TM-70-1022-11

TECHNICAL MEMORANDUM

SKYLAB VENTING PROPULSION

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TITLE- Skylab Venting Propulsion

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DATE- December 22, 1970

FILING CASE NO(S)- 620

AUTHOR(S)- P. G. Smith

FILING SUBJECT(S) (ASSIGNED BY AUTHOR(S))- Skylab Program
Venting Propulsion

ABSTRACT

Torque and angular momentum accumulation associated with each Skylab vent are calculated to provide data for assessing attitude control system performance. Magnitude, direction, and time history data are provided for individual vents, and 24 hour "typical" and "worst-case" day profiles are compiled from the individual vent data.

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TECHNICAL MEMORANDUM

1.0 Introduction

Many substances are vented from various parts of Skylab, and whenever this occurs a thrust results, which unless it is directed through the vehicle mass center, imparts a torque to the vehicle. The magnitude, direction, and duration of these torques determines the extent to which they can be nulled by the control moment gyroscope (CMG) attitude control system. This memorandum provides data on magnitudes, directions and time histories of significant Skylab venting torques, and twenty-four hour profiles are included for use by those assessing CMG performance.

2.0 Summary and Conclusions

The Skylab vents mentioned below give rise to propulsive effects of such magnitude that attitude control system performance may be impaired should one CMG fail.

Waste Water Vent - Water accumulates as the CSM fuel cells are used, and if a full tank of water is dumped, an angular impulse of about 5000 ft-lb-sec results. Although the mission baseline calls for fuel cell shutdown after solar array deployment, the option to continue operation until reactant depletion is being kept open until launch. At a 1200 watt power level, a full tank of water would accumulate in four days, but by dumping the tank more often, for example daily, the total impulse could be distributed more evenly.

H_2 and O_2 Relief Vents - With the fuel cells shut down, reactants must be vented from the cryogenic tanks. Initial angular momentum accumulation for the nominal mission is about 900 ft-lb-sec/orbit for H_2 and half this amount for O_2. These values decrease as the tanks empty; thus, momentum/orbit will decrease with time, and the initial value will decrease if delays are experienced in attaining orbit. The O_2 value above (450 ft-lb-sec/orbit) arises from the oxygen expelled from the tanks in excess of that required for metabolic and cabin leakage makeup. If a temporary increase in cabin O_2 partial pressure - about 1/4 psi - is allowed, O_2 venting would be unnecessary.

LOX Tank Vents - If a day's collection of urine (13 lb) enters the tank in liquid form, about 1200 ft-lb-sec will be accumulated in the first orbit with smaller amounts in the five succeeding orbits. A trash dump containing four pounds of water results in about 800 ft-lb-sec in the first orbit. The above values rise to 19,000 and 13,000 ft-lb-sec, respectively, if one of the two "nonpropulsive" vents should freeze shut. (A heater will be placed on one vent to avert this possibility.)

M092 Experiment - This vent lies under the OWS meteroid shield, and the flow will be diffused somewhat. With no diffusion, about 1300 ft-lb-sec accumulate each time the Lower Body Negative Pressure Experiment is performed. MSFC estimates that diffusion will reduce the magnitude to one third of the above value.

That benefits can be obtained from scheduling and choice of options is illustrated by comparing the "typical" and "worst-case" day momentum profiles (Table IV). Angular impulse imparted during most orbits of the typical day is about 200 ft-lb-sec, whereas on the worst-case day most orbits range from 40 to 900 ft-lb-sec.

The data presented here are being used in a simulation of the Skylab CMG attitude control system to see if it performs satisfactorily with only two CMGs in operation.* Results from this work will be available shortly. It appears that all typical day orbits and most worst-case day orbits can be accommodated.

3.0 Venting Sources Considered

Table I, compiled basically from Reference 1, gives the significant vents, their Orbital Assembly co-ordinates, the direction of thrust, the effluent, and the maximum flow rate. Several comments concerning this table are in order.

TABLE I

BASIC VENT DATA

VENT NAME	OA LOCATION (IN.)			DIRECTION COSINES			FLUID/STATE	MAX $\dot{W}$ (LB/SEC)
	X	Y	Z	X	Y	Z		
CM WASTE WATER VENT	1038.4	8.3	− 72.5	.537	− .095	.839	H_2O/L	.0628*
SM FUEL CELL H_2 PURGE VENT	1081.5	−77.0	− 0.8	0	1.000	.010	H_2/G	2×10^{-4}
SM FUEL CELL O_2 PURGE VENT	1124.5	76.7	− 7.0	0	− .996	.091	O_2/G	1.5×10^{-3}
SM H_2 RELIEF VENT	1081.5	−77.0	− 0.8	0	1.000	.010	H_2/G	2.14×10^{-5}*
CM O_2 RELIEF VENT	1035.8	30.2	− 64.8	.537	− .357	.765	O_2/G	4.83×10^{-5}*
AM CONDENSATE VENT	742.2	−29.1	57.0	0	.454	−.891	H_2O/L	.05
AM MOL. SIEVE VENT	768.7	±26.0	69.0	0	∓ 1.000	0	H_2O, CO_2, O_2, N_2/G	1.45×10^{-4}
OWS URINE DUMP SYSTEM	106.0	±52.9	±118.7	0	∓ .407	∓.914	H_2O/G	3.8×10^{-3}*
OWS TRASH DUMPS	106.0	±52.9	±118.7	0	∓ .407	∓.914	H_2O/G	2.8×10^{-3}*
M092 LOWER BODY NEG. PRES. EXPT.	302.0	−81.8	101.0	0	.629	−.777	O_2, N_2/G	2.27×10^{-3}
M479 ZERO-G FLAM. EXPT.	949.3	39.6	22.9	−.866	− .433	−.250	EXH. PROD., O_2, N_2/G	2.8×10^{-3}

