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Design of the Saturn S-IV Stage Propellant Utilization System

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Introduction

The SIV vehicle, which is presently being designed and manufactured by Douglas Aircraft, is the second stage of the initial, or C-I, configuration of the Saturn booster. It is powered by six 15,000 pound Pratt and Whitney rocket engines which use liquid hydrogen and liquid oxygen as propellants. The total propellant load is 100,000 pounds divided in the ratio of 5 pounds of oxygen to 1 of hydrogen. With this load the nominal burning time is 467 seconds. The C-I launch vehicle is designed to be capable of orbiting a satellite weighing more than 20,000 pounds.

If this vehicle is to reach its maximum capability it must be able to burn almost all of the propellant which has been loaded. This essentially means that when one propellant has been depleted the amount of the other propellant remaining, which is an unusable residual must be small. A typical open-loop engine mixture ratio history is shown in Figure 6. This curve shows the ratio of the propellants being burned (lbs. of oxygen per lb. of hydrogen) as a function of flight time with the assumption that all the parameters that influence this ratio are at their predicted values. Also shown is a band over which this mixture ratio can vary if these influencing parameters vary to their limits. It will be noted that during most of the flight the nominal mixture ratio is near the engine manufacturers design value of 5:1. The slow increase in ratio during flight is due primarily to the gradual warming up of the hydrogen, thus reducing both its density and the mass being pumped into the engine.

Previous propellant utilization practice, on kerosene fueled ballistic missiles, has been to attempt to determine this nominal curve by analysis and monitoring of numerous test flights. The operational vehicles would then be loaded so that if this nominal curve were followed simultaneous depletion would result. The possible open-loop errors were small enough to be accepted.

There are several reasons why this method would not be satisfactory on the SIV vehicle. First, because of the cost of the vehicle the number of test flights will be limited to a number insufficient to predict an accurate nominal curve. Second, as a result of the use of hydrogen as a fuel the open-loop mixture ratio band is significantly wider. In fact, these engine mixture ratio errors, combined with a reasonable loading error, could result in as much as 3,000 lbs. residual propellant.

On the SIV there is a loss of about 1.1 pound of payload for each pound of unexpanded propellant. Therefore, a 3,000 lb. propellant residual would result in a loss of 3,300 lbs. of payload. For this reason a requirement for closed-loop control of propellant utilization was established. For this purpose a system would be installed in the vehicle which would continuously sense the amount of each propellant remaining in the tanks and regulate the engine mixture ratio to insure near-simultaneous depletion of both propellants.

System Requirements

The requirements and functions of the Propellant Utilization (PU) system on the Saturn SIV vehicle are as follows:

1. To provide sufficient flow control to deplete both propellants to 500 pounds or less while maintaining the Engine Mixture Ratio (EMR) to 5 pounds Lox per pound LH_2 ± 10% ("Lox" and "LH_2" are terms used repeatedly in this paper for Liquid Oxygen and Liquid Hydrogen)
2. To control the loading of propellants by providing the ground support equipment with an accurate indication of the propellant masses.
3. To provide propellant mass information during flight for telemetry.
4. To provide signals for propellant depletion logic, and for the fuel tank pressurization system.

System Analysis

System Operational Outline

The PU system as shown in Figure 1 consists of capacitance sensors for measuring propellant masses, a summing device for comparing mass signals, a shaping network for periodic disturbance attenuation, and six valve assemblies for changing Lox flow as a function of mass error. Since the sensor measures fluid mass, it can be represented by a gain C. (see Figure 2) It is in one leg of a servo balanced bridge. When unbalanced by a propellant mass change, it is rebalanced by

