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CENTAUR LAUNCH VEHICLE PROPELLANT UTILIZATION SYSTEM

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and Andrew J. Stofan*

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Cleveland, Ohio*



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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

The development history, configuration, and operation of the Centaur propellant utilization system is described. The system used capacitance mass sensors to sense boiling liquid oxygen and liquid hydrogen in the propellant tanks. The system electronics utilized signal levels in the nanoampere range for control. The system operation was verified on nine Atlas-Centaur flights; end propellant residuals were controlled to less than 20 kilograms of liquid hydrogen out of a total tanked propellant weight of 13 600 kilograms.

CONTENTS

	Page
SUMMARY	1
INTRODUCTION	1
DEVELOPMENT HISTORY	2
CAPACITANCE-PROBE MASS SENSING	3
CAPACITANCE MASS SENSOR (PROBE) TESTS	7
SYSTEM CONFIGURATION AND OPERATION	10
COMPONENT DETAILS	11
Capacitance Mass Sensors (Probes)	11
Liquid-hydrogen probe	11
Liquid-oxygen probe	11
Electronics Package	12
Propellant difference computer (bridge)	12
Error signal conditioner amplifier	14
Valve servobridge amplifier	14
Liquid-hydrogen and liquid-oxygen quantity bridge amplifiers	14
Radiofrequency interference filter	15
Quadrature rejection network	15
Servopositioner	15
FLIGHT DATA ANALYSIS	16
FLIGHT EXPERIENCE	17
CONCLUDING REMARKS	17
APPENDIX - SYMBOLS	19
REFERENCES	20

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SUMMARY

In an upper-stage space vehicle, it is desirable to minimize propellant residuals at the end of powered flight. The variations in propellant density, tank volumes, engine mixture ratio, etc., greatly increase the probability of excessive propellant residuals. A propellant utilization system is, therefore, desired to sense the propellant masses and manage propellant outflow during powered flight to compensate for these variations, and result in minimum propellant residuals and increased available payload capability. The development history, configuration, and operation of the Centaur propellant utilization system is described.

Tests conducted at NASA Lewis Research Center indicated that the mass of a cryogenic propellant could be accurately gaged by using a concentric-cylinder capacitance probe. Data from these tests were used to develop a nonperforated, coaxial-tube capacitance mass probe to sense boiling liquid oxygen and liquid hydrogen in the Centaur propellant tanks. A solid-state electronics package, using signal levels in the nanoampere range from the sensing probes, was also developed. A unique harmonic drive was used for proportional control of a liquid-oxygen flow control valve to continuously adjust the operating mixture ratio of the Centaur engines.

The operation of the Centaur propellant-utilization system has been verified by nine Atlas-Centaur flights. The propellant residuals have been less than 20 kilograms of liquid hydrogen (i. e., liquid hydrogen remaining at liquid oxygen depletion) out of a total tanked propellant weight of 13 600 kilograms.

INTRODUCTION

In a bipropellant space vehicle, it is desirable to minimize propellant residuals at the end of powered flight. The variations in propellant density, tank volumes, and engine mixture ratio during flight, and from flight to flight, greatly increase the probability of

excessive propellant residuals. If excessive propellant residuals occur, payload capability is reduced. In order to compensate for these variations, and to minimize propellant residuals, a propellant-utilization system is desired to sense the propellant masses and manage propellant outflow during powered flight.

A basic propellant-utilization system continuously compares the mass of the fuel with the mass of the oxidizer remaining in the propellant tanks during powered flight. A deviation in the mass ratio from the desired ratio generates an error signal. This signal is amplified and used to alter the propellant consumption by the engines until the mass ratio in the tanks returns to the desired value. This system reduces the residual of the lightest propellant at the depletion of the heaviest propellant (minimum residuals).

The purpose of this report is to acquaint the reader with the design and operation of the Centaur launch vehicle propellant-utilization system. Because Centaur uses liquid hydrogen and liquid oxygen as propellants, many problems had to be resolved to obtain a working, accurate system. The system development history, fundamentals of capacitance-probe mass sensing, special capacitance-probe tests conducted at Lewis Research Center, and the system design and operation are presented.

DEVELOPMENT HISTORY

Several methods of sensing propellant mass, either directly or indirectly, were considered for use on the Centaur upper-stage vehicle, which uses liquid hydrogen as fuel and liquid oxygen as the oxidizer. The following sensing methods were considered (ref. 1):

- (1) Point level sensors that would sense the propellant level at selected points in the tank
- (2) A nuclear source and counter system that would pass radioactive particles through the propellant mass (Because the mass of the propellant attenuates the particle penetration, not all particles pass completely through the propellant. A counter located at the opposite end of the tank would sense the number of particles that did pass through the propellant. This number is proportional to the propellant mass.)
- (3) A continuous capacitor that would sense the change in capacitance of the probe as the proportion of liquid and gas in the probe changes. (The dielectric is different between the gas and liquid.)

For the first sensing method, the liquid outflow from the propellant tanks during engine firing would cause liquid level sensors located at different levels in the tanks to indicate successively "dry". The mass of propellant remaining in the tank at the time the sensor indicates dry is calculated by multiplying the propellant density by the tank vol-

ume at the sensing point. This method requires an accurate knowledge of the propellant density and tank volume at the sensing point. For the Centaur, an accurate density measurement is difficult. The Centaur uses boost pumps to supply Net Positive Suction Head (NPSH) to the engine turbopumps. No make-up pressurization gas is added to the propellant tanks during engine firing. This results in decaying tank pressures since mass is leaving the tanks to supply the engines during firing. A state of thermodynamic equilibrium is maintained at the liquid-to-vapor interface by bulk boiling of the cryogenic propellants. The bubbles created by boiling alter the liquid density significantly from that for a saturated nonboiling liquid. The bubbles and the continuous decay of ullage pressure make the use of a propellant mass-sensing method that requires an accurate knowledge of propellant density undesirable.

The second sensing method, the nuclear source and counter mass-sensing system, was in its early development stage at the time of the selection of the Centaur system and therefore did not allow a meaningful comparison of its advantages.

The third sensing method, the continuous capacitance mass sensor, was the one chosen for Centaur. As shown later, it senses mass directly. Preliminary design evaluations made in 1963 indicated a continuous sensing and proportional control system to be advantageous for Centaur. This system showed an increase in overall system control margin, reduction of random system errors, and the limiting of step input control signals to the engine mixture ratio control. Also, knowledge of capacitance gaging was available, since this method had been used quite extensively in aircraft. The continuous capacitance sensor had also been proven feasible for accurate gaging of subcooled cryogenic liquids. Since Centaur propellants would be boiling, the effects of bubbles, density gradients, and propellant motion had to be investigated to determine if the capacitance sensing method would be adequate.

CAPACITANCE-PROBE MASS SENSING

The capacitance mass-sensing probe is basically two coaxial tubes as shown in figure 1. The tubes act as plates of a capacitor, and the medium between the tubes is the dielectric. In the Centaur, the medium is the propellant, both in liquid and gaseous form. The capacitance value of the probe is proportional to the mass of the dielectric medium in the tank. The relation is derived as follows:

For a concentric-cylinder capacitor, the capacitance is (ref. 2)

$$C = \frac{K\epsilon L}{\log_{10} \frac{r_{out}}{r_{in}}} \quad (1)$$

where

C capacitance

K constant of proportionality

ϵ dielectric constant of medium = $\frac{\text{capacitance in medium}}{\text{capacitance in vacuum}}$

L length of capacitor

r_{out} inner radius of outer cylinder

r_{in} outer radius of inner cylinder

If, however, the tank in which the capacitor (probe) is installed is noncylindrical, or nonsymmetrical, or the probe is not mounted longitudinally (i. e. , it is mounted at an angle in the tank), then the inner tube may be contoured so that the capacitance of the probe at any medium level in the container will be a true indication of the propellant mass. The inner tube is shape to conform to the tank cross-sectional area through the relation

$$\log_{10} \frac{r_{\text{out}}}{r_{\text{in}}} = \frac{K_A}{A} \quad (2)$$

where

K_A constant of proportionality

A tank (container) cross-sectional area

An approximate relation between the dielectric constant and the density of the propellant (both liquid and gas) contained in the sensing probe is the Clausius-Massotti equation (ref. 3):

$$\frac{\epsilon - 1}{\epsilon + 2} = \frac{4\pi N_1 \alpha_0}{3} \quad (3)$$

where

N_1 number of molecules per cubic centimeter

α_0 polarizability per molecule for the fluid (a constant for practical applications)

A more rigorous equation relating fluid density and dielectric constant has been derived by Böttcher (ref. 4). However, the equation is quite lengthy and the error introduced by using the Clausius-Massotti equation is small. The Clausius-Massotti equation

simplifies the mathematics and for a low-density fluid (such as hydrogen) is relatively accurate.

