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MCDONNELL DOUGLAS TECHNICAL SERVICES CO.
HOUSTON ASTRONAUTICS DIVISION

SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

DESIGN NOTE NO. 1.4-2-12

THE SHUTTLE ORBITAL MANEUVERING SYSTEM P-V-T PROPELLANT QUANTITY GAGING ACCURACY AND LEAK DETECTION ALLOWANCE FOR FOUR INSTRUMENTATION CONDITIONS

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 OMS propellant remaining based on the real gas P-V-T relationship for the propellant tank pressurant, helium. The computed propellant quantity contains a gaging uncertainty due to random instrumentation measurement errors and propellant loading uncertainties.

The OMS P-V-T propellant quantity gaging error was determined for four sets of instrumentation configurations and accuracies with the propellant tank operating in the normal constant pressure mode and in the blowdown mode. The instrumentation inaccuracy allowance for propellant leak detection was also computed for these same four sets of instrumentation. These gaging errors and leak detection allowances are presented in tables designed to permit a direct comparison of the effectiveness of the four instrumentation sets.

The results of this study show the magnitudes of the improvements in propellant quantity gaging accuracies and propellant leak detection allowances which can be achieved by employing more accurate pressure and temperature instrumentation.

2.0 INTRODUCTION

This document presents the results of a second error analysis performed on the OMS P-V-T propellant gaging module detailed in Reference (A). The first error analysis, Reference (B), defined the OMS propellant quantity gaging error for the current definition of the 3σ limits on the propellant loading accuracy and the instrumentation accuracy with the propellant tanks operating in the constant pressure mode. In this second error analysis, the gaging error was determined for the current baseline instrumentation as well as for three other improved accuracy instrumentation sets with the propellant tanks operating in both the constant pressure mode and the blowdown mode. The instrumentation inaccuracy allowance which would be required in a propellant leakage detection program was also calculated for each of the four instrumentation sets.

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 remaining in the tank was computed in pounds rather than in percent.

   This module contains 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 are assumed to reduce the systematic errors inherent in the software to insignificance. 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 (C) and shown in Figure (1).

3. The propellant tank volume is given in Reference (D).

4. The volume of the propellant lines from the propellant tank to the engine valves is not included in the propellant supply system volume in the propellant gaging module.

5. The propellant tank normal operating pressure is given in Reference (D).

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

7. When the Shuttle is on the launch pad the propellant loading tolerance is ±0.5% of the total propellant loaded into the tank.

8. When the Shuttle is in orbit the gaging error for the OMS capacitance probe propellant quantity gaging system is ±1.7% of

