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SATURN S-IV CRYOGENIC WEIGH SYSTEM

PART II: WEIGH OPERATIONS

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SATURN VEHICLE WEIGHT CONTROL SECTION

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PART II: WEIGH OPERATIONS

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ABSTRACT

Two basic methods for mass determination are: (1) direct measurement, (2) volume and density determination. Both methods or variations have been used to determine space vehicle propellant mass with varying degrees of success. Stringent propellant loading accuracy requirements of ±0.5 percent for the Saturn S-IV Stage have led to the development of a Cryogenic Calibration Weigh System. The method employs accurate electronic force transducers and measuring systems as the standard and experimental weighings have verified achievement of better than the required accuracy.

INTRODUCTION

The S-IV Stage, upper stage of the Saturn I vehicle, utilizes liquid hydrogen and liquid oxygen as its propellants. Continuous capacitance mass sensors in each of the propellant tanks provide the stimuli to the propellant utilization and loading system. Accurate calibrations of the mass sensors are essential to control propellant loading and to assist in minimizing residuals at engine cut-off for the successful fulfillment of the stage mission. The need for propellant utilization is covered in Part I of this series.

The cryogenic calibration method with a weigh system as the standard was developed for the S-IV Stage of Saturn I. Thermal and pressure effects on the propellant tank geometry are minimized by using the actual propellants as the calibration fluids and simulating the pressures to be experienced by the stage under loading conditions. Results from the cryogenic calibration of S-IV-9 (fourth flight stage) indicate that accuracy well within the ±0.5 percent loading requirement was achieved.

In order to provide an accurate standard, a ±0.05 percent tolerance was assigned to the weigh system electronics during the design phase. Subsequent repeatability tests demonstrated that the electronic system which includes force transducers, measuring unit, and recorders, is within ±0.03 percent. The absolute accuracy of the readings is within ±0.05 percent which, for a test stand weigh system, constitute an advancement in the "state-of-the-art". The usual accuracy for this type of system is approximately ±0.1 to ±0.25 percent. The weigh system design for the S-IV was also constrained by limitations resulting from the use of test stands converted from the THOR Program at the Douglas Sacramento Test Center.

The purpose of this paper is to present system design considerations, description of the equipment, operation, and test results of the S-IV weigh system and factors in the development of a potential S-IVB Cryogenic Calibration Weigh System.

S-IV WEIGH SYSTEM DESCRIPTION AND OPERATION

GENERAL

During the cryogenic calibration operation in the stage acceptance test sequence, the S-IV stage is raised in a vertical position in the test stand by means of the weigh ring supported by three pylons and force transducers linkages (Reference Figure 1). The stage is enclosed by upper and lower environmental covers over the liquid hydrogen and liquid oxygen tanks respectively.

The purpose of the environmental covers is to prevent the formation of ice or condensation on the stage (Environmental Control is covered in Part III of this series). Test stand wind screens are provided to minimize wind loads.

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CRYOGENIC CALIBRATION WEIGH SYSTEM

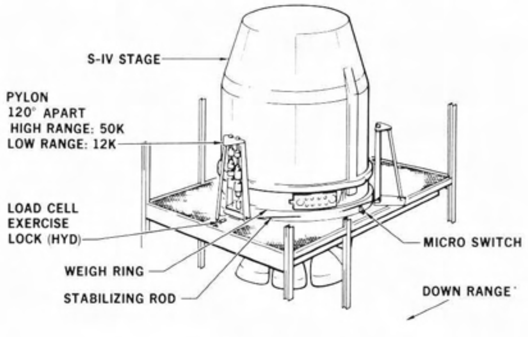

FIGURE 1

The stage propellant tanks are calibrated separately. The procedure developed for the S-IV Stage requires filling the liquid oxygen (LOX) tank and calibrating the mass sensor during the draining cycle. Weight readings are obtained at static points in approximately 5 percent increments. The liquid hydrogen (LH_2) tank calibration requires an additional step in the loading procedure. The LOX tank is filled and pressurized prior to loading the LH_2 tank to minimize stresses in the common bulkhead. If the LH_2 at -423°F were loaded with the LOX side of the bulkhead at ambient temperature, a large thermal gradient would exist. Upon completion of the LH_2 loading, the LOX tank is drained and the LH_2 calibration performed in a manner similar to that for the LOX tank.

