AEROSPACE INFORMATION REPORT

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TWO PENNSYLVANIA PLAZA, NEW YORK, N.Y. 10001

AIR 1184

Issued January 1973
Revised

FUEL GAGING SYSTEM ACCURACIES

1. PURPOSE

This AIR identifies those sources-of-error which adversely affect the performance of airborne capacitance-type fuel quantity gaging systems.

2. SCOPE

It is intended to provide capacitance gaging system "specifiers" with the necessary tools to make value judgements concerning the various errors typically encountered in systems of this type. Thus, in addition to merely identifying the error-causes, descriptions are given concerning the basic factors from which these error-causes derive. This knowledge, when complemented with appraisals of the relative costs of minimizing the error-causes, will furnish the system specifier with a powerful tool with which to optimize gaging system accuracy, and thus, to obtain the "best possible" overall system within the constraints imposed by both design and budgetary considerations.

Since the subject of capacitance gaging accuracy is quite extensive, and in some instances very complex, no attempt is made herein to present an all-inclusive and fully comprehensive evaluation of the subject. Rather, the <u>major</u> contributors to gaging system inaccuracy are discussed. Furthermore, emphasis in these discussions is given to simplicity-of-approach and clarity, somewhat at the expense of completeness.

3. GENERAL REQUIREMENTS

There are numerous ways in which the contributors to gaging system inaccuracy may be classified. Parameters for such classification may be general (e.g., temperature-induced errors, geometrical errors, etc.) or particular (e.g., tank errors, tank-unit errors, indicator errors, etc.). Indeed, the variety of possible classifications is limited only by the imagination of the classifier, and by the goals sought by the particular classification.

In the present instance, in which the goal is to acquaint the specifiers of gaging systems with the potential sources of gaging system error, the following four broad categories for classification of error-causes are thought to be applicable:

1. Error-causes which are mainly the airframe manufacturer's responsibility.
2. Error-causes which are jointly the responsibility of the airframe and the gaging system manufacturers.
3. Error-causes which are mainly the gaging equipment manufacturer's responsibility.
4. Error-causes for which neither the airframe nor the gaging system manufacturer is responsible.

4. DETAILED REQUIREMENTS

4.1 Error-Causes Which are Mainly the Airframe Manufacturer's Responsibility: Unlike many instruments and systems which are typically installed in modern aircraft, the fuel quantity gaging equipment must 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 influence, and are influenced by the airframe's basic design. Thus, in effect, to optimize the gaging system, its preliminary design should proceed in parallel with that of the airframe.

a. Tank Geometry Description: The most important factor in the design of a typical aircraft fuel gage is the definition of the quantity of fuel carried; this, in turn is dependent upon the number of tanks and the particular geometry of each tank.

This subject has a very significant bearing upon fuel gage design. For as the number and geometrical complexity of the tanks increases the difficulty in accurately defining the fuel contents also increases.

Insofar as the subject of accuracy is concerned, the airframe manufacturer's responsibility is to devise means of describing the actual tank's physical shape in the most realistic manner possible. Inaccuracies in such description, or in the ease of interpreting this description produce "built-in" errors in the gaging system which are beyond the power of the gaging system manufacturer to eliminate.

Some typical methods of furnishing this description are as follows:

1) Accurate internal dimensioned drawings of the tank, with appropriate cross-sectional information.

2) Analytic geometrical description of the complete tank or of those sections of the tank which are sufficiently "regular" to permit such description.

3) In cases where the tank cavity is composed of both regular and irregular volumes, combinations of methods 1) and 2) are used.

4) The results of actual fill-and-drain measurements performed on full-sized or scaled-down models of the tank.

b. When external dimensions are provided, as applicable, tank wall thicknesses are 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.

Additional information which must be furnished by the airframe manufacturer includes the location of filling ports, fuel expansion space, and residual fuel volumes. This permits the gage manufacturer to assess the amount of actual useable fuel and to design the gage accordingly.

Wing Twist and Deflection - When wing tanks are to be gaged, in addition to the above it is necessary to describe wing twist and deflection characteristics both as function of fuel load and distribution, gross weight, and of particular flight regimes of interest.

c. Tank Tolerances: For capacitive fuel measurements the dimensional stability (mfr. tolerance) of the tanks is an extremely important factor.

d. Stay-Out Areas: Another consideration relating to tank structure is the usual limitations placed on the gaging vendor with respect to certain tank-unit locations. The very marriage of the gaging components to the airframe, and the fact these gaging elements and the airframe structure impose mutual constraints upon one another potentially influence gaging accuracy. Thus, in situations where a particular location is sought for a tank-unit on the grounds of producing ideality of the gaging accuracy, and this location interferes with requirements for proper structural integrity of the airframe, a compromise location for the tank-unit must be found. This compromise, by definition, prejudices the gaging system's accuracy. The airframe manufacturer usually classifies these unacceptable regions for tank-unit locations as "stay-out" areas.

e. Pitch and Roll: Probably the most significant cause of fuel gage errors, therefore, and 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 gage is to perform with particular accuracies.

