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ERROR ANALYSIS OF THE SHUTTLE ORBITAL MANEUVERING SYSTEM P-V-T PROPELLANT GAGING MODULE

MISSION PLANNING, MISSION ANALYSIS AND SOFTWARE FORMULATION

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1.0 SUMMARY

The Shuttle orbital maneuvering system (OMS) pressure-volume-temperature (P-V-T) propellant gaging module computes the quantity of usable propellant remaining in the OMS propellant tanks based on the real gas P-V-T relationship for the propellant tank pressurant agent, helium. The computed propellant quantity will contain a gaging uncertainty due to random instrumentation measurement errors, propellant loading uncertainties, and simplifying assumptions in the module software. The magnitude of this gaging uncertainty must be specified for the propellant gaging module to be used effectively.

An investigation of the OMS P-V-T propellant gaging module has revealed that the gaging errors due to the combined effects of random instrumentation measurement errors, propellant loading uncertainties, and simplifying assumptions in the software are nonlinear over the range of the usable propellant quantity gage (0-100%), with the largest error being at the zero point. When the OMS propellant tanks in the orbiter vehicle pods are filled to contain 100% of the maximum usable propellant, the gaging error at the zero point was determined to be 9.5% for the fuel and 9.5% for the oxidizer. When the OMS propellant tanks initially contain 50% of the maximum usable propellant, the largest gaging error is still 9.5% for the fuel and 9.5% for the oxidizer.

2.0 INTRODUCTION

This document presents the results of an error analysis performed on the OMS P-V-T propellant gaging module detailed in Reference (A). These results are based upon the current definition of the 3σ limits for the nominal propellant loading conditions and the assumed tolerances on the instrumentation measurement error sources. The computed propellant gaging errors are considered to be the 3σ gaging errors for the OMS P-V-T propellant gaging module.

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 9 - where a helium bottle stretch expression applicable for a fiber wrapped bottle was used instead of one applicable for a titanium bottle, and b) Block 16 - where the quantity of deliverable propellant was computed in pounds rather than in percent remaining.

In this module, an attempt was made to minimize the systematic errors inherent in the software by including the best available algorithms for propellant density, propellant vapor pressure, helium compressibility, helium solubility in the propellants, and helium bottle stretch under pressure. These algorithms add to the module software storage allocation but are assumed to reduce the systematic errors to insignificance. Therefore, only the propellant gaging errors due to random instrumentation measurement error sources and propellant loading uncertainties will be considered in this analysis.

2. The OMS baseline pressurant/propellant system and instrumentation are given in Reference (B) and shown in Figure (1).

3. The propellant tank volume is given in Reference (C). The volume of the propellant lines from the propellant tank to the [illegible] is not included in the propellant supply system volume in the propellant gaging module. When the OMS crossfeed lines are used, or when payload bay kits are used to carry additional propellant, it is not possible to determine which propellant tankage system fills each propellant line.

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

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

6. The propellant loading tolerance is 0.5% of the total propellant loaded into the tank.

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

8. The 3σ tolerance on the helium bottle volume at ambient pressure is ± 30.0 cubic inches.

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

10. The full scale ranges of the pressure and temperature instrumentation are identified in Reference (F). This reference quotes an instrumentation accuracy (3σ tolerance) of $\pm 5.0\%$ of the full scale range for both the pressure and temperature measurements. These values appear to be unduly pessimistic and are taken directly from the instrumentation specification accuracy requirements. In the case of the pressure instrumentation, this accuracy is guaranteed over