Since α_0 is considered constant, equation (3) can be stated as

$$\frac{\epsilon - 1}{\epsilon + 2} = K_0 N_1 \quad (4)$$

where

$$K_0 \equiv \frac{4\pi\alpha_0}{3}$$

But since N_1 is the number of molecules per cubic centimeter, which is proportional to the density of the fluid by definition, equation (4) can be rewritten as

$$\frac{\epsilon - 1}{\epsilon + 2} = K_1 \rho \quad (5)$$

where

K_1 constant of proportionality including K_0

ρ density of fluid

Equation (5) can also be rewritten as

$$\epsilon - 1 = 3K_1 \rho (1 - K_1 \rho)^{-1} \quad (6a)$$

Expanding $(1 - K_1 \rho)^{-1}$ in a binomial series where $N = 1$ results in

$$3K_1 \rho (1 - K_1 \rho)^{-1} = 3K_1 \rho \left[1 + K_1 \rho + \frac{1}{2} (K_1 \rho)^2 + \dots \right]$$

But, for Centaur propellant conditions of

Saturated liquid hydrogen at 22 K:

$$K_1 \rho = 0.06$$

Saturated liquid oxygen at 94 K:

$$K_1\rho = 0.10$$

Therefore, equation (6) may be written as

$$\epsilon - 1 \approx 3K_1\rho \quad (6b)$$

This derived equation then establishes the relation between the dielectric constant and the density of the fluid.

In a vacuum, the capacitance of the probe represents conditions of zero mass within the probe. When immersed in a medium such as liquid and/or gaseous hydrogen, the capacitance changes from the vacuum capacitance. This change can be related to the mass as follows:

$$\begin{aligned} \Delta C &= (\text{Capacitance})_{\text{medium}} - (\text{Capacitance})_{\text{vacuum}} \\ &= \left[\frac{K(\epsilon)L}{\log_{10} \frac{r_{\text{out}}}{r_{\text{in}}}} \right] - \left[\frac{K(\epsilon_{\text{vac}})L}{\log_{10} \frac{r_{\text{out}}}{r_{\text{in}}}} \right] \end{aligned}$$

But

$$\epsilon_{\text{vac}} = 1$$

Therefore,

$$\Delta C = \frac{K(\epsilon - 1)L}{\log_{10} \frac{r_{\text{out}}}{r_{\text{in}}}} \quad (7)$$

Combining equations (7), (2) and (6b) results in

$$\Delta C = \frac{K(3K_1\rho)L}{\frac{K_A}{A}} = \frac{3K_1K}{K_A} (\rho AL)$$

Since A and ρ are both functions of the length of the probe,

$$\text{Mass in probe} = \int_0^L \rho A \, dL$$

Therefore,

$$\Delta C = K_M \int_0^L \rho A \, dL \quad (8)$$

where

$$K_M = \frac{3KK_1}{K_A}$$

Equation (8) then gives the final relation between the capacitance and the mass for a capacitance sensor, as used in the Centaur vehicle.

CAPACITANCE MASS SENSOR (PROBE) TESTS

Tests were conducted at the NASA Lewis Research Center to investigate the feasibility of accurately gaging a boiling cryogenic propellant. The specific areas investigated in the tests were (1) the accuracy with which a perforated or nonperforated probe could gage a boiling cryogenic fluid (fig. 2), (2) the capacitance error which could be caused by a systematic bubble distribution within the nonuniform electric-field density of concentric cylinder capacitors, and (3) a potential mass sensing error caused by a restriction to bubble flow resulting in a change in fluid-column height in the sensing probe.

The tests were conducted in a vacuum-insulated, 0.85-cubic-meter container that was filled with liquid hydrogen. The container was filled to a preselected level, and the cryogenic fluid was brought to its saturation point by means of a submersed heater. The pressure in the container was then reduced (ramped down) at a rate selected to simulate the pressure decay in the Centaur propellant tanks during engine firing. The probes within the tank were run completely submerged and also at various levels of partial submergence.

The first set of tests employed two concentric cylindrical capacitance probes that were identical except that the outer cylindrical jacket on one probe was perforated (see fig. 2). The other probe was open only at the top and bottom. The probes were 178 cen-

timeters long, with inner and outer electrode radii (r_{in} and r_{out}) of 1.27 and 2.54 centimeters, respectively. The nominal capacitance of the probes was 155 picofarads in gaseous hydrogen and 190 picofarads in liquid hydrogen.

The tests conducted to establish the accuracy with which a perforated or nonperforated probe could gage a boiling cryogenic fluid showed that when the probes were completely submersed, both gaged the mass of the liquid hydrogen within 0.2 percent of the calculated value. The calculated value was determined by the following method:

(1) The density of saturated, nonboiling liquid hydrogen was determined by the measured tank pressure and temperature.

(2) The tank pressure was then reduced or ramped down, causing the liquid to boil vigorously; this resulted in an increase in liquid level within the tank. A new liquid hydrogen bulk density was calculated by using the tank volume and the measured change in liquid level.

When the liquid level was below the top of the probes, the perforated probe error in indicating mass was approximately 1 percent. The error in mass sensing was caused by the following factors: (1) the liquid within the probe has a lower density than in the remainder of the tank because of the many nucleation points within the probe that promote bubbles, and (2) the liquid height within the perforated probe was the same as the height in the tank and could not compensate for density changes. In contrast, the nonperforated probe compensated for the lower density within the probe by a corresponding change in liquid height within the probe as is shown in figure 3. The equation for hydraulic balance is

$$\rho_{g,1}L_{g,1} + \rho_{l,1}L_{l,1} = \rho_{g,2}L_{g,2} + \rho_{l,2}L_{l,2} \quad (9)$$

or, the mass in the tank is proportional to the mass in the probe.

$$M_{\text{tank}} = KM_{\text{probe}} \quad (10)$$

Equation (8) showed that the measured capacitance is proportional to the mass in the probe.

$$\Delta C = K_M M_{\text{probe}}$$

Combining equations (8) and (10) yields

$$\Delta C = \frac{K_M}{K} M_{\text{tank}}$$

Therefore, the measured capacitance is proportional to the mass in the tank.

The nonperforated probe was chosen for the Centaur propellant utilization system because it inherently provided a better measurement.

It was also noted during the testing that the fluid within the nonperforated probes would go into oscillations during rapid depressurization cycles. For optimum system performance, the natural frequency of the oscillation within the probe must not be tuned to the frequency of oscillations introduced by rapid pressure changes or propellant sloshing within the tank. This problem was solved on the flight hardware by adding a flow restriction device to the probes. This will be discussed in a subsequent section.

Five nonperforated probes of varying sizes were tested to determine the effects of bubbles within the probe on mass-sensing accuracy. The probes were all 178 centimeters long. The electrode radii were varied as the following sketch and table I indicate.

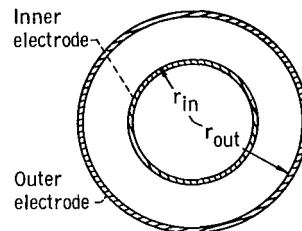


TABLE I. - TEST-PROBE DIMENSIONS

Probe	Outer-electrode inside radius,	Inner-electrode outside radius,	Radius ratio,	Electrode gap,	Nominal capacitance,	
	r_{out}' cm	r_{in}' cm	r_{out}/r_{in}	$r_{out} - r_{in}'$ cm	Liquid hydrogen	Gaseous hydrogen
1	3.72	2.38	1.56	1.34	274	225
2	3.72	2.87	1.30	.85	464	380
3	2.46	1.59	1.55	.87	281	230
4	1.21	.80	1.51	.41	300	245
5	1.21	.32	3.78	.89	95	78

The capacitance error which could be caused by a systematic bubble distribution within the nonuniform electric-field density within the concentric cylindrical capacitors was investigated with probes 2, 3, and 5. These probes had different radius ratios with a constant gap. The potential error caused by a restriction to bubble flow within the probe was investigated with probes 1, 3, and 4. These probes had different gaps with a constant radius ratio. The test results showed that the ability of the five probes to gage propellant mass was essentially the same (less than ± 0.2 percent uncertainty).

SYSTEM CONFIGURATION AND OPERATION

The Centaur propellant utilization system consists of three major components, as shown in figure 4. These are

- (1) Capacitance mass sensors (probes) in each propellant tank to sense the liquid-oxygen and liquid-hydrogen masses
- (2) An electronics package to house circuitry for comparing propellant masses, for telemetering propellant quantity and flow control valve angle data, and for generating correction signals to the engine liquid-oxygen flow control valves
- (3) Servopositioners to move the liquid-oxygen flow control valves in response to correction signals from the electronics package (One servopositioner is mounted on each of the two Centaur engines.)

