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MCDONNELL DOUGLAS TECHNICAL SERVICES CO.
HOUSTON ASTRONAUTICS DIVISION

SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

DESIGN NOTE NO. 1.4-2-9

ERROR ANALYSIS OF THE SHUTTLE REACTION CONTROL SYSTEM PROPELLANT GAGING MODULE

MISSION PLANNING, MISSION ANALYSIS AND SOFTWARE FORMULATION

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1.0 SUMMARY

The Shuttle reaction control system (RCS) pressure-volume-temperature (P-V-T) propellant gaging module contains a constant bias for gaging inaccuracy resulting from random instrumentation measurement errors and from propellant loading uncertainties. This bias is required to adjust the computed RCS propellant quantity down to a level at which the upper limit of uncertainty will not result in a gage reading higher than the actual usable propellant remaining.

An investigation of the RCS propellant gaging module has revealed that the gaging errors due to the combined effects of random instrumentation measurement errors and propellant loading uncertainties are non-linear over the range of the propellant quantity gage (0-100%), with the largest error occurring at the zero point. When the RCS propellant tanks are filled to contain 100% of the maximum usable propellant, the largest gaging error was determined to be 3.9% for the fuel and 5.4% for the oxidizer. When the RCS propellant tanks initially contain 50% of the maximum usable propellant, the largest gaging error increases to 4.0% for the fuel and 5.6% for the oxidizer.

2.0 INTRODUCTION

This document presents the results of an error analysis performed on the RCS propellant gaging module detailed in Reference (A). These results are based on the current definition of the 3σ limits for the nominal propellant loading conditions and instrumentation measurement error source tolerances. The computed propellant quantity gaging errors are considered to be the 3σ gaging errors and they should serve as a basis for determining mission RCS propellant requirements.

The following assumptions were used throughout the analysis:

1. The propellant gaging software module is identical to that defined in Reference (A) except for a) Block 17 - where a helium bottle stretch expression for a fiber wrapped bottle was used, b) Block 28 - where values of SOLPRS(J) (the constants used to compute the helium solubility in the propellants) applicable to a propellant tank operating pressure of 246 psia were used, and c)Block 30 - where the quantity of deliverable propellant was computed in pounds rather than in percent remaining.

This software contains the best available expressions for propellant density and vapor pressure as a function of temperature, helium compressibility as a function of pressure and temperature, helium solubility in the propellants, and helium bottle stretch as a function of internal pressure. Therefore, it is deemed that any systematic errors introduced into the propellant gaging module by the use of simplifying approximations in the software are negligible when compared to the random instrumentation measurement errors and propellant loading uncertainties.

2. The RCS baseli… helium/propellant supply systems and instrumentation configurations are given in Reference (B) and shown in Figure (1).

3. The propellant tank and line volumes are presented or inferred in Reference (C).

4. The propellant tank normal operating pressure is given in Reference (C).

5. The propellant loading, and usable and unusable propellant quantities are given in Reference (C).

6. The propellant loading tolerance is presented in Reference (C).

7. The helium bottle volume is given in Reference (D).

8. The 3σ tolerance on the helium bottle volume at ambient pressure is ±12.0 cubic inches.

9. The helium line volumes are given in Reference (E).

10. The pressure and temperature instrumentation full scale ranges and system accuracies (3σ tolerances) are identified in Reference (F). These system accuracies are obtained by matching each instrument with the appropriate sensor calibration constants discussed in Section 8.4 of Reference (A). The 3σ tolerances quoted are assumed to be the total measurement errors resulting from the sensor errors and the calibration errors. In this analysis, the pressure sensing accuracy has been adjusted to reflect the use of the average pressure obtained from two sensors.

