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SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

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ENTRY REACTION CONTROL SYSTEM PROPELLANT ANALYSIS

FLIGHT CONTROL INTEGRATION

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1.0 SUMMARY

This design note documents an analysis which investigated the effects of winds, sideslip angle feedback, and the data reference (air or inertial) on the Reaction Control System (RCS) propellant requirements during Entry. It was determined that in the presence of a 3 σ crosswind an additional 188 pounds of RCS propellant was required for Entry control which is within the present 200 pound allotment for winds. The absence of air data information does result in slightly higher RCS propellant demands.

This analysis was conducted under contract Number NAS 9-13970, Task Order Number C0203.

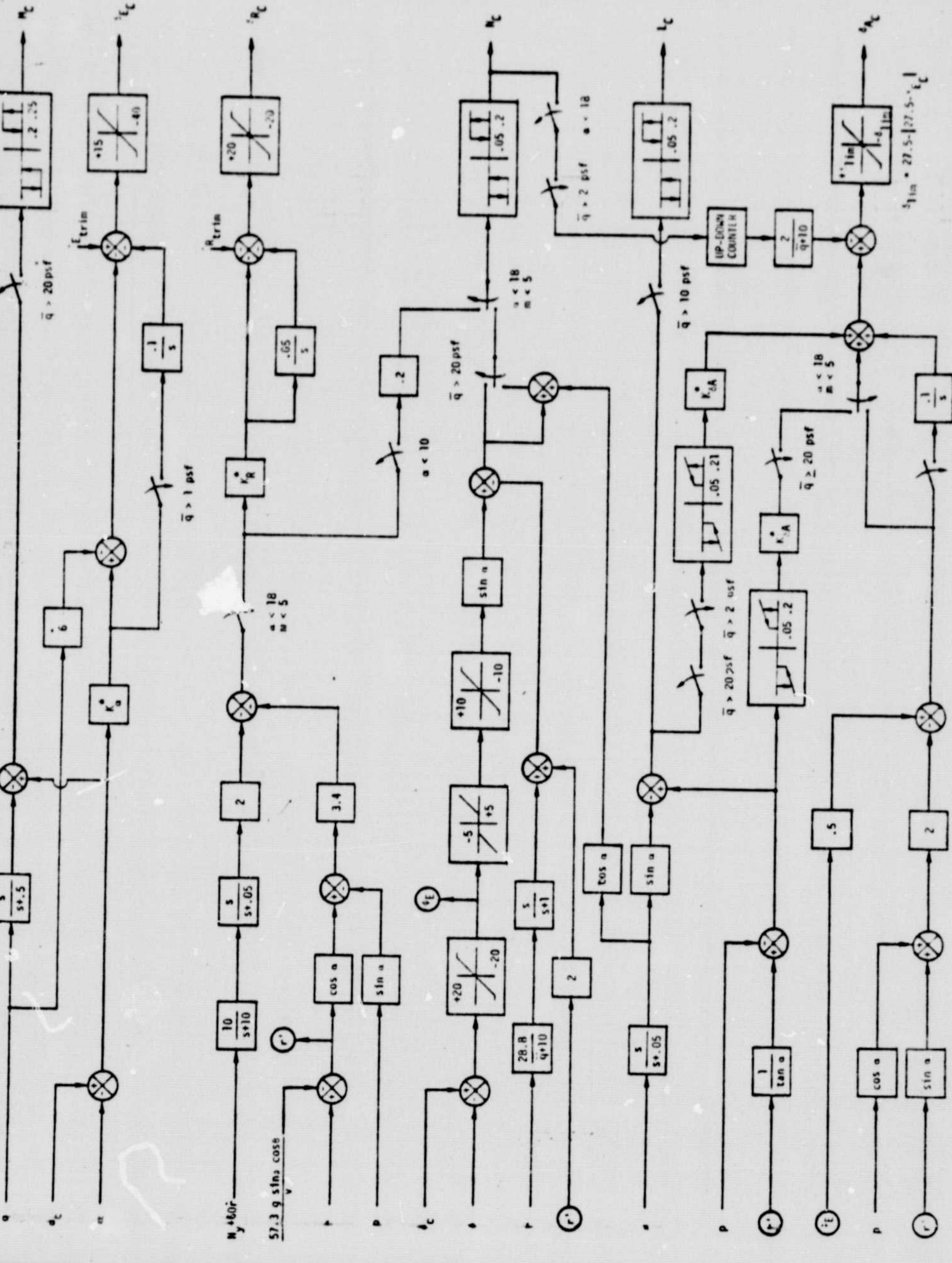
2.0 INTRODUCTION

The present baseline control system utilizes angle of attack (α), sideslip angle (β), and bank angle (ϕ) feedback data in controlling the Orbiter during Entry. There has been some concern in using β feedback in the presence of a crosswind without the benefit of air data information. A β measurement derived from the inertial system will not have any knowledge of the wind. Under this condition a β feedback controller normally requires additional propellant to maintain an angle relative to the wind. This analysis briefly investigates this phenomenon and the resulting propellant requirements in a wind environment during the Entry flight regime.

3.0 DISCUSSION

The data presented in this discussion were obtained from the Space Shuttle Functional Simulator (SSFS), Reference (1) and Reference (2). The Guidance and Control (G&C) for this analysis were the 30.5° constant angle of attack guidance, Reference (3), and the Rockwell International (RI) System X Entry FCS, Reference (4). Figure (1) is a block diagram of the RI System X Entry FCS. The sideslip angle feedback, depicted in Figure (1) as β, is utilized in the lateral-directional channel from the initiation of the Entry flight phase to a dynamic pressure ($\bar{q}$) of 20. Lb/Ft^2 to aid in bank angle maneuver coordination.