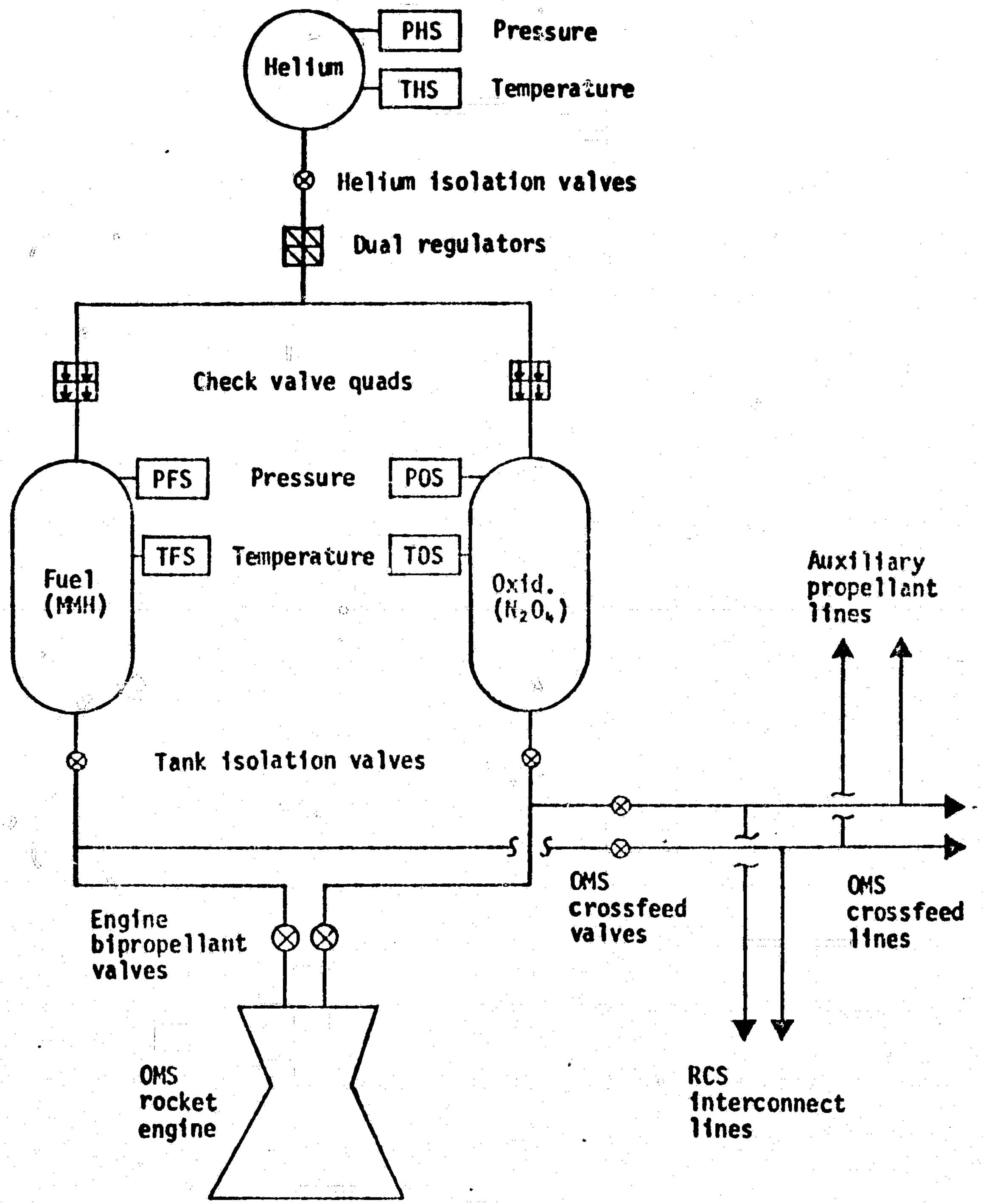

Figure 1. - Shuttle OMS baseline pressurant/propellant system and instrumentation.

tank capacity. This quantity is the propellant loading tolerance to be used in a P-V-T propellant leakage detection program or in the P-V-T gaging program with the propellant tanks operating in the blowdown mode.

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

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

11. The helium line volumes are given in Reference (F).

12. The full scale ranges of the pressure and temperature instrumentation are identified in Reference (G) and presented in Table I.

13. The measurement accuracies (3σ tolerances) for the four instrumentation sets used in this analysis are presented in Table II.

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

15. The 3σ tolerance on the difference between the initial ullage temperature and the sensor measurement is ±5.0 °F for skin temperatures and ±2.4 °F when temperature probes are used.

16. The 3σ tolerance on the difference between the operating propellant temperature (bulk tank temperature) and the ullage

TABLE I

OMS OPERATIONAL FLIGHT INSTRUMENTATION MEASUREMENT RANGES

MEASUREMENT	MEASUREMENT RANGE (FULL SCALE)
Helium Supply Pressure	0 to +5000 psia
Helium Supply Temperature	-200 to +200 °F
Propellant Ullage Pressure	0 to +400 psia
Propellant Ullage Temperature	0 to +160 °F

TABLE II

CONFIGURATIONS AND ACCURACIES OF THE
FOUR OMS INSTRUMENTATION SETS EXAMINED

INSTRUMENTATION SET NUMBER	NUMBER OF INSTRUMENTS PER BOTTLE/TANK		INSTRUMENTATION ACCURACY (PERCENT OF FULL SCALE)	
	PRESSURE	TEMPERATURE	PRESSURE	TEMPERATURE
1	1	1	±3.2	±1.5 (skin)
2	1	1	±1.4	±1.5 (skin)
3	2	1	±1.4	±1.5 (skin)
4	2	1	±1.4	±1.5 (probe)

temperature is ±10.0 °F for skin temperatures and ±5.0 °F when temperature probes are used..

17. While this analysis was performed for one of the two identical baseline OMS tankage systems housed in pods on the Shuttle aft fuselage, the gaging errors and leak detection allowances obtained are assumed to also be applicable to the OMS payload bay tankage system.

18. A representative value of 5500 pounds of propellant (total of fuel plus oxidizer) is required for the orbit insertion burn.

19. 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 purpose of the 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.

The baseline OMS is housed in two pods attached one on each side of the orbiter vehicle aft fuselage. The OMS tankage system in each pod consists of a pressurant (helium) supply bottle, a fuel (monomethylhydrazine) tank, an oxidizer (nitrogen tetroxide) tank, helium lines, propellant lines, and tank pressurization controls as shown in Figure (1). Operational flight instrumentation measures the pressure and temperature in each helium bottle and propellant tank.

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 system volumes and propellant loadings.