In addition to the continuous mass sensors, there are point level sensors located near the bottom of each tank that indicate three different liquid levels.

In the determination of propellant mass, the bias tare is contributed by the stage, weigh ring, environmental enclosures and restraints. Ullage gas temperature and pressure are monitored and recorded in each tank to provide tare corrections. In the liquid oxygen tank, the ullage gas tare correction requires the determination of the concentrations of gaseous oxygen and the helium pressurization gas. Gaseous hydrogen is used to pressurize the hydrogen tank and no ullage gas samples are necessary.

Liquid temperature sensors are also monitored during the tests to maintain a subcooled propellant condition. Periodic venting is required when the propellant in the tank being calibrated approaches the saturated condition.

Simultaneously with the weight readings, mass sensor readings are obtained. Other parameters recorded are skin temperatures, environmental cover inlet and outlet temperatures and pressures, ambient temperature and barometric pressure.

These are used to correct for skin temperature variations between calibration and static firing or launch conditions, changes in environmental cover gas mass tare, and air buoyancy effects.

WEIGH SYSTEM ELECTRONICS

The weigh system electronics consists of three general classes of component; force transducers, measuring units, and recording units (Reference Figure 2). The force transducers are located in the test stand pylons, the measuring console is in the test stand terminal room, and the recording units, which also contain the monitoring panels, are in the blockhouse.

CRYOGENIC CALIBRATION WEIGH SYSTEM
MEASURING AND RECORDING BLOCK DIAGRAM

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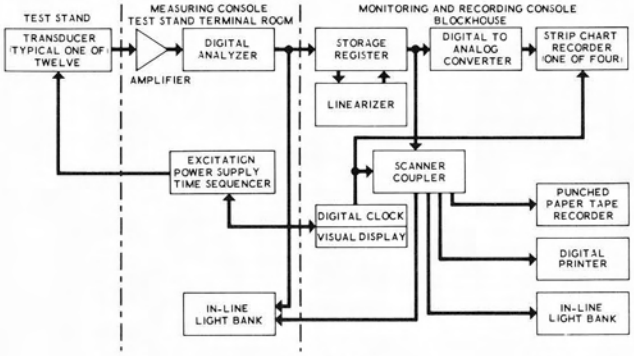

FIGURE 2

FORCE TRANSDUCERS

The force transducers are of the bonded strain gage, universal type, 2 millivolt (mv) output per volt input, used in tension. A total of twelve (12) transducers, six (6) of 12,000 pound capacity and six (6) of 50,000 pound capacity, are mounted into three pylons. Each pylon contains a "string" of two 12,000 pound capacity transducers in series and a "string" of two 50,000 pound capacity transducers for a dual range capability (Reference Figure 3).

In either the high or low range operation, the proper selection of the hydraulic actuators connecting each of the string assemblies to the pylons raises the weigh ring at three points. The total capacity of the low range transducers is 36,000 pounds and the capacity of the high range is 150,000 pounds. The redundancy in having two identical capacity transducers in series for each string enables the comparison of one transducer readout against the other, as well as providing a backup system.

