SAE Aerospace
An SAE International Group

# AEROSPACE INFORMATION REPORT

AIR1184

Issued 1-73
Revised 3-27-89
Reaffirmed 2007-12

REV. A

## CAPACITIVE FUEL GAUGING SYSTEM ACCURACIES

**ABSTRACT:** This document presents a concise overview of error sources in capacitive fuel gauging systems. The subject matter is directed at individuals who are responsible for specifying gauging system accuracies and, therefore, need insight into the predominant error sources in capacitive fuel gauging systems and means to minimize the errors. A brief introduction to capacitive fuel gauging is also included as background reference.





**TO PLACE A DOCUMENT ORDER:** Tel: 877-606-7323 (inside USA and Canada)
Tel: 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org

**SAE WEB ADDRESS:** http://www.sae.org

TABLE OF CONTENTS

1. PURPOSE:

This report identifies those sources or causes of error which adversely affect the accuracy of airborne capacitance-type fuel quantity gauging systems.

2. SCOPE:

This report is intended to identify the necessary analytical tools to enable making value judgments for minimizing the various errors typically encountered in capacitance systems. Thus, in addition to identification of error sources, it describes the basic factors which cause the errors. When coupled with appraisals of the relative costs of minimizing the errors, this knowledge will furnish a tool with which to optimize gauging system accuracy, and thus, to obtain the optimum overall system within the constraints imposed by both design and budgetary considerations.

Since the subject of capacitance accuracy is quite complex, no attempt is made herein to present a fully-comprehensive evaluation of all factors affecting gauging system accuracy. Rather, the major contributors to gauging system inaccuracy are discussed and emphasis is given to simplicity and clarity, somewhat at the expense of completeness.

An overview of Capacitive Fuel Gauging operation is provided in the Appendix.

3. GENERAL REQUIREMENTS:

There are numerous ways in which the contributors to gauging system inaccuracy may be classified. Parameters for such classification may be general (e.g., temperature-induced errors, geometrical errors, etc.) or specific (e.g., tank errors, tank unit errors, indicator errors, etc.). Indeed, the variety of possible classifications is virtually unlimited.

For the purpose of this report, four broad categories for classification of error-causes are listed:

( i) Errors controlled by the airframe manufacturer.

( ii) Errors jointly controlled by the airframe manufacturer and gauging system supplier.

(iii) Errors mainly controlled by the gauging system supplier.

( iv) Errors not controlled by the airframe manufacturer or the gauging system supplier.

4. DETAILED REQUIREMENTS:

4.1 Errors Controlled by the Airframe Manufacturer: Unlike many instruments and systems which are typically installed in modern aircraft, the fuel quantity gauging equipment should be considered as a system which is irrevocably "married" to and which becomes an integral part of the aircraft. With respect to the tank units particularly, their locations and geometries are influenced by the airframe's basic design. Thus, to optimize the gauging system, its preliminary design should proceed in parallel with that of the airframe.

4.1.1 Fuel Tank Description: An important factor in the design of a typical fuel gauge system is the definition of the fuel containment which, in turn, is dependent upon the number of tanks, the geometry of each tank, and the quantity of fuel to be carried in each tank.

This subject has a significant bearing upon fuel gauge system design. For, as the number and geometrical complexity of the tanks increase, the difficulty in accurately defining the fuel contents at ground and different flight conditions also increases. A further complication is the effect on tank geometry due to change in tank shape and attitude caused by wing twist and deflection for those tanks contained within the wing structure.

With regard to accuracy, the airframe manufacturer's responsibility is to devise a means of describing the actual tank's physical shape in the most realistic manner, and in a way that can be simply and accurately interpreted by the gauging supplier. Inaccuracies in such description, or in the ease of interpreting this description, produce "built-in" errors in the gauging system.

Some typical methods of furnishing this description are as follows:

1. Accurate internal dimensioned drawings of the tank, with appropriate cross-sectional information including dimensioned description of internal structure and equipment.

2. Analytic geometrical description of the complete tank or of those sections of the tank which are sufficiently "regular" to permit such description. This is usually accomplished by computer analysis output by printouts, tape or cards and in the form of x, y, z coordinates. It is desirable that the form of output be suitable for direct usage in the math model or computer program of the supplier to reduce effort and errors.

3. Combinations of (1) and (2) are used especially in cases where the tank cavity is composed of both regular and irregular volumes.

4. Results of actual fill-and-drain measurements performed on scaled-down or preferably full-sized models of the tank. This is an excellent means to help reduce errors and can be performed in addition to other forms of tank definition. This method by itself may not be sufficient because of large variations in aircraft attitudes and wing twist and deflection affecting fill-and-drain results at various flight conditions.