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

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 fuel
WOOI = 3424.5 lb oxidizer

The equation in Block 9 (Reference (A)) used to compute the helium supply system volume was changed as follows to include a helium bottle stretch expression applicable for a fiber wrapped bottle.

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

The equations in Block 16 (Reference (A)) were changed as follows in order to compute the quantity of deliverable propellant remaining in pounds.

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

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

3.1 Instrumentation Sets

The configurations and accuracies of the four instrumentation sets used in this analysis are presented in Table II.

Instrumentation set 1 is the baseline OMS instrumentation assumed for the OMS P-V-T propellant gaging module error analysis described in Reference (B). These instruments are standard off-the-shelf items where no special selection or calibration has been made to obtain improved measurement accuracy.

Instrumentation set 2 consists of the same basic instrumentation as set 1, with one pressure measurement and one temperature measurement in each helium bottle and propellant tank. However, in set 2, special selection and calibration of the instruments are performed to insure that the improved measurement accuracies quoted in Table II are obtained.

Instrumentation set 3 consists of two pressure measurements and one temperature measurement per helium bottle and propellant tank. These instruments have the same measurement accuracies as those in set 2. However, the effective pressure measurement accuracy is increased by using the average of the two pressure sensor readings. This instrumentation set is comparable to the one assumed for the reaction control system (RCS) P-V-T propellant gaging module error analysis given in Reference (H).

Instrumentation set 4 contains the same number of instruments with the identical measurement accuracies as set 3. The propellant tank skin temperature sensors used in sets 1, 2, and 3 are replaced by temperature probes. Use of temperature probes permits the assumption of a smaller tolerance on the difference between the ullage temperature and the sensor measurement.

3.2 Normal Operating Mode

The OMS P-V-T propellant gaging module, described in Reference (A), was designed to function during the normal operating mode of the OMS propellant tankage system. In the normal operating mode, the propellant tank pressure is maintained near the nominal operating pressure of 250 psia by the regulators in the helium lines.

Table III identifies the OMS P-V-T gaging random error sources and tolerances for the four instrumentation sets when the OMS propellant tankage system is operating in the normal (constant pressure) mode. The gaging errors due to these random error sources are 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 nominal conditions.

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

TABLE III

OMS NORMAL OPERATING MODE P-V-T GAGING RANDOM ERROR SOURCES AND TOLERANCES FOR FOUR INSTRUMENTATION SETS

RANDOM GAGING ERROR SOURCE	3σ TOLERANCE ON ERROR SOURCE			
	SET 1	SET 2	SET 3	SET 4
<u>Initial Conditions</u>				
Fuel Weight	±23.4 lb	±23.4 lb	±23.4 lb	±23.4 lb
Oxidizer Weight	±38.8 lb	±38.8 lb	±38.8 lb	±38.8 lb
Helium Pressure	±160.0 psia	±70.0 psia	±49.5 psia	±49.5 psia
Helium Temperature	±6.0 °F	±6.0 °F	±6.0 °F	±6.0 °F
Fuel Ullage Pressure	±12.8 psia	±5.6 psia	±4.0 psia	±4.0 psia
Fuel Ullage Temperature	±5.0 °F	±5.0 °F	±5.0 °F	±2.4 °F
Oxidizer Ullage Pressure	±12.8 psia	±5.6 psia	±4.0 psia	±4.0 psia
Oxidizer Ullage Temperature	±5.0 °F	±5.0 °F	±5.0 °F	±2.4 °F
<u>Operating Conditions</u>				
Helium Bottle Volume	±30.0 in^3	±30.0 in^3	±30.0 in^3	±30.0 in^3
Helium Pressure	±160.0 psia	±70.0 psia	±49.5 psia	±49.5 psia
Helium Temperature	±6.0 °F	±6.0 °F	±6.0 °F	±6.0 °F
Fuel Ullage Pressure	±12.8 psia	±5.6 psia	±4.0 psia	±4.0 psia
Fuel Propellant Temperature	±2.4 °F	±2.4 °F	±2.4 °F	±2.4 °F
Fuel Ull./Prop. Temp. Var.	±10.0 °F	±10.0 °F	±10.0 °F	±5.0 °F
Oxidizer Ullage Pressure	±12.8 psia	±5.6 psia	±4.0 psia	±4.0 psia
Oxid. Propellant Temp.	±2.4 °F	±2.4 °F	±2.4 °F	±2.4 °F
Oxid. Ull./Prop. Temp. Var.	±10.0 °F	±10.0 °F	±10.0 °F	±5.0 °F

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.

