0		0.00	
1	42.446	85.176	127.906	170.636	213.366	750.500	1.1365	6.7260	5047.9			0.07
0	20.000	40.000	60.000	80.000	100.000	0.000	1.1365	6.7260	0.0		0.00	
Harness Stray Capacitance - Assume any bias error is removed by adjusting software parameters										picoFarads		
1	42.746	85.176	127.906	170.636	213.366	750.668	1.1365	6.7260	5049.0	0.3		0.09
0	20.300	40.000	60.000	80.000	100.000	0.668	1.1365	6.7260	4.5	0.3	0.09	
1	42.446	85.476	127.906	170.636	213.366	750.664	1.1365	6.7260	5049.0	0.3		0.09
0	20.000	40.300	60.000	80.000	100.000	0.664	1.1365	6.7260	4.5	0.3	0.09	
1	42.446	85.176	128.206	170.636	213.366	750.663	1.1365	6.7260	5049.0	0.3		0.09
0	20.000	40.000	60.300	80.000	100.000	0.663	1.1365	6.7260	4.5	0.3	0.09	
1	42.446	85.176	127.906	170.936	213.366	750.662	1.1365	6.7260	5049.0	0.3		0.09
0	20.000	40.000	60.000	80.300	100.000	0.662	1.1365	6.7260	4.5	0.3	0.09	
1	42.446	85.176	127.906	170.636	213.666	750.662	1.1365	6.7260	5048.9	0.3		0.09
0	20.000	40.000	60.000	80.000	100.300	0.662	1.1365	6.7260	4.4	0.3	0.09	
Tank Geometry Variation - Capacity of actual fuel tank does not match the tank study data										Percentage		
1	42.446	85.176	127.906	170.636	213.366	750.750	1.1365	6.7260	5049.5	0.1		0.10
0	20.000	40.000	60.000	80.000	100.000	0.000	1.1365	6.7260	0.0	0.1	0.00	
Tank Study Error - Fuel quantity from profiles does not match the actual volume										Gallons		
1	42.446	85.176	127.906	170.636	213.366	754.000	1.1365	6.7260	5071.4	4		0.53
0	20.000	40.000	60.000	80.000	100.000	4.000	1.1365	6.7260	26.9	4	0.53	
										3σ Sys Error %:	**0.628**	**0.824**
										2σ Sys Error %:	**0.419**	**0.549**