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TYPICAL PYLON
TRANSDUCER
STRING
INSTALLATION

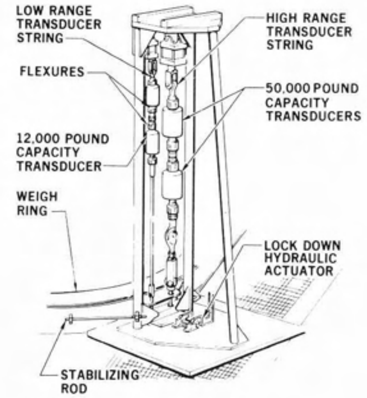


FIGURE 3

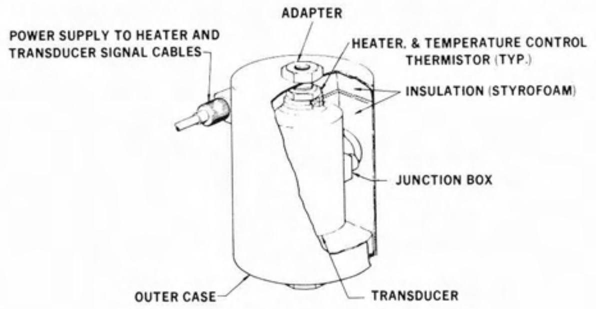
Dual range capability not only enhances the system resolution but also increases the transducer signal output level. Due to the difference in the propellant densities and to the engine mixture ratio of 5 to 1, the maximum loading of liquid hydrogen is approximately 17,000 pounds and that of liquid oxygen is 85,000 pounds. As the maximum 2 mv per volt output occurs at the full scale capacity of the transducers, the output during hydrogen mass sensor calibration would have been only one-fifth of that during a LOX calibration (excluding tare weight) without the dual range capability. Resolution is further increased by a technique where each transducer is subjected to approximately a 90 volt pulsed-input instead of the usual constant 10 to 15 volts for a maximum output of approximately 180 mv. This is possible due to the twenty-pulse-per-second interrogation; each pulse is of two milliseconds duration for a total of 40 milliseconds each second. Thus, the power consumption is substantially less than that for a normal continuous transducer operation. The six high or low range transducers are interrogated sequentially. This cycle is repeated 20 times per second. Although the transducers were temperature compensated by the manufacturer for zero load and modulus effects (0.0013 percent of full scale per 1°F change and 0.0008 percent of full scale per 1°F change respectively), each transducer is provided with electrical heaters at both extremities and insulated with styrofoam (Figure 4). The heaters are thermistor controlled and set at 115 ±5°F to provide stability and repeatability of the transducer readings over the wide temperature range which is experienced at the Sacramento Test Center.

MEASURING UNIT

The measuring unit consists of the excitation supply, transducer heater monitor and controls, amplifiers and the digital analyzer. This unit is located in the test stand terminal room. Serial transfer of the signals from the transducers numbered one through six is routed to each of the respective amplifiers on the proper high or low range channels. The amplifier gain is approximately 60. The signals are then routed to a solid state digital analyzer for binary coded decimal (BCD) conversion. The digital analyzer as well as the excitation power supply unit is temperature-controlled to enhance system stability. The 30,000 binary bit outputs of the digital-voltmeter-type-analyzer are then transmitted in parallel to the blockhouse recording unit for further conditioning. The transducer zero and span setting are made at the measuring unit. The span settings are determined by repeated dead weight application at approximately the capacity of the transducers during the weigh system calibrtion.

BLOCKHOUSE RECORDING AND MONITORING CONSOLE

The recording and monitoring console consists of remote controls for the terminal room console, recording equipment, monitoring and recorder control panels, weight computor (transducer linearizers) and a digital clock.



TRANSDUCER TEMPERATURE CONTROL

FIGURE 4

The digitized (BCD) data, transmitted by means of coaxial cables from the terminal room, enter a storage register. The data are received in sets of six blocks, one block for each transducer, four milliseconds apart.

The stored data are then input to the weight computor for linearization. Each transducer has a unique linearity which is determined by a dead weight calibration. The resulting non-linearity correction for each transducer is then programmed in the miniature computor contained within the recording console by means of switch setting positions. Two sets of gates are provided for each transducer linearizer channel. The first set provides 15 coarse corrections where each gate corresponds to 2,000 incremental bits. The second fine-correction-set of 10 gates corresponds to 200 bits. The linearizer adds back into the storage register at a rate of 40 times every two seconds.

The linearized data are then routed from the storage register through a set of eight gates which also performs the first step of scale factoring, the changing of bit data into weight data. Since 30,000 bits are equal to full scale, the low range has two and one half bits per pound and the high range has one bit equal to two pounds.

