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TECHNICAL MEMORANDUM

EFFECT OF VENTING AND LEAKAGE TORQUES ON ATTITUDE CONTROL OF THE SKYLAB ORBITAL ASSEMBLY BY CMGS

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SUBJECT: Effect of Venting and Leakage Torques on Attitude Control of the Skylab Orbital Assembly by CMGs - Case 620

DATE: March 2, 1971

FROM: W. Levidow

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Introduction

It is desirable that attitude control of the Skylab Orbital Assembly (OA) be maintained by the CMGs without assistance from the TACS, even should one of the 3 CMGs fail. To accomplish this, the CMGs must counteract all disturbance torques and provide torque to execute bias momentum dump (desaturation) maneuvers.

A large fraction of the bias momentum accumulated by the CMGs results from venting and leakage torques. Most of these are continuous, but others, particularly those due to urine and trash disposal, can be intermittent and thus subject to scheduling. This memorandum investigates the impact of venting and leakage torques on CMG momentum management and shows that unaided control with 2 CMGs can be achieved.

The memorandum begins with a brief explanation of the disturbance torques. This is followed by a discussion of CMG momentum limitations in handling these torques and in executing the dump maneuvers. The CMG control capability under several venting and leakage conditions is then presented. Finally, the momentum centering task required during the mission to attain a 2 CMG capability is described.

Disturbance Torques

The significant disturbance torques acting on the vehicle are those due to venting, leakage, aerodynamic drag and gravity-gradient. The origin and nature of these torques will be discussed briefly and the resulting bias momentum to be dumped indicated.

A. Venting

The venting torques[1] considered here result in per orbit bias momentum as shown in Table 1. The components are given along the OA X, Y, Z geometric axes, the +Z axis being directed toward the ATM. Some venting torques may be considered

Table 1

Venting Bias Momentum, ft-lb-sec/orbit

Vent	H_x	H_y	H_z	$\|\underline{H}\|$
Fuel Cell				
SM H_2	- 54	9	-928	930
CM O_2	- 13	370	-190	430
AM Molecular Sieve	16	30	21	40
Trash (4 lb water)				
1st orbit, first 82°	-167	232	52	291
next 278°	-286	395	90	495
2nd orbit	-121	168	38	210
Urine (3 Bags)				
1st orbit, first 108°	-388	536	121	673
next 252°	-278	386	87	483
2nd orbit	-398	551	125	691
3rd orbit	-374	518	117	650
4th orbit	-251	348	100	440
5th orbit	-132	183	41	229
Urine (1 Bag)				
1st orbit	-250	-345	- 78	433
2nd orbit	-195	-270	- 61	338
3rd orbit	-129	-178	- 40	223
4th orbit	- 64	- 89	- 20	111
5th orbit	- 26	- 36	- 8	45

uniform from orbit to orbit over one day and others are intermittent, their occurrence depending upon scheduled crew action.

The uniform venting torques are:

1. Fuel Cell

   With the CSM fuel cells shut down, reactants are vented from the cryogenic tanks. All of the H_2 and some of the O_2 are vented overboard. The remaining O_2 replenishes the cabin atmosphere. The values shown in Table 1 are for an orbit at the beginning of the mission; they decrease with time as the tanks empty. The H_2 venting bias momentum halves in 12 days and the O_2 in 4 days.

2. Molecular Sieve

   The molecular sieve consists of two canisters that remove CO_2 from the cabin atmosphere. The canisters are alternately vented to vacuum for 15 minute periods each.

The venting torques that may be scheduled are:

1. OWS Trash Disposal

   Present estimates are that there will be five disposals per day into the waste tank of trash in storage bags. One disposal will contain 4 lbs of water and each of the others 2 lbs of water. The bags may leak or burst sometime after disposal due to the reduced pressure in the unpressurized waste tank. In this study the worst case assumption is made that the bags burst immediately upon disposal. Part of the water quickly evaporates. The balance freezes and then sublimes over two orbits. The venting torque varies with time, particularly during the first orbit after disposal. For simulation purposes, the first orbit was divided into two intervals of constant torque, each of which approximates the actual torque and results in equivalent bias momentum over the interval. The bias momentum values of Table 1 are for the 4 lb trash disposal; the 2 lb values are proportionately less.