11. The initial and operating pressure and temperature measurements are made by the same set of instrumentation.

12. The 3σ tolerance on the difference between the initial ullage temperature and the sensor measurement is ±5.0 °F.

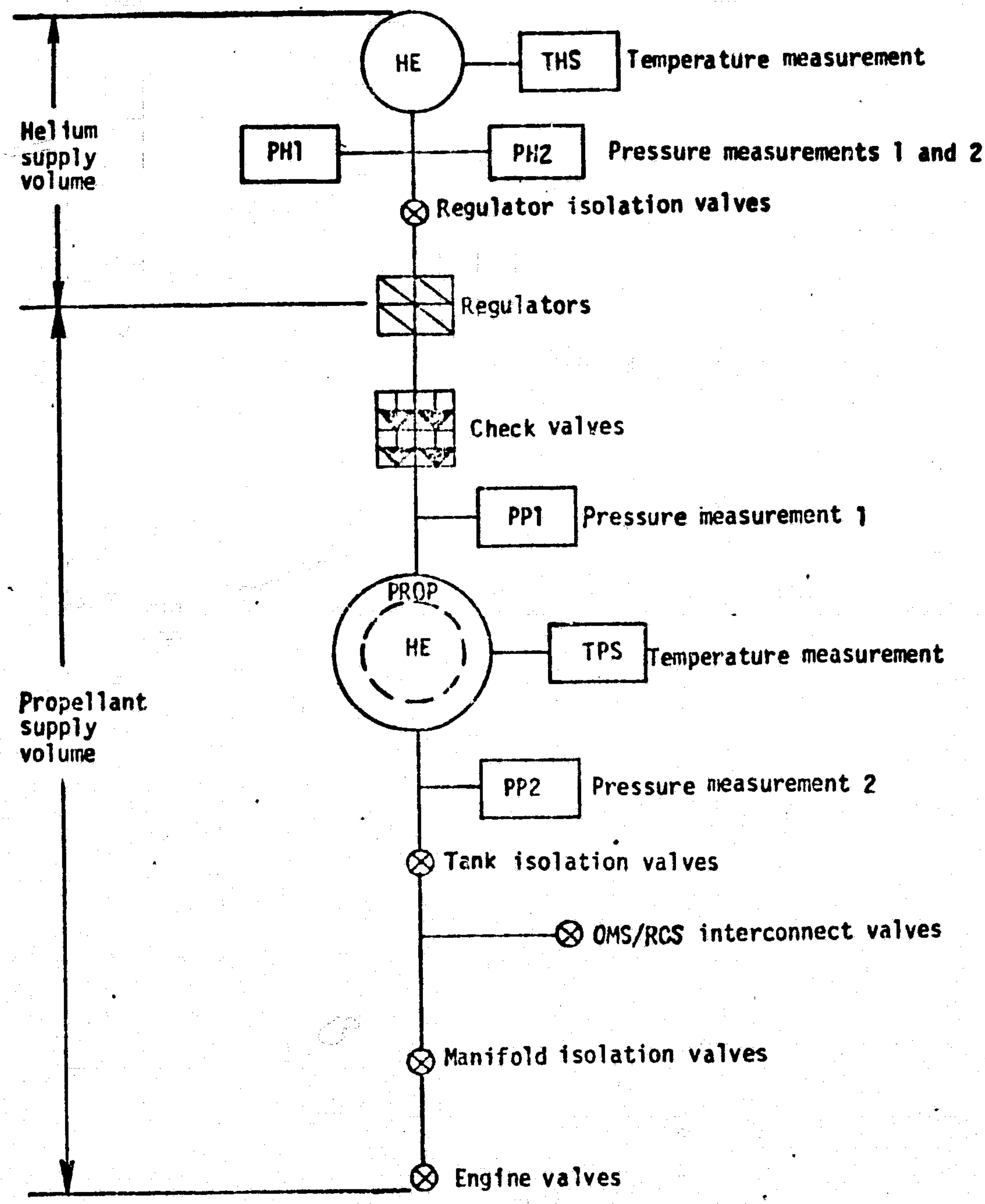

Figure 1.- Shuttle RCS helium and propellant supply systems and instrumentation for each fuel and oxidizer tank.

13. The 3σ tolerance on the difference between the operating propellant temperature (bulk tank temperature) and the ullage temperature is ±10.0 °F.

14. This analysis was performed for one of the two identical baseline aft RCS modules. The gaging error obtained is assumed to also be applicable to the forward RCS module since there are only small differences in propellant quantities and line volumes between the RCS forward and aft module pressurant/propellant tankage systems.

15. The propellant quantity in a tank is expressed as a percentage of the maximum usable propellant contained in the tank when it is filled to its rated capacity.

3.0 DISCUSSION

The purpose of the RCS propellant gaging module under examination is to enable the computation of the usable propellant remaining in the propellant tanks based on the real gas pressure-volume-temperature (P-V-T) relationship for the propellant tank pressurant agent, helium. The computed quantities of propellant remaining are made available to the Shuttle crew by means of a digital panel gage reading or a cathode-ray-tube (CRT) display, or both. These displays allow the crew to perform in-flight RCS propellant monitoring and management and also provide a propellant leakage detection capability.