4.1.2 "IN-TANK" Hardware and Wing Deflection: When external dimensions are provided, as applicable, tank wall thickness is required to be furnished to permit determination of actual internal volume. Furthermore, consideration must be given to the presence of internal tank structure and hardware. Particularly, the dimensions and locations of baffling, plumbing, surge boxes, pumps, etc. should be specified in order to permit proper computation of that portion of the tank cavity devoted only to the fuel. It is pointed out that baffling which causes differential fuel levels in the tank during various flight conditions may produce a significant error which should be addressed. This can cause a significant error during flight conditions because of the difficulty in providing accurate differential fuel level data and the difficulty in minimizing these error sources.

Additional information which must be furnished by the airframe manufacturer includes the location of filling ports, fuel expansion space, any explosion suppressant materials, and residual fuel volumes. This permits the gauge manufacturer to assess the amount of actual usable fuel and to design the gauge accordingly.

It is also pointed out that wing tanks affected by twist and deflection could have significant errors. It is therefore necessary to describe wing twist and deflection characteristics both as functions of fuel load and distribution of gross weight, and of particular ground conditions and flight regimes of interest. Flight factors affecting wing twist and deflection can include items such as aircraft speed, altitude, attitude, weight distribution and configurations including flaps, air brakes and landing gear position.

4.1.3 Tank Tolerances: For capacitive fuel measurements, the dimensional stability (manufacturing tolerance) of the tanks is an extremely important factor which could be considered as part of the inaccuracies that could result.

4.1.4 Stay-Out Areas: Another consideration related to tank structure is the usual limitations placed on the gauging supplier with respect to certain tank unit locations. The very marriage of the gauging components to the airframe, and the fact that these gauging elements and the airframe structure impose mutual constraints upon one another, potentially influence gauging accuracy. Thus, in situations where a particular location is sought for a tank unit on the basis of achieving ideality of gauging accuracy, and avoiding interferences and maintaining proper structural integrity of the airframe, a reasonable compromise location for the tank unit must be found. By definition, this compromise prejudices the gauging system accuracy. The airframe manufacturer usually classifies these unacceptable regions for tank unit locations as "stay-out" areas.

4.1.5 Pitch and Roll: Probably the most significant cause of fuel gauge errors and, therefore, the one which has the greatest influence upon the number and location of tank units, is the airframe manufacturer's specification of aircraft pitch and roll attitudes under which the gauge is to perform with particular accuracies.

In the gauge's operation fuel volume is inferred from the length of the wetted portion(s) along the probe(s). Practically speaking, this length is determined as a function of the volume of fuel in the tank when the tank is in its "normal" attitude. This function, which relates fuel volume and wetted length, generally is non-linear and is usually linearized by "characterizing" the probe or by characterizing the probe(s) signal(s) if a computerized gauging system is employed.



Starting with a particular known function between wetted length and fuel volume with the tank in normal attitude, if the tank's attitude is changed, this function will also change. This change can be especially marked when the tank is almost full or almost empty, because the top of the tank will probably be partly wetted in the former case, or the bottom of the tank will be partly uncovered in the latter case. If, in these cases, appreciable amounts of fuel are permitted to exist above the uppermost sensing point or below the lowermost sensing point, the inference of fuel volume from the measurement of wetted length will be commensurately in error. The magnitudes of these errors for a given array of probes of course depend on the particular attitudes specified. Conversely, if the range of attitudes is restricted, it is generally possible to minimize the number of probes and yet achieve acceptable errors.

The extremes of attitude requirements are associated with fighter aircraft. High attitudes, such as 60 deg nose-up coupled with aircraft acceleration while in this attitude, can easily create a condition where "gaps" in gauging might exist. Inverted flight poses yet another unique situation for fighters. The desired or "tolerated" fuel quantity reported under these extremes must be addressed early in the design cycle.

Therefore, in order to minimize gauging errors or to minimize the number of probes required to achieve particular specified accuracies, the airframe manufacturer must exercise discretion in the establishment of aircraft attitude versus accuracy requirements. For example, in wing tanks the requirement for high accuracy under roll conditions in combination with twist and deflection should be scrutinized with utmost care.

4.1.6 Water Contamination: In order to avoid contact and/or partial immersion of capacitance probes in accumulated liquid water, fuel tanks should be designed to allow water accumulation areas to be below the lowest probe sensing point. Scavenging systems are employed in some aircraft to ensure that water is drawn out of these low areas and recirculated to the boost pumps to preclude accumulation of significant quantities of water.

## 4.2 Errors Jointly Controlled by the Airframe and Gauging System Manufacturers:

4.2.1 Number of Tank Units and Locations: Because of the mutual influence of tank unit location and airframe structure upon one another, it is most advantageous for this function to be carried out cooperatively between the gauging and airframe manufacturers.

The following steps, or "rules of thumb", suggest one procedure for near-optimum probe location in a typical tank. Note, however, that tank "stay-out" areas must be considered as additional constraints on the problem.