2. OWS Urine Dump

Urine is collected from the crew in three separate bags each day. These are also assumed to burst immediately when placed in the waste tank. As with the trash, a portion evaporates quickly and a portion freezes and then sublimes. Table 1 shows the effect of disposing three bags at a time and one bag at a time. The three bag disposal results in a far less uniform torque during the first orbit than the one bag disposal. As with the trash, the first orbit after the three bag disposal was divided into two intervals of constant torque each.

Other venting sources such as Experiment M092 (Lower Body Negative Pressure), Experiment M479 (Zero-G flammability) and OWS LOX Initial Blowdown are not considered here because their bias torques are very small or they occur so infrequently that they have a negligible effect.[1]

B. Leakage

Leakage torque is due to cabin atmosphere leaking out of the pressurized modules. Depending upon the magnitude and direction of each leak, the resulting bias momentum[4] can have a magnitude (H_ℓ) ranging from zero to a maximum of 1450 ft-lb-sec/orbit. The maximum value is attained by assuming:

1. Leak rates are the maximum allowable per module.
2. Leaks occur in each module at a location farthest from the OA mass center.
3. The leakage thrust vector passes through and is normal to the OA longitudinal axis. All leaks produce torque in the same direction.

Since the occurrence of the maximum is highly unlikely, two more reasonable estimates of leakage momentum were selected for this study - half-maximum (H_ℓ=725) and r_{ss} (H_ℓ=431)[4]. The r_{ss} value is the root sum square of separate module contributions, assuming maximum leaks at the module centers instead of in the worst location.

The direction of the leakage bias momentum vector is unknown, but for this study it is assumed, for each orbit, to be fixed in the OA in the direction perpendicular to the orbital plane during solar pointing. This is its worst case direction for two reasons. First, the cyclic CMG momentum excursion due to gravity-gradient torque is also perpendicular to the orbital plane. The two then combine directly over a portion of the orbit, maximizing the resultant CMG momentum excursion. And second, although the momentum sampling and desaturation commands adjust the roll angle (ν_z) about the sun line for minimum bias momentum buildup, ν_z cannot compensate for a bias momentum perpendicular to the orbital plane. This momentum must be dumped by nighttime maneuvers.

C. Aerodynamic Drag

The magnitude of aerodynamic torque depends upon Beta (β) and is directed approximately perpendicular to the orbital plane. The maximum occurs at β=0, and for a conservative air density model results in a bias momentum vector of approximately 150 ft-lb-sec per orbit directed northerly.

D. Gravity-Gradient

The gravity-gradient torque has a large cyclic component perpendicular to the orbital plane and approximately in the YZ plane of the OA. Along the X axis there is a varying but undirectional torque whose magnitude depends upon β. For the vehicle considered here (docked configuration with principal moments of inertia of 661,000, 4,486,000 and 4,419,000 slug-ft^2 and flying in a 230 NM, 50° inclination orbit) the maximum gravity-gradient bias momentum is approximately 350 ft-lb-sec per orbit.

CMG Momentum Variations

CMG momentum changes result from two actions. The first is in counteracting the disturbance torques on the vehicle; cyclic components result in cyclic momentum and bias components result in bias momentum the latter of which must be dumped during orbital night.

The second action is in supplying torque to the vehicle for executing the momentum dump maneuvers. These maneuvers consist of three constant angular velocity rotations, the first occuring over 1/4 the nightime dump interval, the second over 1/2 the interval, and the third over the remaining 1/4 interval. In general, the larger the momentum to be dumped, the larger the angular velocities. Hence, four rather large CMG momentum changes are required to impart the four velocity changes to the vehicle. The dump interval at each β is the largest dark interval that can be centered about desaturation midnight, with a minimum of 54°* on each side.