Figure 1: Rockwell X Entry Flight Control System



This analysis consisted of four runs for the same entry initial conditions. The Orbiter was initialized with a vehicle latitude and longitude of 0.0° and 17.2°, an airport latitude and longitude of 0.0° and -120.567°, and a heading of 180.0°. These initial conditions were selected because the wind profile used for this analysis would basically produce a crosswind effect. A X-axis and Z-axis center of gravity offset of 0.0 inches and a Y-axis center of gravity offset of 2.28 inches were used throughout the analysis.

AVEH5, GRAV3, RCS14, MASS23, AERO21, and ACS12 are the SSFS math models which are common to each run. WIND6 is the wind profile math model; and it is shown in Figure (2). Details of all the math models can be found in Reference (2).

4.0 RESULTS

The RCS on-time and propellant required were monitored for each run and tabulated in Table (1) and Table (2), respectively. In Table (1) on-time is the summation of the RCS firing durations about the roll, pitch and yaw axis. Propellant required in Table (2) was computed assuming that each thruster produced 875.0 pounds of thrust and that the specific impulse was 289.0 seconds.

Run (1) is the no wind case with the baseline FCS and resulted in a total RCS propellant requirement of 532.0 pounds. Run (2) is identical to the first run except a crosswind was applied. In the second run perfect air data knowledge is assumed. This run required a total of 720.3 pounds of RCS propellant. The disturbance created by the wind required an additional 188.3 pounds of propellant. This is lower than the 200.0 pound allotment for winds during the Entry flight regime but not significantly lower. This 200.0 pound allotment may be marginal or even inadequate since preliminary results indicate that the latest baseline Entry autopilot, Reference (5), requires more RCS propellant for control than the autopilot used in this analysis.

Run (3) is the same as Run (2) except the SSFS was modified to delete air data knowledge in obtaining sideslip, bank angle and angle of attack information. The propellant consumed at 1000.0 seconds, flight