1. Establish the maximum admissible error.

2. Approximate the tank by a simplified geometric shape if the tank shape is not already very regular. Examples of such simplifications of tank shape might be prisms, pyramids, or suitable combinations of these located adjacent to one another.

3. Note the characteristic cross sections which tend to dominate the top- and bottom-errors. These are the cross sections where one of the simplified geometric shapes borders with another, or where it ends. These cross-sections are normally characterized by some extreme property; i.e., the largest cross section, or the one where horizontal walls become oblique, etc.

4. Determine the required number of probes - Generally, the top-and bottom-errors are the deciding factors. For example, if the bottom-error is too large when only one probe is used additional probes will be required to satisfy the accuracy requirements at the specified attitudes.

5. Locate the probes - After the number of required probed is determined, their location at the top and bottom cross-sections, that is, the simplified cross sections, is also generally determined. If the tank differs appreciably from its approximate geometric shape in a certain region, a corresponding shift of the probes is indicated at that place.

6. Evaluate the maximum errors - When the probes have been tentatively located, analytical (computer) determination of the necessary probe characterization and the resultant errors are determined. Accuracy over the entire flight attitude envelope is studied. Appropriate attitude-weighted error allocation is considered at this point. Furthermore, it is possible to have the computer derive the errors resulting from incremental movement of the probes from their tentative locations. The results of such computations are then analyzed, and final "optimum" probe locations are selected.

4.2.2 Installation Considerations: There may be no class of equipment whose performance can be degraded more drastically by improper installation than capacitance-type fuel quantity gauging systems. Recognizing this, the gauging system manufacturer and airframe manufacturer must collaborate effectively in this area to ensure accurate, trouble-free performance of the gauging equipment. In an actual installation, the superimposed effects of humidity, fuel contamination, temperature, altitude, vibration and shock, fuel sloshing, fuel characteristic variations, external subsystem usage, etc., all act simultaneously and adversely upon the gauging system. Many of these influences can be worsened by the frequent cycling of humidity, temperature, and altitude produced by typical short-haul mission profiles, and by operation from bases where fuel cleanliness may be poorly controlled.

In view of these potential difficulties, it is not sufficient that individual gauging components merely satisfy their own particular specifications; it is also necessary that they be made to interact with one another and with the aircraft to produce an accurate and reliable gauging system during actual service use.

1. Single-Point Ground - The benefits of the implementation of single-point grounding are known to greatly outweigh its cost. The basic approach to proper implementation is to have a signal return collection point within the indicator associated with each fuel tank, and to have all signal circuitry connected thereto, each by an individual wire, to prevent circulating ground currents. From this point, a single wire is brought through a pin in the instrument's connector and returned to airframe structure external to the unit. The power return (usually 115 volt, 400 Hz), the case ground and, as applicable, the lighting ground, should each have individual egress from the instrument, and may be returned to the airframe structure in any convenient acceptable fashion.

   By adopting this approach, all of the signal currents are confined within the gauging system, and none is permitted to take an uncontrolled path through the airframe, wherein it could be influenced by spurious external causes. In addition to the precautions already noted, care must be taken in the indicator design to minimize the capacitance between the input-signal lead and the indicator case. Otherwise, should the case potential be other than that of the single-point ground, unwanted signals could be coupled into the system through this capacitance.

   Where electrostatic and electromagnetically-induced coupling of spurious signals into the gauging system's external wiring is concerned, the use of single-point grounding along with reasonable separation (2 to 3 inches minimum) between gauging equipment leads and external current-carrying conductors is sufficient to ensure trouble-free performance.

4.2.2 (Continued):

Extreme care must be taken in maintaining shield continuity of the shielded conductor employed to transmit the signal from the inner tube (Hi-Z) in conventional "AC" fuel gauging systems. The coupling of any synchronous AC signal on this conductor will introduce a potentially large error in the reported fuel quantity. This problem is undoubtedly the most frequent cause for maintenance on AC gauging systems.

2. DC Gauging System Shielding - The modern DC system transmits a pulsating unidirectional "DC" current as a signal from the tank to the signal conditioner. The twisted-triplex signal conductor used in DC systems is virtually immune to AC pickup in the audio-frequency range. In some applications, a simple braided shield over these conductors is needed to add high-frequency immunity to the system. Multi-point grounding of this shield is acceptable and results in a more reliable system.

3. Sensor Mounting Tolerances - The tolerances in the location of the mounting brackets (for internally mounted tank units) or the flange plates (for externally mounted tank units) should be taken into account. These errors can be of the order of tank dimensioning tolerances (see 4.1.3).



4.3 <u>Errors Controlled by the Gauging Equipment Manufacturer</u>:

4.3.1 <u>Generation of Height-Volume Data</u>: The gauging system manufacturer is often called upon to generate height-volume data from the tank geometry descriptions furnished by the airframe manufacturer. Sometimes, however, the airframe manufacturer has the capability and desires to furnish the height-volume data directly to the gauging system manufacturer, by means of in-house computer studies of the tank geometry for ground and flight attitudes, including wing twist and deflection if applicable.

