DOUGLAS PAPER NO 3180

6/65

SATURN S-IV CRYOGENIC WEIGH SYSTEM

PART I: PROPELLANT UTILIZATION

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TO BE PRESENTED AT THE
IEEE 1965 AEROSPACE CONFERENCE
FEATURING
FLIGHT VEHICLE ELECTRICAL/ELECTRONIC SYSTEMS
HOUSTON, TEXAS
JUNE 20-24, 1965

DOUGLAS MISSILE & SPACE SYSTEMS DIVISION

SPACE SYSTEMS CENTER — HUNTINGTON BEACH, CALIFORNIA

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PART I: PROPELLANT UTILIZATION

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ABSTRACT

In order to achieve maximum vehicle efficiency, it is essential that the vehicle propellants be loaded to desired values and that these propellants approach simultaneous depletion at the end of powered flight. To accomplish precise loading and assure minimum residuals, a highly accurate and repeatable, vehicle located, propellant management (PM) or propellant utilization (PU) system must be used. As the ability to load propellants to predetermined values depends directly on the ability of the system to accurately sense the propellant masses, it is essential that the system be calibrated with respect to propellant mass under conditions resembling those to be experienced during final loading and powered flight. The use of a cryogenic weigh system will reduce the unknown factors in capacitance sensor element shaping, tank geometry, and propellant properties to a degree which will permit the determination of propellant masses to within 0.25%.

This paper describes the basic purpose for a cryogenic weigh system in connection with the calibration of the Saturn Propellant Utilization System used on the S-IV stage.

INTRODUCTION

The Saturn S-IV stage, which is manufactured by the Douglas Aircraft Company, Inc., is the second stage of the C-1 configuration of the Saturn vehicle. It is powered by six Pratt and Whitney RL10-A3 rocket engines which develop a total thrust of approximately 90,000 pounds. The propellants used in these engines are liquid oxygen and liquid hydrogen. The total propellant load is approximately 100,000 pounds and is burned in an approximate engine mixture ratio of five pounds of oxygen to one pound of hydrogen (5:1).

The Saturn C-1 launch vehicle is designed to be capable of orbiting a payload of more than 20,000 pounds. However, for every pound of unexpended propellant in the S-IV stage, there is a resultant loss of about 1.1 pounds of payload. A propellant residual of 1000 pounds in the S-IV stage would result in the loss of more than 5% of the vehicle's payload capability.

It is evident that to obtain maximum overall vehicle efficiency, it is essential that the vehicle propellants be accurately loaded to predetermined values and that the propellants approach simultaneous depletion at the end of S-IV powered flight. To accomplish this precise loading and to assure maximum propellant utilization, a highly accurate and repeatable vehicle-located propellant management (PM) or propellant utilization (PU) system is required. This system must be capable, during loading, of providing the ground support equipment with accurate indication of the on-board propellant masses. During flight, the system must continually monitor the amount of remaining propellants and accordingly regulate the ratio of propellants consumed by the engines (engine mixture ratio) to obtain and maintain a 5 to 1 usable mass ratio.

SYSTEM DESIGN

REQUIREMENTS

The basic design requirements for the Saturn S-IV stage propellant utilization system were as follows:

1. Control the loading of propellants by providing the ground support equipment with an indication of mass to within ± 0.5% (with a design goal of ± 0.25%).
2. Limit propellant residuals to 500 pounds by controlling the engine mixture ratio between the limits of 4.4:1 and 5.6:1.
3. Provide in-flight propellant mass history for telemetry to an accuracy of ± 0.5% of total propellant mass.
4. Provide signals from the PU system for tank step pressure and engine depletion logic.

SENSOR SELECTION

One of the most important decisions to be made in the design of a propellant utilization system is ~~that concerned with~~ the selection of the sensing device used to measure the propellants in the tanks. While the electronics required to process the information obtained from the sensing device

S-IV PROPELLANT UTILIZATION ELECTRONICS ASSY

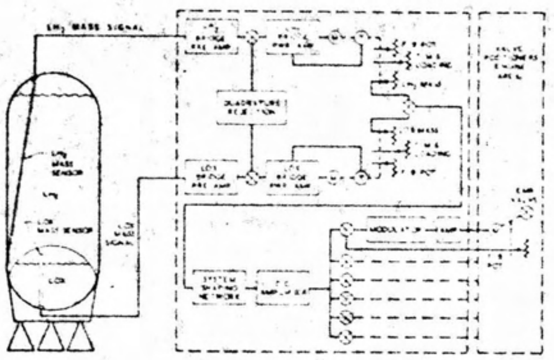

FIGURE 1

is fairly complex, it is reasonably straightforward, and the majority of design concerns the handling of low level analog signals. However, the controlling portion of the system can be no more accurate than the information supplied to it by the propellant sensors.