There are three RCS modules in the orbiter vehicle; one forward in the nose, and one in each of the two pods attached on the orbiter vehicle rear fuselage. Each module contains RCS thrusters, a fuel (monomethylhydrazine) tank, an oxidizer (nitrogen tetroxide) tank, and a separate helium bottle to pressurize each propellant tank. Operational flight instrumentation measures the pressure (2 sensors) and temperature (1 sensor) in each helium bottle and propellant tank as depicted in Figure(1). The average pressure measurement in each helium/propellant supply system is used to improve the accuracy of the propellant gaging module. While all helium bottles are assumed to have the same nominal volume at ambient pressure and all propellant tanks are assumed to have equal volumes at the common operating pressure of 246 psia, the helium and propellant line volumes in the forward module are different from those in the two aft modules. These differences in line volumes are small when compared to the total helium and propellant system volumes. Therefore, the propellant gaging accuracy computed for one of the two identical baseline aft RCS modules is assumed to also be valid for the forward RCS module.

This analysis was performed for a baseline aft RCS module with the following helium/propellant system volumes and propellant loadings.

RCS Helium/Propellant System Volumes (in^3)

Helium Supply System	Fuel	Oxidizer
Helium bottle volume (14.7 psia)	3283.2	3283.2
Helium line volume	29.9	30.5

Propellant Supply System	Fuel	Oxidizer
Helium line volume (246 psia)	45.3	45.3
Propellant tank volume (246 psia)	31161.0	31161.0
Propellant line volume (246 psia)	1136.7	1091.7
Total propellant system volume (246 psia)	32343.0	32298.0

RCS Propellant Loading, Rated System Capacity (lb)

	Fuel	Oxidizer
Total propellant loaded	947.0	1523.0
Tank residual propellant	19.0	31.5
Line residual propellant	36.0	57.0
Total usable propellant	892.0	1434.5

The other program constants used in this study are listed below.

CHPI = 0.0 psia
CHPS = 1.0 nd
CHTI = 0.0 °F
CHTS = 1.0 nd
CPPI = 0.0 psia
CPPS = 1.0 nd
CPTI = 0.0 °F
CPTS = 1.0 nd
R = 4632.9 psia-in^3/lb-°R
SOLPRS(1) = .00001888 lb helium/lb fuel
SOLPRS(2) = .00003817 lb helium/lb oxidizer
VPDEL = 166.5 in^3

The equation in Block 17 was changed as follows to contain a helium bottle stretch expression applicable to a fiber wrapped titanium bottle rather than one for a titanium only bottle.

$$VHS = VHL(I,J) + VHAM\ [1.003 + PHS(I,J)(1.1666 \times 10^{-6})]^3$$

The equation in Block 30 was changed as follows to compute the quantity of deliverable propellant remaining in pounds rather than in percent of the maximum deliverable propellant.

$$QPD(I,J) = RHOP\ (VPS(I,J) - VHU) - WPUU(I,J)$$

The RCS instrumentation ranges, random error sources, and tolerances are listed in Table I. The tolerances on the helium and ullage pressure measurements were decreased from ±56.0 psia and ±5.6 psia respectively to ±39.6 psia and ±4.0 psia to reflect the use of the average pressure obtained from two sensors. The initial and operating pressure and temperature measurements are made by the same set of sensors.

For this analysis, the RCS propellant gaging program was initialized with the helium bottle pressures at 3600 psia and the propellant tank pressures at 115 psia. All helium bottle and propellant tank temperatures were initialized to 70 °F. These are the currently planned nominal loading and pressurizing conditions while the vehicle is on the launch pad. At these nominal conditions, the helium loading (WHI) corresponding to an initial deliverable propellant load of 100 percent was computed for each helium/propellant tankage system. Throughout this document, the terms usable propellant and deliverable propellant are used interchangably. All propellant which is not trapped in the tank or the lines is assumed to be deliverable and usable.

The propellant quantity gaging errors at program initialization due to the initial random error sources in Table I must now be determined. The gaging error due to the propellant loading tolerance is simply the 3σ tolerance multiplied by the total propellant loaded aboard. The gaging errors due to the other four initial random error sources in Table I must be computed using the propellant gaging module.