Four strip chart recorders are provided. These recorders are of the extended-range-type capable of continuously recording either high or low range. The method employed to obtain the extended range capability is to convert the last 500 bits of the digitized data back into analog signals by means of a digital to analog converter. The remaining data are retained in digital form in the storage register and routed to Royson Printers. The printers activate every two seconds and record directly onto the strip chart to aid in the data reduction. In this manner the eleven inch width of the strip chart represents 1000 pounds and 200 pounds respectively for the high and low range traces of the individual transducers. The one-quarter-second response of the recorders per span shift coupled with the variable chart speed is adequate for obtaining dynamic weight readings during the propellant drain cycle.

In addition to the strip chart recorders, there are two additional modes of recording the weight data. The first consists of a paper punch tape and a spare unit. The second is a digital printer. The purpose of the punch tape is to provide computer-programming-capability of the data reduction and tare corrections necessary for the cryogenic calibration. The punched tape is converted to magnetic tape and input directly to a IBM 7090 computer. The digital printer provides a "quick look" of the linearized, but otherwise uncorrected, raw data. Both the punched tape and printed tape contain identical information updated every two seconds.

WEIGH SYSTEM MECHANICAL COMPONENTS

The mechanical components of the weigh system are located on the test stand and in the terminal room. These include the pylon assemblies, weigh ring, (Reference Figure 1) environmental cover system, and hydraulic units.

Past experience with electronic weighing devices indicates that the greatest source of mechanical errors result from force misalignment, excessive deflection of the test equipment, and constraints. Experience indicated that for the best repeatability, a tension system was desirable. In order to provide a tension system, three pylons were located about a weigh ring at 120 degree intervals. The purpose of the weigh ring is to provide a rigid support for the stage in the vertical weighing position. Two stabilizing rods are attached to the weigh ring at each of the pylons to prevent rotational and translation movements of the weigh ring with minimal vertical restraint required for weighing. Weigh ring clearance is indicated by three limit switches.

In order to minimize force misalignment and errors due to induced bending moments, cross-web-type flexural pivots are used. Each string has one flexural pivot above and below each transducer and terminates with two spherical rod end bearings. The rod end bearings provide ease of transducer string removal from the pylons for dead weight calibrations or repairs as well as to provide initial alignment. The entire string is calibrated as a unit. Two flexural pivots are used to obtain the maximum force alignment and repeatability. In Douglas-conducted tests, it was discovered that errors as large as ±0.2 percent could result from induced moments. With two flexures, errors due to the moment were reduced to ±0.006 percent.

HYDRAULIC SYSTEM

The hydraulic system consists of three sets of actuators. One set is used to raise the stage, another for transducer string lockdown, and the third for off-stand calibration. The first two sets are controlled from the blockhouse. Each transducer-string is connected to an actuator for raising the stage. During normal operation, the actuators raise the transducer strings and engage the weigh ring supporting the stage at each of three lifting ears. Prior to the weighing operation, a lockdown actuator in each pylon is used to engage the transducer string at the lower extremity to the restraining bar by means of a locking plate. The stage raising actuator can thus be used to provide identical forces to each of the two transducers in the string for exercising or comparison.

A single 3,000 psig hydraulic power unit is used to provide the working pressure for all three sets of actuators.

WEIGH SYSTEM CALIBRATIONS AND CHECKOUTS

GENERAL

In previous test-stand-weigh-systems, it was difficult to calibrate or checkout the transducers and associated instrumentation accurately. The S-IV Weigh System was designed to incorporate many of the features lacking in the previous systems. The first consideration was an accurate calibration standard. This standard consists of 60,000 pounds of class "C" tolerance (±0.006 percent) dead weights. The second consideration was the isolation of the test stand mechanical component effects from the transducer and instrumentation.

For the calibration of the electronic components, the transducer strings are removed from the test stand pylons and installed one or two strings at a time into an off-stand calibration fixture (Reference Figure 5). While the dead weights provide the capability of calibrating and checking the entire system, malfunctions between the transducer and the final recording unit are more difficult to isolate. Further, the removal of the transducer strings and subsequent dead weight calibration for checkout requires considerable effort and is performed only at three month intervals. A simpler method is using the pylon lockdown system previously mentioned for comparing one transducer reading against the other by applying identical forces to each transducer string. This checkout is not a calibration, nor is it intended to replace dead weights. By the use of a multi-position standardizer load cell simulator, it is possible to simulate transducer analog output incrementally without the transducers. This method of substituting the transducer and cable at each transducer terminal of the measuring console, checks the integrity of the system downstream of the transducers