Each of the 3 CMGs has a spin angular momentum of 2300 ft-lb-sec, but because of gimbal stops, only about 2250 ft-lb-sec can be provided in some directions. For attitude control without TACS assistance, the CMG momentum excursion is limited then to a spherical envelope of 4500 ft-lb-sec radius for 2 CMGs and 6750 ft-lb-sec for 3 CMGs.

Average Momentum Excursions

Since a significant part of the CMG momentum excursion is the result of accelerating the vehicle to the dump maneuver angular velocities, it is prudent to limit these excursions by avoiding unusally large momentum dump commands in any one orbit. Accordingly, the maximum excursion over one day would be most contained if the venting bias momentum were accumulated and dumped uniformly over the day instead of in bursts. A look at the CMG momentum excursion under a fictitious "average" venting is useful for it serves as a reference from which schedules of urine and trash disposal can be investigated. It represents the best that can be obtained under any disposal schedule. "Average" venting is defined by a constant venting torque such that the bias momentum over one day is the same as would result from the intermittent urine and trash disposals. Figure 1a shows the resulting momentum excursion along the Y and Z geometric axes for $\beta=-25°$ and leakage momentum of 725 ft-lb-sec. The origin is defined as the center of the circle of minimum radius that contains the excursion. Dashed lines are the momentum changes required to accelerate the vehicle during dump maneuvers . Arrow heads show the direction of these changes.

Point A corresponds to the momentum at orbital 6 AM, B at noon, C at 6 PM and D at the initiation of the first dump maneuver. It is interesting to observe that the excursion from A to B, which is due mainly to gravity-gradient torque, is nearly perpendicular to the orbital plane. From D to E the OA is accelerated by CMG torquing to the first dump angular velocity, which is maintained from E to F. From F to G the OA is accelerated to the second velocity which is maintained from G to H (midnight) to I. From I to J the OA is accelerated to the third angular velocity which is maintained until the OA is brought to rest in a solar inertial attitude at L. At 6 AM it is back to A.

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*Telephone conversation December 1970 with H. Kennel, MSFC.

The circle marked 2 CMG represents the 4500 ft-lb-sec envelope. Since the X axis momentum never exceeds 500 ft-lb-sec, the radial distance between this circle and the nearest point inside represents the margin for 2 CMG operation. Table 2 shows the 2 CMG margins for several values of β and the two assumed values of leakage bias momentum.

Table 2

2 CMG Configuration Momentum Margins (ft-lb-sec), "Average" Venting

Leakage Momentum (ft-lb-sec)	Beta						
	+73°	+45°	+25°	0°	-25°	-45°	-73°
725	1080	1110	1060	670	540	580	620
431	1120	1150	1100	1040	920	800	840

It should be recalled that since the direction of the leakage bias momentum vector is unknown, it was considered in the worst direction for each β, perpendicular to the orbital plane. The leakage momentum vector can actually be perpendicular to the orbital plane at only one value of β. Therefore the margins shown are the lower bounds; they cannot all be as small as shown. The margins will also improve with time as the fuel cell bias momentum diminishes after cell shutdown.

The margins above were obtained for fictitious uniform venting of urine and trash. The margins for realistic disposal schedules are discussed next.

Control Capability with Disposal Bags that Burst

The more uniformly the urine and trash are disposed over the day, the more nearly will the margins of the previous section be realized. Table 3 shows three disposal schedules that have been investigated. The items disposed during each orbit in a day are shown.

In schedule A, the individual urine bags and trash are disposed in different orbits. In B and B' they are disposed in the same orbit, but as discussed later the disposal point in orbit for B is different from that for B'. Schedule A makes for more uniform venting but B and B' requires less crew activity. In C, all three urine bags are disposed in the same orbit once a day.