An extensive investigation was initiated by the Douglas Aircraft Company which included consideration of more than 30 different possible methods in which the quantity of a cryogenic propellant could be measured. This list was reduced to six systems which required further study. These systems included: 1) point level sensors, 2) acoustic wave guide, 3) hot wire, 4) sonar, 5) differential pressure, and 6) capacitance. The first four systems were discarded due to the inability to maintain high accuracy levels both during propellant loading and depletion. The two systems selected for further study were differential pressure and capacitance.

The differential pressure system (difference in pressure between tank top and bottom due to hydrostatic head) had seen considerable use, both by Douglas and others, in ballistic missile PU systems. However, the S-IV stage required a system sensitivity with an order of magnitude higher than that required in a ballistic missile. This is due to the very low density of liquid hydrogen and the low vehicle acceleration at burnout. The capacitance sensor was considered to be the best method for determining cryogenic propellant mass on the S-IV stage.

There has been a relatively long history of experimentation with this type of device. Some of the earlier results were not very satisfactory and alienated a large portion of interested engineers. However, additional study has considerably improved the state of the art of the capacitance sensing device. Studies have shown that capacitance sensors could be built to have the precision and accuracy of the best differential pressure transducers available. The capacitance sensor has an additional advantage over the differential pressure transducer of having fewer precision parts and no hysteresis effects. Of course, other factors such as the ability to shape the sensor to give an output which is linear with mass and the associated simplification of the electronics portion of the PU system also have had some influence on the decision to select a capacitance system.

SENSOR DESIGN

The mass sensors designed for the Saturn S-IV stage PU system are co-axial capacitors and are located in the propellant tanks as shown in figure 1. When the tank is empty, the capacitance of the sensor is proportional to the dielectric constant of the gas between the plates (E_G). As the tank is filled and the propellant is allowed to flow between the plates of the capacitor, the capacitance of the unit will increase due to the gas between the capacitor plates being displaced by a liquid with a higher dielectric constant (E_L). If the capacitor were of uniform cross-section, its capacitance increase would be proportional to both the immersed length and the liquid dielectric constant less the gas dielectric constant, $E_L - E_G$. Since the dielectric constant of all gasses is very nearly 1 (unity), this last proportionality constant can be regarded as $E_L - 1$.

If the liquid propellant dielectric constant (E_L) is known, the use of a capacitance sensor will give an indication of the liquid level in the tank. Since the capacitance of a sensor varies inversely with the distance between the electrodes, the next logical step is to create a sensor which will give a direct volume readout in a tank of non-uniform cross-section. This can be accomplished by making the spacing between the electrodes at any level a function of the tank cross-section at that level (see figure 2). If $E_L - 1$ of the liquid being measured is proportional to the propellant density, as is the case with LOX and LH_2, the system will then give a direct mass readout.

SHAPED CAPACITANCE SENSOR

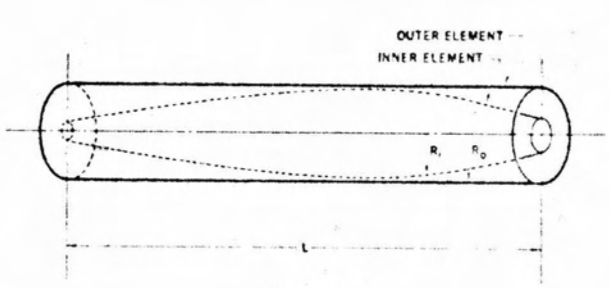

FIGURE 2

CLAUSIUS-MOSOTTI EQUATION

The dielectric constants of liquid hydrogen and liquid oxygen are closely described by the Clausius-Mosotti equation. This equation is defined as:

$$\frac{E_L - 1}{E_L + 2} = K\rho$$

Where: E_L = dielectric constant of the liquid

ρ = density of the liquid

K = constant dependent on the polarizability of the particular liquid

If E_L is near 1.0, then $E_L - 1$ is nearly linear with ρ. Since the dielectric constant of liquid oxygen is about 1.48 and that of liquid hydrogen is about 1.22, this condition is then satisfactorily fulfilled.