A block diagram of the system is shown in figure 5. The system is powered by a transformer from the vehicle's 115-volt, 400-hertz power supply. Approximately 90 seconds after the Centaur engines are started, a signal from the vehicle programmer enables system control. System control is started at this time because the probes do not extend the full length of the propellant tanks. This time is approximately the time that the propellant levels are expected to pass the tops of the probes. The sensing probes in the tanks provide a signal proportional to the mass of propellant remaining in the tank at any time. These signals are sent to the propellant difference computer (bridge) located in the electronics package. In the propellant difference computer, the signals from the probes are compared, and if the sensed masses are in the desired ratio the summed current from the bridge is zero (the bridge is nulled). For Centaur, this mass ratio of oxygen to hydrogen is 5:1. However, if variations in tanked propellants and propellant usage during flight cause the sensed residual propellant masses to deviate from the desired ratio, an error signal is produced by the propellant difference computer. This signal is amplified and drives a servomotor in each servopositioner. The servopositioner output shaft is splined to the liquid-oxygen engine flow control valve located downstream of the turbopump on each Centaur engine. This valve regulates liquid-oxygen flow from the tank to the engine. If the error signal indicates excess liquid-oxygen mass in the tank, the flow-control valve is opened to increase oxygen flow. If the error signal indicates excess liquid-hydrogen mass, the flow-control valve is closed to conserve oxygen until the desired ratio is returned in the tank. The mixture-ratio control is limited to ± 12 percent about the 5:1 ratio.

System control continues until approximately 25 seconds prior to the expected engine shutdown. At this time, the bridge is nulled by a command from the vehicle programmer. This causes the valve to return to the desired position. This is done because the probes do not extend to the bottoms of the tanks, and system control is lost when the liquid level depletes below the bottom of the probe.

COMPONENT DETAILS

Capacitance Mass Sensors (Probes)

The Centaur capacitance mass sensors (probes) are basically variable capacitors made up of coaxial electrode tubes with the cryogenic liquid and/or gas as the dielectric. The internal tubes are contoured to match the tank shape through the relation given in equation (2) of this report. The tubes are continuous, and the space between the tubes is open to fluid flow only at either end. This reduces the effects of tank density gradients on the sensor mass indications. Thus, density differences, inside to outside of the probe, are compensated by the difference in liquid level between the inside and outside of the probe, as shown in figure 3. This manometer action causes the probe to give an accurate indication of the total mass in the tank, gas and liquid, between the top and bottom of the probe.

A short, small-diameter tube is attached to the bottom end of each probe. Liquid inflow and outflow in the probe passes through this tube. The size of this "inertia" tube was selected to detune the liquid in the probe from expected sloshing frequencies in the tanks, thus isolating the system from tank sloshing effects and eliminating the oscillation problem noted during development testing. See reference 5 for analysis and design data of the inertia tube.

Liquid-hydrogen probe. - A sketch of the liquid-hydrogen probe is shown in figure 6. The tubes that form the probe are manufactured from aluminum to minimize weight and for ease of construction. The inner tube is swaged to the required contour, and the outer-tube diameter is constant for the length of the probe. Plastic "buttons" maintain proper spacing between the tubes. The gap between the tubes in the cylindrical portion of the tank is 1.3 centimeters. This gap was chosen to provide the maximum gap between the tubes without severely reducing the capacitance of the probe. The choice was based on data from the probe tests previously discussed herein. Axial motion of the inner tube relative to the outer tube was eliminated by clamping the tubes together at the lower end by a cap assembly. The probe was mounted to the tank by four supports attached to T-shaped brackets welded to the tank skin. The probe was fixed to the bracket at the lower end by four bolts. Relative motion between the probe and the tank was allowed at the other three attachment points by pins and slotted holes. A photograph of the installed probe is shown in figure 7.

The capacitance of the hydrogen sensor is about 510 picofarads when completely immersed in gaseous hydrogen at 22 K. When completely immersed in liquid hydrogen, the capacitance is about 620 picofarads. Total probe weight is 7.5 kilograms.

Liquid-oxygen probe. - The liquid-oxygen probe is also manufactured from aluminum. This probe, however, contains a third tube, which is at ground potential and is the

main structural member. A sketch of the liquid-oxygen probe is shown in figure 8. The probe is mounted to the vehicle thrust structure (barrel) in the oxygen tank, as shown in figure 9. The probe is canted at a 0.12-radian angle.

The capacitance of the oxygen sensor when completely immersed in 100 K gaseous oxygen is about 170 picofarads. When the sensor is completely immersed in liquid oxygen, the capacitance is about 250 picofarads. The total probe weight is 3.2 kilograms.

Electronics Package

The Centaur propellant utilization electronics package, shown in figure 4, is located on the vehicle aft bulkhead. It is a foam-filled package and is thermally insulated from the aft bulkhead. The package input power is 115 volts, 400 hertz, 35 volt-amperes at an average lagging power factor of 0.85 and 28 volts dc at 6 watts minimum and 19 watts maximum. Housed in the electronics package are various subcircuits in modular form (fig. 10). The more important modules are the propellant difference computer (bridge), the error signal conditioner amplifier, the valve servobridge amplifiers, the propellant quantity bridge amplifiers, a radio frequency interference filter, and a quadrature rejection network. The functions of each of the subcircuits are discussed in the following sections. A more detailed description and a mathematical analysis of the electronics package subcircuits can be found in reference 6.

Propellant difference computer (bridge). - The propellant difference computer sums the signals from the capacitance mass sensors (probes) and generates the correction signal supplied to the servopositioners. A simplified bridge circuit is shown in figure 11. In the figure, C_O , C_H , and C_D represent the liquid-oxygen probe capacitance, the liquid-hydrogen probe capacitance, and the dry adjustment capacitor, respectively. The liquid-oxygen sensing portion of the bridge (C_O) is supplied with power that is phase shifted 180° relative to the liquid-hydrogen sensing portion (C_H).

Assuming the quadrature current is balanced (i. e., $i_q = 0$), the basic equation of the bridge is

$$i_O + i_D + i_H = i_S \quad (11)$$

where

i_O current in oxygen portion

i_D current from dry adjust

i_H current in hydrogen portion
 i_S summing junction current (error signal)

Also shown in the bridge circuit are the potentiometers V_E , V_C , and V_Q . The potentiometer V_E is used to correct the bridge to compensate for expected systematic and random rate errors during flight. Included in this compensation are the following:

- (1) Effect of probe shrinkage (The system is calibrated at room temperature, and the probe shrinks when subjected to the cryogenic temperatures of the propellants. This shrinkage causes the capacitance to change.)
- (2) Effects of gas sensed by the probe when not filled with liquid (When the liquid levels in the tanks are below the tops of the probes, the system has to compensate for the gas masses above the liquid levels. These masses are not at a 5:1 ratio as are the liquids.)
- (3) A system bias to ensure that liquid oxygen depletes first, since it is the heaviest propellant

The potentiometer V_C is used to compensate for the liquid-hydrogen boiloff during the coast phase of a two-burn mission. It also compensates for propellant losses at the first engine shutdown, and for propellants used during engine preconditioning prior to the second engine start. If these effects were not compensated for, the system would have to correct during the second engine firing period. The potentiometer V_Q is used to eliminate the quadrature voltage and to prevent saturation of the amplifiers.

The propellant difference bridge is balanced prior to flight by adjusting the bridge to a null with potentiometers V_H and V_D . Checkout capacitors are inserted in parallel with the tank sensing probes. These capacitors simulate the capacitance values of the probes when filled with gaseous hydrogen/oxygen and with liquid hydrogen/oxygen. The basic circuit equations satisfied at bridge null are

Empty (filled with gas):

$$V_H C_H = V_D C_D + V_O C_O \quad (12)$$

Full (filled with liquid):

$$V_H (C_H + \Delta C_H) = V_D C_D + V_O (C_O + \Delta C_O) \quad (13)$$

where

V_H voltage of hydrogen potentiometer
 V_O voltage of oxygen potentiometer
 V_D voltage of dry adjust potentiometer

- C_H capacitance of hydrogen probe when filled with hydrogen gas
- ΔC_H change in capacitance of hydrogen probe from C_H when filled with liquid hydrogen
- C_D dry adjust capacitor
- C_O capacitance of oxygen probe when filled with oxygen gas
- ΔC_O change in capacitance of oxygen probe from C_O when filled with liquid oxygen

Error signal conditioner amplifier. - The error signal conditioner amplifier amplifies the error signal from the propellant difference bridge to an acceptable level for use by the valve servobridge.