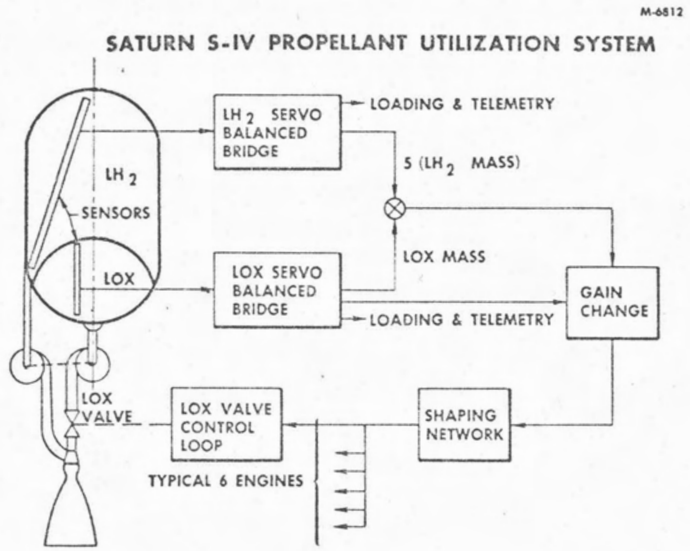


Figure 1

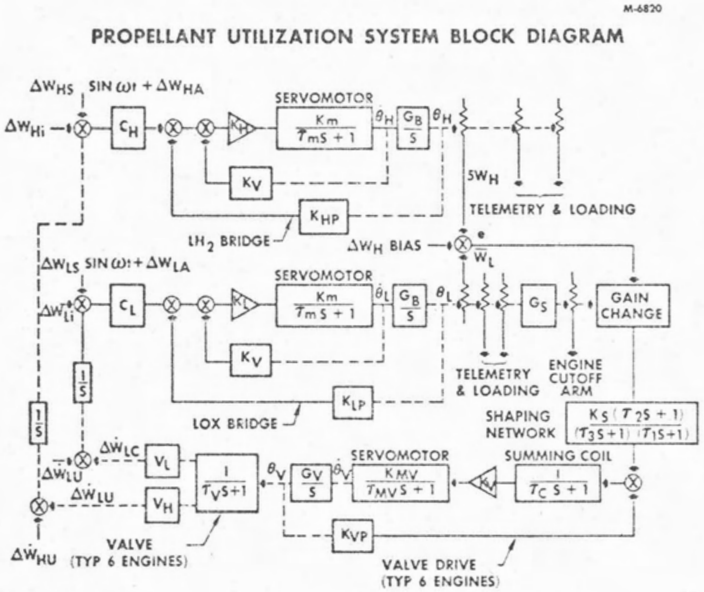


Figure 2

the servomotor and feedback potentiometer. In rebalancing the bridge, the motor shaft also provides mass signals for PU valve actuation, loading, mass telemetry, and switching. The generalized bridge assembly closed loop transfer function is:

$$\theta_C \quad \boxed{\frac{K K_m G_B}{S(\tau_M S + 1 + K_M K_V) + K K_m G_B K_P}} \quad \theta_o$$

Its damped frequency is 42 rad. per sec. with a damping ratio of .7. Velocity feedback was necessary to prevent pot damage from limit cycling. Its effect is shown analytically in Figure 3. Without velocity feedback, limit cycling occurs at a frequency of 6 cps. With sufficient velocity feedback it doesn't occur. A bridge of this type is used with each sensor, and the difference of their output signals is the mass error.

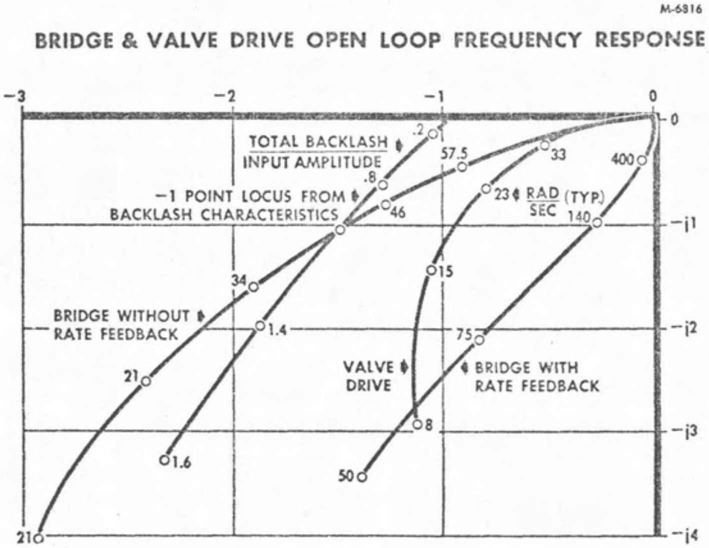


Figure 3

The valve positioning loop for each of the six engines is also described in Figure 2. The closed loop transfer function for this loop is:

$$\theta_c \;\; \boxed{\dfrac{K_{MV} K_V G_V}{S(\tau_c S+1)(\tau_m S+1)+K_{MV} K_V G_V K_P}} \;\; \theta_V$$

Its damped frequency is 25 rad. per sec with a damping ratio of ≈.8. A nyquist stability plot of the valve loop is also shown in Figure 3. It can be seen that limit cycling is no problem in this loop.

The valve lag shown in Figure 2 has a bandpass of 10 cps. Since the engine mixture ratio is defined as Lox flow divided by LH_2 flow. Valve gain can also be expressed in terms of percent EMR change per degree of valve. Total valve travel is mechanically limited to ±60°. Total EMR change for ±60° valve is 4.5 to 5.5 or ±10%.

The shaping network transfer function is also shown in Figure 2. Although primarily designed to attenuate slosh, it also is used to provide desired system performance and stability characteristics. The band pass of this network (.01 rad/sec) is much lower than that of any other element in the major loop.