COMPENSATION FOR TEMPERATURE CHANGES

In any practical capacitive gauging system there are second order error sources that must be taken into consideration. One of these arises from the extreme temperature ranges over which the sensors must operate and the thermal expansion characteristics of the material used in the construction of the sensors. In any system in which the sensors operate in a varying temperature environment, the resulting expansion would cause a capacitance change which must be taken into account. The capacitance of a coaxial type capacitor is given by the equation:

$$C = \frac{L}{\ln(R_o/R_i)} AE$$

Where: L = length of the capacitor

R_o = radius of outer element

R_i = radius of inner element

E = dielectric constant of media between electrodes

A = constant

For a capacitor with both electrodes of the same material and uniform cross-section (no shaping of the inner element), $\ln(R_o/R_i)$ will not change as the capacitor expands or contracts, so the capacitance change will be proportional only to the change in length. By making the capacitor

CAPACITANCE CHANGE WITH GAS TEMPERATURE

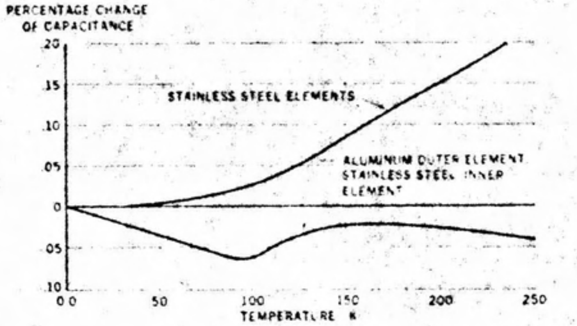

FIGURE 3

electrodes out of materials with different expansivities, it is possible to make $\ln(R_o/R_i)$ vary nearly proportionally to L over the range of temperatures expected and therefore have a unit whose capacitance is very nearly constant over a wide temperature range (see figure 3).

PRELIMINARY SENSOR DESIGN

Using a sensor which has the inner element shaped to provide a mass readout presents additional problems which must be taken into account during the selection of sensor element material. During the actual sensor design, a computer program was prepared to aid in the design of a sensor which had a sensor capacitance vs. liquid propellant height function which matched the propellant tank volume vs. tank height function. For simplicity, it was assumed that the gas above the liquid was at a fixed temperature and that the sensor electrodes were at the temperature of the fluid medium in which they were immersed. This program was then used to design a number of sensors with various combinations of electrode materials and different ratios of the inner and outer electrode diameters. The response of each of these designs, when immersed in gas at various temperatures and pressures, was determined with the aid of the computer program. Based on this information, the material combination and diameter ratio R_o/R_i which gave the smallest capacitance change over the range of temperatures and pressures expected in the tank at the end of flight was selected for final sensor design. The optimum material combination was an aluminum outer element and a stainless steel inner electrode for both the hydrogen and oxygen. The diameter ratios, however, for the LOX and LH2 mass sensors were different.

FINAL SENSOR DESIGN

Having determined all of the required parameters (diameter ratios and types of material) a more refined computer program was developed for the design of the actual vehicle mass sensors. This program was similar to the first one with provisions for inclusion of the conditions expected during loading and flight. The more critical predicted vehicle parameters utilized were gas, liquid, and electrode temperatures as a function of liquid propellant level and tank volume vs. tank height curves. Of course, many physical constants and relationships were required in addition to the above parameters. The program then enabled the computer to vary the shape of the inner electrode in order to bring the sensor capacitance versus liquid propellant level curve into correspondence with the tank mass versus liquid level curve under the given vehicle environmental conditions. The program was written to print out the final answer as a normalized sensor capacitance vs. sensor height curve which assumed the electrodes to be in air or nitrogen of ambient temperature and pressure. This was done to simplify fabrication of the sensors.