The gaging errors due to the initial and operating random error sources in Table III were computed at 100 percent (%) propellant quantity remaining in the tanks. The initial random error sources in Table III cause an error in the computed value of WHIR at module initialization. This error in WHIR is assumed to set up constant propellant quantity biases in the module which carry over directly to all operating conditions.

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 values which produced computed quantities of propellant remaining of 75%, 50%, 25% and 0% respectively. At each of these four propellant quantity levels, the errors in QFD and QOD for each operating random error source in Table III were computed. For each propellant quantity level examined (100%, 75%, 50%, 25%, and 0%), the errors in 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.

3.3 Blowdown Operating Mode

If helium supply pressure to the propellant tanks is lost, it is possible to ignite the OMS engine (or to continue a firing) by using the existing trapped propellant tank gas pressure in a blowdown mode of operation. During a blowdown operation, the propellant tank pressure will decay and engine performance will be degraded. The OMS system is normally operable so long as the tank ullage pressure and engine chamber pressure remain above prescribed minimum values. The latest estimate for the minimum engine chamber pressure is 90 psia corresponding to a minimum ullage pressure of 158 psia.

The OMS P-V-T propellant gaging module, with small modifications, can be designed to function during both the normal and blowdown modes of operation. The first change to the module must be to dimension the variable VHAM in Block 9 to obtain the following equation .

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

Now, any failed helium supply system can be eliminated from the program by setting the appropriate VHL(I) and VHAM(I) to values of zero. The pressurant/propellant tankage system with the failed helium supply system will now operate in the blowdown mode while the other two pressurant/propellant tankage systems can continue to operate in the normal operating mode. The P-V-T gaging module will compute the propellant remaining for both modes of operation but different gaging accuracies will apply to each operating mode. These gaging accuracies will be discussed later.

The change to the OMS P-V-T propellant gaging module described in the paragraph above is the only one required to enable the module to function in a blowdown mode of operation. However, there are other desirable changes which could be made to reduce the gaging error when the module is functioning during a blowdown mode of operation. The following additional equations should be added to Block 9 to compute the propellant supply system volumes as a function of the propellant tank pressures.

$$VFS = VFL(I) + (HEBOTL)\ VPAM[1.0 + PFS(I)(C)]^{3}$$

$$VOS = VOL(I) + (HEBOTL)\ VPAM[1.0 + POS(I)(C)]^{3}$$

where:

1. VFS and VOS, the fuel and oxidizer supply system volumes respectively, no longer need to be subscripted variables.
2. VFL(I) and VOL(I) are the helium and propellant line volumes for the fuel and oxidizer systems respectively.
3. VPAM is the volume of the propellant tank at ambient (14.7 psia) pressure.

4. C is a constant describing the propellant tank stretch under pressure.
5. The remaining variables (HEBOTL, PFS(I), POS(I)) have the same definitions and uses given in Reference (A).

The changes given in the paragraph above are desirable because they eliminate systematic gaging errors (as large as 0.8% for blowdown at 75% propellant remaining) from the propellant gaging program during a blowdown mode of operation. These systematic errors cannot be combined with the random errors using the RSS method. Instead, the systematic gaging errors must be added linearly to the RSS of the random gaging errors.

When a helium supply system develops a leak, the affected propellant system should be operated in the normal mode so long as the nominal propellant tank operating pressure can be maintained. Time permitting, the following steps should be taken before initialization of the blowdown mode of operation.

1. Close the helium isolation valve for the affected pressurant/propellant system.
2. Halt all usage of propellant from the affected propellant system until the helium weight factor (WHIR(I)) can be recomputed for that propellant system. This can be accomplished by utilizing the OMS crossfeed capability.

3. Save all current values of WHIR(I).

4. Set the module first pass flag (N) to zero.

5. Set the helium supply volume constants (VHL(I) and VHAM(I)) for the failed pressurant system to zero.

6. Set the helium solubility constants (SOLPRS(1) and SOLPRS(2)) to zero.

7. Input the weights (in pounds) of propellants in the tanks (WFL(I) and WOL(I)) for the failed pressurant/propellant tankage system. These quantities are obtained (in percent) from the capacitance probe propellant quantity gaging system.

8. Calculate the new values of WHIR(I) for all propellant tankage systems using the ground computer. The propellant tank pressures and temperatures should be allowed sufficient time to reach stable conditions before the new values of WHIR(I) are calculated.

9. Reenter into the program the saved values of WHIR(I) (from step 3) for the propellant tankage systems operating in the normal mode. The value of WHIR(I) for the propellant tankage system operating in the blowdown mode is already in the program, having been computed in step 8.