An open loop frequency response plot for the PU system is given in Figure 4 for normal (.2 #/sec per pound Lox error) and initial (.04 #/sec/#) system steady state gain. (The gain change will be explained later in detail.) In obtaining this

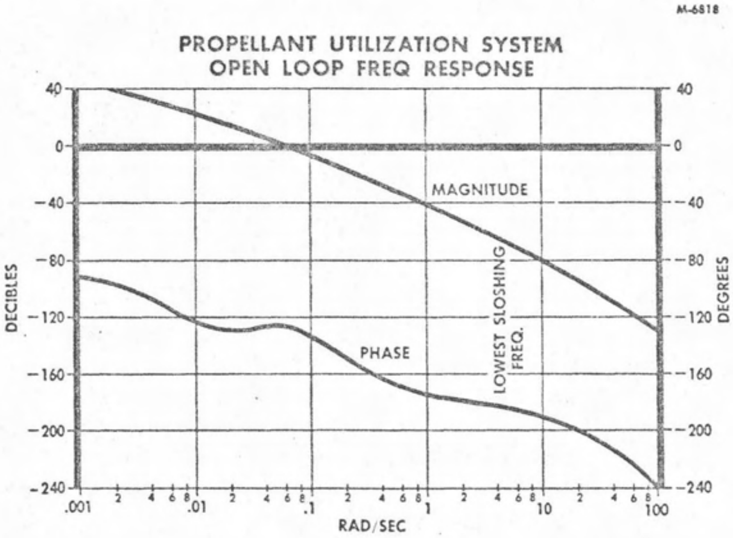


Figure 4

frequency response information, it was found that no measurable change occurred in the area of interest when the bridge loop, valve loop, and valve dynamics were replaced with their respective steady state gain. This conclusion is substantiated by the relative "Root to Origin" distances observed on the Root Locus Plot in Figure 5.

System Flow Equations

As was stated in the previous section, the LH_2 bridge output signal which represents LH_2 mass times the desired tank mixture ratio is subtracted from the Lox bridge output signal. This difference is defined as mass error.

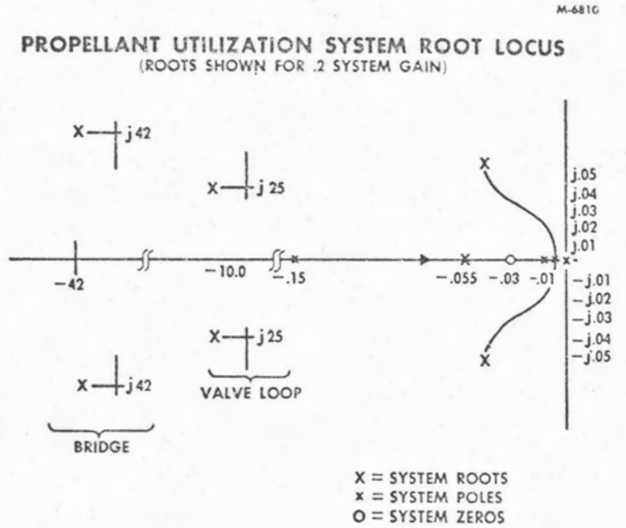


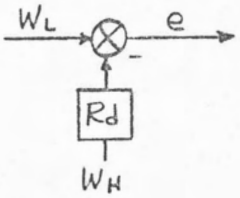
Figure 5

Symbolically, mass error $e = W_L - RdW_H$

where W_L = Lox mass

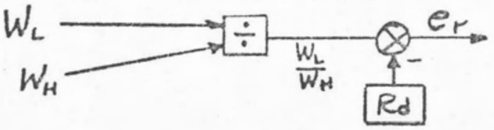
W_H = LH_2 mass

Rd = 5 = desired tank mass ratio



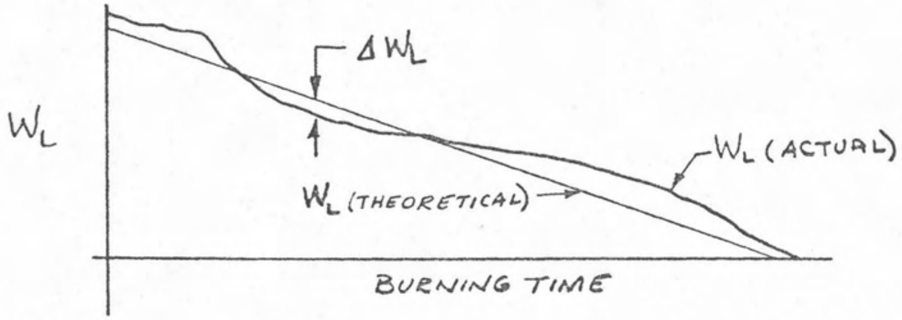
Another method considered for comparing propellant masses is a ratio error signal.

$$\text{Ratio error} \quad e_r = \frac{W_L}{W_H} - Rd = \frac{W_L - RdW_H}{W_H}$$



The gain of this type of system increases to infinity as $W_H \rightarrow 0$. Primarily because of this gain change characteristic, the ratio error system was not used.

The actual propellant weights W_L and W_H can be divided into a theoretical weight plus a weight pertubation.



If $W_L = W_{LT} + \Delta W_L$

and $W_H = W_{HT} + \Delta W_H$

then $e = W_{LT} + \Delta W_L - Rd\,(W_{HT} + \Delta W_H)$

Where W_{LT} and W_{HT} represent the theoretically correct values of propellant mass. W_L and W_H represent mass pertubations due to tolerances and disturbances.