In the gage'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.

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 will be especially marked when the tank is almost full or almost empty, in that the top of the tank will become partly wetted in the former case, or the bottom of the tank will become partly uncovered in the latter. 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. Of course, the magnitudes of these errors for a given array of probes 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.

Therefore, in order to minimize gaging errors or to minimize the number of probes required to achieve particular specified accuracies, the airframe manufacturer must exercise discretion in the establishment of his aircraft attitude requirements. In wing tanks, the requirement for performance under roll conditions should be scrutinized with utmost care.

4.2 Error-Causes Which are Jointly the Responsibility of the Airframe and Gaging System Manufacturers:

a. Tank-Unit Quantity 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 gaging 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) Determine 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. Normally, these cross sections are characterized by some extreme property (i.e., the largest cross section, or the one where horizontal walls become oblique, etc.).

4.2 Continued:

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

5) Locate the probes: After the number of probes is determined (the larger of the numbers necessary to keep top- or bottom-errors below the given limit), their location at the top and bottom cross sections (i.e., 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 based upon the above steps, automatic computer determination of the necessary characteristics and of the resultant errors is practical. Furthermore, it is possible to have the automatic computer derive the errors resulting from the probes being moved incrementally from their tentative locations. The results of such communications are then analyzed, and final "optimum" probe locations are selected.

b. Installation Considerations: There is probably no class of equipment whose performance can be degraded more drastically by improper installation than capacitance-type fuel quantity gaging systems. Recognizing this, it is up to the gaging system manufacturer and airframe manufacturer to collaborate effectively in this area to insure accurate, trouble-free performance of the gaging equipment. In an actual installation the superimposed effects of humidity, fuel contamination, temperature, altitude, vibration and shock, fuel sloshing, fuel characteristic variations, external sub-system usage, etc., all act simultaneously and adversely upon the gaging system. Often, many of these influences are 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 gaging 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 gaging system during actual service use.

1) Single-Point Ground: The benefits of single point grounding implemented are known to greatly outweigh its costs. 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 (115 - volt, 400Hz) power return, 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 fashion.

By adopting this approach, all of the signal currents are confined within the gaging 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.

Insofar as coupling of spurious signals (electrostatically and by electromagnetic induction) into the gaging system's external wiring is concerned, the use of single-point grounding along with reasonable separation (2 to 3 in. minimum) between gaging equipment leads, and external current-carrying conductors is sufficient to insure trouble-free performance.

4.3 Error-Causes Which are Mainly the Gaging Equipment Manufacturer's Responsibility:

a. Generation of Height-Volume data: The gaging 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 desire to furnish the height-volume data directly to the gaging system manufacturer, by means of in-house computer studies of the tank geometry.

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 straight-line segments. The errors induced by such approximations can be made quite small 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 limited in nature (i.e., when the sections are given at relatively largely spaced intervals) the tank geometry must be further approximated by straight-line segments between the various sections. This can potentially lead to additional errors.

Frequently, due to schedule requirements, information given the gaging 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, or upon the scope of the changes, or upon economic considerations, the gaging system vendor will elect to either resubmit the new information for computer analysis (in which case no additional errors beyond those already described will result) or to adjust 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 gage designers are well-equipped to handle situations of this kind, and can operate on the existing data with minimum accuracy compromise.

b. Tank-Unit Characterization: When the tank-unit locations are established, and the "system constant" (usually given in units of picofarads/gallon) is determined, another specially designed computer program is 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 gage 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.

In this manner, by sequential exchange of information between the gage designer and the automatic computer, optimum characterization of the tank-units in their selected locations is attained.

c. Component Design:

1) Tank Units: It is generally recognized 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. Insofar 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, and the measurement of their electrical capacitance is used to determine the quantity of fuel remaining. Furthermore, the inner element is constructed so as to have 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. There are several important factors which affect the capacitance-per-unit-length, and thus the accuracy of the tank-unit. Among these are the following:

4.3 Continued:

a) 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. With respect to the outer tube ID standard mill tolerances are on the order of $\pm$ 0.004 in. ($\pm$ 0.10 mm). This is frequently suitable for tank-unit designs; however, where closer tolerances are required, secondary operations are performed to reduce these tolerances to acceptable levels. Considering the OD of the inner element, and remembering also that the OD is varied to accomplish the necessary characterization, various methods are used by the different gaging manufacturers to produce inner tubes. The most predominant method of manufacture is to use spun tubes. This method produces elements having higher structural strength, well controlled wall thicknesses, and typical OD tolerances of $\pm$ 0.002 to 0.003 in. ($\pm$ 0.05 to 0.76 mm). Where improved accuracy is needed, spun tubing can be obtained, at additional cost, with $\pm$ 0.001 in. ($\pm$ 0.025 mm) OD tolerance.

b) Transitions - Another factor influencing tank-unit accuracy is the precision with which inner tube OD transitions take place, and the linear distance over which these transitions occur. Once again, properly executed spun tubing can be made to yield satisfactory performance in this area.

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

d) Stray Capacitance - Stray 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. Stray capacitance of itself does not detract from gaging accuracy, since its effects are adjusted out of the measuring system by means of the indicator's empty adjustment. However, variations of stray capacitance (principally as functions of temperature, and entrapped moisture in these paths) can adversely affect accuracy. Thus, good design practice dictates the minimization of stray 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.

e) "Reference" Capacitors - For gaging systems requiring improved accuracy, it is customary to furnish reference capacitors which are normally fully submerged in the fuel, and which sense the fuel's di-electric properties. Since, in a typical tank there are usually several tank-units, 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 diminuition. Thus, it is important when specifying compensated (or reference capacitor) systems, that the tolerance on the capacitance of the reference capacitor be closely controlled.

2) Indicators: Indicators are typically 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.

4.3 Continued:

2) Indicators (Cont'd:

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 its 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 satisfactorily linear potentiometer.

3) Several new methods of improving gaging characteristics have been developed and are available where their use is warranted. No lengthy discussion shall be attempted here, but these methods and their advantages will be listed.

METHOD	ADVANTAGE
Full height compensated probes	Better average capacitance index
High frequency exitation	Reduce effects of resistive currents (Contamination)
Signal conditioners adjacent to tanks	Eliminates long runs of Co-ax cable

4.4 Error-Causes for Which Neither the Airframe nor the Gaging System Manufacturer is Responsible:

a. Fuel Characteristics: The single most significant factor concerning capacitance-type gaging system accuracy, over which neither the airframe or the gaging manufacturer has control, is the fuel itself. In virtually all capacitance-type gaging 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.

All other factors being kept constant, the accuracy of a given gaging 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 gage (i.e., one in which a fully submerged reference tank-unit is employed) this error can be reduced to approximately ± 1.5% of indication.

b. Fuel Contamination: In addition to the old problems of entrained and dissolved water in aircraft fuels, newer problems have developed due to the presence of bacterial growth in these liquids, and also due to high fuel transfer rates contingent to modern aircraft turn-around 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 antistatic additives in the fuels. Besides these contaminants, jet fuels are excellent media for the growth of fungal organisms. Thus the gaging 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 or its density by amounts which would produce measureable 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, gaging errors can be introduced by virtue of their potentially adverse influence on indicator sensitivity (i.e., the production of indicator sluggishness).

4.4 Continued:

b. Fuel Contamination: (Continued)

With respect to fuel conductivity, well-designed compensated gages can tolerate conductivities in the region of 300 picomho/meter without accuracy degradation. Uncompensated gages are less tolerant to this factor, and approximately 200 picomho/meter is a reasonable upper limit on conductivity for this type of gaging system.

Considering insulation resistance degradation, well-designed tank-units employ long leakage paths between the sensing elements to discourage contamination build-up. 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-cause influencing the accuracy of airborne capacitance-type fuel quantity gages. Even from this simplified treatment, it can be seen that appreciable skills and experience are required of the gage 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 gage manufacturer enter the picture.

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 gage accuracy is the ability to describe the fuel's state insofar as tank geometry and attitude is concerned. Since this is the foundation upon which the gage's accuracy structure rests, it would be valuable to consider a possible approach to optimizing this description, and thereby to permit the reduction of errors introduced in this step of gage design. The following procedure, if properly implemented, would permit such optimization. It would be recognized however, that improvements of this type are usually made at some kind of sacrifice. In the present case, the sacrifice is in terms of schedule time, and in the added amount of coordination and liaison necessary between the airframe and gaging 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 and aircraft attitude information are furnished to the gaging 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. Having such information available during early phases of aircraft design, rather than after structure, fuel system hardware, etc., become well established, is beneficial in that it increases the likelihood of the airframe manufacturer being able to choose optimum locations for these units. It is obvious that acquiring such information at an early phase greatly assists the work of the airframe manufacturer's structure and weights personnel.

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

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.