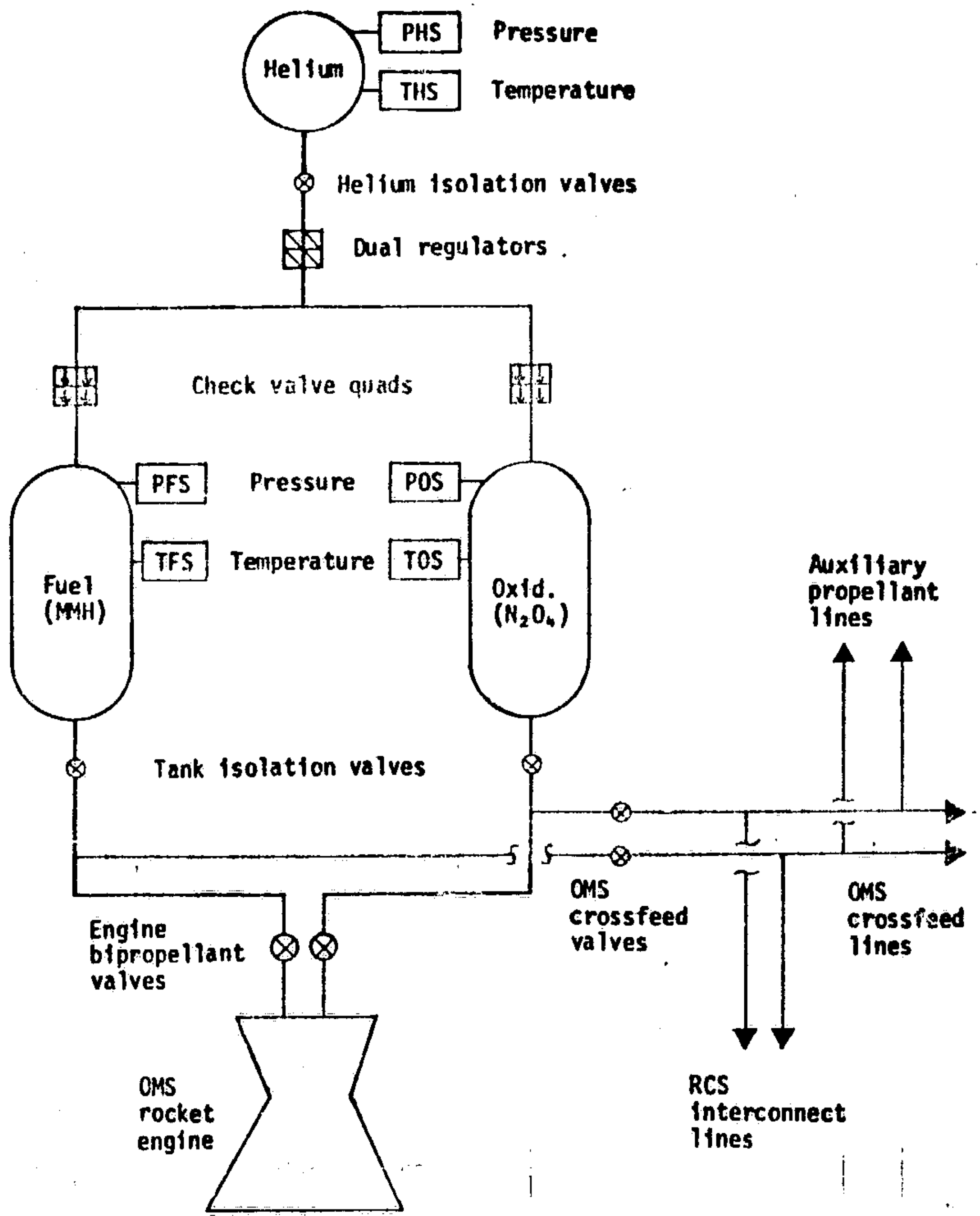

Figure 1. - Shuttle OMS baseline pressurant/propellant system and instrumentation.

a wide range of temperature. If the temperature operating range is reduced, the pressure transducer accuracy can be increased significantly.

After consultation with NASA instrumentation personnel, an "expected instrumentation accuracy" of ±3.2% and ±1.5% of the full scale range, for the pressure and temperature measurements respectively, was deemed suitable for this error analysis. The 3σ tolerances quoted are assumed to be the total measurement errors for standard off-the-shelf instruments where no special selection or calibration has been made to obtain improved measurement accuracy.

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.

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 OMS housed in pods on the Shuttle aft fuselage. The gaging error obtained in assumed to also be applicable to the OMS payload bay tankage system, since there are only small differences in loaded propellant quantities and line volumes between an OMS payload bay kit and an OMS pod pressurant/propellant tankage system.

15. The total amount of propellant (fuel plus oxidizer) required for the OMS orbit insertion burn must be specified because this propellant quantity affects the computation of the initial helium weight factor at program initialization. This propellant quantity is a mission dependent variable. For this study a representative value of 5500 pounds of propellant was assumed for the orbit insertion burn.

16. 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. Throughout this document, the terms "usable propellant" and "deliverable propellant" are used interchangeably. All propellant which is not trapped in the tank is assumed to be deliverable and usable.

3.0 DISCUSSION

The primary purpose of tne OMS P-V-T propellant gaging module is to compute the quantity of usable propellant remaining in the OMS tanks from sensed pressure and temperature data. By monitoring the propellant quantity over a period of time when there is no OMS propellant usage, the software module can also be used to provide a propellant leakage detection capability.