Since $W_{LT} - Rd\, W_{HT} = 0$, $e = \Delta W_L - Rd \Delta W_H$. This equation can be expanded to include those disturbances which make up ΔW_L and ΔW_H.

$$\begin{aligned} e &= \Delta W_{Li} + \Delta W_{LS} \sin \omega t + \Delta W_{LA} + \int \left(\Delta \dot{W}_{LU} - \Delta \dot{W}_{LC} \right) dt \\ &- 5 \left[\Delta W_{Hi} + \Delta W_{HS} \sin \omega t + \Delta W_{HA} + \int \left(\Delta \dot{W}_{HU} - \Delta \dot{W}_{HC} \right) dt \right. \end{aligned}$$

ΔW_{LC} and ΔW_{LU} are flow changes from the propellant utilization flow control valve.

ΔW_{Li} and ΔW_{Hi} are initial loading errors. These errors result from loading inaccuracies, boiloff variations during boost phase, and variations in the amount of engine prestart cooldown propellants used. Since the same capacitance sensors are used for loading and propellant utilization, the loading errors as seen by the PU system will probably be less than the actual loading errors. Thus difference would be in the sensor inaccuracy. A maximum loading error equivalent to 750# Lox was used to study system performance.

$\Delta \dot{W}_{LU}$ and $\Delta \dot{W}_{HU}$ represent uncontrolled flow rate errors. These errors are caused principally by propellant temperature and tank ullage pressure variations. The total effect of these variations on engine mixture ratio is shown in Figure 6.

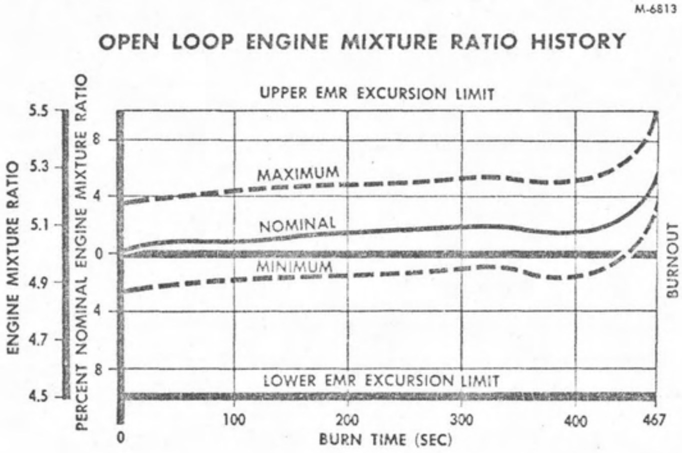


Figure 6

ΔW_{LS} and ΔWH_s are sloshing disturbances. The sensor will give erroneous propellant mass information if the fluid surface is not perpendicular to the vehicle centerline. Sloshing is a fluid surface tilt which is periodic and can be attenuated in the system electronics. The equations used in this analysis describing slosh are $\Delta \dot{W}_{LS} = 400 \sin 2.5t$

$$\Delta \dot{W}_{HS} = 450 \sin 2.0\, t$$

$$\text{Thus}\quad e\ (\text{slosh only}) = 400 \sin 2.5t - 5\ 450 \sin 2t$$

$$= 2650 \text{ max.}$$

These sloshing errors, being primarily from very low damped LH_2 are expected to exist to some extent for the total burning period. The shaping network shown in Figure 2 is designed primarily to reduce this disturbance by 47 db at the LH_2 slosh frequency. Thus valve movement is reduced ± 30° or ± .25 EMR.

ΔW_{LA} and ΔW_{HA} represent non-periodic errors from fluid surface tilt. Any time the resultant total thrust vector is not parallel to the vehicle centerline, a fluid surface tilt condition results. If, for example, the vehicle C.G. through which the thrust vector must act were not on the vehicle centerline, a surface tilt condition would occur.

Gain Change Requirement

For total system response analysis, the open loop transfer function can be stated:

$$KGH = \frac{K_L(\tau_2 S + 1)}{S(\tau_3 S + 1)(\tau_1 S + 1)}$$

Where K_L + Total Loop Gain

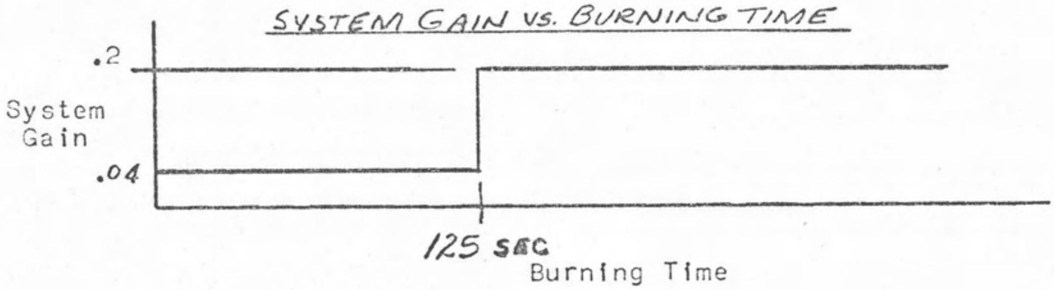
From this, the velocity constant C_V can be obtained.