In step 6 above it is assumed that the propellants are saturated with dissolved helium at the start of the blowdown operation and that no helium will come out of solution at a later time. Actually, some helium will come out of solution as the propellant tank ullage pressure decreases due to propellant consumption. This will result in an optimistic computation of propellant quantity remaining. The gaging error due to this error source was not considered in this analysis since the primary objective was to determine the propellant quantity gaging errors due to instrumentation measurement errors.

Table IV presents the propellant tank ullage pressures as a function of propellant quantity remaining for operations in the blowdown mode. It is unlikely that the OMS system will operate at ullage pressures below 158 psia. Therefore, if blowdown operations are started with more than 40% propellant remaining in the tanks, operation of that tankage system may have to be terminated before all the usable propellant is consumed.

The OMS blowdown operating mode P-V-T gaging random error sources and tolerances for the four sets of instrumentation are shown in Table V. There are no gaging error sources from the helium supply system, since, in the blowdown operating mode, the pressurant system is eliminated from the program. The initial propellant weight uncertainty is now ±1.7% compared to the ±0.5% uncertainty on the

TABLE IV

OMS P-V-T PROPELLANT GAGING PROGRAM ULLAGE PRESSURES FOR PROPELLANT TANK BLOWDOWN MODE OF OPERATION

PROPELLANT QUANTITY AT START OF BLOWDOWN	ULLAGE PRESSURE AS A FUNCTION OF PROPELLANT QUANTITY REMAINING (psia)				
	100%	75%	50%	25%	0%
100%	250.0	51.4	31.9	24.4	20.4
75%	-	250.0	141.3	99.0	77.4
50%	-	-	250.0	174.2	134.6
25%	-	-	-	250.0	192.2

launch pad. The remaining random gaging error sources concerning propellant tank ullage pressures and temperatures are identical to the similar error sources in Table III. The systematic error sources, namely, the changes in propellant tank volumes as the ullage pressures decrease, are not considered in the computation of the total propellant gaging error. It is assumed that these systematic error sources are removed by incorporating the appropriate propellant tank stretch equations in Block 9 of the propellant gaging module.

An OMS propellant tankage system blowdown operation starting at the 100 percent propellant quantity level was briefly examined and was

TABLE V

OMS BLOWDOWN OPERATING MODE P-V-T GAGING RANDOM ERROR SOURCES AND TOLERANCES FOR FOUR INSTRUMENTATION SETS

RANDOM GAGING ERROR SOURCE	3σ TOLERANCE ON ERROR SOURCE			
	SET 1	SET 2	SET 3	SET 4
<u>Initial Conditions</u>				
Fuel Weight	±79.7 lb	±79.7 lb	±79.7 lb	±79.7 lb
Fuel Ullage Pressure	±12.8 psia	±5.6 psia	±4.0 psia	±4.0 psia
Fuel Ullage Temperature	±5.0 °F	±5.0 °F	±5.0 °F	±2.4 °F
Oxidizer Weight	±131.9 lb	±131.9 lb	±131.9 lb	±131.9 lb
Oxid. Ullage Pressure	±12.8 psia	±5.6 psia	±4.0 psia	±4.0 psia
Oxid. Ullage Temperature	±5.0 °F	±5.0 °F	±5.0 °F	±2.4 °F
<u>Operating Conditions</u>				
Fuel Ullage Pressure	±12.8 psia	±5.6 psia	±4.0 psia	±4.0 psia
Fuel Prop. Temperature	±2.4 °F	±2.4 °F	±2.4 °F	±2.4 °F
Fuel.Ull./Prop.Temp.Var.	±10.0 °F	±10.0 °F	±10.0°F	±5.0 °F
Oxid. Ullage Pressure	±12.8 psia	±5.6 psia	±4.0 psia	±4.0 psia
Oxid. Prop. Temperature	±2.4 °F	±2.4 °F	±2.4 °F	±2.4 °F
Oxid.Ull./Prop.Temp.Var.	±10.0 °F	±10.0 °F	±10.0 °F	±5.0 °F

rejected as being an unrealistic case. Table IV shows that for a blowdown from 100% quantity the propellant tank ullage pressure quickly drops to an unacceptable value. It is assumed that a helium supply system failure with this much propellant in the tanks will probably result in a mission abort.

Propellant tankage systems which are designed to operate only in the blowdown mode (such as the Shuttle auxiliary power unit (APU) fuel tank system) typically require an initial ullage volume of at least 29% of the total tank volume for successful operation. For the OMS propellant tankage system, an initial propellant load of 75% equates to an initial ullage volume of 28.5% of the total tank volume.