The OMS P-V-T propellant gaging module is to be placed in a ground based computer where telemetered system pressure and temperature data will be used as input quantities. This software module, used as a backup OMS propellant gaging system, may also be placed in the systems management function of the Shuttle onboard computer.

The baseline OMS is housed in two pods attached one on each side of the orbiter vehicle aft fuselage. The OMS system in each pod consists of a pressurant (helium) supply bottle, a fuel (monomethylhydrazine) tank, an oxidizer (nitrogen tetroxide) tank, tank pressurization regulators and controls, a propellant distribution system, and a bipropellant, pressure-fed, gimbaled rocket engine. Operational flight instrumentation measures the pressure (1 sensor) and temperature (1 sensor) in each helium bottle and propellant tank. This Shuttle OMS baseline pressurant/propellant system and instrumentation is shown in Figure (1).

The OMS propellant loading can be increased by installing pressurant/propellant supply kits in the payload bay. The auxiliary tankage and pressurization components contained in each payload bay kit (PBK) are identical to those utilized in the OMS pods. There are only small differences in line volumes and loaded propellant quantities between the two tankage systems.

This error analysis of the OMS P-V-T propellant gaging module was performed on an OMS pod pressurant/propellant tankage system with the following [illegible] and propellant [illegible].

OMS Helium/Propellant System Volumes (in^3)

Helium Supply System	Fuel/Oxidizer
Helium bottle volume (14.7 psia)	29548.8
Helium line volume	40.7

OMS Helium/Propellant System Volumes (in^3), Continued

Propellant Supply System	Fuel	Oxidizer
Helium line volume (250 psia)	83.2	61.1
Propellant tank volume (250 psia)	156487.7	156487.7
Total propellant system volume (250 psia)	156570.9	156548.8

OMS Propellant Loading, Rated System Capacity (lb)

Propellant Load Description	Fuel	Oxidizer
Total propellant loaded in tank	4689.5	7759.0
Tank residual propellant	58.2	121.5
Total usable propellant	4631.3	7637.5

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
NOMSTS = 2 nd
NPBK = 0 nd
PMR = 1.65 lb oxidizer/lb fuel
R = 4632.9 psia-in^3/lb-°R
SOLPRS(1) = 0.00001919 lb helium/lb fuel
SOLPRS(2) = 0.00003883 lb helium/lb oxidizer
WFOI = 2075.5 lb
WOOI = 3424.5 lb

A helium bottle stretch expression applicable for a fiber wrapped bottle was used instead of one applicable for a titanium bottle. Therefore, the equation used to compute the helium supply system volume in Block 9 was changed to read as follows.

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

The equations in Block 16 were changed to read as follows in order to compute the quantity of deliverable propellant remaining in pounds rather than in percent of the maximum deliverable propellant.

$$QFD(I) = WFL(I) - WFE - WFUU(I)$$

$$QOD(I) = WOL(I) - WOE - WOUU(I)$$

The OMS instrumentation ranges, random error sources, and tolerances are listed in Table I. The initial and operating pressure and temperature measurements are made by the same set of sensors.

For this analysis, the OMS P-V-T propellant gaging program was initialized with the helium bottle pressure at 4600 psia and the propellant tank pressures at 250 psia. The helium bottle and propellant tank temperatures were initialized to 70 °F. At these nominal loading conditions, the helium weight factor (WHIR) corresponding to an initial propellant load of 100 percent was computed for the helium/propellant tankage system. Throughout this analysis, the propellant quantity is expressed as a percentage of the maximum deliverable propellant for a full tank load.

Section 10.0 of Reference (A) explains why there is a gaging error (independent of the error sources in Table I) at initialization of the propellant gaging module. The amount of helium required to saturate the propellant load at the nominal operating conditions in space is subtracted out of the helium weight factor at module initialization. Hence, the gaging module believes that there is less helium, and therefore, more propellant, in the propellant tank than is really the case. For this reason, the gaging errors due to the initial random error sources enumerated in Table I were not computed at the true module initialization conditions.

The bottle and tank temperatures were kept at a constant 70 °F, the ullage pressures were maintained at 250 psia, and the helium bottle pressure was decreased to a value 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. Therefore, the gaging errors due to the initial random error sources in Table I were computed at these "nominal starting conditions".