Valve servobridge amplifier. - The valve servobridge amplifier receives the output signal of the error signal conditioner amplifier and supplies an amplified signal to the servopositioner servomotor to position the liquid-oxygen flow control valves at the desired position.

Liquid-hydrogen and liquid-oxygen quantity bridge amplifiers. - These modules in the electronics package receive signals from the hydrogen and oxygen portions of the propellant difference bridge and condition the signal for landline and telemetry display. A simplified schematic of the liquid-oxygen quantity bridge amplifier is shown in figure 12. The liquid-hydrogen quantity bridge amplifier is identical. The liquid-oxygen quantity bridge amplifier is calibrated by using the following relations: Assuming the quadrature currents from the main bridge are balanced, the basic equation of the quantity bridge is

$$i_{eo} = i_{EO} + i_{FO} + i_O \quad (14)$$

where

- i_{eo} oxygen-quantity error current
- i_{EO} current through empty oxygen potentiometer
- i_{FO} current through full oxygen potentiometer
- i_O current from oxygen portion of propellant-difference computer

Rewriting equation (14) in terms of capacitances and voltages for empty probe conditions (probe filled with gas, and i_{eo} and i_{FO} equal 0) results in

$$V_{EO}C_{EO} = -V_O C_O \quad (15)$$

For full conditions (probe filled with liquid) equation (14) reduces to

$$V_{FO}C_{FO} = -V_O \Delta C_O \quad (16)$$

where

- V_{EO} voltage of the empty potentiometer in the oxygen-quantity bridge
 C_{EO} capacitor in the oxygen-quantity bridge representing empty conditions
 V_{FO} voltage of the full potentiometer in the oxygen-quantity bridge
 C_{FO} capacitor in the oxygen-quantity bridge representing full conditions

Similar equations are used for the liquid-hydrogen quantity bridge and amplifier.

Radiofrequency interference filter. - The radiofrequency interference filter eliminates conductive interference generated by other electrical equipment on the Centaur vehicle.

Quadrature rejection network. - The quadrature rejection network reduces quadrature voltage to ensure that the valve servoamplifiers do not become saturated.

Servopositioner

The servopositioner, shown in figure 13, is an electro-mechanical device that operates the liquid-oxygen flow valve on the engines to control engine mixture ratio in response to the error signal from the propellant-difference computer. The servopositioner consists of a servomotor, a gear train, and an output-shaft assembly as shown in figure 13. Photographs of a sectioned servopositioner are shown in figure 14.

Three potentiometers are driven off the gear train at a 1:1 ratio with the output shaft. Two of these potentiometers are used for landline and flight valve-position indications, respectively. The voltage across the third potentiometer, proportional to the output-shaft position (i. e. , the flow-control valve position) feeds back to sum with the error signal generated by the propellant-difference computer. When the valve reaches a position at which the feedback voltage equals the error-signal voltage, the control signal to the servopositioner is zero, and the valve position remains fixed.

The output shaft of each servopositioner is mechanically restricted in travel angle about the desired position. This is required to prevent the engine mixture ratio from exceeding operating limits.

The gear reduction ratio from the servomotor to the output shaft is 3200:1. The final reduction stage, 102:1, is accomplished by a patented unique "harmonic drive" assembly (ref. 7). A pinion gear (fig. 15), driven by the motor, drives a coupling gear attached to a ball bearing having a slightly elliptical outer race. The inner race is pressed onto a thin-walled, flexible, nonrotating housing that is internally splined. The

output shaft is splined externally to mate with the flexible spline at two opposite tangent points (along the minor axis of the inner bearing race). As the output shaft spline contains two less teeth than the flexible spline (204 to 206), one rotation of the coupling gear (outer bearing race) advances the output shaft two teeth, thus providing a gear reduction ratio of 102:1.

FLIGHT DATA ANALYSIS

Data telemetered from the system during flight consist of the liquid-oxygen flow control valve positions (one for each engine) and two propellant quantity measurements (one for hydrogen and one for oxygen). Typical data from these measurements are shown in figures 16 and 17.

The valve positions during flight are read in degrees. The valve position at any time in flight, in conjunction with engine calibration data, determines the engine burning mixture ratio. These data are then used in evaluation of engine performance.

The total propellant quantities are measured in 40 increments of zero to 5 volts dc. The 5-volt dc range represents one turn of a potentiometer. The potentiometer is a single-turn type. The active part of the potentiometer is 345° , and the dead band is 15° . The ramp is then calibrated across the 345° of rotation, and the 15° is used to reset the output voltage back to 5 volts. Each turn, or "ramp", is given an equivalent mass of propellant. For example, the liquid-oxygen and liquid-hydrogen quantities are usually calibrated at 268 kilograms and 52 kilograms per ramp, respectively. Fractions of a ramp are proportioned linearly to the calibrated kilograms per ramp.

The system operation lends itself readily to evaluation of the propellant quantities and engine flowrates. Also available as reference points from flight data are the events of the liquid levels passing the top and bottom of each probe and enabling and disabling of system control by command from the vehicle programmer. These data, in conjunction with known tank volumes, calculated propellant densities, and calibrated engine mixture ratio as a function of flow control valve angle, allow an accurate evaluation of propellant residuals at the end of powered flight.

FLIGHT EXPERIENCE

As of the time of this writing, nine Centaur vehicles have successfully flown with a propellant utilization system controlling propellant outflow during Centaur powered flight. The operation of the system has been very nearly as predicted. The liquid hydrogen remaining at theoretical liquid-oxygen depletion, which is a measure of the system accu-

TABLE II. - PROPELLANT-UTILIZATION

FLIGHT-PERFORMANCE SUMMARY

Atlas-Centaur flight	Liquid hydrogen remaining at theoretical liquid-oxygen depletion, kg
1	18.1
2	11.2
3	13.0
4	2.3
5	8.2
6	^a -1.1
7	^a -2.2
8	2.5
9	5.8

^aNegative value means that this additional amount of liquid hydrogen was needed to deplete the liquid oxygen at a 5 to 1 ratio of oxygen to hydrogen by mass.

racy, has been less than 20 kilograms. This 20 kilograms compares with a total tanked propellant weight of 13 600 kilograms. These data are summarized in table II.

CONCLUDING REMARKS

To minimize propellant residuals, and increase payload capability, a propellant utilization system is used during powered flight of the Centaur vehicle.

Tests conducted at NASA Lewis Research Center showed that accurate mass sensing of a boiling cryogenic was possible with a cylindrical capacitance probe. These data aided in developing the Centaur propellant utilization system.

The propellant utilization system developed for Centaur consists of

1. Liquid-hydrogen and liquid-oxygen nonperforated concentric cylindrical capacitance probes
2. A solid-state electronics package consisting of a difference bridge and several servoamplifiers
3. Two harmonic drive assemblies used for proportional control of the liquid-oxygen flow control valve

Each of these components developed was of a unique design. The capacitance probes were the first used to measure mass of a boiling cryogenic propellant and had capacitance levels in picofarads. The solid-state electronics used the low-level nanoampere currents

from the probes to produce control signals to the flow control valves. The harmonic drive used for the liquid-oxygen flow valve control was unique with a high gear reduction ratio in minimum weight and volume.

The system concept has been verified by nine Atlas-Centaur flights. The average system error at liquid-oxygen depletion was less than 20 kilograms (i. e. , liquid hydrogen remaining at liquid-oxygen depletion) out of a total tanked propellant weight of 13 600 kilograms.

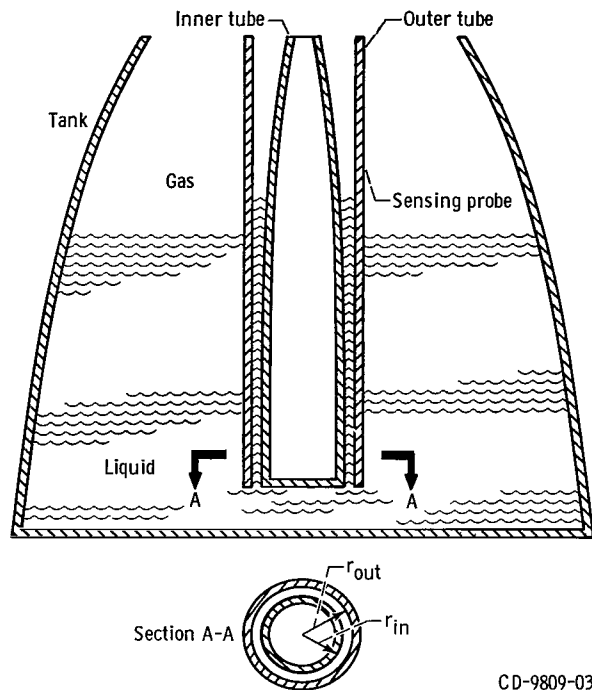
Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 29, 1968,
491-05-00-02-22.