Three initial propellant quantity levels (75%, 50%, and 25%) were chosen for this analysis of the OMS P-V-T propellant gaging program functioning in a blowdown operating mode. The 75% propellant quantity level approximates the minimum initial ullage volume discussed in the previous paragraph. The 25% propellant quantity level approximates the amount of propellant required for the OMS deorbit burn. The gaging errors were computed at the 75%, 50%, 25%, and 0% quantity levels.

Starting with an initial propellant load of 75 percent, the OMS P-V-T propellant gaging program was initialized with the propellant ullage pressures at 250 psia and the propellant ullage temperatures at 70 °F. At these nominal operating conditions, the helium weight factor (WHIR) corresponding to an initial propellant load of 75% was computed for the propellant tankage system. The gaging errors due to the intital and operating random error sources in Table V were computed at the 75% propellant quantity level. Note that since the propellant tanks are no longer operating in a constant pressure mode, the errors in QFD and QOD due to the initial random error sources must now be computed at each successive propellant quantity level examined. In the normal (propellant tank constant pressure) operating mode, once computed at program initialization, these errors are assumed to remain constant for all succeeding operating conditions.

Maintaining the propellant ullage temperatures at the nominal operating values of 70 °F, the propellant tank ullage pressures were reduced to values which produced successive decreases of 25% in the computed quantities of propellant remaining until all the usable propellant was expelled from the tanks. At each propellant quantity level examined, the errors in QFD and QOD for all initial and operating random error sources in Table V were computed. At each of these same propellant levels all of these computed errors in QFD and QOD 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 in the two paragraphs above was repeated with initial propellant loads of 50% and 25% to compute the OMS blowdown mode propellant gaging errors over a wide range of operating conditions.

3.4 Propellant Leak Detection

The discussion of the assumptions, error sources, tolerances, etc., for determining the OMS P-V-T propellant leak detection allowance has been placed in the appendix.

4.0 RESULTS

The results of this error analysis performed on the OMS P-V-T propellant gaging module are presented in the three subsections below.

4.1 Normal Operating Mode Gaging Accuracy

Table VI presents the effect of instrumentation accuracy on the OMS P-V-T propellant quantity gaging accuracy for the normal (constant pressure) operating mode of the propellant tankage system. Starting with an initial propellant loading of 100 percent, the total gaging errors are shown for 100%, 75%, 50%, 25%, and 0% propellant quantity remaining respectively. The gaging errors for initial propellant loadings of less than 100% were not examined in this study. However, Reference (B) shows that for instrumentation set 1, starting with an initial propellant loading of 50%, the computed gaging errors at 50% and 0% are almost identical to the gaging errors computed at these same quantity levels when starting with an initial propellant loading of 100%.

TABLE VI

EFFECT OF INSTRUMENTATION ACCURACY ON THE OMS P-V-T PROPELLANT QUANTITY GAGING ACCURACY FOR THE NORMAL OPERATING MODE

INSTRUMENTATION SET	INITIAL PROPEL-LANT QUANTITY	GAGING ERROR AS A FUNCTION OF PROPELLANT QUANTITY REMAINING (%)				
		100%	75%	50%	25%	0%
1	100%	8.0	8.2	8.5	8.9	9.5
2	100%	4.2	4.2	4.4	4.6	4.9
3	100%	3.5	3.5	3.6	3.8	4.0
4	100%	3.4	3.4	3.4	3.5	3.6

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 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. Consequently, the fuel and oxidizer quantities remaining in the tanks cannot be computed independently but must be computed jointly with the use of the propellant mixture ratio.

The maximum gaging error ranges from a high of 9.5% for instrumentation set 1 to a low of 3.6% for set 4. For all instrumentation sets, the range of gaging errors from 100% propellant remaining to 0% remaining is small with set 4 having an almost constant gaging error for all quantities of propellant remaining.

4.2 Blowdown Operating Mode Gaging Accuracy

Table VII presents the effect of instrumentation accuracy on the OMS P-V-T propellant quantity gaging accuracy for the propellant tanks operating in the blowdown mode. The blowdown operations were begun at the 75%, 50%, and 25% propellant quantity levels. At the start of each blowdown operation, when the propellant tank internal pressure is 250 psia, the propellant gaging errors are small. This situation prevails because in the blowdown mode of operation, the large, nearly constant gaging error due to the measurement errors in the helium supply pressure and temperature does not exist. As the propellant tank ullage pressure decreases, the total gaging error increases due to the measurement errors in propellant weight, propellant tank ullage pressure, and oxidizer temperature. The largest total gaging error occurs at 0% propellant remaining. For all instrumentation sets, the range of gaging errors from the start of blowdown to the 0% propellant remaining level is much greater