The gaging error due to the propellant loading tolerance is equal to the 3σ tolerance multiplied by the total propellant loaded into the tank. The gaging errors, due to the other initial random error sources in Table I, were determined by simulating in the propellant gaging module, one at a time, each error source and comparing the computed propellant quantity (QFD, QOD) with that obtained at the "nominal starting conditions". The variances of QFD and QOD for

TABLE I

OMS 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	±23.4 lb
Initial Oxidizer Weight		±0.5	±38.8 lb
Initial Helium Pressure	0 to +5000 psia	±3.2	±160.0 psia
Initial Helium Temperature	-200 to +200 °F	±1.5	±6.0 °F
Initial Fuel Ullage Pressure	0 to +400 psia	±3.2	±12.8 psia
Initial Fuel Ullage Temperature			±5.0 °F
Initial Oxidizer Ullage Pressure	0 to +400 psia	±3.2	±12.8 psia
Initial Oxidizer Ullage Temperature			±5.0 °F
Operating Helium Bottle Volume			±30.0 in³
Operating Helium Pressure	0 to +5000 psia	±3.2	±160.0 psia
Operating Helium Temperature	-200 to +200 °F	±1.5	±6.0 °F
Operating Fuel Ullage Pressure	0 to +400 psia	±3.2	±12.8 psia
Operating Fuel Propellant Temp.	0 to +160 °F	±1.5	±2.4 °F
Operating Fuel Ull./Prop. Temp. Var.			±10.0 °F
Operating Oxidizer Ullage Pressure	0 to +400 psia	±3.2	±12.8 psia
Operating Oxid. Propellant Temp.	0 to +160 °F	±1.5	±2.4 °F
Operating Oxid. Ull./Prop. Temp. Var.			±10.0 °F

each operating random error source in Table I were also computed at these nominal starting conditions of pressure and temperature.

Maintaining the nominal operating helium and propellant temperatures at 70 °F, and the nominal operating ullage pressures at 250 psia, the helium bottle pressure was reduced to a value which produced computed quantities of propellant remaining of 50% and 0% respectively. At each of these two propellant quantity levels, the variances of QFD and QOD for each operating random error source in Table I were computed.

When WHIR is computed at module initialization, the variances of QFD and QOD due to the initial random error sources in Table I are assumed to set up constant propellant quantity biases in the module which carry over directly to all operating conditions. For each of the three levels of QFD and QOD examined (100%, 50%, 0%), the variances of QFD and QOD 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 errors in pounds. These gaging errors were then converted to a percentage 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 loading tolerance for an initial propellant load of less than 100% is unknown at this time. For this analysis, a loading tolerance of 0.5% of the total propellant loaded into the tank has been assumed for all propellant loads.

4.0 RESULTS

Table II presents the OMS P-V-T 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 9.5% for both the fuel and the oxidizer. The total gaging errors are always identical for both the fuel and the oxidizer because in the OMS tankage system both propellant tanks are pressurized by the same helium bottle. Therefore, the fuel and oxidizer quantities remaining in the tanks cannot be computed independently but must be computed jointly using the propellant mixture ratio, PMR.

TABLE II

OMS 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%
<u>Initial Conditions</u>							
Fuel Weight	±23.4 lb	23.4	23.4	23.4	-	-	-
Oxidizer Weight	±38.8 lb	-	-	-	38.8	38.8	38.8
Helium Pressure	±160.0 psia	248.1	248.1	248.1	409.4	409.4	409.4
Helium Temperature	±6.0 °F	79.1	79.1	79.1	130.6	130.6	130.6
Fuel Ullage Pressure	±12.8 psia	6.9	6.9	6.9	11.4	11.4	11.4
Fuel Ullage Temperature	±5.0 °F	8.5	8.5	8.5	14.0	14.0	14.0
Oxidizer Ullage Pressure	±12.8 psia	6.5	6.5	6.5	10.7	10.7	10.7
Oxidizer Ullage Temperature	±5.0 °F	12.0	12.0	12.0	19.8	19.8	19.8
<u>Operating Conditions</u>							
Helium Bottle Volume	$\pm 30.0\ in^3$	0.1	2.4	4.7	0.1	4.0	7.8
Helium Pressure	±160.0 psia	248.1	263.8	282.3	409.4	435.2	465.7
Helium Temperature	±6.0 °F	79.1	57.9	35.1	130.6	95.5	58.0
Fuel Ullage Pressure	±12.8 psia	6.9	67.4	128.0	11.4	111.3	211.2
Fuel Propellant Temperature	±2.4 °F	4.1	8.0	11.9	6.7	13.2	19.7
Fuel Ull./Prop. Temp. Var.	±10.0 °F	16.9	33.3	49.7	27.9	55.0	82.1
Oxidizer Ullage Pressure	±12.8 psia	6.5	67.1	127.8	10.7	110.8	210.9
Oxidizer Propellant Temp.	±2.4 °F	5.8	12.9	20.0	9.5	21.2	32.9
Oxid. Ull./Prop. Temp. Var.	±10.0 °F	24.0	53.7	83.5	39.6	88.6	137.7
3σ Gaging Error, Pounds of Prop. (RSS)		370.8	393.5	438.5	611.9	649.4	723.6
3σ Gaging Error, Percent of Max. Del. Prop.		8.0	8.5	9.5	8.0	8.5	9.5