*THESE ARE CALCULATED RATHER THAN GIVEN VALUES. THE METHOD OF CALCULATION IS GIVEN ELSEWHERE IN THIS MEMORANDUM

The first three lines (waste water vent and the purge vents) represent one mode of operation in which all three fuel cells operate at a 1200 watt level until reactants are depleted (about 10 days). The fourth and fifth lines (relief vents) represent an alternative mode in which fuel cells are shut down twenty-four hours after docking. In this case the remaining reactants are expelled from the tanks and vented. The choice of mode will be made before launch.

The molecular sieve vents are nominally nonpropulsive; the upper signs refer to one vent of the pair, and the lower signs refer to the other vent.*

The urine dump and trash dump systems empty into the LOX tank, which then vents to space through a pair of so-called nonpropulsive vents. Again, the two sets of signs refer to the two opposing vents.

4.0 Results for Individual Vents

Results are summarized in Table II, to which the following comments apply. The direction cosines apply to either the torque or the angular momentum magnitudes given in the columns to the right. The torque given is the largest that will occur during the mission. Likewise, worst day max H/orbit is the largest angular impulse that will occur in one orbit of the mission. Typical day max H/orbit denotes the largest angular impulse that will occur in one orbit of a "typical" day. Note that there may be orbits in either the typical or worst days in which the impulse is much smaller than the max value stated.

4.1 CSM Fuel Cells

Two options are considered here. Option 2 is baseline, but option 1 will be kept open as an alternative until launch.

Option 1 - Fuel Cells Operate

Liquid water vents from the CM waste water vent under 25 psia of bladder pressure.** Thrust and flow rate may be obtained from Appendix A, formulas (A-6) and (A-9), respectively, and Table II gives the resulting torque and

---

* Data obtained from Ed Carmody, McDonnell Douglas-East, November 2, 1970.

**This figure obtained from Roger Tanner, MSC, June 26, 1970.

TABLE II

RESULTS FOR INDIVIDUAL VENTS*

VENT NAME	DIRECTION COSINES X	Y	Z	MAX T FT-LB	MAX H/ORBIT TYP. DAY**	MAX H/ORBIT WORST DAY**
CM WASTE WATER VENT	.012	−.993	−.120	3.5	1130	4530
SM FUEL CELL H_2 PURGE VENT	−.058	−.010	.998	1.5	NEGLIGIBLE	
SM FUEL CELL O_2 PURGE VENT	.053	−.091	−.994	3.2	NEGLIGIBLE	
SM H_2 RELIEF VENT	−.058	−.010	.998	0.17	210	930
CM O_2 RELIEF VENT	−.030	−.866	−.440	.076	0	430
AM CONDENSATE VENT	−.138	.882	.450	.042	NEGLIGIBLE	
AM MOL. SIEVE VENTS	.405	−.749	−.524	.0072	40	40
OWS URINE DUMP SYSTEM	−.576	−.797	−.180	0.94	1160	1160
OWS TRASH DUMPS	−.576	−.797	−.180	0.70	790	790
M092 LOWER BODY NEG. PRES. EXPT.	−.051	−.776	−.628	1.4	420	1270
M479 ZERO-G FLAM. EXPT.	.103	.335	−.937	1.4	0	510

* COMPUTED RELATIVE TO A MASS CENTER LOCATION OF (646.7, −2.1, −25.3) IN. IN ORBITAL ASSEMBLY COORDINATES

** FT-LB-SEC/ORBIT; 1 ORBIT = 5600 SEC

angular momentum accumulation. The waste water tank holds 92 lb, and at the assumed power level, 20 lb/day of water are generated. We assume that typically water is dumped every day, and in the worst case, it is allowed to accumulate for four days, the respective dumping times being 320 sec and 1280 sec.

Thrust for the fuel cell purge vents is obtained by the method of Reference 2. Due to the short purge intervals, the angular momenta associated with these vents is negligible compared to that of the waste water vent.

Option 2 - Fuel Cells Shut Down

Hydrogen is vented from the cryogenic storage tanks at a rate that depends on how full the tanks are (see Appendix B). The peak flow rate, which occurs at fuel cell shutdown, is used for the worst-case day in Table II, and a 56-day-average flow rate is used for the typical day.

Similarly, oxygen is vented from the storage tanks. Most of this O_2 is used to replenish the cabin atmosphere, and the excess, if any, is assumed to be vented overboard. Flow rate calculations are covered in Appendix B; the worst-case day again occurs at fuel cell shutdown, but since overboard venting lasts for six days at most,the typical day flow rate is zero.

4.2 AM Condensate Vent

Thrust is calculated as shown in Appendix A. Only about five minutes is required to dump a three-day accumulation (full tank) from the AM condensate vent; hence, the angular momentum associated with this vent is negligible.

4.3 AM Molecular Sieves

Thrust is calculated by the method of Reference 2 and is essentially constant over the mission. Thrust imbalance for the pair of vents is taken to be 5 percent of the total flow,* and impingement on the MDA, OWS and solar arrays is calculated in Appendix C. Imbalance and impingement together give rise to the numbers shown in Table II.

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*Obtained from R. E. Tinius, MSFC, October 21, 1970.

