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REPORT MDC E0603

SPACE SHUTTLE

AUXILIARY PROPULSION SYSTEM

DESIGN STUDY

PHASE A REPORT

REQUIREMENTS DEFINITION

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY • EAST

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PHASE A REPORT
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15 FEBRUARY 1972 | REPORT MDC E0603

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CONTRACT NO. NAS 9-12013

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ABSTRACT

This report presents the analyses and rationale used to develop requirements for the oxygen-hydrogen Auxiliary Propulsion Systems evaluated in the "Space Shuttle Auxiliary Propulsion System Design Study," (Contract NAS 9-12013). The requirements presented apply to a fully reusable Space Shuttle vehicle system using internal, reusable main engine propellant tanks in both the orbiter and booster stages.

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1. INTRODUCTION

To provide the technology base necessary for design of the Space Shuttle, the NASA has sponsored a number of technology programs related to Auxiliary Propulsion Systems. These programs have included a series of system studies aimed at providing the design data necessary for selection of preferred system concepts and for delineation of requirements for complementing component design and test programs. The first of these system studies considered a broad spectrum of system concepts, but because of high vehicle impulse requirements coupled with safety, reuse and logistics considerations, only cryogenic oxygen and hydrogen were considered as a propellant combination. Additionally, unknowns in thruster pulse mode ignition and concerns with the distribution of cryogenic liquids served to eliminate liquid-liquid feed systems from the list of candidate concepts. Therefore, only systems which delivered propellants to the thrusters in a gaseous state were considered for the Reaction Control System (RCS). The results of these early studies, reported in References A through D, indicated that, among the many options for implementation of a gaseous oxygen hydrogen system, an approach using heat exchangers to thermally condition the propellants and turbopumps to provide system operating pressure, would best satisfy requirements for a fully reusable Space Shuttle. These study programs focused attention to this general system type, but did not examine in depth several viable approaches for turbopump system design and control. To fill this need the NASA contracted with McDonnell Douglas Astronautics Company - East in July 1971 for additional study of the Shuttle Auxiliary Propulsion Systems. This contract (NAS 9-12013) titled "Space Shuttle Auxiliary Propulsion System Design Study" was under the technical direction of Mr. Darrell Kendrick, Propulsion and Power Division, Manned Spacecraft Center, Houston, Texas.

As originally defined, this design study was a five phase program considering only oxygen and hydrogen propellants. Reference E provides an executive summary of program results and Reference F provides a detailed description of the program plan for each of the five program phases listed below:

1. Phase A Requirements Definition
2. Phase B Candidate RCS Concept Comparisons
3. Phase C RCS/OMS Integration
4. Phase D Special RCS Studies
5. Phase E System Dynamic Performance Analysis.

Phase A defined all design and operating requirements for the Auxiliary Propulsion System design effort. The results of this phase are the subject of this report. In Phase B, detailed design and control analyses for the three most attractive gaseous oxygen-hydrogen Reaction Control System concepts were conducted. Reference G provides a detailed description of Phase B effort. Phase C was aimed at defining the potential for integration of the RCS and the Orbit Maneuvering System (OMS). As defined by the original contract, only oxygen and hydrogen were considered in this phase. However, vehicle studies which were concurrent with this design effort, showed that smaller Shuttle orbiters with external, expendable main engine tankage would provide a more cost effective vehicle approach. The result of this change in vehicle design was a significant reduction in APS requirements and this, coupled with a companion Shuttle program decision to allow scheduled system refurbishment, allowed consideration of systems using earth storable propellants for auxiliary propulsion. Thus, in November of 1971, the NASA issued a contract change order that extended the scope of Phase C to include earth storable monopropellant and bipropellant systems, and redirected Phase E to provide a final performance analysis of storable propellant systems. Reference H provides documentation of Phase C effort on oxygen-hydrogen and Reference I reports the results of both Phase C and E effort on earth storable propellant systems. In addition to the principal contract effort in Phases B and C, the study included an exploratory effort to evaluate two alternatives to gaseous oxygen-hydrogen RCS using turbopumps that had not been previously considered. Reference J documents the results of these latter Phase D studies.

The body of this report provides a description of the analyses and rationale used to develop RCS and OMS requirements for the system design study. The vehicle requirements and characteristics on which the propulsion requirements are based were a part of the original contract definition and were issued by NASA as a "Space Shuttle Vehicle Description and Requirements Document (SSVDRD)." Appendix A, attached, summarizes pertinent sections of the SSVDRD for reference purposes.