For the case when the tank description is given in terms of scale drawings with cross-sectional information, it is often necessary to approximate the curvilinear envelopes of these sections by straightline segments. The errors induced by such approximations can be made negligible by increasing the number of segments; however, this is limited by the economics of both preparing the data and of computer time for their utilization.

When the furnished cross-sectional information is listed in nature (i.e., when the sections are given at relatively largely spaced intervals), the tank geometry must be further approximated by straightline segments between the various sections. This can lead to additional errors.

Frequently, due to schedule requirements, information given the gauging system manufacturer is preliminary in nature, and during the design phase the airframe manufacturer alters either the envelope or the location of auxiliary equipment within the tank. Depending upon the state of the design at that time, upon the scope of the changes, or upon economic considerations, the gauging system supplier will elect to resubmit the new

4.3.1 (Continued):

information for computer analysis. In this case no additional errors beyond those already described will result, or adjustment of the initial computer data to suit the new requirements. In the latter case, it is possible to introduce additional errors into the height-volume data; however, experienced gauge designers are well-equipped to handle situations of this kind, and can operate on the existing data with minimum accuracy compromise.

4.3.2 Tank Unit Characterization: When the tank locations are established, and the "system constant" (usually given in units of picofarads/gallon) is determined, another specially designed computer program can be utilized to establish optimum characterization of each tank unit in the normal tank attitude. The computer then simulates the various specified pitch and roll attitudes, and, as applicable using twist and deflection, computes the measuring errors under these conditions on the assumption of ideally characterized tank units.

At this point the gauge designer reviews the error data and evaluates the relative magnitudes of the errors in the various attitudes and for the various fuel volumes considered. If it is necessary to reduce errors in certain regions in order to stay within specification limits, tank unit locations are adjusted or the normal attitude characterization is compromised slightly, and the revised data are submitted for recomputation. For this reason, it is pointed out that too stringent accuracy requirements for extreme conditions are not desirable because of the adverse effect on accuracy achieved at normal attitudes.

In this manner, through sequential exchange of information between the gauge designer and the airframe manufacturer, optimum characterization of the tank units in their selected locations is attained.

In computerized gauging systems the employment of "linear" profile on tank units is made possible. The information which converts height to volume can be contained in system software in the form of lookup tables. If individual tank units can be addressed at the computer interface, "common level" techniques can be used to further reduce attitude errors in computerized systems. This enhancement is possible only if "in tank" and system wiring is configured to permit access to each tank unit.

4.3.3 Component Design: It is generally recognized at this time that tank units of all-metal construction (as opposed to fiberglass, and other plastic types) permit achievement of highest accuracy and reliability with minimum manufacturing costs. As far as accuracy is concerned, the major portions of the tank unit are the sensing elements themselves. These are typically two, concentric, cylindrical elements between which the fuel is permitted to rise or fall, and the measurement of their electrical capacitance is used to determine the quantity of fuel remaining. Furthermore, for profiled tank units the inner element has a varying diameter, which in turn yields a varying capacitance-per-unit-length. In this manner the characterization of the tank unit to produce a constant capacitance-change per unit of fuel volume change is achieved. For linear tank units the inner element has a constant diameter, with the tank profile being contained in the associated Fuel Quantity Gauging Computers memory. There are several important factors which affect the capacitance-per-unit-length, and thus the accuracy of the unit. Among these are the following:

(1) Tubing Tolerances - In order to achieve the desired capacitances, manufacturing tolerances must be placed on the inside diameter of the outer tube, and on the outside diameter of the inner tube. Aluminum tubing can be obtained for the outer tube with an inside diameter tolerance, depending on tube diameter, or as little as ±0.0005" (±0.013 mm).

Considering the outside diameter of the inner element, and remembering also that the outside diameter is varied to accomplish the necessary characterization, various methods are used by different gauging manufacturers to produce inner tubes. Spun tubing and nickel electroformed tubing are the most predominant.

Spun tubing produces elements having high structural strength, well controlled wall thicknesses, and typical outside diameter tolerances of ±0.002 to 0.003 in (±0.05 to 0.076 mm). Where improved accuracy is needed, spun tubing can be obtained at additional cost, with ±0.001 in (±0.025 mm) outside diameter tolerance.

Nickel electroformed tubing is manufactured by preparing a machined, aluminum mandrel with the varying outer diameters required, electroplating nickel on the surface of the mandrel, and then dissolving the mandrel, leaving a nickel tube with the desired profile. The outside diameter tolerance on a tube of this type is ±0.002 in (±0.050 mm). For a linear (constant outside diameter) tube of this type an outside diameter tolerance of ±0.0002 in (±0.005 mm) can be achieved. This process results in a high-strength, light weight inner tube.