$$C_V = \lim_{S \to 0} S(KGH)$$
$$= K_L = .2$$

The theoretical residual from **un**controlled rate errors $(\Delta \dot{W}_{LU})$ then **is**: $\frac{\Delta \dot{W}_{LU}}{C_V}$ or $\Delta \frac{\dot{W}_{LU}}{.2}$

The maximum EMR variation in Figure 6 can be approximated with a value of 5 ± .3. In units of $\Delta \dot{W}_{LU}$ + .3 EMR = 10.8#/sec. Therefore $\frac{\Delta W_{LU}}{.2} = \frac{10.2}{.2} = 51.6$ pounds theoretical residual. The total residual will include the effects of sensor errors and system hardware errors.

The engine manufacturer has stated that the EMR remain within 4.5 to 5.5 during burning. If valve flow pertubations ($\Delta \dot{W}_{LC}$) are added to the uncontrolled deviations ($\Delta \dot{W}_{LU}$) the EMR can be 5.8. This condition can occur if the polarity of ΔW_{Li} is opposite that of $\Delta \dot{W}_{LU}$. A condition of this type was used as one parameter in evaluating system transient performance. To keep the engine mixture ratio within the prescribed limit, it was necessary to use reduced system gain until a definite relationship between ΔW_{Li} and $\Delta \dot{W}_{LU}$ was established. To satisfy this EMR excursion limit requirement as well as keep residuals from uncontrolled rate errors to a minimum, the following gain change program was developed.


SYSTEM GAIN VS. BURNING TIME

System Performance

System response data has been obtained for various system disturbances. Because of the gain change characteristic, the analog computer was primarily used. The disturbances and associated response curves shown in Figure 7 are representative of the studies made. It was assumed in obtaining these curves

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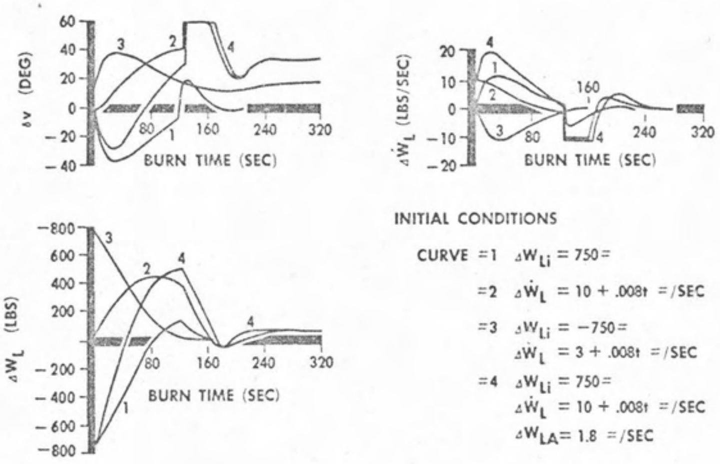
SYSTEM RESPONSE CURVES



INITIAL CONDITIONS

CURVE =1 $\Delta W_{Li} = 750$=

=2 $\Delta\dot{W}_L = 10 + .008t$ =/SEC

=3 $\Delta W_{Li} = -750$=

$\Delta\dot{W}_L = 3 + .008t$ =/SEC

=4 $\Delta W_{Li} = 750$=

$\Delta\dot{W}_L = 10 + .008t$ =/SEC

$\Delta W_{LA} = 1.8$ =/SEC

Figure 7

that $\Delta W_H = 0$, and all disturbances were introduced as lox disturbances. The relatively high bondpass of the servobalanced bridges make this a valid simplification. Lox rate errors are introduced as shown in Figure 7. It is assumed that these errors are not erratic and will generally be of one sign. The system is not expected to correct for the sudden rise in EMR late in flight. It has been established however that a positive EMR deviation indicates excess Lox flow, and the resulting mass at burnout will be LH_2. This mass is not expected to exceed 75 lbs.

The LH_2 sensor will be biased to read empty with a remaining mass of LH_2 in the tank. The effect of this bias can best be explained with an example.

Assume

Lox sensor accuracy = .2% of total mass

= .002 (83,333) = 167#

LH_2 sensor accuracy = .002 (16,667) = 33#

Condition A: If the Lox sensor read low, and the LH_2 sensor high, residuals from sensor error would be $W_L + LW_H$ (5)

= 167 + 33 (5) = 332#

Condition B: If the Lox sensor read high and the LH_2 sensor low, residuals from sensor error would be $33 + \frac{167}{5} = 66$ lbs.

If the LH_2 sensor were biased to read 45 lbs. low; Condition (A) above would result in 332 - 5 (45) = 107 lbs. residuals, and Condition (B) above would result in 66 + 45 = 111 lbs. residuals. Thus residual propellants at burnout due to sensing errors can be reduced by this LH_2 bias.