4.4 OWS Urine Dump System

Four methods of dumping urine into the LOX tank are currently under consideration:

a) dump as an unconfined liquid,

b) dump in bags that will burst on entering tank,

c) dump in bags having filters that will pass gas but not liquid, and

d) dump in sealed bags that will not burst.

Methods a and b are treated here because they represent the most severe case. Behavior of the filters in method c is poorly understood, and method d of course results in no venting.

Thirteen pounds of urine are dumped each day. Flow rate is obtained from Reference 3, enc. 7, by assuming flow rate to be proportional to tank pressure, and specific impulse calculations are covered in Appendix D. Three factors influence the net propulsive effect of the LOX tank vents, flow imbalance, nozzle misalignment, and OWS solar array impingement. Flow imbalance, due mainly to the fact that one leg of the plumbing is about 30 inches longer than the other, amounts at most to about five percent.* Misalignment error calculations are covered in Appendix E, and impingement force coefficients are taken from Table I of Reference 4. The three effects are summarized below in terms of torque per unit thrust (ft-lb/lb).

	T_x/F	T_y/F	T_z/F
imbalance	.035	-2.059	.917
misalignment	$\pm$ .045	$\pm$ .377	$\pm$ .826
impingement	-1.588	.225	- .590
total (upper signs)	-1.508	-1.457	1.153
total (lower signs)	-1.598	-2.211	- .499

The values for the lower signs are used, since they appear to be worst case.

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*This information supplied by Larry Lannon, McDonnell Douglas-West, August 10, 1970.

Values shown in Table II, which are based on a single 13 lb dump, are for the orbit in which the dump occurs; venting decreases to zero over the succeeding five orbits are shown in the figure.

4.5 OWS Trash Dumps

Present estimates are that there will be five trash dumps per day in perforated bags; one bag will contain 4 lb of water, and each of the others will contain 2 lb of water.* Calculations are similar to those for the urine dump, except that flow rate is based on enc. 8 of Reference 3. Venting requires two orbits, and values for the first orbit of the 4 lb dump are shown in Table II.

4.6 M092 Lower Body Negative Pressure Experiment

Flow rate is estimated to be 2 cfm,** venting lasts 15 minutes, and the experiment is assumed to be performed every other day. As the vent is located under the OWS meteoroid shield, diffusion acts to reduce the net effective thrust. Worst-case values in Table II are for flow unimpeded by the meteoroid shield, and typical values in the table are simply one-third of the worst-case values.***

4.7 M479 Zero -G Flammability Experiment

There are six experiment sessions, which we assume to occur on different days. Each session comprises twelve short, equal-magnitude ventings spaced 5 minutes apart; the total accumulation for one session is as shown in Table II.

5.0 Momentum Profiles for Typical and Worst-Case Days

Here we synthesize composite 24-hour momentum profiles from the individual time histories just discussed. Such a synthesis is only an estimate because mission timelines have not been established yet. Therefore, these profiles just serve as examples of what might occur.

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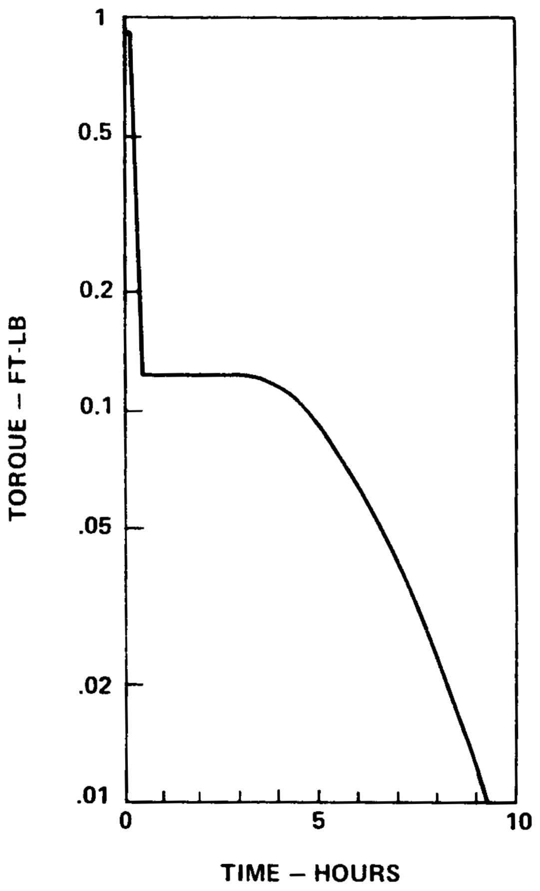
* Information from R. E. Tinius, MSFC, October 21, 1970.

** "Experiment Requirements Document for Inflight Lower Body Negative Pressure," MSC-KW-D-69-23 REVA, September 1970, paragraph 4.1.6b.

***One-third factor suggested by R. E. Tinius, MSFC, November 12, 1970.



VENTING TORQUE DUE TO A 13 LB
URINE DUMP (BASED ON REF. 3, ENC. 7)

Two profiles are presented, one called worst case, in which options are chosen and scheduling is done so that the total daily momentum accumulation is large and much of it is concentrated in one orbit, and one called typical, in which decisions are made and scheduling is done with a view toward reducing total accumulation and keeping the rate of accumulation uniform. No significance beyond this should be ascribed to "worst case" or "typical". Table III lists specific differences between the two profiles.

Results for the two profiles are given in Table IV.