Linear inner tubes are also made by a "centerless" grinding process employing thin-walled aluminum or stainless steel tubing. Outside diameter tolerances, depending on tube diameter and length of as little as ±0.0002 in (±0.005 mm) are possible using this method.

4.3.3 (Continued):

(2) Transitions - Another factor influencing tank unit accuracy is the precision with which inner tube outside diameter transitions take place, and the linear distance over which these transitions occur.

Properly executed spun tubing can be made to yield satisfactory performance in this area.

Electroformed nickel tubing has the advantage of being able to accommodate a larger number of largely different diameter transitional changes in a given length of tubing.

(3) Concentricity - Concentricity between the tubes is another factor influencing tank unit accuracy. However, due to symmetry considerations, unless the actual eccentricities are extreme (uniform over the length of the tube), this is not usually a significant contributor to tank unit inaccuracy.

(4) Dead Capacitance - Dead capacitance is that portion of the total measured capacitance of a tank unit which is not influenced by the presence or absence of fuel. It is produced by capacitive paths between the inner and outer sensing tubes (and their associated wiring) caused by the presence of anti-vibration buttons, cross-pins, terminal-boards, etc. Dead capacitance itself does not detract from gauging accuracy, since its effects are adjusted out of the measuring systems by means of the system's empty adjustment. However, variations of dead capacitance (principally as functions of temperature, and entrapped moisture in these paths) can adversely affect accuracy. Thus, good design practice dictates the minimization of dead capacitance in tank unit design on the basis that if this factor is initially small, capacitance variations caused by the aforesaid environments will be negligible.

(5) Stray Capacitance - Stray capacitance is undesirable and can cause measurement errors. The whole chain from the tank unit through to the electronic signal conditioner is susceptible. Stray capacitance between the ends of the tank units and tank surfaces, for instance, can be minimized by the use of end caps. Wiring shield integrity (especially for conventional AC systems) must be maintained over the total wire length including connectors (see 4.2.2).

(6) "Reference" Capacitors (K-Cells) - For gauging systems requiring high accuracy, it is customary to furnish reference capacitors (commonly referred to as compensators) which are normally fully submerged in the fuel, and which sense the fuel's dielectric properties. Since there are usually several tank units in a typical tank, there is a tendency for the manufacturing tolerances of these units to cancel one another. However, since there is generally only one reference capacitor in a given tank, the influence of its tolerances are "felt" by the system without diminution. Thus, it is important when specifying compensated (or reference capacitor) systems that the tolerance on the capacitance of the reference capacitor be closely controlled.

4.3.3 (Continued):

Methods to eliminate the need for reference capacitors have been developed by the gauging industry. Among these are "full-height" and "temperature-weight" compensation. Each method offers both advantages and disadvantages which should be evaluated for the particular application.

4.3.4 <u>Indicators</u>: The term "indicator" refers to self-contained gauging electronics with integral displays. In systems with electronics split from the cockpit, an indicator contains primarily display related components.

(1) Analog (Electromechanical) - This family of indicators most commonly consists of instrument servos having a pointer, counter, or combinations of these which display the fuel quantity remaining in their associated tanks. Functionally, they are composed of bridge measuring circuits, servo amplifiers, servo motors and "rebalance" potentiometers, with suitable mechanisms interconnecting the rotating components. With respect to accuracy, the dominant factors are deadspot and linearity.

Deadspot is primarily determined by the combined gains of the bridge, amplifier and motor. In well-designed instruments the bridge gain is essentially fixed by the use of temperature-stable and controlled tolerance piece-parts. The amplifier gain is stabilized by use of negative feedback, and the motor is enclosed by the amplifier's feedback loop so that variations in its sensitivity do not materially affect the overall deadspot.

Linearity is primarily determined by the rebalance potentiometer; however, in cases where counter displays are used, the design of the interconnecting mechanism can influence effective linearity. Similarly, in pointer display applications, pointer concentricity with the dial and linearity of index spacing influence overall linearity. With respect to the rebalance potentiometer itself, care must be given in this design to assure resistance element linearity, concentricity of the element in its supporting structure, and concentricity of the wiper with respect to the resistance element. The resistance element should have a very low temperature coefficient of resistivity in order that thermal gradients within the instrument not adversely affect an otherwise satisfactory linear potentiometer.

(2) Digital (Solid-State) - This family of indicators employs no wear-related elements such as servo motors, rebalance potentiometers or gearing, and therefore, offers improved reliability and maintainability. The digital readout of fuel content eliminates operator "reading" error. Deadspot is virtually eliminated in this type of indicator. The display format is typically incandescent, light emitting diode (LED) or liquid crystal display (LCD).

4.3.4 (Continued):

The digital indicator may be further enhanced with the addition of a microprocessor. This "smart" subset of digital indicators offers extensive built-in test and system health monitoring features, and operation in degraded modes due to failures and/or discontinuities, as well as the flexibility of firmware updating to incorporate changes due to fuel properties or other gauging characteristics into preexisting hardware. Depending upon the gauging system architecture, enhancements such as attitude error correction can be added to greatly reduce overall system error.