APPENDIX - SYMBOLS

A	area	V_Q	voltage of quadrature rejection potentiometer
C	capacitance, or capacitor	α_o	polarizability per molecule
ΔC	change in capacitance	ϵ	dielectric constant
i	current	ρ	density
K	constant of proportionality	Subscripts:	
K_A	constant of proportionality	D	dry
K_M	$3KK_1/K_A$	EO	empty oxygen conditions
K_o	$4\pi\alpha_o/3$	eo	oxygen quantity error signal
K_1	constant of proportionality which includes K_o	FO	full oxygen conditions
L	length	g	gas
LH ₂	liquid hydrogen	H	hydrogen
LO ₂	liquid oxygen	in	inner
M	mass	l	liquid
N_1	number of molecules per cubic centimeter	O	oxygen
r	radius	out	outer
V	voltage	q	quadrature
V_C	voltage of coast bias potentiometer	S	summed
V_E	voltage of error bias potentiometer	vac	vacuum
		1	state or condition 1
		2	state or condition 2

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Figure 1. - Basic capacitance mass sensing probe.

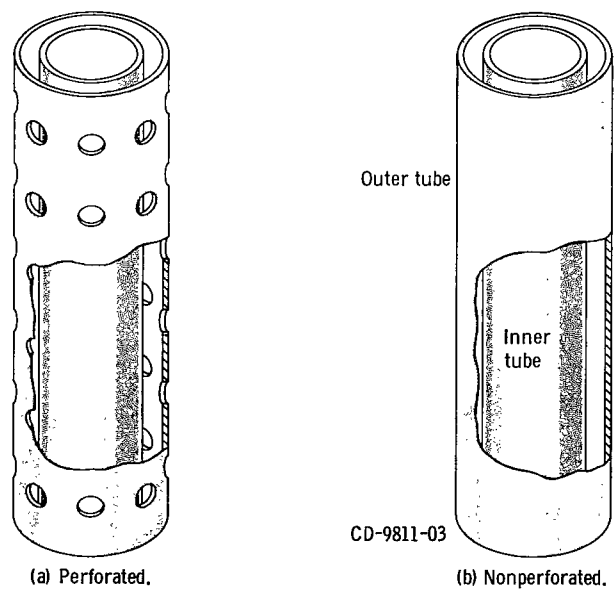


Figure 2. - Capacitance probe types.

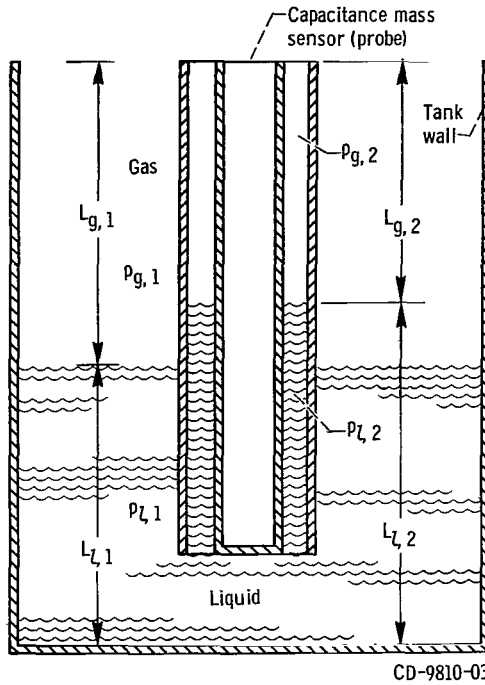


Figure 3. - Manometer effect in nonperforated capacitance mass sensor.

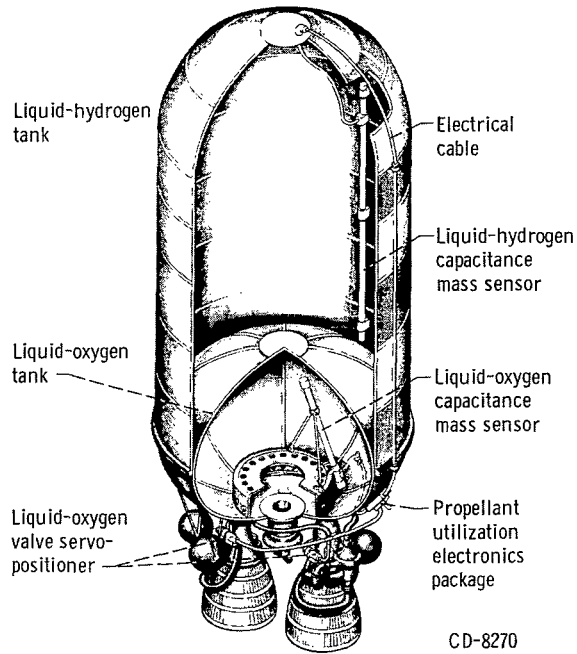


Figure 4. - Centaur propellant utilization system.

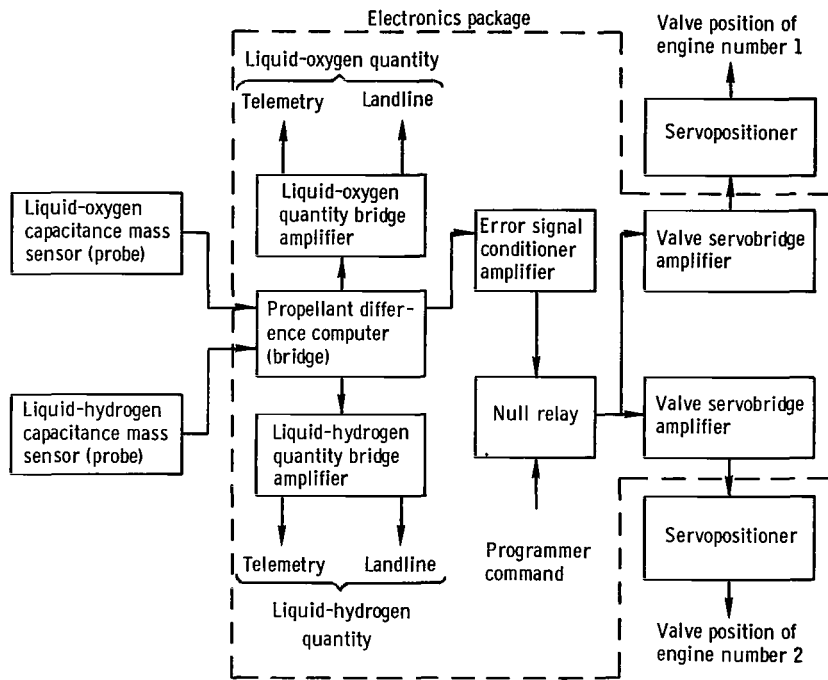


Figure 5. - Block diagram of Centaur propellant utilization system.