For the initial random error sources given in Table I, the largest gaging error is due to the tolerance on the helium pressure. This gaging error is three times the magnitude of the next largest gaging error which is due to the tolerance on the helium temperature. All other gaging errors due to initial random error sources are small in comparison to these two largest errors.

At zero deliverable propellant remaining, the four largest gaging errors due to operating random error sources are caused by the tolerances on 1) the helium pressure 2) the fuel ullage pressure, 3) the oxidizer ullage pressure, and 4) the oxidizer ullage/propellant temperature variation. The gaging error due to the helium pressure error tolerance is again much larger than the gaging error due to any other source.

Table III presents the OMS P-V-T propellant quantity gaging accuracy as a function of deliverable propellant remaining for an initial deliverable propellant loading of 50%. While the gaging error components due to individual error sources may 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 still 9.5% for the fuel and 9.5% for the oxidizer.

5.0 CONCLUSIONS

The error analysis results contained in this document define the accuracy of the OMS P-V-T propellant gaging module for the current baseline OMS system configuration, nominal loading conditions, error sources cited, and other assumptions listed in Section 2.0. The gaging accuracy would have to be updated for any significant deviation from these assumptions.

For P-V-T propellant gaging programs in general, the tolerances on the pressurant/propellant pressure measurements traditionally cause large gaging errors. In this propellant gaging module, these gaging errors are magnified by the fact that the assumed pressurant/propellant full scale measurement accuracy is only ±3.2% for the pressure compared to ±1.5% for the temperature. The comparable full scale measurement accuracies for the reaction control system (RCS) instrumentation are ±1.4% for the pressure and ±1.5% for the temperature. If the OMS instrumentation pressure measurement accuracy can be increased, the largest components of the total gaging error can be reduced.

TABLE III

OMS 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 Conditions					
Fuel Weight	±11.9 lb	11.9	11.9	-	-
Oxidizer Weight	±19.7 lb	-	-	19.7	19.7
Helium Pressure	±160.0 psia	247.9	247.9	409.1	409.1
Helium Temperature	±6.0 °F	79.4	79.4	131.0	131.0
Fuel Ullage Pressure	±12.8 psia	67.5	67.5	111.4	111.4
Fuel Ullage Temperature	±5.0 °F	16.7	16.7	27.5	27.5
Oxidizer Ullage Pressure	±12.8 psia	67.2	67.2	110.8	110.8
Oxidizer Ullage Temperature	±5.0 °F	26.8	26.8	44.2	44.2
Operating Conditions					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Helium Pressure	±160.0 psia	247.9	263.6	409.1	434.9
Helium Temperature	±6.0 °F	79.4	58.1	131.0	95.9
Fuel Ullage Pressure	±12.8 psia	67.5	128.1	111.4	211.4
Fuel Propellant Temperature	±2.4 °F	8.0	11.9	13.2	19.7
Fuel Ull./Prop. Temp. Variation	±10.0 °F	33.4	49.8	55.0	82.1
Oxidizer Ullage Pressure	±12.8 psia	67.2	127.9	110.8	211.0
Oxidizer Propellant Temperature	±2.4 °F	12.9	20.0	21.2	32.9
Oxid. Ull./Prop. Temp. Var.	±10.0 °F	53.7	83.5	88.7	137.8
3σ Gaging Error, Pounds of Propellant (RSS)		398.8	440.0	658.1	726.0
3σ Gaging Error, Percent of Max. Del. Prop.		8.6	9.5	8.6	9.5

6.0 REFERENCES

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