TABLE III

DIFFERENCES IN THE PROFILES

VENTING FUNCTION	TYPICAL DAY	WORST-CASE DAY
CSM FUEL CELLS	FUEL CELLS SHUT DOWN; NO O_2 VENTING, 56-DAY AVERAGE H_2 VENTING (CONTINUOUS)	FUEL CELLS ACTIVE; FOUR DAY WASTE WATER COLLECTION VENTED AT BEGINNING OF ORBIT 1
AM MOL. SIEVES	CONTINUOUS VENTING	CONTINUOUS VENTING
OWS URINE DUMP	URINE IN SEALED BAGS (NO VENTING)	URINE DUMP AT BEGINNING OF ORBIT 1
OWS TRASH DUMPS	TRASH IN SEALED BAGS (NO VENTING)	4 LB DUMP AT BEGINNING OF ORBIT 1, 2 LB DUMPS AT BEGINNING OF ORBITS 4, 7, 10, 13
M092 EXPERIMENT	PERFORM AT BEGINNING OF ORBIT 1 USING TYPICAL DAY VALUE FROM TABLE II	PERFORM AT BEGINNING OF ORBIT 1 USING WORST DAY VALUE FROM TABLE II
M479 EXPERIMENT	OMIT (THIS EXPERIMENT IS PERFORMED ONLY SIX TIMES DURING THE MISSION)	PERFORM AT BEGINNING OF ORBIT 1

TABLE IV

COMPOSITE ANGULAR MOMENTUM ACCUMULATIONS (FT-LB-SEC/ORBIT)

ORBIT	TYPICAL DAY				WORST-CASE DAY			
	MAG.	DIR. COSINES			MAG.	DIR. COSINES		
1	370	−.047	−.978	−.205	7290	−.145	−.944	−.297
2	190	.021	−.167	.985	920	−.547	−.813	−.199
3	190	.021	−.167	.985	670	−.544	−.819	−.206
4	190	.021	−.167	.985	850	−.546	−.815	−.201
5	190	.021	−.167	.985	360	−.498	−.836	−.229
6	190	.021	−.167	.985	110	−.300	−.894	−.332
7	190	.021	−.167	.985	420	−.510	−.831	−.222
8	190	.021	−.167	.985	130	−.346	−.886	−.310
9	190	.021	−.167	.985	40	.405	−.749	−.524
10	190	.021	−.167	.985	420	−.510	−.831	−.222
11	190	.021	−.167	.985	130	−.346	−.886	−.310
12	190	.021	−.167	.985	40	.405	−.749	−.524
13	190	.021	−.167	.985	420	−.510	−.831	−.222
14	190	.021	−.167	.985	130	−.346	−.886	−.310
15*	190	.021	−.167	.985	40	.405	−.749	−.524

*THERE ARE ACTUALLY ABOUT 15.4 ORBITS/DAY, BUT THE REMAINDER IS NEGLECTED

6.0 Acknowledgement

Many people assisted in this work. In addition to the NASA and contractor personnel mentioned, the writer is grateful for help provided by G. W. Craft, A. S. Haron, D. S. Lopez, D. A. Mills, J. J. Sakolosky, T. C. Tweedie, and G. M. Yanizeski.

P. G. Smith

1022-PGS-mef P. G. Smith

Attachments

APPENDIX A

Thrust and Flow Rate for Liquid Venting

The thrust F is

$$F = \dot{m}V_e + A_e p_e \qquad \text{(A-1)}$$

where $\dot{m} = \dot{w}/g$ is the mass flow rate, V is velocity, A is cross-sectional area, and p is pressure; subscript e refers to conditions at the exit plane. From continuity

$$\dot{m} = \rho A_e V_e \qquad \text{(A-2)}$$

where ρ denotes mass density. If $V_o = 0$ in the reservoir, we get from the Bernoulli equation

$$p_e = p_o - \frac{1}{2}\rho V_e^2 \qquad \text{(A-3)}$$

From these relationships

$$F = 2A_e(p_o - p_e) + A_e p_e \qquad \text{(A-4)}$$

$$= A_e(2p_o - p_e) \qquad \text{(A-5)}$$

Observe that p_e lies between p_o and zero in value, probably closer to zero. Thus, approximately

$$F = 2A_e p_o \qquad \text{(A-6)}$$

If $p_e << p_o$ we see by comparison of (A-1) and (A-4) that the first term on the right hand side dominates the second term. In this case, approximately

$$F = \dot{m} V_e \qquad \text{(A-7)}$$

and by use of (A-2)

$$F = \frac{\dot{w}^2}{\rho g^2 A_e} \qquad \text{(A-8)}$$

With this same assumption that $p_e << p_o$, we obtain from (A-2) and (A-3) that, approximately

$$\dot{w} = A_e g \sqrt{2 \rho p_o} \qquad \text{(A-9)}$$

APPENDIX B

Minimum Flow Rate for SM Cryogenic Storage Tanks

HYDROGEN TANKS

The specified heat leak is 7.25 Btu/hr per tank at 140°F. The tanks' environment in Skylab, however, will run between -3 and +16°F,* so we need the heat leak at these temperatures. If heat transfer is by conduction

$$\dot{q}_1 = K_1(T_e - T_H) \tag{B-1}$$

and if by radiation

$$\dot{q}_2 = K_2(T_e^4 - T_H^4) \tag{B-2}$$

where $\dot{q}_i$ are the heat leak rates, K_i are constants, T_e is the environmental temperature, and T_H is the temperature of the contents. Using the specified heat leak and $T_H = 64°R$ (Reference 5, Figure 8-7), one can find K_1 and K_2. Then one can compute $\dot{q}_1$ and $\dot{q}_2$ as functions of H_2 quantity by using the T_H vs. quantity plot of Reference 5, Figure 8-7 (p_H = 260 psia). It turns out that $\dot{q}_1$ and $\dot{q}_2$ are nearly independent of quantity, and $\dot{q}_1 = 5.5$ Btu/hr, $\dot{q}_2 = 2.8$ Btu/hr. Since radiation is predominant in this application, we take $\dot{q} = 4.0$ Btu/hr.