The disposal point in orbit is important because of the planned momentum sampling and desaturation procedures. Nightime dump maneuvers are based on CMG momentum sampling during the previous 6 AM to 6 PM orbital interval. But from Table 1, trash and urine disposal results in a larger bias momentum accumulation during the first half orbit after disposal than in the second half. Hence, if disposal occurred at 6 AM, the CMG sampling would indicate a larger orbital bias momentum for the first orbit than actually occurs, and large dump maneuvers would be commanded. It is desireable to time the disposal so that the sampling indicates less than the bias momentum of the first orbit, and thereby postpone some of the dumping to subsequent orbits during which momentum accumulation is small. This avoids unusually large dump maneuvers and large CMG excursions during the first night following disposal. Smoothing out of the momentum dumping can be accomplished by scheduling the disposals during the daylight hours at a time significantly removed from 6 AM and 6 PM. Not only will this limit the first night's maneuver, but the sampling will result in an increment of ν_Z (roll about the Z axis) at sunrise. This attitude change produces a gravity-gradient torque in the following orbit which tends to counteract the disposal venting torques. ν_Z will slowly revert back to its steady state value on subsequent orbits as the venting dissipates.

Table 3

Disposal Schedule

Orbit	A	B,B'	C
1	U		
2	T	U+T	T
3			
4	U		3U
5	T	U+T	T
6			
7	U		
8	T	U+T	T
9			
10			
11	T*	T*	T*
12			
13			
14	T	T	T
15			

A - noon disposal

B - noon disposal

B' - midnight disposal

C - trash at noon, urine 30° after noon

U - 1 urine bag

3U - 3 urine bags

T - 2 lb water trash

T* - 4 lb water trash

Disposals A and B occur at noon. The trash of C is disposed at noon but the three urine bags are disposed 30° of orbit after noon. The disposals of B' are at midnight which, although less favorable from a momentum standpoint, might be a more convenient time for the crew to perform this task.

Figure 1b shows the CMG momentum excursion for the orbit of maximum excursion for disposal schedule C and H_ℓ= 725 ft-lb-sec. The increase in the momentum change required to accelerate the vehicle for the larger maneuvers is evident and accounts mainly for reducing the 2 CMG margin from 540 to 190 ft-lb-sec.

Figure 2 displays the maximum momentum excursion from center for the several disposal schedules at selected values of β and H_ℓ=725. The momentum saturation limits for 2 and 3 CMGs are indicated by the horizontal dotted lines. The margins are represented by the distance between the vertical schedule lines and the horizontal CMG limit lines.

The effect of a smaller assumed leakage momentum of H_ℓ=431 was also investigated in conjunction with disposal schedule C. Its CMG momentum excursion is shown by a short bar through the C lines. Reduced leakage will reduce the momentum excursions for the other schedules by similar amounts.

Table 4 lists the margins corresponding to Figure 2.

Table 4

2 CMG Momentum Margins (ft-lb-sec)†

	Disposal Schedule					Non-Burst Bags
Beta	A	B	B'	C	C (H_ℓ=431)	
73	1070	1070	1040	1030	1150	960
45	970	980	680	680	890	1020
25	920	940	530	550	840	980
0	600	370	130	190	520	860
-25	520	320	210	190	520	700
-45	420	340	120	200	330	540
-73	560	460	60	160	300	540

†H_ℓ = 725 ft-lb-sec, except as noted

The results for schedules A, B, and C show that the margins tend to decrease as greater quantities of liquid are disposed in the same orbit. Although schedule C has the smallest margin of the three, it is within the 2 CMG limit and is in accordance with current plans to dispose all three urine bags at the same time.

As expected, midnight disposal, schedule B', results in considerably smaller margins.

Although the indicated 2 CMG margins are small, particularly for negative values of β, they have been obtained under the assumptions that the leakage torque is perpendicular to the orbital plane for all values of β, and that the initial fuel cell venting torque persists throughout the mission. These assumptions are conservative and indicate smaller margins than will be experienced during the mission.