SENSOR DESIGN SUMMARY

In the discussions above, second order error sources and temperature changes were described and taken into account during the detailed design of the mass sensor. It was shown that these errors can be minimized through the proper design and shaping of the sensor. Normalization of the capacitance portion of the sensor capacitance vs. liquid level height curve further reduces these errors by eliminating all errors due to constant error sources. This normalization, while allowing the sensors to be built to any convenient base capacitance, reduces all errors in design to sensor non-linearities. This, of course, assumes that an accurate system will be available to calibrate the full and empty points of the sensor with respect to propellant mass vs. sensor capacitance.

SYSTEM CALIBRATION

To maintain the high accuracy required for the overall PU system performance, a full calibration, empty calibration, and sensor linearity test must be performed on each vehicle and tank combination to eliminate uncertainties due to sensor shaping, tank geometry, and tank environment.

FULL CALIBRATION

Calibration of the capacitance sensor while the tank is full is basically straightforward. When the vehicle tank is filled with propellant, the capacitance output from the sensor is recorded (using the propellant utilization electronics assembly). At each point the capacitance output is recorded and the mass of propellant in that particular tank is determined and compared with the sensor capacitance value. This is repeated for various values of mass and the results tabulated and plotted to form a sensor capacitance vs. mass curve for the full region of the sensor.

Because the sensors are temperature compensated, and the temperature of the liquid propellants will vary only slightly, very little change in capacitance can be expected due to variation in the propellant temperatures. In addition, when the propellants are near the sensors' full points, only a small portion of the sensor's inner element is exposed to gas; thus, gas pressure and gas temperature have little effect on the full point calibration accuracy.

The only remaining factors that must be considered for sensor full calibration are those of sensor shaping accuracy and tank geometry. Since each of these factors is due primarily to manufacturing tolerances, each combination of tank and sensor has a mass vs. capacitance relationship which is unique. The largest errors encountered in predicting a tank mass vs. sensor capacitance calibration without actual propellant loading are those due to uncertainties in tank geometry. The tank volume versus tank height relationship for a particular vehicle is known to a 3 sigma accuracy of 1.1% and 1.5% at the full point for LOX and LH_2 respectively. This, plus the inaccuracies associated with predicting sensor capacitance for given heights of liquid propellant, prevents the theoretical determination of propellant mass vs. sensor capacitance to accuracies better than 2.5 percent. Since this accuracy is unacceptable, a cryogenic loading (fill and drain) of each tank is required. Such a loading reduces the uncertainty in the determination of capacitance at the full point to less than 0.1 percent, which is the resolution and repeatability of the sensor, electronics, and recording equipment. The one remaining (and most difficult) problem then is that concerned with the accurate determination of the propellant mass in the tank.

FULL MASS DETERMINATION - DENSITY VOLUME METHOD

One means by which the propellant masses can be determined is the density-volume (ρV) method. The temperatures and pressures of the propellant are measured at various liquid levels to determine the density of the propellant. The propellant volumes are then derived from point level sensor data and cryogenic volume versus height curves obtained from prior water calibrations of the tank in question. The mass for any liquid level is then the product of these two values. If this method is used, there are errors in the resulting mass which stem from volumetric calibration inaccuracies and the inability to accurately determine liquid level height, liquid temperature and pressure. The inaccuracy (3σ) of mass obtained by such a method is approximately 1.7 percent of full load for both LOX and LH_2 (see figures 4 and 5) and is predicated on extensive and highly accurate tank instrumentation. Using the instrumentation presently available on the S-IV vehicles, this inaccuracy would be considerably larger. This inaccuracy then yields an unacceptable mass versus capacitance calibration curve error band of at least 1.7 percent for each propellant.