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*Obtained from Ray Zajac, North American Rockwell, August 24, 1970.

Flow Rate vs. Quantity

We desire the flow rate $\dot{w} = dw/dt$ given the heat leak $\dot{q} = dq/dt$. The missing factor, dq/dw, which is plotted vs. quantity in Figure B-1, comes from Reference 5, Figure 8-6a.* Figure B-2 is obtained by dividing $\dot{q}$ by the values in Figure B-1.

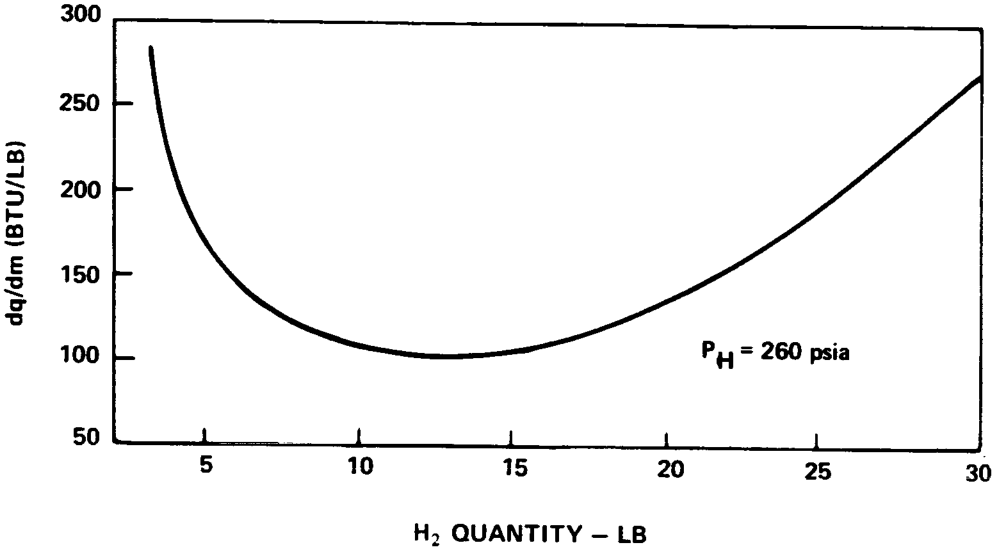

FIGURE B-1 - dq/dw VS. QUANTITY

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*The symbol m for mass is conventional in this work, but since lb units are used, we switch to w to maintain consistency with other parts of the memorandum.