Section 11.0 of Reference (A) details three reasons (independent of the error sources in Table I) why there is a gaging error at initialization of the propellant gaging module. This gaging error is due to the fact that the module initialization conditions are different from the normal operating conditions. At module initialization, the helium which will later be dissolved in the propellant is subtracted

TABLE I

RCS INSTRUMENTATION RANGES, RANDOM ERROR SOURCES, AND TOLERANCES

RANDOM GAGING ERROR SOURCE	MEASUREMENT RANGE (FULL SCALE)	MEASUREMENT ACCURACY (PERCENT OF FULL SCALE)	3σ TOLERANCE ON ERROR SOURCE
Initial Fuel Weight		±0.5	±4.7 lb
Initial Oxidizer Weight		±0.5	±7.6 lb
Initial Helium Pressure	0 to +4000 psia	±1.4	±39.6 psia
Initial Helium Temperature	-75 to +175 °F	±1.5	±3.8 °F
Initial Ullage Pressure	0 to +400 psia	±1.4	±4.0 psia
Initial Ullage Temperature			±5.0 °F
Operating Helium Bottle Volume			±12.0 in^3
Operating Helium Pressure	0 to +4000 psia	±1.4	±39.6 psia
Operating Helium Temperature	-75 to +175 °F	±1.5	±3.8 °F
Operating Ullage Pressure	0 to +400 psia	±1.4	±4.0 psia
Operating Propellant Temperature	0 to +160 °F	±1.5	±2.4 °F
Operating Ull./ Prop. Temp. Variation			±10.0 °F

out of the helium loading and the propellant tanks are pressurized to 115 psia instead of the operating pressure of 246 psia. For these reasons the initial module gaging error was not computed at the true module initialization conditions.

The bottle/tank temperatures were kept at a constant 70 °F while the propellant tank pressures (ullage pressures) were increased to the normal operating pressure of 246 psia and the helium bottle pressures were reduced to values which produced computed quantities of propellant remaining of 100% for both the fuel and the oxidizer. This marks the start of the operating conditions for which the propellant gaging module was designed. The variance of the quantity of deliverable propellant (QPD) was now computed for the four remaining initial random error sources in Table I. The variance of QPD for each operating random error source in Table I was also computed at these conditions of pressure and temperature. All variances of QPD due to the initial random error sources are assumed to carry over directly to all operating conditions. That is, the variances of QPD due to the initial random error sources in Table I set up a constant propellant quantity bias in the program when WHI is computed at module initialization.

Maintaining the nominal operating temperature of 70 °F and the nominal ullage pressure of 246 psia, the helium bottle pressures were reduced to values which produced computed quantities of propellant remaining of 50% and 0% respectively. At each of these two propellant quantity levels, the variance of QPD for each operating random error source in Table I was computed.

For each of the three levels of QPD examined (100%, 50%, 0%), the variances of QPD due to the initial and operating random error sources were combined by the root-sum-square (RSS) method to determine the total propellant quantity gaging error in pounds. These gaging errors were then converted to a percent of the total deliverable propellant based on a full tank load.

The procedure outlined above to calculate the gaging error for an initial propellant load of 100% was repeated to determine the gaging error for an initial propellant load of 50% of the maximum usable propellant. The propellant loading tolerance for an off-load (less than 100% propellant load) is unknown at this time. Therefore, for this analysis, a loading tolerance of 0.5% of the total propellant loaded aboard has been assumed for all propellant loads.

4.0 RESULTS

Table II shows the RCS propellant quantity gaging accuracy as a function of deliverable propellant remaining for an initial deliverable propellant loading of 100%. The total gaging errors are non-linear over the range of propellant quantity remaining with the largest gaging error occurring at zero deliverable propellant remaining. The largest gaging errors are 3.9% for the fuel and 5.4% for the oxidizer.

For the initial random error sources given in Table I, the two largest gaging errors are due to the tolerances on the helium pressure and the helium temperature. The tolerance on the operating helium pressure causes a large, nearly constant, gaging error for all quantities of propellant remaining. The gaging error due to the tolerance on the operating ullage pressure is small at 100% propellant quantity remaining and is inversely proportional to the amount of propellant remaining. The gaging error due to the tolerance on the operating ullage/propellant temperature variation is also inversely proportional to the amount of propellant remaining, becoming the largest gaging error at zero deliverable propellant remaining.

At zero deliverable propellant remaining, the three largest components of the total propellant quantity gaging error, in order of descending magnitude, are due to the tolerances on 1) the operating ullage/propellant temperature variation, 2) the operating helium pressure, and 3) the operating ullage pressure. For the oxidizer, the gaging error due to the uncertainty in the true ullage temperature is twice the magnitude of the gaging error due to any other error source.

Table III presents the RCS propellant quantity gaging accuracy as a function of deliverable propellant remaining for an initial deliverable propellant loading of 50%. While the gaging error contributions due to some error sources vary considerably from their values for an initial propellant load of 100%, the total gaging error is only slightly changed. The maximum gaging errors are 4.0% for the fuel and 5.6% for the oxidizer.