OFF-STAND CALIBRATION FIXTURE

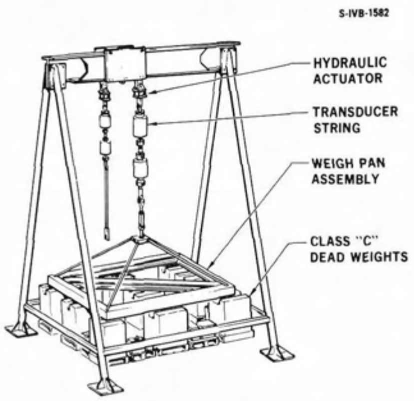


FIGURE 5

and cables. The recording system may also be isolated from the measuring units by inserting digitized signals rather than analog signals with the self-contained binary bit inserter. This unit is used to check the strip chart recorders, inline light banks, digital printer and punched tape units.

The following is a brief description of the off-stand calibration and tare repeatability tests.

OFF-STAND CALIBRATION

Periodic calibrations are performed to ascertain the status of the weigh system electronics. The A-frame test fixture provides accurate calibration, with minimum effects from the test stand mechanical components.

Calibrations include tests for transducer and instrumentation zero and span stability, transducer linearity, accuracy of the self-contained transducer linearizer and load-simulating standardizer. Results of the low range transducer tests conducted prior to calibration of the S-IV-9, indicated that the following specified tolerances were met:

Test	
Zero instability	Not to exceed ±0.01% full scale
Span instability	Not to exceed ±0.02% full scale
Accuracy	Within ±0.05 from 50% full scale to full scale and with a linear variation from ±0.05% at 50% full scale to ±0.08% at 20% full scale.

TARE REPEATABILITY TESTS

Prior to initial weigh system usage, a series of tare repeatability tests were performed with the stage installed on the weigh ring. The non repeatability of the stage constraints, with the environmental system operating, was approximately ±17 pounds.

S-IV CRYOGENIC CALIBRATION RESULTS

The weigh system data are corrected for tare weight, changes in ullage gas masses, and change in air buoyancy to determine the propellant mass. Results of a LOX tank calibration for the S-IV-9 are shown in Table 1.

The accuracy of the cryogenic calibration was verified by summing all of the independent errors for the total combined propellant load. The result of the rss (root-sum-square) summation for S-IV-9 was ±0.11 percent for a conservative estimate of one sigma probability. The three-sigma value of the loading accuracy of ±0.34 percent is well within the guaranteed requirements of ±0.5 percent. Table 2 presents the magnitude of weigh system, procedural, and mass sensor errors at the 100 percent loading region.

FUTURE WEIGH SYSTEM

Currently, a potential weigh system is under consideration for the S-IVB Stage cryogenic calibration. This stage contains approximately twice the amount of propellants as the S-IV. The existing S-IV weigh system and test stand components can not accomodate the increased stage dimensions or weight.

Since two new test stands were required, the S-IVB weigh system was included in the initial test stand design. A single-point-suspension system was selected.

The single-point system greatly simplifies the electronic design. The number of transducers and associated cabling is reduced to one-third of that required for a three-point-suspension system. By incorporating a self-contained or modular concept, where the force transducer and instrumentation as well as the principal hydraulic units are installed as a portable kit unit, the same kit may service more than one stand (Reference Figure 6).