Control Capability with Non-Burst Disposal Bags

If most of the urine and trash disposal bags do not break, the accumulated bagged liquid in the waste tank alters the mass properties of the OA. If 10% of the disposed liquid is assumed vented, the estimated[2] 1σ principal moments of inertia early in the Skylab 4 mission are 717823, 4729510, 4667303 slug-ft^2. As indicated in Table 4 and Figure 2, the margins with non-burst bags are larger than the burst-bag cases studied.

In connection with non-burst bags, the maximum leakage (H_ℓ = 1450 ft-lb-sec) was also simulated. It produced a negative margin of 200 ft-lb-sec at β =-25° but positive margins at the other β's tested. This worst case leakage condition is highly unlikely.

Centering of Momentum Variations

To obtain the best margins it is necessary to center the CMG momentum variation on the line drawn between the two most distant points (K and F, Figure 1b) on the CMG YZ momentum plot. This task can be accomplished with the aid of the Mission Control Center by monitoring the YZ momentum excursions orbit by orbit and noting, for the orbits of maximum excursion, the difference between the actual and desired center of the momentum variations. The difference can then be minimized by periodically adjusting e_{BY} and e_{BZ}, the normalized desaturation bias input to the momentum desaturation command equations[3]. Although not critical for the 3 CMGs this task may be required to avoid the use of TACS with only 2 CMGs.

Conclusions

The Skylab Orbital Assembly can be controlled in the solar inertial attitude and the dump maneuvers can by executed with 2 CMGs without aid from the TACS. This can be done in the presence of venting torques and a conservative model (half the maximum possible magnitude and always in the worst direction) of leakage torque.

If the urine and trash disposal bags burst when placed in the waste tank the CMG momentum margin depends on the disposal schedule. The more constant the resulting venting torque, the greater is the margin.

Adequate 3 CMG margin is obtained with any disposal schedule but with 2 CMGs the schedule becomes more important. Daylight disposal of the three urine bags together on one orbit and the trash on other orbits results in a 2 CMG margin of 160 ft-lb-sec for the worst orbit. This procedure is suggested and is in accordance with current planning to dispose all three urine bags at the same time.

Disposing the urine bags individually on separate orbits yields greater margins and could be resorted to if necessary.

Orbital midnight disposals may be more convenient but result in smaller margins because of the planned momentum sampling and desaturation procedures.

If most of the urine and trash bags do not burst, greater margins result. In spite of the increasing inertias, an assumed 10% sublimation results in a 2 CMG margin of 540 ft-lb-sec at a time corresponding to early in the Skylab 4 mission.

Attainment of 2 CMG margins requires centering the CMG momentum excursions within the allowable range. This can be accomplished during the mission by monitoring the CMG momentum excursion at the Mission Control Center as the mission progresses and periodically adjusting the excursion center by means of input to the desaturation command equations in the ATM computer.

Acknowledgement

R. W. Grutzner computer programmed the momentum sampling and desaturation maneuver equations. His assistance is gratefully acknowledged.