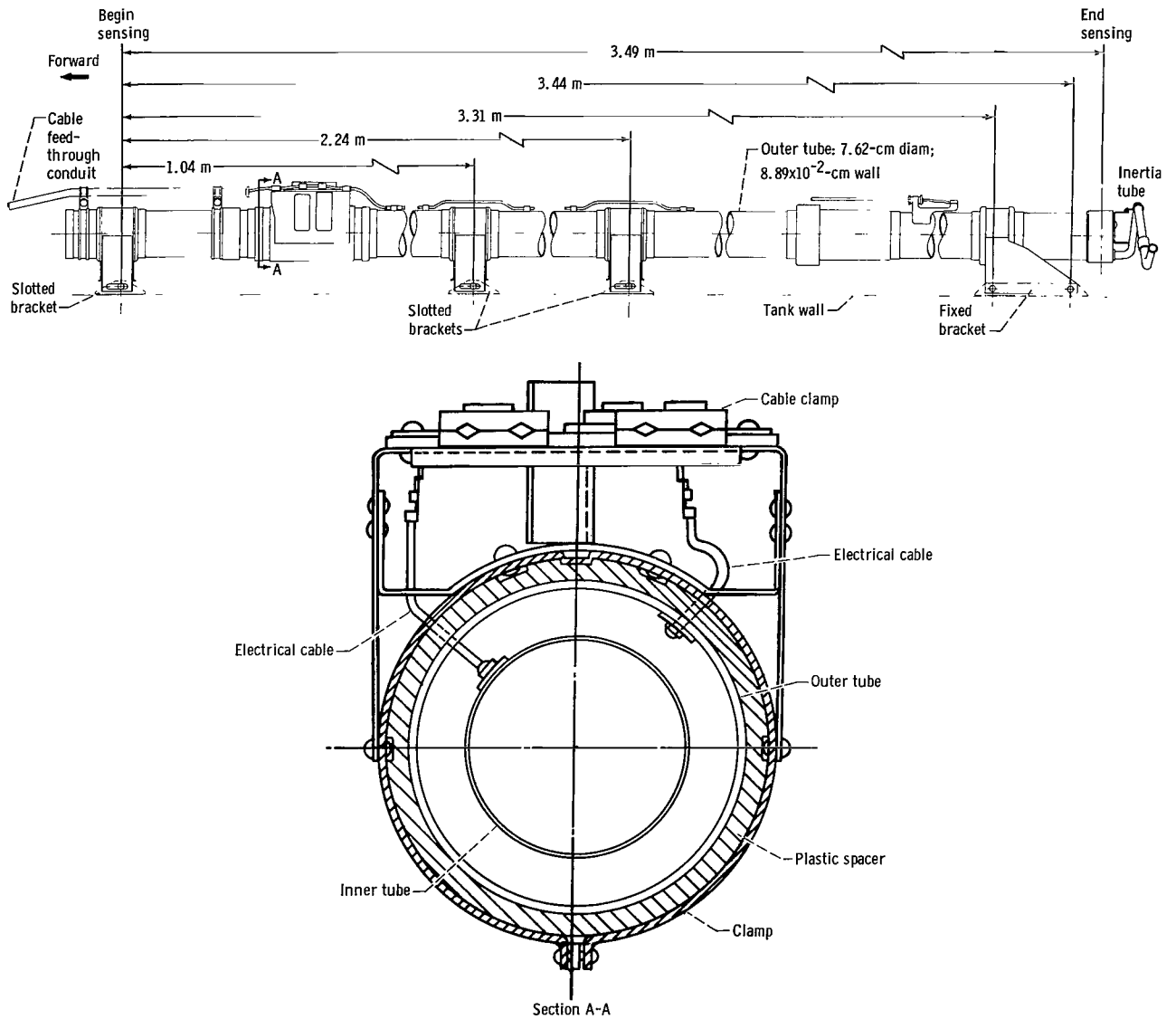


Figure 6. - Centaur liquid-hydrogen propellant utilization capacitance mass sensor (probe).



Figure 7. - Liquid-hydrogen capacitance mass sensor installed in tank.

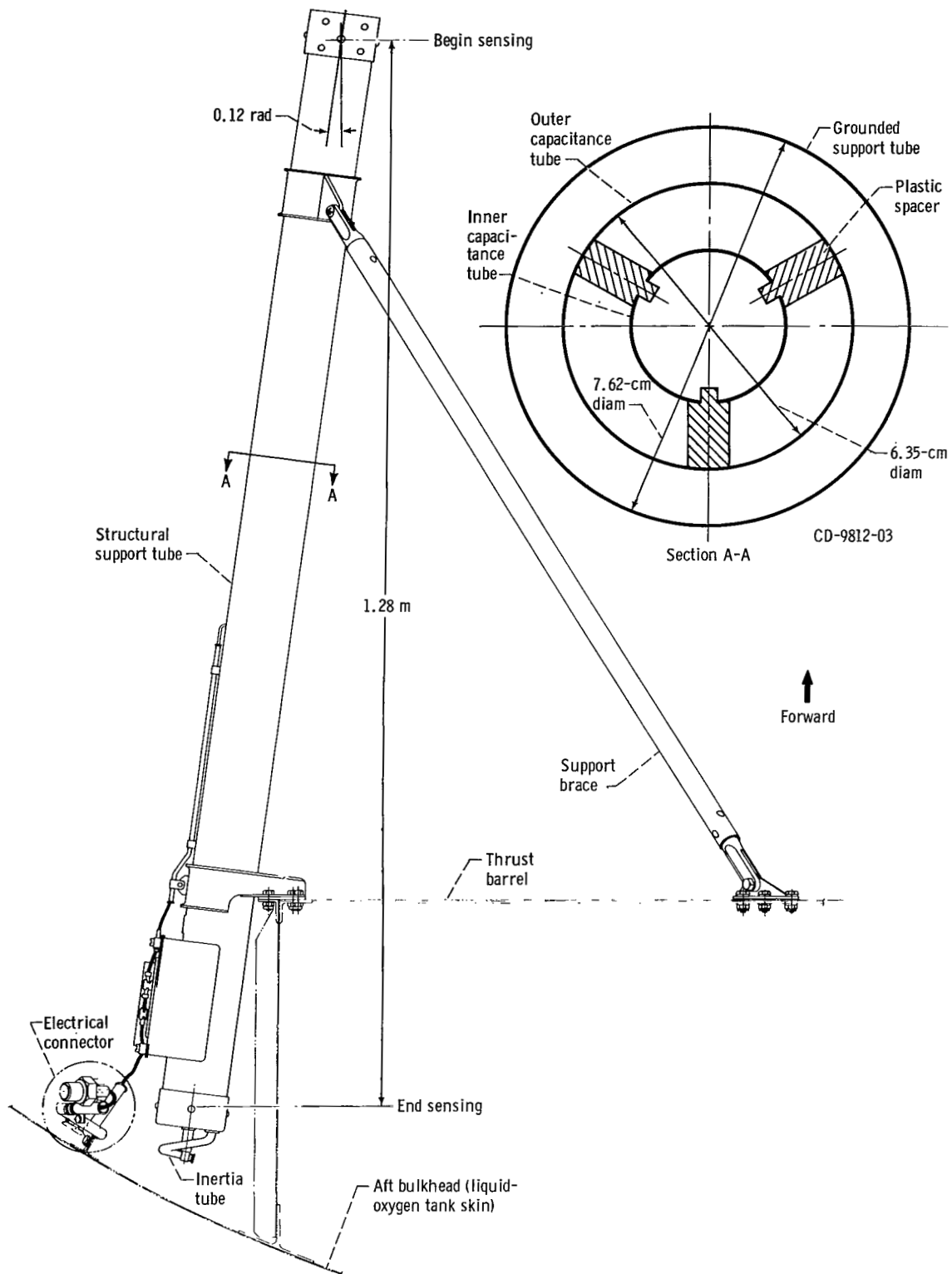


Figure 8. - Centaur liquid-oxygen propellant utilization capacitance mass sensor (probe).

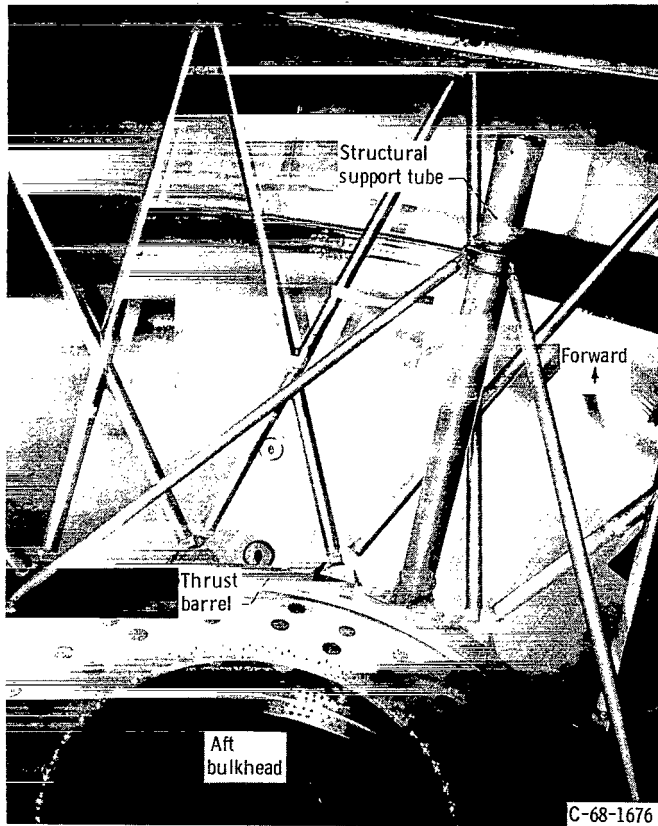


Figure 9. - Liquid-oxygen capacitance mass sensor installed in tank.