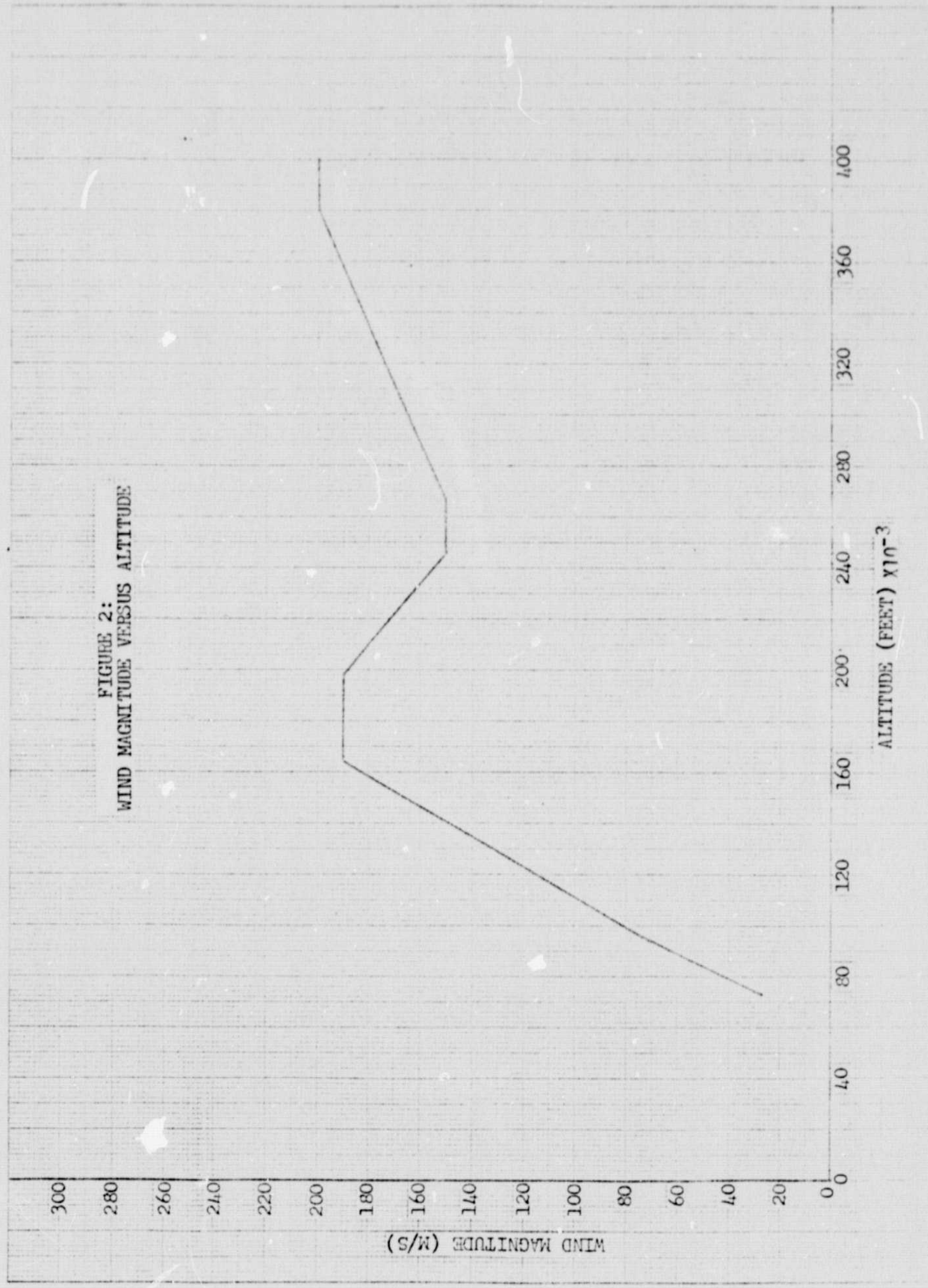


FIGURE 2:
WIND MAGNITUDE VERSUS ALTITUDE

TABLE 1: ENTRY RCS PROPELLANT REQUIREMENTS

RUN NUMBER	FLIGHT TIME (SEC)	DYNAMIC PRESSURE (LB/FT2) **	RCS ON-TIME* ROLL TIME (SEC)	PITCH TIME (SEC)	YAW TIME (SEC)	TOTAL TIME (SEC)	SSFS RUN CHARACTERISTICS
1	340.	10.	24.8	3.2	10.9	38.9	LAT=0.° LONG=17.2° HEADING= 180.0° AP LAT=0.°. AP LONG=-120.567° RI X DAP MASS23 Δ Y CG= -.28 in. AVEN5 AERO21 Δ X CG= 0.0 in. GRAV3 ACS12 Δ Z CG= 0.0 in. RCS14 NO WINDS
	700.	20.	24.8	3.2	54.1	82.1	
	1800.	81.2	24.8	3.2	83.8	111.8	
	2500.	TAEM	24.8	3.2	147.7	175.7	
2	340.	10.	32.0	3.4	11.7	47.1	SAME AS RUN NO. 1 EXCEPT o WIND= WIND6 FROM NORTH TO SOUTH o SIDESLIP, BANK, AND ATTACK ANGLES COMPUTED FROM AIR DATA INFORMATION
	690.	20.	32.0	3.8	58.0	93.8	
	1800.	81.1	32.0	3.8	89.0	124.8	
	2490.	TAEM	32.0	3.8	202.1	237.9	
3	340.	10.	28.0	4.6	14.9	47.5	SAME AS RUN NO. 1 EXCEPT o WIND= WIND6 FROM NORTH TO SOUTH o SIDESLIP, BANK, AND ATTACK ANGLES HAS NO AIR DATA KNOWLEDGE
	410.	20.	28.0	5.2	28.1	61.3	
	1800.	80.7	28.0	5.2	89.4	122.6	
	2490.	TAEM	28.0	5.2	227.8	261.0	
4	340.	10.	40.6	3.4	19.2	63.2	SAME AS RUN NO. 1 EXCEPT o WIND= WIND6 FROM NORTH TO SOUTH o BANK AND ANGLE OF ATTACK HAVE NO AIR DATA KNOWLEDGE o SIDESLIP FEEDBACK DELETED FROM RI X DAP
	570.	20.	40.6	3.4	50.4	94.4	
	1800.	80.7	40.6	3.4	90.8	134.8	
	2490.	TAEM	40.6	3.4	242.0	286.0	

** ROLL JETS TURNED OFF $\bar{q}$=10.; PITCH JETS TURNED OFF $\bar{q}$= 20.; SIDESLIP FEEDBACK REMOVED $\bar{q}$= 20.; TAEM INDICATES TAEM INTERFACE; 1800. IS TIME POINT PRIOR TO TRANSITION PHASE OF ENTRY FLIGHT REGIME

* ON-TIME IS SUMMATION OF RCS JET PULSE DURATIONS