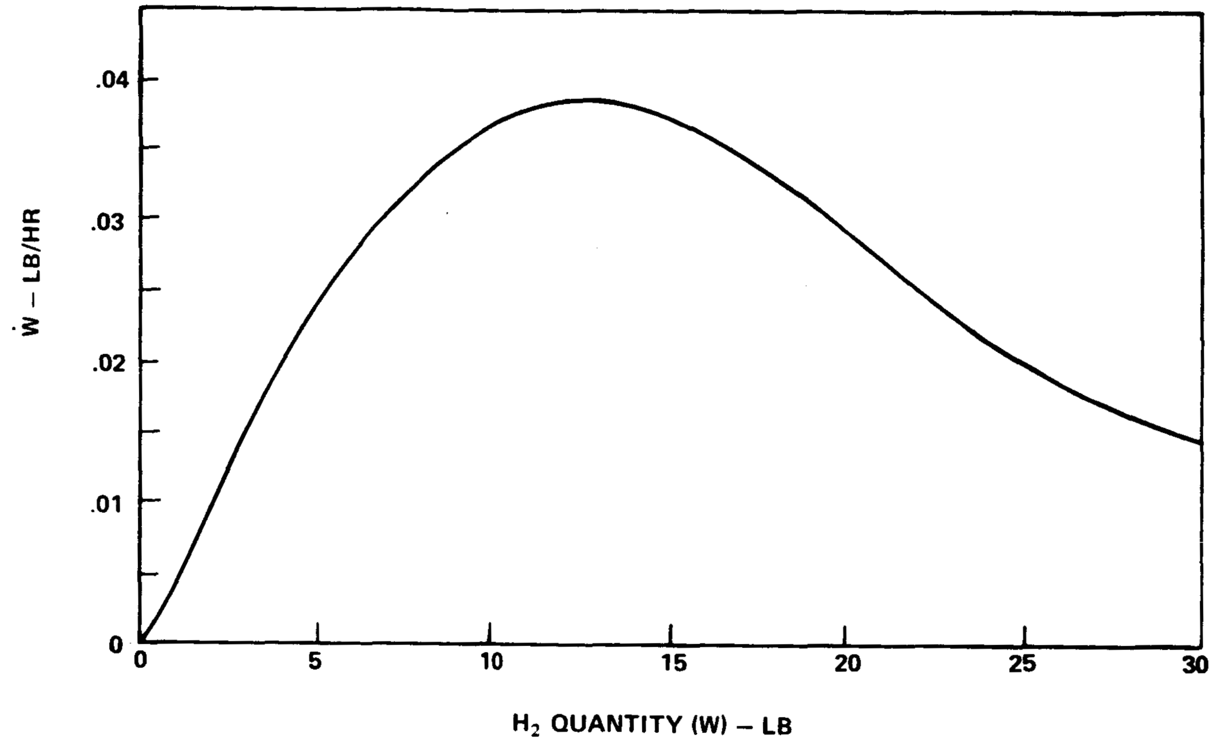

FIGURE B-2 - FLOW RATE VS. QUANTITY

Flow Rate vs. Time

This is obtained by integrating the reciprocal of Figure B-2 backward in quantity to get a plot of time vs. quantity. The boundary condition used is that t = 0 when quantity w = 12 lb. This condition corresponds to the nominal mission, which with respect to venting is also worst case because, as can be seen from Figure B-2, any slippage in the schedule will result in a smaller initial value of w and a corresponding smaller peak value of $\dot{w}$.*

By use of the time vs. quantity relation just described, the abscissa of Figure B-2 can be relabeled to give the desired flow rate vs. time plot shown in Figure B-3. Note that this figure gives the total flow from both tanks

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*This information obtained from Walter Scott, MSC, October 29, 1970.

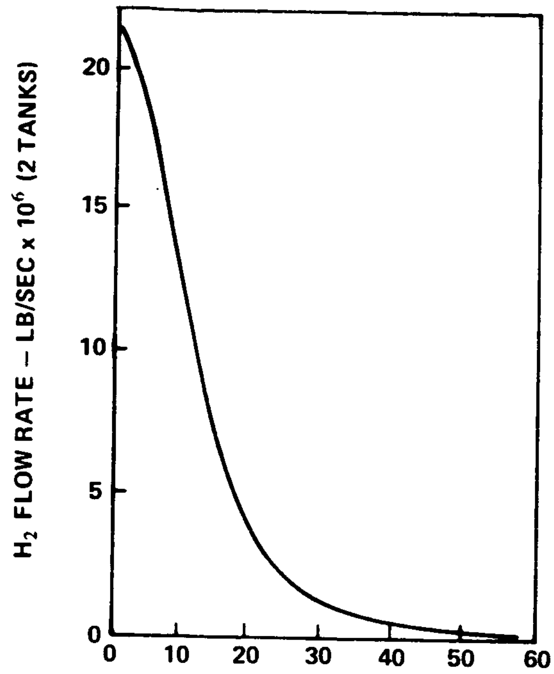

FIGURE B-3 - H_2 FLOW RATE VS. TIME

OXYGEN TANKS

The calculations for these tanks proceed in the same way as those for the hydrogen tanks just discussed, and the figures are based on an intital quantity of 112.5 lb per tank for the nominal mission.* Loss of O_2 from the cabin atmosphere due to leakage and metabolic needs is estimated at 0.55 lb/hr.* Figure B-4, from which venting thrust is calculated, shows the flow rate from both tanks in excess of the 0.55 lb/hr. This excess may either be vented overboard or it may be added to the cabin atmosphere, in which case it will raise the O_2 partial pressure by 0.24 psi. If there is less than 62 lb left in each tank at fuel cell shutdown, there will be no excess flow.

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*Obtained from Mr. Scott.

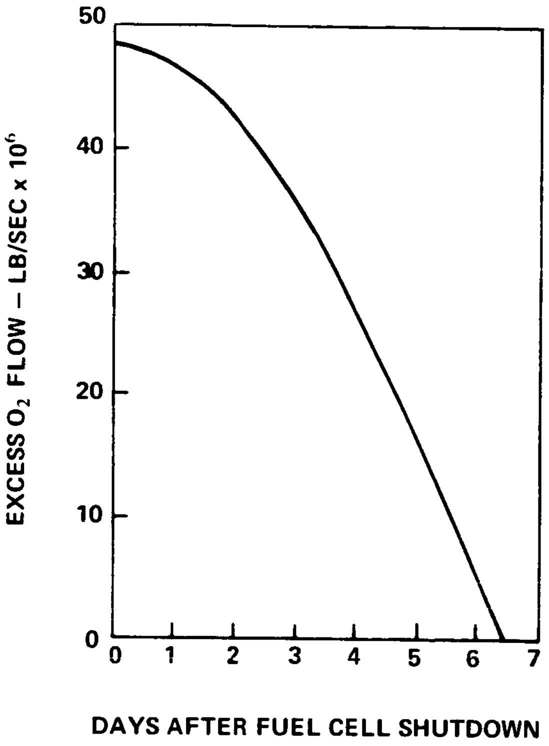

FIGURE B-4 - O_2 FLOW RATE VS. TIME

APPENDIX C

Molecular Sieve Impingement Analysis

The flow field is calculated by the method of Hill and Draper (Reference 6), which has been suggested by NASA (see Reference 7). Specifically, Hill and Draper propose the following formula for distribution of the mass flux per unit solid angle, $d\dot{m}/d\Omega$, as a function of θ, the angle off of the vent axis.

$$\frac{(d\dot{m}/d\Omega)_{\theta}}{(d\dot{m}/d\Omega)_{\theta=0}} = e^{-\lambda^2(1-\cos\theta)^2} \qquad \text{(C-1)}$$