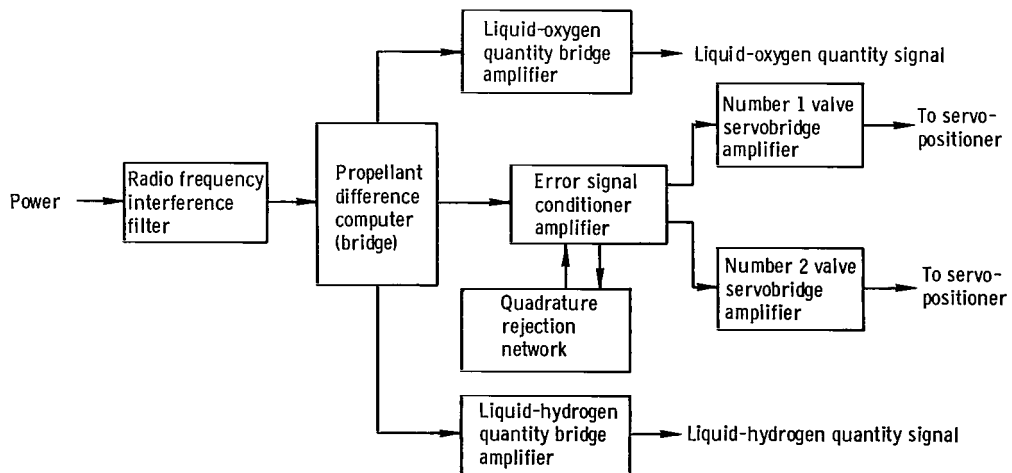


Figure 10. - Block diagram of major subcircuits in Centaur propellant utilization system electronics package.

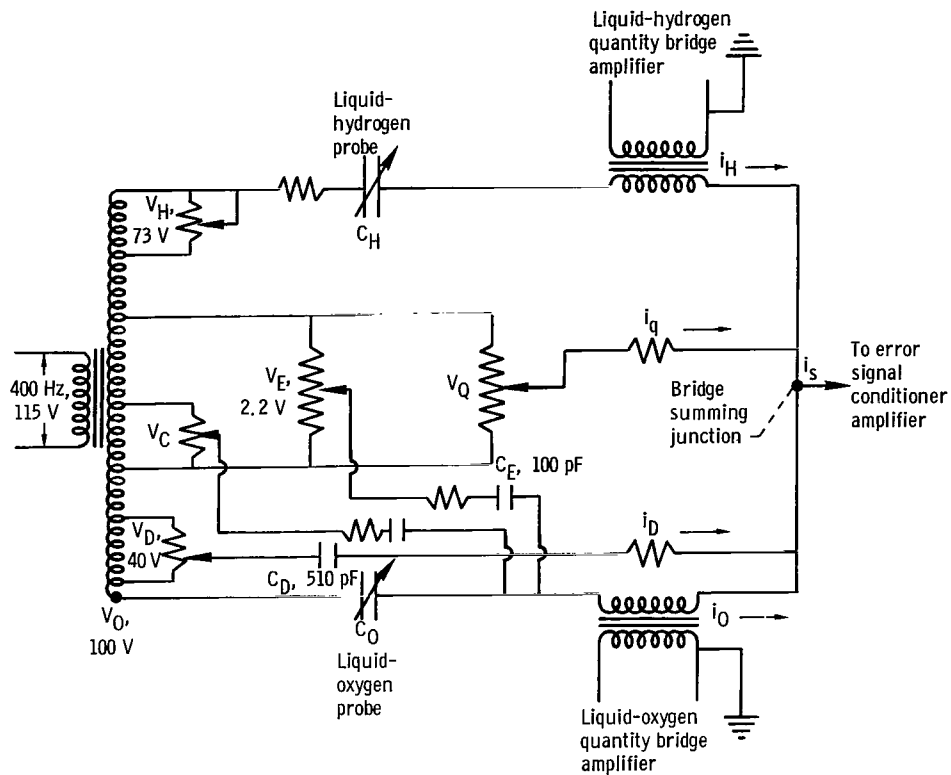


Figure 11. - Simplified Centaur propellant utilization system bridge schematic.

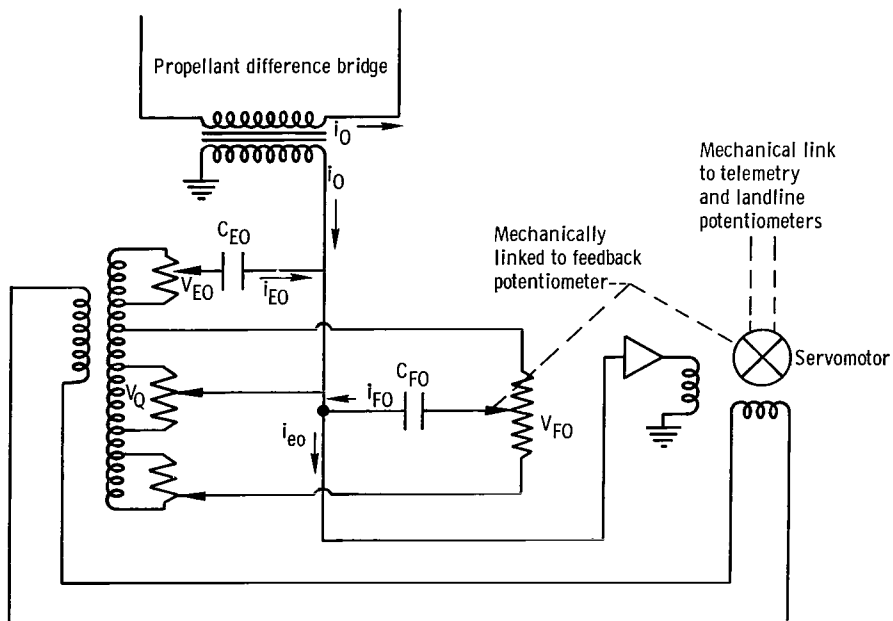


Figure 12. - Simplified schematic of liquid-oxygen propellant quantity bridge amplifier.

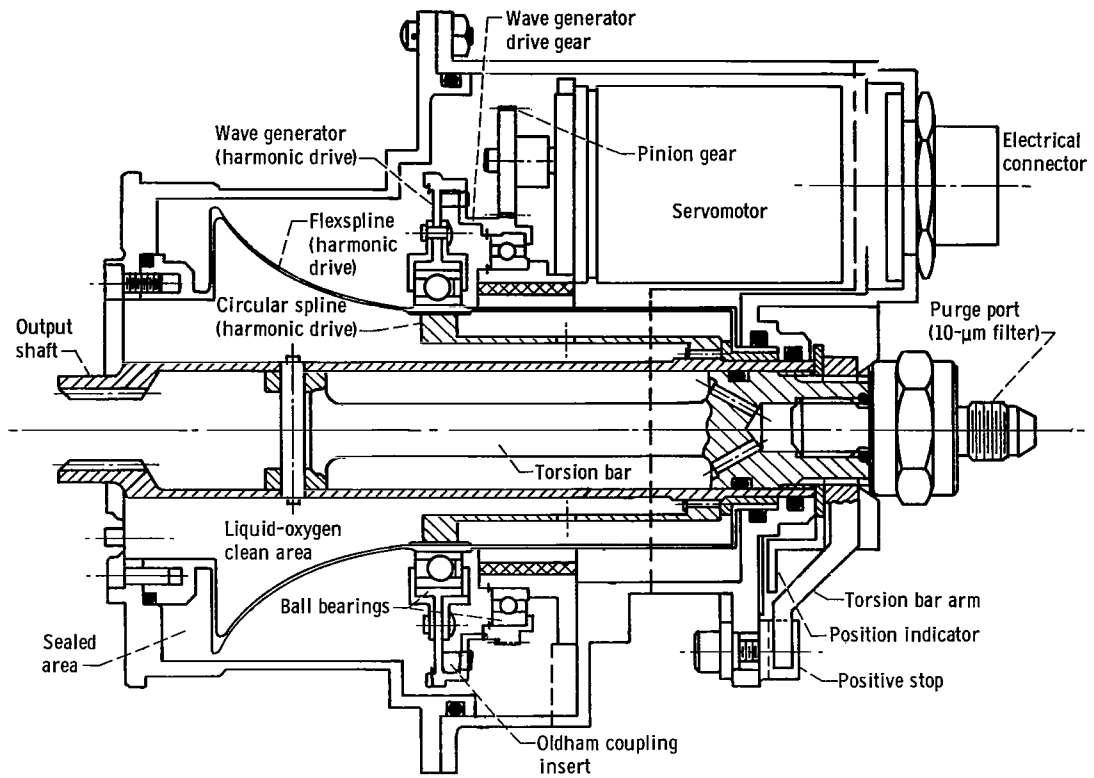


Figure 13. - Cross section of propellant utilization servopositioner.