4.3.5 Modern Fuel Gauging System Enhancements: Several new methods of improved gauging characteristics have been developed and are available where their use is warranted. No lengthy discussion is attempted here, but these methods and their advantages are shown below:

| METHOD | ADVANTAGE |
|---|---|
| Full height compensated probes | Eliminates discrete (tank mounted) reference capacitor and reduces errors due to fuel density variation stratification within a tank |
| Temperature-weight compensated probes | Eliminates discrete reference capacitor and reduces errors due to fuel density variation stratification within a tank |
| High frequency AC excitation | Reduces effects of errors due to resistive currents (fuel contamination) |
| Signal conditioners adjacent to tanks | Eliminates long runs of shielded cable |
| High frequency pulsating DC systems | Eliminates shielded wiring and shielded connectors and reduces effects of resistive currents |
| Precalibrated systems (both AC and DC) | Eliminate installation adjustments and reduces maintenance |
| Zero based or "negated" DC probes | Flexibility in tank-electronics hardware since "tank empty" is the same as "no tank" |
| Computerized gauging systems employing densitometers | Measure fuel density thereby reducing errors caused by dielectric versus density variation |

4.4 Errors Not Controlled by the Airframe or the Gauging Systems Manufacturer:

4.4.1 Fuel Characteristics: The single most significant factor affecting capacitance-type gauging system accuracy, over which neither the airframe nor the gauging manufacturer has control, is the fuel itself. In virtually all capacitance-type gauging systems, the fuel property which influences accuracy is the so-called capacitance index. This factor is defined as follows: (K-1)/d, in which K is the fuel's dielectric constant, and d is its density. Fuel specifications do not explicitly control this factor; however, by means of test programs conducted by various agencies, the probable values of (K-1)/d have been ascertained for various classes of aviation fuels over the temperature ranges of interest. Military specifications provide the formulas for (K-1)/d for use in design of gauging systems for use with various fuels. As refinery method and fuel characteristics change, more accurate information could be used to improve accuracy.

All other factors remaining constant, the accuracy of a given gauging system of the uncompensated type is directly proportional to the variation of (K-1)/d for the class of fuels being used. As an example, for JP-4 fuels, the possible error which may be introduced due to variation of this factor is about ±4% of indication. By using a compensated-type of gauge (i.e., one in which a fully submerged reference tank unit is employed), this error can be reduced to approximately ±1.5% of indication.

Further accuracy improvements can be obtained by determining density more accurately and providing this as a further correction factor.

4.4.2 Densitometers: In computerized systems where increased accuracy is desired, devices which measure fuel density directly can be utilized. One of these devices relies on the resonant frequency of a vibrating element being a function of fuel density. A fuel density accuracy of ±0.5% 3 sigma can be achieved with these devices resulting in gauging system with an accuracy of ±1%.

Other sensors that do not measure density directly but infer it from other parameters are also available; one such sensor measures the absorption by the fuel of a radiation source.

A limitation of densitometers is that they must be placed in locations that are representative of all of the fuel being gauged in order to obtain the most realistic fuel density value.

4.4.3 Fuel Contamination: In addition to the old problems of entrapped and dissolved water in aircraft fuels, other problems have occurred due to the presence of bacterial growth in these liquids, and also due to high fuel transfer rates contingent to modern aircraft turnaround requirements. To combat the influence of bacteria, biocidal additives have been developed and are often added to the fuels. Tank-cleaning procedures using various detergents and other cleaning agents leave residues in the tanks which later appear as fuel contaminants. To combat the static electricity produced by the high pumping rates, it is now customary to include anti-static additives in the fuels. Besides these contaminants, jet fuels

4.4.3 (Continued):

are excellent media for the growth of fungal organisms. Thus, the gauging system components which are immersed in the fuel are subject to the degrading influences of all these contaminants.

In general, these contaminants do not affect the fuel's dielectric constant nor its density by amounts which would produce measurable errors; rather, they increase the fuel's conductivity. In addition, there is a tendency for the moisture and other contamination to reduce the insulation resistance of the tank units. If these latter phenomena are uncontrolled, gauging errors can be introduced by virtue of their potentially adverse influence on indicator sensitivity (i.e., the production of indicator sluggishness), particularly in 400 Hz systems.

With respect to fuel conductivity, well-designed compensated 400 Hz gauges can tolerate conductivities in the region of 300 picomho/meter without accuracy degradation. Uncompensated 400 Hz gauges are less tolerant to this factor, and approximately 200 picomho/meter is a reasonable upper limit on conductivity for this type of gauging system. High frequency systems can reduce significantly, the error caused by anti-static additives, water and other contaminants.