Sufficiently far from the vent, λ approaches the value

$$\lambda = [\sqrt{\pi}\ (1-C_F/C_{F_{max}})]^{-1} \qquad \text{(C-2)}$$

The thrust coefficient ratio $C_F/C_{F_{max}}$ can be obtained from equations (10) and (30) of Reference 8. For a mean specific heat ratio $\gamma=1.34$ (Reference 1, p. 71) and unit area ratio

$$C_F/C_{F_{max}} = 0.6656$$

and

$$\lambda = 1.69$$

The unknown factor $(d\dot{m}/d\Omega)_{\theta=0}$ in (C-1) can by determined by using (C-1) in a continuity relationship

$$\dot{M} = \int_{4\pi} \frac{d\dot{m}}{d\Omega}\, d\Omega$$

$$= 2\pi (d\dot{m}/d\Omega)_{\theta=0} \int_0^{\pi} e^{-\lambda^2(1-\cos\theta)^2} \sin\theta \, d\theta$$

The integral in θ above can be reduced to the error integral, which is tabulated in Reference 8. The result is

$$(d\dot{m}/d\Omega)_{\theta=0} = \frac{\dot{M}\lambda}{\pi} \qquad \text{(C-3)}$$

Since impingement is nearly symmetrical in the +y and -y directions, the impingement torque is essentially parallel to the y axis. Thus, we compute just the torque T=RF about the y axis, where R is the effective lever arm and F is the impingement force on a surface of solid angle Ω. For perfectly elastic collisions

$$F = 2\varepsilon \frac{d\dot{m}}{d\Omega} \Omega V \qquad \text{(C-4)}$$

where ε is the cosine of the angle between the streamline and the surface normal and where V is the flow speed. Use of (C-1), (C-3) and (C-4) in T=RF yields

$$T = K\varepsilon R\Omega e^{-\lambda^2(1-\cos\theta)^2} \qquad \text{(C-5)}$$

where

$$K = \frac{2}{\pi} \dot{M} V \lambda$$

has the value 4.56×10^{-3} slug-ft/sec^2 for the molecular sieve vents. The approach is now straightforward:

determine which surfaces the molecular sieve effluent can impinge upon;

divide these surfaces into sufficiently small subsurfaces;

calculate ε, R, Ω, and θ for each subsurface;

calculate T for each subsurface using (C-5); and

add the individual torques to find the total impingement torque.

This approach was used on the following surfaces:

OWS solar arrays (mostly shadowed by the OWS);

ATM solar arrays (mostly shadowed by the OWS, STS, and MDA);

STS and MDA (broken into 24 subsurfaces); and

AM truss meteoroid curtain (broken into 10 subsurfaces).

In each case impingement torques were computed for only one vent of the pair, and the results were doubled (this is accounted for in the numerical value of K). The resulting total torque is 6×10^{-3} ft-lb, the major portion of which comes from the STS/MDA surfaces.

APPENDIX D

Specific Impulse for the LOX Tank Vents

By use of a specific heat ratio $\gamma=1.28$ for water and an area ratio $A_e/A_t = (4/1.215)^2$ for the nozzle, one obtains from Reference 8 (eqn (19), p. 67) a pressure ratio

$$\frac{p_e}{p_c} = .009015$$

where e denotes conditions at exit and c denotes conditions in the tank (chamber).* Use of this pressure ratio and the value $T_c = 510°R$** in formula (16), p. 62, of Reference 8 gives

$$V_e = 2878 \text{ ft/sec}$$

Furthermore, one obtains from eqn (13), p. 60, of the same reference

$$p_c = 2.23 \times 10^5 \dot{m} \text{ lb/ft}^2$$

where $\dot{m}$ is the nozzle mass flow rate. It follows from the above pressure ratio that $p_e=201 \dot{m}$ lb/ft^2, and from eqn (A-1)

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* Mean free path calculations for this vent indicate that continuum theory is valid here.

**Suggested by D. P. Woodard.

$$I = \frac{F}{\dot{m}g} = \frac{V_e}{g} + \frac{A_e p_e}{\dot{m}g} = 89.9 \text{ sec} \qquad \text{(D-1)}$$

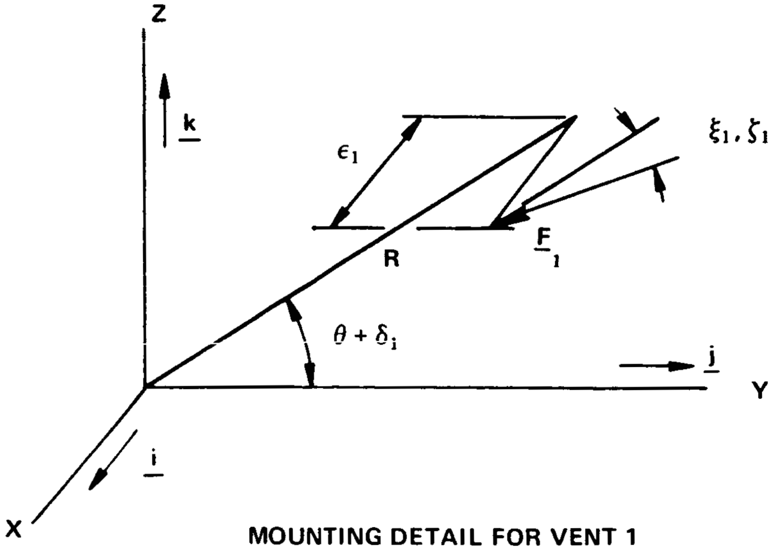
I is the specific impulse of one LOX tank nozzle.