W. Levidow

1022-WL-mef W. Levidow

Attachment
References
Figures 1 & 2

REFERENCES

1. Smith, P. G., "Skylab Venting Propulsion", Bellcomm Technical Memorandum TM-70-1022-18, December 22, 1970.

2. S+E-ASTN-SAE Program WP97B, MSFC, October 7, 1970, Run 45F, Event 15.

3. Skylab A ATM Digital Computer Program Requirements Document, S&E-ASTR-SG, July 1, 1970, Chapter 10.

4. Smith, P. G., "Skylab Leakage Propulsion Models", Bellcomm Memorandum for File B71 03005, March 2, 1971.

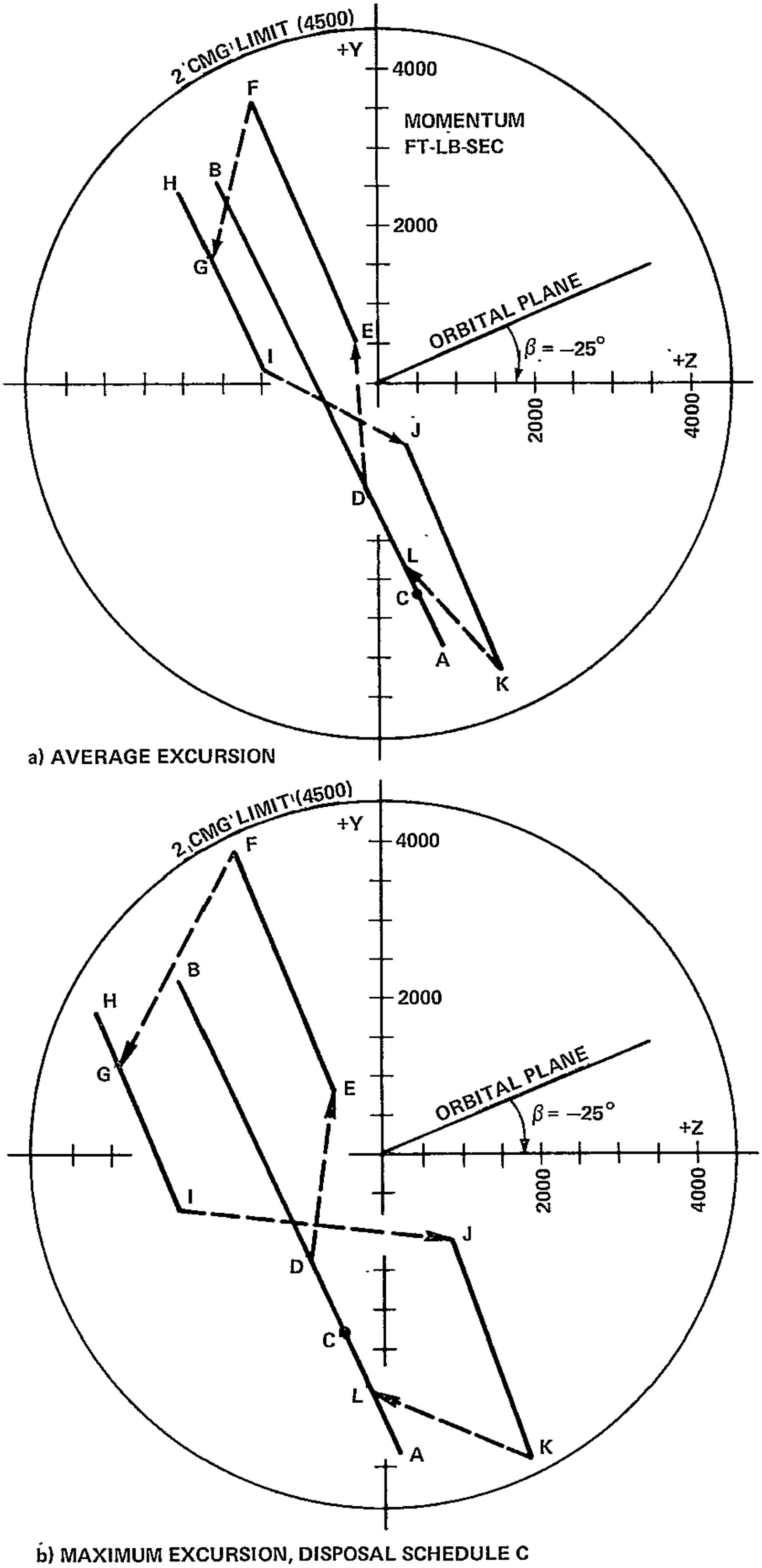
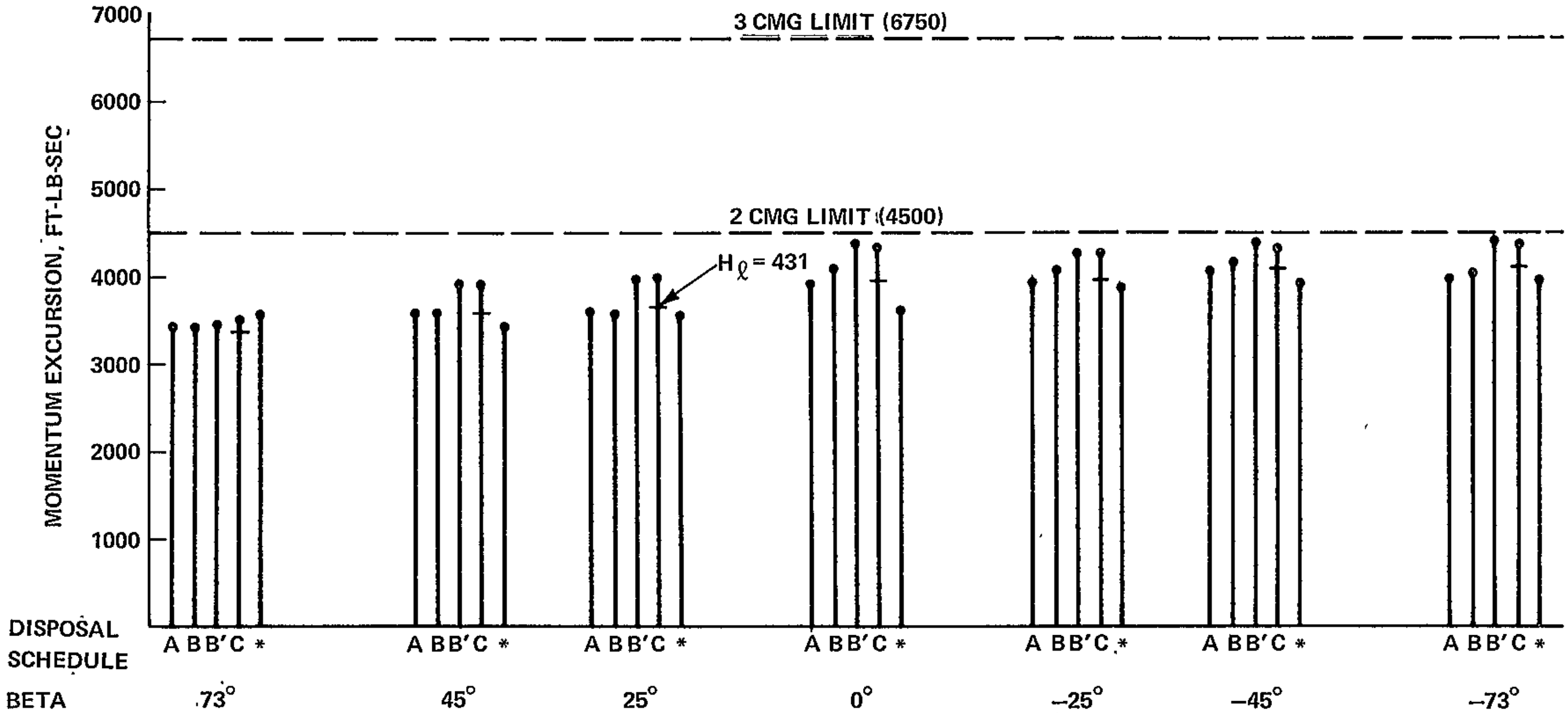


FIGURE 1 - MOMENTUM EXCURSIONS, BETA = −25° (LEAKAGE BIAS MOMENTUM = 725 FT-LB-SEC, NORMAL TO ORBITAL PLANE)



A – 1 URINE BAG AND TRASH IN DIFFERENT ORBITS, NOON DISPOSAL
B – 1 URINE BAG AND TRASH IN SAME ORBIT, NOON DISPOSAL
B′ – SAME AS B BUT MIDNIGHT DISPOSAL
C – 3 URINE BAGS IN SAME ORBIT
* – NON-BURST DISPOSAL BAGS

FIGURE 2 - CMG MAXIMUM MOMENTUM EXCURSION (LEAKAGE BIAS MOMENTUM = 725 FT-LB-SEC, NORMAL TO ORBITAL PLANE)