5.0 CONCLUSIONS

The error analysis results contained in this document represent the

TABLE II

RCS P-V-T PROPELLANT QUANTITY GAGING MODULE ACCURACY

Initial Loading Contains 100% of Maximum Deliverable Propellant

RANDOM GAGING ERROR SOURCE	3σ TOLERANCE ON ERROR SOURCE	GAGING ERROR AS FUNCTION OF DELIVERABLE PROPELLANT REMAINING (lb)					
		FUEL			OXIDIZER		
		100%	50%	0%	100%	50%	0%
Initial Fuel (Oxidizer) Weight	±4.7 lb (±7.6 lb)	4.7	4.7	4.7	7.6	7.6	7.6
Initial Helium Pressure	±39.6 psia	14.2	14.2	14.2	24.9	24.9	24.9
Initial Helium Temperature	±3.8 °F	8.8	8.8	8.8	15.2	15.2	15.2
Initial Ullage Pressure	±4.0 psia	1.2	1.2	1.2	2.8	2.8	2.8
Initial Ullage Temperature	±5.0 °F	3.6	3.6	3.6	9.5	9.5	9.5
Operating Helium Bottle Volume	±12.0 in³	0.2	1.8	3.4	0.5	3.1	5.7
Operating Helium Pressure	±39.6 psia	14.2	15.1	16.0	24.9	26.3	27.8
Operating Helium Temperature	±3.8 °F	8.8	6.1	3.3	15.2	10.8	6.2
Operating Ullage Pressure	±4.0 psia	1.2	8.4	15.7	2.8	15.1	27.4
Operating Propellant Temperature	±2.4 °F	1.7	3.2	4.7	4.5	9.1	13.7
Operating Ull./Prop. Temp. Variation	±10.0 °F	7.1	13.3	19.4	18.9	38.2	57.4
3σ Gaging Error, Pounds of Propellant (RSS)		25.5	29.0	35.2	47.4	60.0	78.0
3σ Gaging Error, Percent of Maximum Deliverable Propellant		2.9	3.3	3.9	3.3	4.2	5.4

TABLE III

RCS P-V-T PROPELLANT QUANTITY GAGING MODULE ACCURACY

Initial Loading Contains 50% of Maximum Deliverable Propellant

RANDOM GAGING ERROR SOURCE	3σ TOLERANCE ON ERROR SOURCE	GAGING ERROR AS FUNCTION OF DELIVERABLE PROPELLANT REMAINING (lb)			
		FUEL		OXIDIZER	
		50%	0%	50%	0%
Initial Fuel (Oxidizer) Weight	±2.5 lb (±4.0 lb)	2.5	2.5	4.0	4.0
Initial Helium Pressure	±39.6 psia	14.6	14.6	25.6	25.6
Initial Helium Temperature	±3.8 °F	7.4	7.4	12.9	12.9
Initial Ullage Pressure	±4.0 psia	8.4	8.4	15.1	15.1
Initial Ullage Temperature	±5.0 °F	6.6	6.6	19.0	19.0
Operating Helium Bottle Volume	±12.0 in^3	1.0	2.6	1.9	4.5
Operating Helium Pressure	±39.6 psia	14.6	15.6	25.6	27.1
Operating Helium Temperature	±3.8 °F	7.4	4.6	12.9	8.4
Operating Ullage Pressure	±4.0 psia	8.4	15.6	15.1	27.4
Operating Propellant Temperature	±2.4 °F	3.2	4.7	9.1	13.7
Operating Ull./Prop. Temp. Variation	±10.0 °F	13.3	19.4	38.1	57.4
3σ Gaging Error, Pounds of Propellant (RSS)		30.2	36.1	63.4	80.5
3σ Gaging Error, Percent of Maximum Deliverable Propellant		3.4	4.0	4.4	5.6

accuracy of the RCS propellant gaging module for the current baseline RCS system configuration, nominal loading conditions and the error sources cited. These results will have to be updated for any significant change to the assumptions listed in Section 2.0.

Of all the gaging error sources considered, the operating ullage/propellant temperature variation causes the largest gaging error when the quantity of oxidizer remaining in the tank is 75% or less. If this uncertainty in the knowledge of the ullage temperature can be decreased by using a propellant tank temperature probe, the total propellant quantity gaging accuracy can be significantly improved.

6.0 REFERENCES

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