Capacitance Sensors

Sensor Requirements

The selection of a sensing system is probably the most important decision to be made in the design of a Propellant Utilization System. Ultimately, the success of the system will turn on this decision since the controller can be no more accurate than the information supplied to it by the sensors. Accordingly, an extensive investigation of liquid gaging methods was undertaken, culminating in the choice of capacitance sensing for this system. Although the capacitance gage has found extensive use in industrial and aircraft fuel gaging applications this is the first time it has been applied to a propellant utilization system, and it has been found necessary to make several "state-of-the-art" improvements in its design.

The prime requirement of sensing system is, of course, accuracy. This requirement can be conveniently subdivided:

1. Zero stability: The sensor shall indicate zero propellant at the exact time the tank is emptied. This indication must not be degraded over the expected range of vehicle enviromental conditions.
2. Linearity: When there is liquid in the tank the sensor shall accurately indicate its mass.

The reason for the first requirement is clear, for a sensor zero shift will cause an error which will directly add to propellant residual. The requirement that the measured parameter be propellant mass is not as obvious. There are several reasons: first, the engines are most efficient when they are run at their calibrated mass mixture ratio; and second, mass measurements are required both on the ground, for propellant loading and in flight for vehicle performance evaluation.

One way of determining the mass of propellant in a vehicle tank would be to determine the position of the liquid-gas interface and from this compute the liquid volume. The propellant mass could then be obtained by use of a calculated density or one which had been obtained by use of a measuring device located near the bottom of the tank. With cryrogenic propellants there are a number of objections to a technique of this type. First, the interface may be fairly undefined and perturbed by boiling or sloshing; and second, there is apt to be considerable density stratification throughout the length of the tank so that a density sample taken at one place in the tank would not be representative.

These disadvantages would be overcome by a gaging system which measured mass by integrating a fluid property related to density over the length of the tank. The capacitance sensor is such a system. In this system a long capacitor is placed in the tank, parallel or nearly parallel to the tank axis. When the tank is empty the capacitance of the unit will be proportional to the dielectric constant of the gas between the plates, which we will call E_G. If the tank is filled and the liquid allowed to flow between the plates, the observed capacitance will increase because some of the gas has been replaced by a liquid with a higher dielectric constant. If the capacitor is of uniform cross-section, its capacitance increase will be proportional to both the immersed length and the liquid dielectric constant minus the gas dielectric constant $(E_l - E_s)$. Since the dielectric constant of all gases is very nearly one, this last proportionality constant can be regarded as $(E_L - 1)$.

If we know E_L, we now have a system which will tell us the level of liquid in the tank. Since the capacitance of the unit is inversely proportional to the distance between its electrodes, we can build a sensor which will give a direct volume readout in a non-uniform cross-section tank by making the spacing between the electrodes at any point a function of the tank cross-section at that point. If $(E_L - 1)$ of the liquid being gaged is proportional to density, as it very nearly is for our propellants, we will have a system which will give a direct mass readout.

The dielectric constant of liquid hydrogen and oxygen is quite closely described by the Clausius-Mosotti equation.

$$\frac{E - 1}{E + 2} = KP$$

Where E = dielectric constant

P = density

K = constant dependent on the polarizability of the material involved.

It can be seen that if E is near 1 that $E - 1$ is almost a direct function of P. Since the dielectric constant of liquid hydrogen is about 1.22 and that of liquid oxygen about 1.48 this condition is fulfilled.

Sensor Design

The sensors used in Saturn SIV are cylindrical with an outer diameter of two inches. Correction for tank geometry is made by varying the diameter of the inner electrode. The mounting method is shown in Figure 1. It can be seen that because of shape of the tank it has been necessary to tilt the hydrogen sensor 18° from the vehicle axis. This sensor is 260 inches long and is, as far as the author knows, the longest capacitance sensor which has been built to date.

Several second order error sources exist in a practical capacitance gaging system. One of these arises from making the electrodes of materials which expand with temperature. In any system in which the sensors operate in a varying temperature environment, the resulting expansion will cause a capacitance change which must be taken into account. The capacitance of a cylindrical capacitor is given by the formula:

$$C = KE \frac{L}{\text{Log } \frac{R_O}{R_I}}$$

Where L = length of the capacitor

R_O= radius of outer electrode

R_I= radius of inner electrode

E = dielectric of media between electrodes

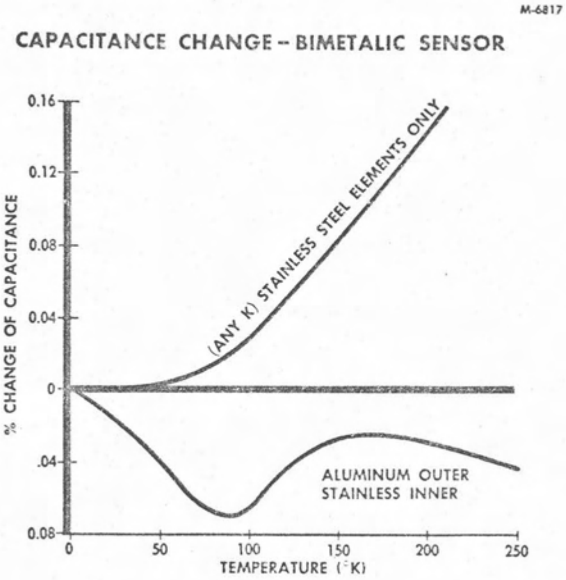
K = constant

For a capacitor with both electrodes of the same material Log R_O/R_I will not change as the capacitor expands and contracts, so the capacitance change will be proportional to the change in

L. By making the electrodes out of materials with different expansivities, it is possible to make Log R_O/R_I vary proportionally to L and thereby make a unit whose capacitance is very nearly constant over a wide temperature range. This is illustrated in Figure 8.