TABLE VII

EFFECT OF INSTRUMENTATION ACCURACY ON THE OMS P-V-T PROPELLANT QUANTITY GAGING ACCURACY FOR THE BLOWDOWN OPERATING MODE

INSTRUMENTATION SET	PROPELLANT QUANTITY AT START OF BLOWDOWN	GAGING ERROR AS A FUNCTION OF PROPELLANT QUANTITY REMAINING (%)			
		75%	50%	25%	0%
1	75%	2.3	5.2	9.6	15.6
2	75%	1.8	3.5	5.8	8.8
3	75%	1.7	3.2	5.2	7.6
4	75%	1.4	2.8	4.5	6.6
1	50%	-	3.5	6.0	9.3
2	50%	-	2.4	3.7	5.4
3	50%	-	2.2	3.3	4.7
4	50%	-	1.7	2.7	3.9
1	25%	-	-	4.8	7.2
2	25%	-	-	3.0	4.2
3	25%	-	-	2.7	3.7
4	25%	-	-	2.1	2.9

than the similar range of gaging errors calculated for the normal operating mode.

The maximum gaging error for the blowdown mode of operation is greater than the maximum gaging error for the normal operating mode when the blowdown mode is initiated with a large quantity of propellant remaining. The reverse is true when a blowdown operation is started with a small amount of propellant remaining. The quantity of propellant remaining at initiation of a blowdown operation which will result in identical maximum gaging errors for either mode of operation is 51% for instrumentation set 1, 44% for set 2, 40% for set 3, and 45% for set 4.

4.3 Propellant Leak Detection Allowance

Table VIII presents the effect of instrumentation accuracy on the OMS P-V-T propellant leak detection allowance. The leak detection allowance increases as the quantity of propellant remaining at the start of the leak detection program decreases. It is unlikely that a leak detection program will be initiated with less than 25% propellant remaining since this is the approximate amount of propellant required for the OMS deorbit burn. At this leak detection program initiation condition, the maximum leak detection allowance ranges from a high of 3.5% for instrumentation set 1 to a low of 1.3% for set 4.

Table IX presents the effect of instrumentation accuracy on the OMS P-V-T propellant leak detection allowance when the ullage/

propellant temperature variations are neglected. The maximum leak detection allowance now ranges from a high of 3.1% for instrumentation set 1 to a low of 1.0% for set 4.

TABLE VIII

EFFECT OF INSTRUMENTATION ACCURACY ON THE
OMS P-V-T PROPELLANT LEAK DETECTION ALLOWANCE

INSTRUMENTATION SET	LEAK DETECTION ALLOWANCE AS A FUNCTION OF PROPELLANT QUANTITY AT START OF PROPELLANT LEAK DETECTION PROGRAM (%)			
	100%	75%	50%	25%
1	0.7	1.5	2.5	3.5
2	0.7	1.1	1.7	2.2
3	0.7	1.1	1.5	2.0
4	0.4	0.7	1.0	1.3

TABLE IX

EFFECT OF INSTRUMENTATION ACCURACY ON THE OMS P-V-T
PROPELLANT LEAK DETECTION ALLOWANCE, NEGLECTING
ULLAGE/PROPELLANT TEMPERATURE VARIATIONS

INSTRUMENTATION SET	LEAK DETECTION ALLOWANCE AS A FUNCTION OF PROPELLANT QUANTITY AT START OF PROPELLANT LEAK DETECTION PROGRAM (%)			
	100%	75%	50%	25%
1	0.4	1.2	2.2	3.1
2	0.3	0.7	1.1	1.6
3	0.3	0.6	0.9	1.3
4	0.2	0.4	0.7	1.0

5.0 CONCLUSIONS

This study has defined the OMS P-V-T propellant gaging accuracy and leak detection allowance for each of the four instrumentation sets described in Table II and for the assumptions listed in Section 2.0. The tolerances on the pressurant/propellant pressure measurements traditionally cause large gaging errors in P-V-T propellant gaging programs. Three pressure measurement accuracies and two temperature instrumentation configurations were examined in this analysis. The results of this study show the magnitudes of the improvements in propellant quantity gaging accuracies and propellant leak detection allowances which can be achieved by employing more accurate pressure and temperature instrumentation.

6.0 REFERENCES

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APPENDIX

PROPELLANT LEAK DETECTION

While the Shuttle vehicle is in orbit, with the OMS operating in a long-term non-firing mode, the primary OMS propellant gaging module (based on a continuous capacitance probe mounted in the propellant tank) will be inoperable because of the zero-gravity condition. Therefore, it may be desirable to provide the Shuttle crew with a means of detecting OMS propellant leakage to preclude the possibility of attempting to deorbit with an insufficient supply of OMS propellant. A computer program can be developed to determine propellant leakage from sensed propellant tank ullage pressures and temperatures. This propellant leak detection program would be similar to the OMS P-V-T propellant gaging program and both programs could use the same set of pressure and temperature instrumentation to provide required input data.