TEST STAND CRYOGENIC CALIBRATION WEIGH SYSTEM

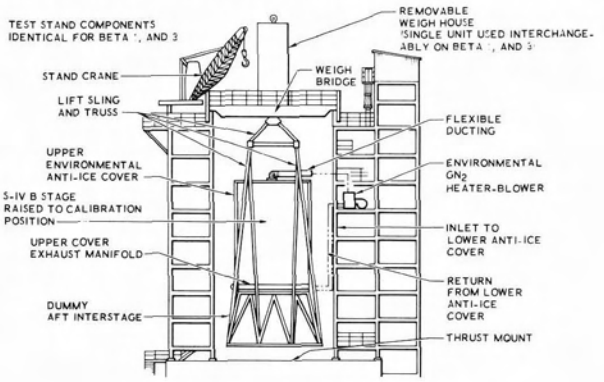


FIGURE 6

TABLE 1. DERIVATION OF LOX PROPELLANT MASS FOR CRYOGENIC CALIBRATION CD 67362 A

(M_G) WEIGH SYS DATA GROSS MASS (LBM)	(M_T) TARE WEIGHT (LBM)	(ΔM_{GAS}) CHANGE IN MASS OF GAS			(Δb) CHANGE IN AIR BUOYANCY (LBM)	(M_P) PROPELLANT MASS (LBM)	($C_{w/s}$) CAPACITANCE (pf)
		He SPHERES	LH_2 ULLAGE (LBM)	LOX ULLAGE (LBM)			
106895	21022	He SPHERES UNPRESSURIZED	-2	-74	5	85954	397.70
106006				-73	5	85064	396.40
105222				-73	5	84280	395.26
104109				-72	4	83165	393.75
103477				-72	4	82533	392.72
101050				-71	4	80105	389.24
96867				-70	4	75921	382.96
92590				-58	3	71631	376.83
88374				-56	3	67413	370.72
83913				-53	3	62949	364.13
79848				-50	3	58881	358.12
75604				-46	3	54633	351.82
71307				-42	2	50331	345.49
67237				-40	2	46259	339.39
62365				-35	2	41382	331.96
58864				-32	2	37878	326.82
54732				-29	2	33743	320.64
50517				-26	2	29525	314.44
46312				-22	2	25316	308.22
42214				-20	1	21215	301.94
41930				-10	1	20921	301.42
33766				- 9	1	12756	289.48
30791				- 1	0	9772	285.20
29300				+ 2	0	8278	283.35
25665				+ 6	0	4639	277.56
24433				+10	0	3403	276.61
23562				+11	0	2531	274.50
22107	21022		-2	+11	0	1076	272.23

$$M_p = M_G - M_T - \Delta M_{GAS} + \Delta b$$

M_p = PROPELLANT MASS (IN TANK ONLY)

M_G = GROSS MASS (STAGE + PROPELLANT + GAS ETC.)

M_T = TARE WEIGHT

ΔM_{GAS} = CHANGE IN MASS OF GAS (GAS IN PROPELLANT TANKS)

Δb = CHANGE IN AIR BUOYANCY

$C_{w/s}$ = ABSOLUTE CAPACITANCE OBTAINED DURING CRYOGENIC CALIBRATION

TABLE 2. DSV-IV-9 PROPELLANT LOADING ERROR ANALYSIS

ERROR CONSIDERED	LH_2 TANK		LOX TANK	
	100% ERROR (lbm)	TARE ERROR (lbm)	100% ERROR (lbm)	TARE ERROR (lbm)
Weigh System Hardware				
1. Electronics	±15	± 4	±25	± 8
2. Dead Weights	± 3	± 1	± 7	± 1
3. Mechanical				
a. Tare Repeatability	±17	± 3	±17	±17
b. On Stand	±20	± 4	±20	±20
Procedural Errors				
1. LOX Ullage	±10	±10	± 2	±13
2. LH_2 Ullage	± 3	±13	± 2	± 2
3. Helium Spheres	± 2	± 2	-	-
4. Upper Cover	± 1	± 1	-	-
5. Lower Cover	± 5	± 5	± 3	± 3
6. Fwd Interstage	± 1	± 1	± 2	± 2
7. Umbilicals (Trapped Propellants)	± 1	-	±11	± 3
8. Residuals	-	± 1	-	± 9
9. Buoyancy	±24	±24	±23	±23
10. Ice Formation	-	-	±15	±15
11. Stage Tilt (Based on ±1/10° tilt at STC)	± 3	-	±20	-
12. Combined Tanking				
a. Pressure Effect	± 3	-	±16	-
b. Temperature Effect	± 3	-	±16	-
13. Stage Tilt (Based on ±1/5° tilt at KSC)	± 6	-	±40	-
14. Tank Skin Temperature	±25	-	-	-
Mass Sensor				
1. Output Measurement (STC)	± 4	-	±21	-
2. Output Measurement (KSC)	± 4	-	±21	-
3. Calibration Equipment	± 4	-	±21	-
4. Bridge Variation	± 8	-	±42	-
5. Empty Capacitance	± 7	-	± 3	-
6. Gas Effect	± 5	-	±11	-