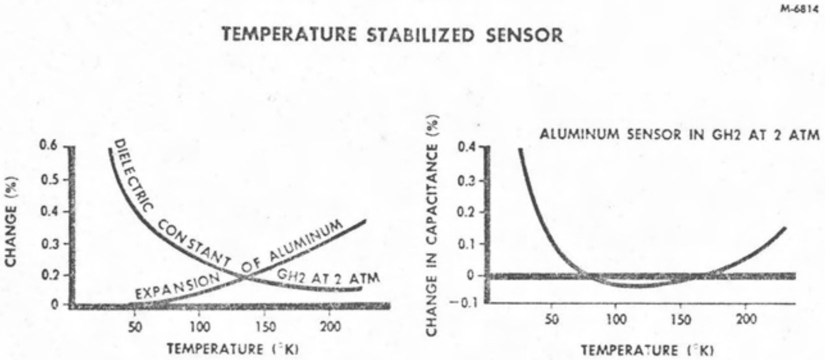
The sensor zero capacitance, or its capacitance when all the propellant in the tank has been expanded is influenced by the temperature and pressure of the residual gas. Of course, this effect will be predicted and allowed for in calibrating the system. However, any error in this prediction will be seen by the system as a zero shift. In the liquid oxygen tank, where the pressurent is helium, which has a very low dielectric constant, this effect is negligible. In the hydrogen tank the residual is hydrogen gas under several atmospheres pressure and its effect can be quite appreciable. Even if we are able to make a reasonably accurate prediction of this effect, the resulting zero shift can be as much as .3% to .4% of full scale. Fortunately it is possible to compensate for the major portion of this error, the part that is due to the uncertainty in the temperature of the residual gas. This is done by designing the sensor so that its change in capacitance with temperature, due to thermal expansivity, balances out the change in ullage gas dielectric with temperature. An example is shown in Figure 9.

It can now be seen that the design of these sensors was a complex process. Since the prime requirement was zero stability this was attacked first. A computer program was



CAPACITANCE CHANGE – BIMETALIC SENSOR

Figure 8



TEMPERATURE STABILIZED SENSOR

Figure 9

written which would design a sensor which had a capacitance vs. liquid level height function which matched the tank volume vs. height function. For simplicity, it was assumed that the gas above the liquid was at a fixed nominal 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 electrode material combinations 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. Based on this information, the material combination and diameter ratio which gave the smallest capacitance change over the range of gas temperature and pressures expanded in the tank at the end of flight was selected for the final sensor design. The optimum material combination was an aluminum outer electrode and a stainless steel inner electrode for both the hydrogen and oxygen sensors. However, the diameter ratios were different.

Having determined these parameters, a more refined computer program was developed for designing the actual vehicle sensors. This program was similar to the first one, with provision for a variable temperature distribution in the gas and in each of the electrodes. In addition, the computer was enabled, by means of an iterative process, to vary the shape of the inner electrode in order to bring the sensor capacitance vs. liquid level curve, considered under the predicted vehicle environment, into correspondence with the tank mass vs. liquid level curve. Further, the program was arranged so the final print out of a capacitance vs. sensor length function would assume room temperature electrodes and dielectrics to simplify fabrication and calibration.

Electronics Assembly

The electronics assembly incorporates the circuitry which supplies propellant mass signals to the ground loading computer and the vehicle telemetry systems. It also creates and shapes the system error signal and generates the electrical commands for positioning the engine mixture ratio valves.

Since this assembly had to be located at some distance from the sensors, a three-wire bridge was chosen for sensor readout. Further, to obtain the necessary accuracy and stability, a balanced bridge. incorporating a servo rebalance loop was used. This circuit is shown in Figure 10 and is typical for both the hydrogen and oxygen sensors.