A Shuttle OMS P-V-T propellant leak detection program would consist of a series of equations to first compute the weight of helium in each propellant tankage system and then to determine the amount and rate of apparent propellant weight change throughout the mission. The most important assumption made in formulating the program is that the weight of helium in the propellant tankage system remains constant. If a helium leak occurs, the program will conservatively interpret the resultant data as a propellant leak. The program will output the amount of apparent propellant weight change and the predicted time, based on current weight change trends, at which the propellant quantity allowance for instrumentation inaccuracy will be exceeded and a propellant leak will be confirmed. An objective of this analysis is to determine the magnitude of the propellant quantity "leak detection allowance" due to instrumentation inaccuracy when each of the four instrumentation sets in Table II is used in an OMS P-V-T propellant leak detection program.

Before initialization of the propellant leak detection program, the helium bottle isolation valve will be closed. In order to minimize the propellant leak detection allowance, the leak detection program will operate only on the propellant tankage system. At some time after helium isolation valve closure at which all propellant tankage system pressures and temperatures are considered to be stabilized, the leak detection program will be initialized by computing the weight of helium in the system.

The random gaging error sources and tolerances for the P-V-T propellant leak detection program will be identical to those shown in Table V. Since the propellant tanks are assumed to be in a constant pressure environment during the leak detection program operation, the gaging errors due to the initial condition random error sources will be constant. Therefore, the gaging errors due to the operating conditions random error sources, shown in Table A-I, will determine the propellant leak detection allowance because these errors are the only ones which change as functions of time.

TABLE A-I

OMS P-V-T PROPELLANT LEAK DETECTION ALLOWANCE RANDOM GAGING ERROR SOURCES AND TOLERANCES FOR FOUR INSTRUMENTATION SETS

RANDOM GAGING ERROR SOURCE	3σ TOLERANCES FOR FOUR INSTRUMENTATION SETS			
	SET 1	SET 2	SET 3	SET 4
Operating Conditions				
Fuel Ullage Pressure	±12.8 psia	±5.6 psia	±4.0 psia	±4.0 psia
Fuel Prop. Temp.	±2.4 °F	±2.4 °F	±2.4 °F	±2.4 °F
Fuel Ull./Prop.Temp.Var.	±10.0 °F	±10.0 °F	±10.0 °F	±5.0 °F
Oxid.Ullage Pressure	±12.8 psia	±5.6 psia	±4.0 psia	±4.0 psia
Oxid. Prop. Temp.	±2.4 °F	±2.4 °F	±2.4 °F	±2.4 °F
Oxid.Ull./Prop.Temp.Var.	±10.0 °F	±10.0 °F	±10.0 °F	±5.0 °F

The error sources and tolerances given in Table A-I may be pessimistic for a leak detection program. Since there is no propellant consumed during the operation of the leak detection program, it can be reasonably assumed that the propellant ullage pressures and temperatures are stabilized. In particular, it can be assumed that the ullage and propellant temperatures are nearly equal. Hence, the operating conditions random gaging error sources due to the ullage/propellant temperature variations can be ignored. The operating conditions random gaging error sources can now be reduced to the four initial condition pressure and temperature error sources given in Table V. Presented in Table A-II are the leak detection allowance random gaging error sources and tolerances when the ullage/propellant temperature variations are neglected.

TABLE A-II

OMS P-V-T PROPELLANT LEAK DETECTION ALLOWANCE RANDOM GAGING ERROR SOURCES AND TOLERANCES, NEGLECTING ULLAGE/PROPELLANT TEMPERATURE VARIATIONS

RANDOM GAGING ERROR SOURCE	3σ TOLERANCE ON ERROR SOURCE			
	SET 1	SET 2	SET 3	SET 4
Operating Conditions				
Fuel Ullage Pressure	±12.8 psia	±5.6 psia	±4.0 psia	±4.0 psia
Fuel Ullage Temperature	±5.0 °F	±5.0 °F	±5.0 °F	±2.4 °F
Oxid.Ullage Pressure	±12.8 psia	±5.6 psia	±4.0 psia	±4.0 psia
Oxid.Ullage Temperature	±5.0 °F	±5.0 °F	±5.0 °F	±2.4 °F

The random gaging error sources are fewer, and the effective temperature tolerances are lower, in Table A-II than in Table A-I, due to a change in assumptions rather than to an improvement in instrumentation measurement accuracy.