Total LH_2 tank calibration

$$\text{error (RSS)} = \pm\sqrt{\Sigma(100\%\ \text{ERRORS})^2 + \Sigma(\text{TARE ERRORS})^2}$$

$$= \pm\ 59\ \text{lbm}$$

Total LOX tank calibration

$$\text{error (RSS)} = \pm\sqrt{\Sigma(100\%\ \text{ERRORS})^2 + \Sigma(\text{TARE ERRORS})^2}$$

$$= \pm\ 99\ \text{lbm}$$

$$\text{Total combined error} = \pm\frac{\sqrt{(59)^2 + (99)^2}}{101{,}400} \times 100 = \frac{115}{101{,}400} \times 100$$

$$= \pm\ 0.113\%\ (1\sigma\ \text{probability})$$

$$\text{or}\quad \pm\ 0.339\%\ (3\sigma\ \text{probability})$$

The reduction of electronic components as well as the shorter cable leads also enhance system reliability. The interchangeable feature, together with the portability, also enables the removal of the entire measuring unit from the test stand for accurate dead weight calibration.

The measuring instrumentation will utilize the same pulse technique as was used for the Orbitran Company S-IV system to interrogate a single dual range, dual bridged transducer. The major difference is in the data recording and conditioning system (Reference Figure 7). The weigh system electronics interfaces with Control Data Corporation CDC 924A computers for the monitoring and recording functions. The CDC 924A computers are components of the Automatic Stage-Checkout Ground Support Equipment and the Ground Instrumentation System required for stage checkout and acceptance firings.

S-IVB CRYOGENIC CALIBRATION WEIGH SYSTEM INSTRUMENTATION

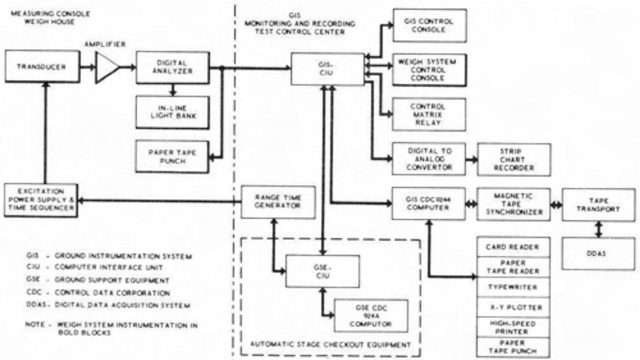


FIGURE 7

CONCLUSION

The cryogenic calibration method with a weigh system as the direct mass measurement standard provides the best means of fulfilling the stringent S-IV propellant utilization and loading accuracy requirements. With the demonstrated weigh system electronic accuracy within ±0.5 percent, achievement of mass sensor calibrations well within ±0.5 percent is possible. Refinements in the calibration technique and system design are expected to result in mass sensor calibration accuracies approaching ±0.25 percent for the S-IVB Stage. The use of the actual cryogenic propellants as the calibration fluids minimizes the errors associated in extrapolation from non-cryogenic loading conditions.

Considering the large amount of data required for each mass sensor calibration, a digital weigh system has distinct advantages for a computer-controlled operation with recording capability.

S-IV experience indicated that the manual data reduction technique required from five to six man-months per calibration. Computer programs can accomplish the same task with approximately one-eighth of the man power.

The single point suspension system planned for the potential S-IVB system simplifies the electronic system design. This simplification not only reduces the number of transducers but also reduces the amount of weight data.

Reliability and accuracy are increased by designing for ease of calibration, including checkout capability, whether a single or multiple-point suspension system is selected.

ACKNOWLEDGMENT

The work presented herein was accomplished by the Missile and Space Systems Division, Douglas Aircraft Company, under the Saturn Program (Contract NAS7-1) sponsored by NASA Marshall Space Flight Center.

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