APPENDIX E

Misalignment of "Nonpropulsive" Vents

Nominally, the OWS "nonpropulsive" vents are mounted on opposite sides of the cylindrical Workshop so that their lines of action coincide. The objective here is to determine what torque is apt to result if the mounting varies from nominal within specified tolerances.

As shown in the figure, the first vent of the pair is nominally mounted at a distance R from the Workshop longitudinal (x) axis and at an angle θ about this axis, and the thrust vector is parallel to the location vector. Let subscripted Greek letters denote small random deviations from nominal. δ_1 is the angular mounting deviation, ϵ_1 is the axial mounting deviation, and ξ_1 and ζ_1 are the angular deviations of the thrust vector relative to the location vector, these being right-hand rotations about x and **z**, respectively, when $\theta=0$. Mounting of the second vent is described similarly, except that the angular location $\theta+\delta_2$ is measured from -y toward -z.



MOUNTING DETAIL FOR VENT 1

The location vectors relative to the mass center (x_c, y_c, z_c) are

$$\underline{r}_i=(\varepsilon_i-x_c)\underline{i}+[\underline{+}R\cos(\theta+\delta_i)-y_c]\underline{j}+[\underline{+}R\sin(\theta+\delta_i)-z_c]\underline{k} \tag{E-1}$$

the upper signs referring to the first vent (i=1) and the lower ones referring to the second vent (i=2). The thrust vectors are

$$\underline{F}_i=\underline{+}F[\zeta_i\underline{i}-\cos(\theta+\delta_i+\xi_i)\underline{j}-\sin(\theta+\delta_i+\xi_i)\underline{k}] \tag{E-2}$$

and the torque is

$$\underline{T} = \underline{r}_1 x \underline{F}_1+\underline{r}_2 x \underline{F}_2 \tag{E-3}$$

If (E-1) and (E-2) are substituted into (E-3) and quadratic and higher terms in the small deviations are dropped, we obtain

$$\begin{aligned}\underline{T}=F\{&[(y_cC+z_cS)(\delta_1-\delta_2)-(R-y_cC-z_cS)\xi_1-(R+y_cC+z_cS)\xi_2]\underline{i}\\ &+[-x_cS(\delta_1-\delta_2)+S(\varepsilon_1-\varepsilon_2)-x_cC(\xi_1-\xi_2)+(RS-z_c)\zeta_1+(RS+z_c)\zeta_2]\underline{j}\\ &+[-x_cS(\delta_1-\delta_2)-C(\varepsilon_1-\varepsilon_2)-x_cS(\xi_1-\xi_2)-(RC-y_c)\zeta_1-(RC-y_c)\zeta_2]\underline{k}\}\end{aligned} \tag{E-4}$$

where $C = \cos\theta$ and $S = \sin\theta$.

Let T_x, T_y, T_z be the $\underline{i}$, $\underline{j}$, $\underline{k}$ measure numbers of $\underline{T}$, and let

$$T = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} \tag{E-5}$$

We desire the covariance, P, of T,

$$P = E\{(T-T_0)(T-T_0)'\} \qquad \text{(E-6)}$$

where E is the expectation operator, where T_0 is the mean of T, and where primes denote transposition. With the assumption that all of the deviations are zero mean and uncorrelated, the elements of P may be computed by inspection from (E-4). For example,

$$P_{11} = E\{T_x^2\}=F^2[(y_cC+z_cS)^2(\sigma_{\delta 1}^2+\sigma_{\delta 2}^2)$$

$$+(R-y_cC-z_cS)^2\sigma_{\xi 1}^2+(R+y_cC+z_cS)\sigma_{\xi 2}^2] \qquad \text{(E-7)}$$

where $\sigma_{\delta 1}^2 = E\{\delta_1^2\}$ is the variance of δ_1, etc. If the deviations are uniformly distributed, as we shall assume, $\sigma^2 = \Delta^2/3$, where $\pm\Delta$ is the tolerance on the deviation under consideration.

Application to LOX Tank Vents

Values for x_c, y_c, z_c, R, and θ come from Tables I and II. The tolerances are*

ε_1, ε_2: ±0.5 inch

δ_1, δ_2, ξ_1, ξ_2, ζ_1, ζ_2: ±0.5 degree

For these values

---

*Supplied by George Carlson, McDonnell Douglas-West, August 10, 1970.

$$\frac{1}{F^2} P = \begin{bmatrix} .0064 & .0057 & .0083 \\ .0057 & .0416 & .0751 \\ .0083 & .0751 & .1719 \end{bmatrix}$$

With a view toward finding a coordinate transformation that will eliminate the substantial off-diagonal elements of P, eigenvalues and eigenvectors of P are calculated. The eigenvalues are

$$.0047F^2, \quad .0085F^2, \quad 0.2067F^2$$

Comparison of the relative magnitudes of these three numbers reveals that the torque uncertainty in the directions of the first two eigenvectors is much less than it is in the direction of the third eigenvector. Thus, in all likelihood, the misalignment torque will be closely aligned with the third eigenvector, and this gives the direction of the misalignment torque. The magnitude is chosen so that there will be about 95% probability that the actual torque will be smaller than the value calculated. This is done by invoking the central limit theorem, which says that misalignment torque will tend toward a Gaussian distribution even if the deviations are not Gaussian, by taking the square root of the third eigenvalue, which gives standard deviation σ, and by multiplying by two, since 2σ gives about 95% assurance that the actual value will be less than the calculated value. The resulting values for misalignment torque are

$$\pm.045F, \quad \pm.377F, \quad \pm.826F$$

E-5

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