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TABLE 2: ENTRY RCS PROPELLANT REQUIREMENTS

RUN NUMBER	FLIGHT TIME (SEC)	DYNAMIC PRESSURE (LB/FT^2) **	RCS PROPELLANT REQUIREMENTS * ROLL WEIGHT (LB)	PITCH WEIGHT (LB)	YAW WEIGHT (LB)	TOTAL WEIGHT (LB)	SSFS RUN CHARACTERISTICS
1	340.	10.	75.1	9.7	33.0	117.8	LAT= 0°. LONG= 17.2° HEADING= 180.0° AP LAT= 0.° AP LONG=-120.567° RI X DAP MASS23 Δ Y CG= 2.28 in. AVEH5 AERO21 Δ X CG= 0.0 in. GRAV3 ACS12 Δ Z CG= 0.0 in. RCS14 NO WINDS
	700.	20.	75.1	9.7	163.8	248.6	
	1800.	81.2	75.1	9.7	253.7	338.5	
	2500.	TAEM	75.1	9.7	447.2	532.0	
2	340.	10.	96.9	10.3	35.4	142.6	SAME AS RUN NO. 1 EXCEPT o WIND= WIND6 FROM NORTH TO SOUTH o SIDESLIP, BANK, AND ATTACK ANGLES COMPUTER FROM AIR DATA INFORMATION
	690.	20.	96.9	11.5	175.6	284.0	
	1800.	81.1	96.9	11.5	269.5	377.9	
	2490.	TAEM	96.9	11.5	611.9	720.3	
3	340.	10.	84.8	13.9	45.1	143.8	SAME AS RUN NO. 1 EXCEPT o WIND= WIND6 FROM NORTH TO SOUTH o SIDESLIP, BANK, AND ATTACK ANGLES HAS NO AIR DATA KNOWLEDGE
	410.	20.	84.8	15.7	85.1	185.6	
	1800.	80.7	84.8	15.7	270.7	371.2	
	2490.	TAEM	84.8	15.7	689.7	790.2	
4	340.	10.	122.9	10.3	58.1	191.3	SAME AS RUN NO. 1 EXCEPT o WIND= WIND6 FROM NORTH TO SOUTH o BANK AND ANGLE OF ATTACK HAVE NO AIR DATA KNOWLEDGE o SIDESLIP FEEDBACK DELETED FROM RI X DAP
	570.	20.	122.9	10.3	152.6	285.8	
	1800.	80.7	122.9	10.3	274.9	408.1	
	2490.	TAEM	122.9	10.3	732.7	865.9	