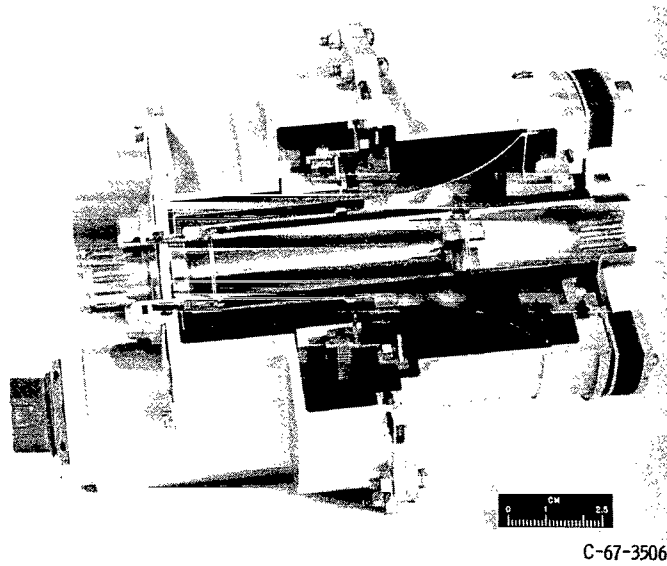


Figure 14. - Sectioned servopositioner.

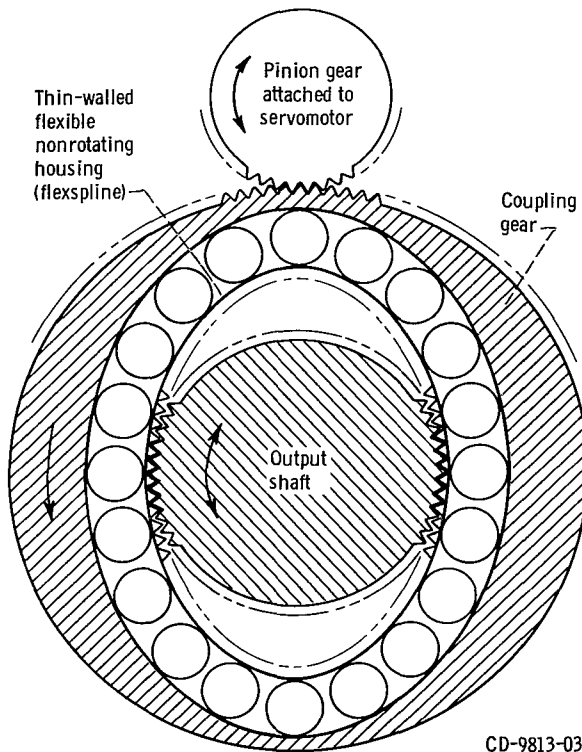


Figure 15. - Schematic of harmonic drive.

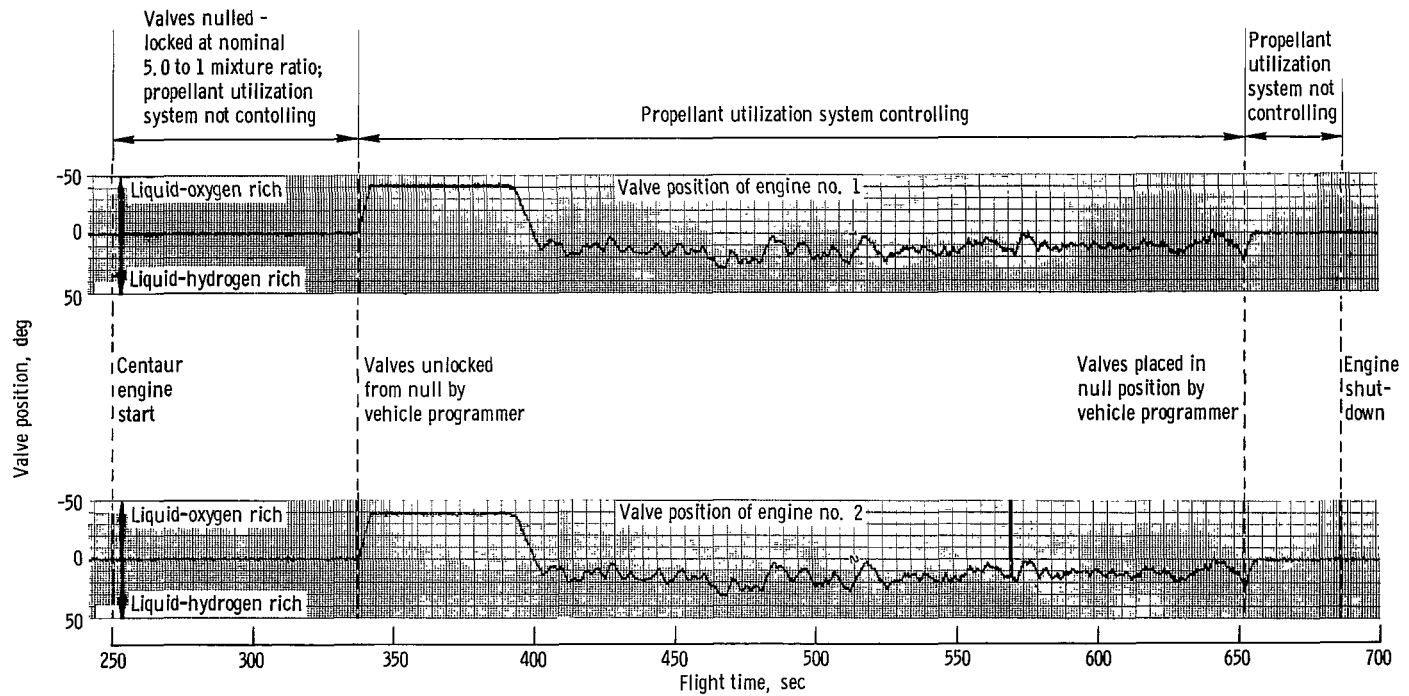


Figure 16. - Typical Centaur propellant utilization system valve-position recording from flight.

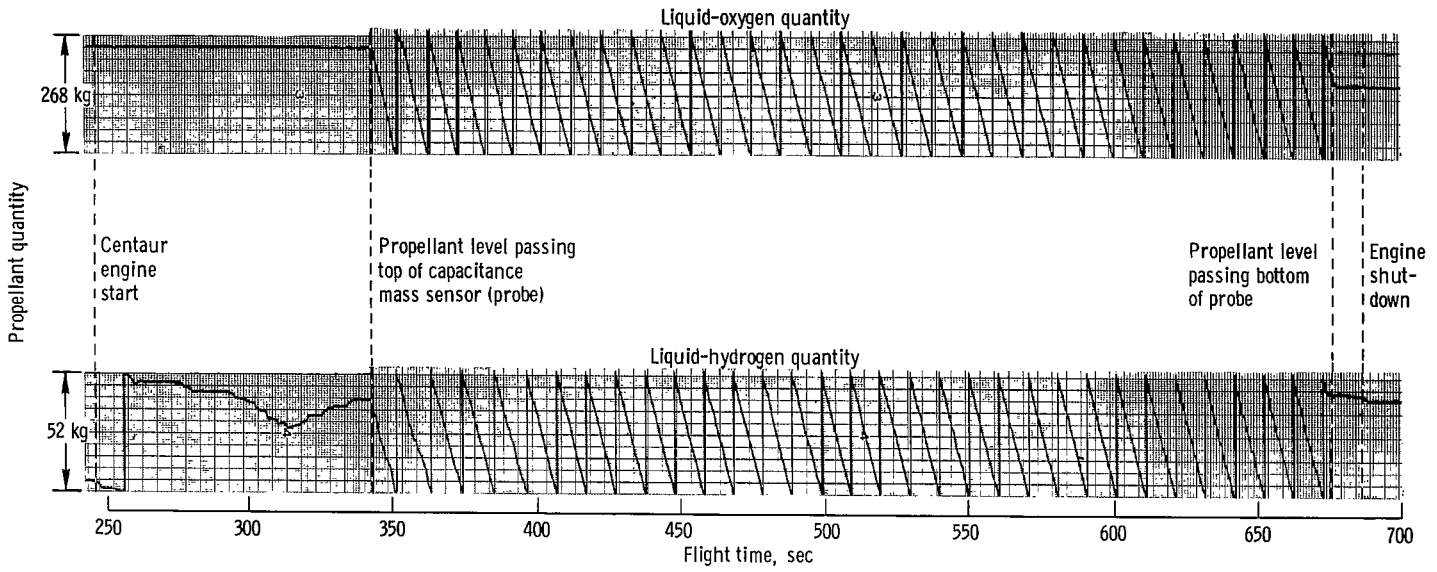


Figure 17. - Typical propellant utilization system propellant-quantity recordings from flight.

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