Another more subtle error source is caused by fuel stratification. This may be caused by temperature gradients within the fuel tank or by light/heavy fuel gradients. Stratification may be "horizontal" or "vertical" or it may be non-existent. Its formation is influenced by such factors as tank aspect ratios, explosion suppressant materials, and refuel and feed system designs and mission profiles. Each application should be evaluated to determine whether fuel stratification is likely to be present; and if so, to what degree. Errors resulting from horizontal stratification may be reduced through the use of distributed compensation techniques. However, as noted in 4.3.3 (5), the disadvantages of these approaches should also be evaluated before selecting a particular compensation method.

Considering insulation resistance degradation, well-designed tank units employ long leakage paths between the sensing elements to discourage contamination buildup. In some applications, it is prudent to treat the tank units with coatings having non-hygroscopic and water-shedding properties.



5. CONCLUSION:

The preceding discussions have attempted to point out the significant error-causes influencing the accuracy of airborne capacitance-type fuel quantity gauges. Even from this simplified treatment, it can be seen that appreciable skills and experience are required of the gauge designer in order to produce equipment suitable for aircraft service. In addition, it has been shown that the airframe manufacturer plays a critical role in the attainment of the accuracy goals. Furthermore, factors which are beyond the control of both the airframe and gauge manufacturer can be significant.

5. (Continued):

The intent of the following discussion is to summarize the highlights of the foregoing, to assess the magnitudes of the errors produced by the error-causing factors and to give some insight concerning the means and costs involved in minimizing the more significant of these errors.

By far, the most dominant factor influencing gauge accuracy is the ability to describe the fuel's state in the tank insofar as tank geometry and attitude are concerned. Since this is the foundation upon which the gauge's accuracy structure rests, it would be valuable to consider a possible approach to optimizing this description, and thereby permit the reduction of errors introduced in this step of gauge design. The following procedure, if properly implemented, would permit such optimization. It should be recognized, however, that improvements of this type are usually made at some kind of sacrifice. The sacrifice can result in adverse schedule time and in the added amount of coordination and liaison necessary between the airframe and gauging manufacturers.



This procedure contains three basic phases of work which are described in the following paragraphs.

1. As early as possible during the aircraft design phase, preliminary tank envelope data, internal equipment envelopes, and aircraft attitude information are furnished to the gauging manufacturer. Based on these data, approximate quantities and locations of tank units are established. Despite the fact that preliminary tank data of this type are incomplete, it is usually possible to establish the number and approximate lengths of the required tank units, and to establish their locations in the tanks with an accuracy of about 2 to 3 inches. Information available during early phases of aircraft design, rather than after design of structure, fuel system hardware, and other affecting items have become well established, is beneficial in that it increases the likelihood that the airframe manufacturer will be able to choose optimum location for these units.

2. After the tank geometry is finalized, the gauging manufacturer may proceed with the task of establishing the exact location and characterization of each tank unit. Completing the first phase of the work earlier shortens the time required for this second phase and enables the gauging manufacturer to make earlier release of his own tooling drawings. At this point, the gauging manufacturer can prepare and submit a predicted error analysis for the gauging system. This analysis would depict the errors anticipated under the various attitude conditions specified.

   Further, for aircraft such as fighters, required system performance during extreme operating attitudes must be specified. For example, a critical fuel "Bingo" warning system might be delayed or inhibited during these extreme flight attitudes. Other critical concerns might relate to center of gravity management systems since these systems typically use fuel content signals from the gauging system; special provisions need to be addressed for such systems at the onset of the design cycle.

5. (Continued):

3. This phase covers the actual liquid calibration of the first production aircraft, and permits comparison of the actual versus the predicted errors. Data obtained during this phase may be used to further minimize any undesirable error spikes by trimming the characterization of one or several of the tank units.

   Needless to say, it is vital that the attitude ranges considered for a given aircraft must be selected very conservatively. Otherwise, the impacts on gauging system cost and complexity can be very severe. Only those attitudes which have real significance in terms of aircraft usage should appear in the specification. Particularly, ground attitudes, normal cruise attitudes, refuel attitudes, and landing attitudes need be specified. All other attitudes, such as high angles of climb, descent, skids, slips, etc., should not require high-accuracy gauging, since accuracy in the more important attitudes could suffer if these other attitudes were permitted to enter gauging specifications.

   For example, at ground attitude, high accuracy may be specified for the upper regions of the tank (say, from 2/3 filled to full). In the cruise attitude, emphasis on accuracy of auxiliary tanks should be over the entire range of fuel quantity (from full to empty). In the cruise and landing attitudes, high accuracy should be specified in main tanks for the lower regions on the tank (say, from 1/3 filled to empty).

   Although it is difficult to generalize in this area (as it will be with respect to many of the subsequent factors) due to the differences in procedures, technical approach, etc., from one manufacturer to another, it is believed that typical descriptions of nominal tank geometry introduce gauging errors of ±1.0 to ±1.5% of indication. The use of numerically controlled drafting machines can probably reduce this error by a factor of 1.5 to 2.0. However, the investment required to introduce these machines, both in terms of the machine costs themselves and in the cost of obtaining skilled operators for them, is a significant balancing factor.