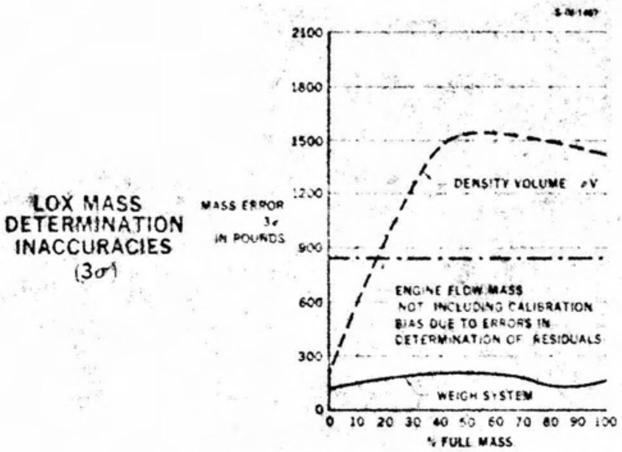

FIGURE 4

FULL MASS DETERMINATION - FLOW MASS METHOD

A more precise method for determining the propellant mass is by the evaluation of engine performance during an actual static vehicle firing. Since engine performance has to be determined for static firings and flight tests, the propellant masses can be determined as a by-product for use in future propellant mass vs. sensor capacitance calibration. Propellant consumption from the start of firing to engine cutoff is first determined from engine performance analyses. This value is then added to the residual mass to obtain the initial total propellant load and mass history. The accuracy of this method of determining mass improves as the firing duration increases and approaches complete propellant depletion. Assuming perfect accuracy in the determination of residuals, this method is capable of determining actual mass to within 1% (see figures 4 and 5). Any errors in the determination of the propellant residuals must, of course, be added to this inaccuracy. The major problem associated with this method is that the calibration cannot be performed until after a static firing. In addition, the residuals (upon which the accuracy of the flow mass method depends) cannot usually be determined from engine performance. Therefore, some other method must be employed to calibrate the PU system prior to the static firing. Without such a calibration, accurate loading would not be possible, and optimum vehicle performance, analysis, and flight predictions would be impaired. Without an accurate calibration prior to the static test, the residual propellants will not be precisely known.

FULL MASS DETERMINATION - WEIGH SYSTEM METHOD

Both methods described above, the density-volume method and the flow mass method, are indirect mass determination processes. The most direct way to determine propellant mass would be to use a weigh system. The weigh system would have to have the capability of weighing masses in the order of 125,000 pounds. A weigh system designed to meet the requirements of 0.5% loading accuracy would have to be highly sensitive, have high resolution and repeatability, and be operationally dependable. Studies performed by DAC indicate that a weigh system could be designed to permit a determination of propellant mass to within 0.25% of fully loaded mass (see figures 4 and 5). This, coupled with the 0.1% inaccuracy in the determination of the sensor capacitance, allows the particular sensor-tank combination to be calibrated to within 0.3%, which is well within the contractual design requirements.

EMPTY CALIBRATION

As noted, the gas temperatures, pressures, and composition have little effect on the full calibration since only a small portion of the inner element is exposed to the gas. As the propellants deplete, however, more and more of the sensor is exposed to gas, until, at empty, the effect of the gas is maximum. Since the gas is not considered to be usable propellant, the sensor must be calibrated to see only the usable liquid propellant and to ignore the mass of gas in the tank. The gas used to pressurize both the liquid oxygen and liquid hydrogen tanks of the Saturn S-IV stage is helium which has a dielectric constant somewhat different from gaseous oxygen and gaseous hydrogen. A change in the proportion of helium present in the tanks at empty can thus change the dielectric constant of the gas between the sensor elements and therefore affect, to a degree, the value of the empty capacitance. In addition, since the dielectric constant of the gasses are, in fact, slightly different than unity, it is apparent that the pressure of the gas can also affect the empty capacitance.

Therefore it is apparent that, as the sensor approaches empty capacitance (capacitance when all the propellant has been expended), the effect of the residual gas pressure, temperature, and

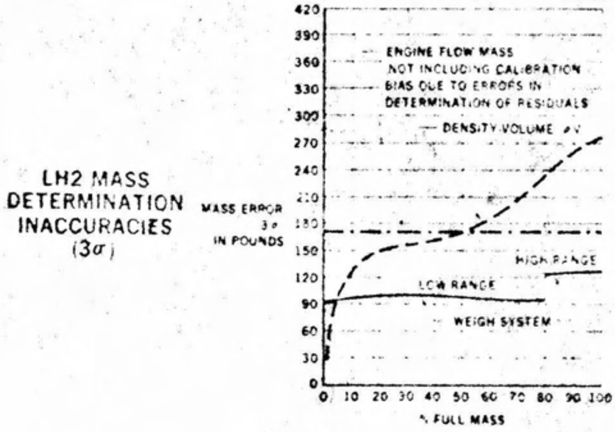

FIGURE 5

composition increases. This empty capacitance is different than the capacitance which is experienced with the sensor in room temperature air at ambient pressures. This is due to the extremely large temperature difference and resultant difference in dielectric constants of the gases. To precisely control propellants for simultaneous depletion, the empty capacitance must be accurately known.