** ROLL JETS TURNED OFF $\bar{q}$= 10.; PITCH JETS TURNED OFF $\bar{q}$=20.; SIDESLIP FEEDBACK REMOVED $\bar{q}$= 20.; TAEM INDICATES TAEM INTERFACE; 1800 IS TIME POINT PRIOR TO TRANSITION PHASE OF ENTRY FLIGHT REGIME

* RCS PROPELLANT WEIGHT COMPUTATIONS ASSUMES THRUST=875. LB AND A SPECIFIC IMPULSE=289 SEC.

time prior to the guidance bank commands during the Entry transition phase, indicates that there is only a small difference between the propellant required with or without air data information. This almost identical propellant usage results because a washout filter processes the β feedback signal (see Figure (1)). Without air data knowledge the β derived from the inertial system does not allow the vehicle to weathercock into the wind and thus causes the vehicle to maintain an angle relative to the wind. Without the washout filter the Orbiter would require propellant to maintain this angle relative to the wind. However, this angle essentially has a steady state value and thus its effects are cancelled by the washout filter.

During the transition phase of the Entry flight regime the Orbiter is acquiring a tangency point on the TAEM alignment circle. Without air data knowledge the vehicle is trying to fly a direct heading to the TAEM alignment circle but is continually being perturbed by the wind. This requires more bank command than the run with air data knowledge where the vehicle weathercocks into the wind. These additional bank commands required approximately 10.0% more RCS propellant.

Run (4) is identical to Run (3) except the sideslip feedback is deleted initially rather than at the nominal dynamic pressure switch point of 20.0 pounds/square foot. With the sideslip angle uncontrolled any change in sideslip is reflected in the roll axis and is damped out by the roll jets. This additional disturbance is reflected in an increase in roll axis propellant requirement up to a dynamic pressure of 10.0 pounds/square foot where the roll jet commands are zeroed. There is no additional increase in propellant requirements until the latter part of the Entry flight. This can be seen by comparing the 1800.0 second time point for Run (3) and Run (4). Again as in Run (3) the absence of air data knowledge required more bank commands than Run (2) during the transition phase and resulted in higher RCS propellant utilization.

5.0 CONCLUSION

Several conclusions can be derived from this brief analysis. The original assumption, that the deletion of the angle of sideslip feedback would result in a RCS propellant savings, was shown to be invalid because the washout filter in the β control loop tends to cancel the effects of any steady state sideslip angle.

Winds can significantly increase the RCS propellant requirements during the Entry flight regime. Although this analysis indicates that the 200.0 pound propellant allotment for winds is sufficient, there is some question that this allotment will be sufficient with the latest baseline Entry autopilot.

The absence of air data information for sideslip, bank angle and angle of attack resulted in an additional propellant cost of approximately 10.0% due to the increase in required bank maneuvers during the final Entry phase prior to TAEM interface.

6.0 REFERENCES

1) Space Shuttle Functional Simulator Engineer/Programmer User's Guide (EXEC 8) Revision 1, Lockheed Electronics Company, Inc., Report Number LEC-0178, dated August 1974.

2) Space Shuttle Functional Simulator, Environments Revision C, JSC Internal Note JSC-06726, Volume III, dated October 1974.

3) Space Shuttle Functional Simulator Entry Guidance Update, Lockheed Electronics Company, Inc., Report Number LEC-4061, dated July 1974.

4) Rockwell International System X Control System, Lockheed Electronics Company, Inc., Report Number LEC-1781, dated January 1974.

5) Breckenridge, R. A., SSFS Implementation of the August 12, 1974 Version of RI System X Entry DAP, Lockheed Electronics Company, INC., Report Number LEC-4862, dated October 1974.