   The specification of unrealistic requirements for tank attitudes introduces cost penalties (not to mention weight, complexity, etc.) which need not be suffered if realistic requirements are used. It is estimated that gauging errors on the order of ±0.5% of full scale plus ±1.5% of indication are introduced by typical specification of tank attitudes. This results from the inability to produce a theoretically perfect array of probes in a given tank, even assuming that these probes are ideally characterized, and they are manufactured perfectly. To reduce these errors (and indeed, merely to achieve them) requires the utmost cooperation between the gauging and airframe manufacturer, as well as considerable technical skills by both. In this vein also, reduction in the number and extent of tank stay-out areas is a goal which must be sought.

5. (Continued):

Maintenance of the specified tank dimensions during aircraft manufacture is a further necessity, if accurate gauging is to be achieved. Due to this factor it is estimated that typical gauging errors of ±1.0 to ±2.0% of indication are introduced by this factor. Once again, the introduction of numerically controlled manufacturing equipment, capable of holding exacting tolerances can probably reduce this error by a factor of 2.0.

In instances where height-volume information must be generated at the required tank attitudes, error resulting from this step are on the order of ±0.5% of indication. In terms of cost trade-offs, input data preparation for height-volume analysis must be such as to balance accuracy versus cost of preparing the data, and of having it processed.

After the tank unit locations are established, they must be characterized, errors determined, and if necessary the tank units may be relocated and/or recharacterized to minimize error extremes at the various attitudes. Typical errors resulting from this operation are ±0.5% of full scale plus ±1.0% of indication. Here again, the skills of the gauge designer should be considered as paramount, if an optimum gauging system is to result. In this phase of design, end item costs are not especially influenced. Here rather, is an interplay involving accuracy versus design costs; i.e., how well the system can be optimized within the framework of schedule and engineering cost constraints.

After this phase of work comes the actual design and manufacture of the system components. Considerable interaction exists between accuracy and end item costs during this phase of work. Questions of tooling, procurement practices, caliber of manufacturing labor, manufacturing and quality control techniques, etc., all influence the balance between costs and accuracy. Only the very skilled gauge manufacturer can balance these variables so as to obtain best accuracy and yet stay within the normal cost restrictions. For typical tank units, accuracies of ±1.0% of indication are reasonable; indicator deadspot error of ±0.2% of full scale, and indicator linearity errors of ±0.5% of full scale are likewise reasonable.

Still when all of the foregoing aspects of gauge specification and design have been controlled and perfected, there are the "uncontrollable" influences of the fuels themselves which must be accounted for. Particularly, capacitance-index variations, and to a lesser extent of effects of fuel moisture and contamination enter the accuracy picture. For uncompensated gauges the errors which result from these factors amount to as much as ±4% of indication. At the expense of adding a submerged compensator and its associated wiring, compensated gauges can reduce these errors to about ±1.5% of indication.

5. (Continued):

Considering the combination of the above errors, in terms of obtaining an appraisal of the accuracy which may be expected of typical gauging systems, it is not meaningful to simply add the various errors algebraically. Since many of the errors are random in nature, a more realistic appraisal may be obtained by using a rss procedure. Using this technique, and the smaller error-values noted in the foregoing paragraphs, the following errors result:

a. For an uncompensated gauge, errors of about 1% of full scale near empty, increasing to about 5% of full scale near full.

b. For a compensated gauge, errors of about 1% of full scale near empty, increasing to about 3.25% of full scale near full.

c. For an advanced computerized system which employs compensation and attitude correction errors may be reduced to ±1% of indication, ±0.5% of full scale.

If the guidelines and recommendations of this document are followed then it can be expected that the system will remain within its accuracy band for a given installation, attitude range and fuel type. However, older installations have required higher maintenace due to their susceptibility to wiring degradation (due to broken or grounding faults on shielded wiring with conventional AC systems), water contamination, microbial growth, etc. Newer installations have addressed these problems (for water contamination, see 4.3.3 and 4.4.5 and for the elimination of coax wiring by the use of DC systems, see 4.3.5). Probably one of the more significant benefits of the newer computerized gauging systems is their ability to perform self-monitoring. These self-checks constantly monitor the integrity of the system providing a warning when the system is out of tolerance or when a fault occurs.

In the last analysis, however, only the experience and skills of both the airframe and gauging manufacturer can keep the gauge system under control in terms of both cost and accuracy. These skills, the setting of realistic goals, and coordination during all phases of the design activity are the prime requisites for achieving optimum gauge performance. Table I summarizes the errors discussed in the text of this paper.

Fig. 1 is also included for reference when referring to military gauging system requirements. There is no direct correlation between Fig. 1 and Table I.