EMPTY CALIBRATION - PROPELLANT DEPLETION METHOD

It is desirable, if possible, to actually measure the capacitance of the sensor at the exact time at which the usable propellant passes below the bottom of the sensor's active region with tank conditions closely resembling those to be experienced during flight. At the moment the liquid passes below the active portion of the sensor, the capacitance from the sensor will level out to a value which is the same as the empty capacitance. This empty value will remain, unchanging, until the tank conditions change (i.e., the sensor electrodes warm up, the gas pressure drops, or the gas composition changes). This capacitance is then equivalent to the mass below the bottom of the inner element. The accuracy of such a method is limited only by the repeatability of the electronics portion of the PU system and the proximity of the tank conditions to those of flight. Since the PU system is repeatable to within .05%, the accuracy of the empty point calibration depends almost entirely on the ability to duplicate flight conditions in the propellant tanks.

Measurement of the sensor capacitance at the exact time at which the propellant passes below the sensitive portion of the sensor under flight conditions, although obviously desirable, may not be possible due to velocity cutoff requirements. The only time this measurement could be successfully accomplished is during a static firing, and during these firings the engines on the S-IV stage, due to engine specifications, are not allowed to run to depletion.

EMPTY CALIBRATION - WEIGH SYSTEM METHOD

Another method of obtaining a sensor empty point calibration, however, is by measuring the sensor capacitance and corresponding propellant masses at several points above (but near) the empty point and extrapolating to zero mass. This again, of course, requires an accurate method for determining mass. Weigh system accuracies in this region have been theoretically determined to be in the order of 120 pounds for LOX and 90 pounds for LH_2 (see figures 4 and 5). There is, however, a problem associated with this method which arises from the inability to duplicate exact flight conditions in the tanks during the weigh tests. The propellants are drained during the weigh tests at rates much slower than those encountered in flight. The net effect is that of warming up the liquid, gasses, and sensor elements to temperatures considerably higher than those encountered during flight. Propellant cooling is accomplished by venting and repressurizing the tanks. This process, however, changes the gas composition and this change, when coupled with the temperature variations, causes an error to be introduced into the mass versus capacitance value. This error is negligable for full loads, but increases as the propellants deplete (ullage volume increases) until, at empty, the error is maximum. Past experience with the S-IV vehicles has indicated that during cold flows employing the weigh system, the LOX empty capacitance increases by approximately 0.1% and the LH_2 empty capacitance increases by about 1.1%. Although gas samples, gas and liquid temperatures, pressures, etc. are recorded during weigh tests, it is difficult to obtain sufficient data to completely eliminate this error. The weigh system is therefore, in itself, not capable of providing empty calibrations to an accuracy greater than 0.2% for LOX and 1.1% for LH_2 (see figures 6 and 7).

OTHER EMPTY CALIBRATION METHODS

Lacking the above capabilities of direct measurement (weigh system), it is possible to determine the capacitance versus mass curve by theoretical conversion of the sensor capacitance obtained in a known, closely controlled environment to the capacitance to be expected in the environment predicted for flight. The problem with this method is that of accuracy. The calibration can be no more accurate than the data used in obtaining it. Although tank geometry, liquid densities, and liquid propellant dielectric constants do not affect the empty capacitance, other parameters required for this type of calibration (electrode temperatures, gas pressures and composition, etc.), together with the inaccuracies usually associated with the measured data and predicted values, would yield an unacceptable inaccuracy of over 1%.

Experience with many previous vehicles and the compilation of the empirical data associated with these vehicles, however, should improve the accuracy of the empty capacitance predictions to within 0.1%. Sensor manufacturing processes can be controlled to a degree which allowed all LOX sensors to have the same capacitance ± 1 picofarad when immersed in air at room temperature and one atmosphere pressure. The same is true for the LH_2 sensors. The close similarity between sensors plus the accumulation of past test results then allows predictions to be made as to the capacitance change caused by a change in environment.