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SERVO-BALANCED CAPACITANCE BRIDGE

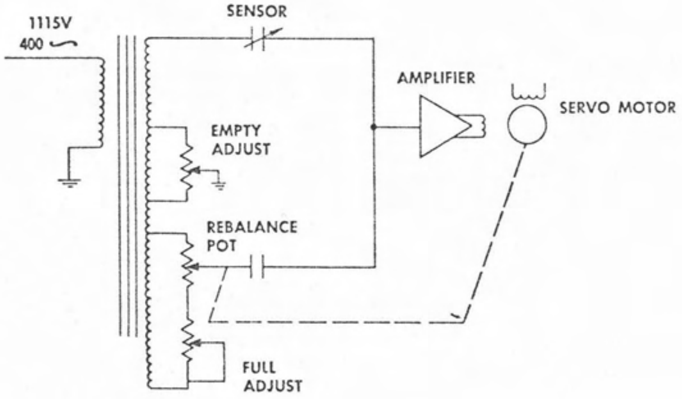

Figure 10

In this circuit the sensor forms one leg of a bridge, the opposite leg is a fixed reference capacitor. The other two legs of the bridge are voltage sources supplied by the secondary of the reference transformer. The output of the bridge is the input to a servo amplifier. If the bridge is initially in balance and the sensor capacitance is increased or decreased by adding or withdrawing propellant , the bridge will be unbalanced and an input supplied to the amplifier. The amplifier in turn will drive a servomotor which repositions the rebalance pot to return the bridge to null. The rebalance pot voltage, or shaft position, change is proportional to sensor capacitance change. This shaft position is the output of the bridge.

It will be noted that the capacitance to ground associated with cable connecting the sensor to the electronics assembly does not add to the stray capacitance of the sensor. This is particular advantage of this form of bridge since this capacitance can easily be larger than the sensor capacitance. However, it is important to avoid capaciter coupling between the two sensor leads since this cannot be distinguished from sensor capacitance. This requirement is met by using shielded cable and coaxial connectors for the high impedance lead.

The rebalance pot is one gang of a four-gang ten-turn potentiometer. The other three gangs are used for loading and course telemetry, fine telemetry, and forming the system error signal. The loading pot is excited with 28 volts DC and the voltage ratio output taken to a digital ratiometer in the ground loading computer. The ratiometer is calibrated to give a readout of the pounds of propellant in the tank and to provide signals for operating the loading valves.

The fine telemetry pot has been incorporated to enable an accurate inflight determination of propellant mass. The accuracy of this measurement would normally be limited by inherent telemetry inaccuracies amounting to about 2% of full scale. To overcome this, the pot is divided into 20 equal segments by tapping; alternate taps are exited by 5 volts DC, with the remainder grounded. This effectively provides a 20 times expanded scale and reduces the telemetry errors to .1%.

Figure 11 shows the method of forming the error signal. The two bridge output pots are excited in parallel from a 100 volt DC source. The bridges have been calibrated so that any time the propellant masses in the tank are at the desired 5:1 ratio the pot wiper positions and therefore wiper voltages are equal. Accordingly, in operation the voltage difference between the wipers is the system error signal. In order to have this signal referred to ground the pot excitation supply is floating and the wiper of the hydrogen output pot is grounded.

The error voltage is first taken to a switched voltage divider which mechanizes the gain change. The gain change switch is driven by the oxygen bridge servo. A RC network is used to shape the error signal. The high attenuation desired in this filter to reject disturbances from propellant slosh and the need to keep the filter capacitors to reasonable size has resulted in the filter presenting a high source impedance to

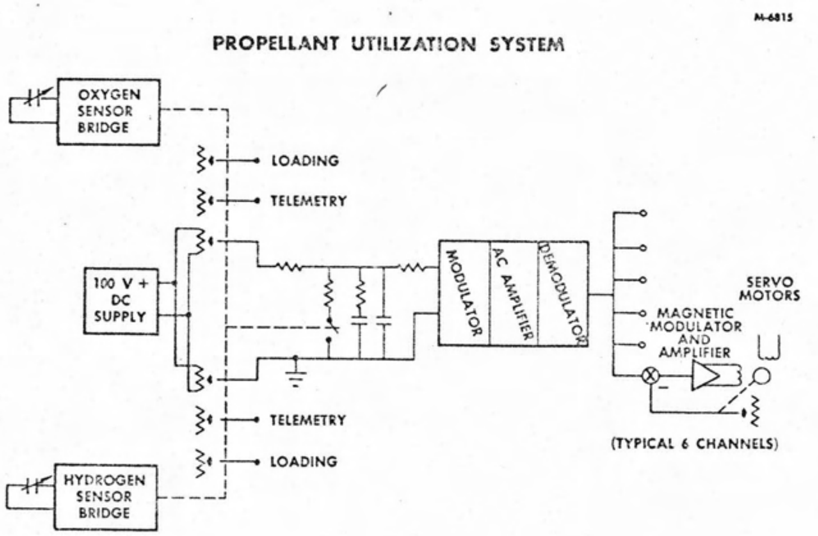
PROPELLANT UTILIZATION SYSTEM

Figure 11

the amplifier which follows it. Efforts to design a sufficiently stable DC amplifier to work from this source were unsuccessful, so a modulator-AC amplifier-demodulator combination was used.

The demodulator output is the command input to six parallel position servos which are used to control the engine mixture ratio valves. DC is used for the command and feedback signals to avoid quadrature problems which would arise from summing two slightly out-of-phase signals. The command and feedback signals for each loop are summed at the input of a magnetic modulator. This modulator is followed by an AC amplifier which drives a servomotor located on the engine.