Empirical evidence has shown that a change in the environment from air at ambient conditions to say, gaseous hydrogen at 45 psia and cryogenic

LOX SENSOR CALIBRATION
INACCURACIES 3σ USING WEIGH SYSTEM

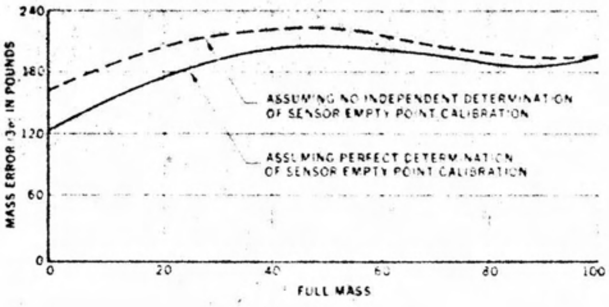

FIGURE 6

temperatures (empty conditions) will cause all S-IV LH2 mass sensors to decrease their capacitance by approximately 0.33 picofarads. Thus, if the capacitance of the sensor is known in air of room ambient conditions, the empty capacitance can be accurately predicted. It must be pointed out, however, that this method is possible only after the results of many repeated tests are available. Also, any change in the actual flight environment from that under which the empirical data were obtained will introduce inaccuracies in the predictions obtained by the use of this method. Accuracies in the order of 0.1 % have been obtained for S-IV vehicles by the use of this method.

SENSOR LINEARITY

The various methods of calibrating the full and empty points have been discussed, as were the various accuracies associated with each method. Assuming, however, that the full and empty point calibrations were perfect, and that the sensor was a perfect sensor, no additional calibration would be required. A straight line passing through the full and empty points would define the mass vs. capacitance relationship for any propellant mass. The sensors, however, are not perfect due mainly to sensor and tank manufacturing tolerances. These tolerances result in non-linearities in the mass versus sensor capacitance relationship. As a result, a calibration must be performed to define this relationship for all propellant mass values. This calibration is subsequently used for the determination of the mass of propellant remaining in the tanks at any time during flight.

The calibration procedure is similar to that used to calibrate the full point. At a particular point, the propellant mass is determined. At the same time the capacitance of the mass sensor is recorded and compared with the mass. This procedure is repeated for various values of propellant mass ranging from full to empty. As the propellant mass depletes, however, the error in capacitance increases due to abnormal tank conditions (as described above). Since the weigh system is not capable, in itself, of providing accurate calibrations in the empty region, the empty point calibration must be determined by some other method. This independently derived empty calibration is then used, together with gas sample temperature and pressure data, to adjust and correct the capacitance values obtained during the weigh test. The weigh data and corrected capacitance values are then utilized to provide an accurate calibration for the complete range of masses including those near empty (see figures 6 and 7). During flight, this calibration and the sensor output are used to provide a propellant mass history.

CONCLUSIONS

The use of a propellant utilization system on the Saturn S-IV stage for loading propellant accurately, providing in-flight propellant mass information, and assuring minimum residuals, assures that increased vehicle efficiency will be obtained on each mission. The accuracy of a capacitance PU system is determined by the design of the propellant mass sensors and the system calibration. Of all the methods available to determine full calibration and sensor linearity, only one method, the cryogenic weigh system, will provide the accuracy required to meet the current overall system design objectives.

ACKNOWLEDGEMENTS

The work presented herein was accomplished by the Missile and Space Systems Division of the Douglas Aircraft Company, Inc., under the Saturn Program sponsored by NASA Marshall Space Flight Center.

The authors would like to extend their thanks to the following people, whose help has been much appreciated: T. Simko, G. A. Matsumoto, G. M. Elgal and T. Kamiya.

LH2 SENSOR CALIBRATION
INACCURACIES 3σ USING WEIGH SYSTEM

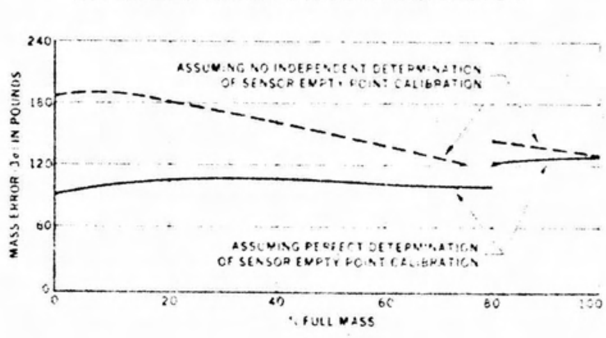

FIGURE 7

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