2. PROPULSION SYSTEM REQUIREMENTS AND CONSTRAINTS

Space Shuttle vehicle configurations and vehicle requirements are summarized in Appendix A. Three baseline Shuttle vehicle missions were defined: (1) an easterly launch mission, intended primarily for delivering and retrieving payloads in a 100 nautical mile circular orbit; (2) a south polar mission consisting of orbiter launch into an orbit of 50 x 100 nautical miles with circularization at apogee utilizing the OMS; and (3) a resupply mission for a space station/space base in a 270 nautical mile orbit. The easterly launch mission is designated the design mission while the south polar and resupply missions are designated reference missions.

General requirements of the SSVDRD applicable to the RCS and OMS include: minimum maintenance with ease of component removal and replacement, a minimum service life of 100 mission cycles over a ten year period with cost effective refurbishment, and 7 days of self-sustaining life for each mission. The SSVDRD further specifies that the RCS and OMS provide sufficient control capability for crew safety after failure of any two critical components, except for OMS operation in an abort mode. In this case the OMS must provide only fail-safe operation after a single failure. The rationale is that the main engine failure constitutes the first system failure.

Requirements of principal interest to the RCS are engine thrust, number of engines, maximum system thrust, total impulse and total impulse expenditure history. Of primary interest to the OMS design is definition of the optimum RCS/OMS velocity allocation. Reference K specifies that the OMS perform all X-axis translation maneuvers equal to or greater than 20 feet per second (fps). All other translation maneuvers are performed by the RCS. Additional requirements of importance to the OMS are engine thrust and number of engines. Studies summarized below define these requirements and show the impact of using common hardware for both stages of the baseline Shuttle vehicle. To accomplish this, the number of RCS thrusters and thrust level were varied to satisfy the vehicle control and maneuvering acceleration requirements. Total impulse expenditures were determined for the three missions using typical minimum impulse bit data as a function of thrust level. RCS weights were then determined as a function of thrust level for both stages, and the penalties incurred by using common thrusters for the two stages were evaluated. A summary of the resultant RCS and OMS requirements is presented in Figure 2-1.

2.1 Reaction Control System Requirements - The orbiter RCS total impulse expenditure for the three missions is shown in Figure 2-2 for varying thrust levels. Both the total impulse and the attitude control portion of that impulse are shown. To develop the curves of Figure 2-2, thrust level was correlated to minimum impulse bit for existing liquid engines. The total RCS impulse includes the maneuvering velocity increments tabulated in Figure 2-3 which are equal to or less than 20 fps in the X direction or are applied in other axes. For illustrative purposes, the RCS total impulse for two thrust levels (representing stage-optimized thrust levels for booster and orbiter, taken independently) is broken down into individual requirements in Figure 2-4. Of principal significance in Figure 2-4 are the fine attitude hold and station keeping requirements. At 2000 lbf-thrust, these constitute an appreciable total impulse requirement, but at 1000 lbf-thrust they represent a minimal percentage of the total.

Total RCS weight was defined utilizing the total impulse requirements together with the thrust level and required number of thrusters. Typical RCS design data based on previous MDAC-E studies were used to determine the sensitivity of payload to thrust, specific impulse and RCS inert weight. The resulting sensitivities, shown in Figure 2-5, allowed comparison of exchanges between booster and orbiter RCS weight. Figure 2-6A presents total RCS weights for both booster and orbiter as a function of thrust level on a stage basis. Orbiter RCS weight minimized near 1000 lbf-thrust, while booster RCS weight minimized at a thrust level of approximately 2000 lbf. Using these data, the effect of using a common thrust level for the orbiter and booster was evaluated. The results are shown in Figure 2-6B. The reference weight in this figure is for stage-optimized thrust levels, i.e., orbiter and booster RCS thrust levels of 1000 and 2000 lbf, respectively. The lower curve of Figure 2-6B shows the payload weight penalty associated with RCS inert weight only, while the upper curves reflect both inert and propellant weight. Both approaches indicate payload weight is maximized at a common thrust of about 1000 lbf for the booster and orbiter. The two failure conditions shown in Figure 2-6B reflect a difference in the criteria used for system design. For the fail safe/ fail safe criteria, the systems are designed by the number of engines and thrust

RCS/OMS DESIGN REQUIREMENTS

		ORBITER	BOOSTER
RCS	NUMBER OF THRUSTERS	33	24
	THRUSTER THRUST (LB)	1,150	1,150
	NUMBER OF CONDITIONERS	3	4
	SYSTEM THRUST (LB)	5,750	11,500
	TOTAL IMPULSE (LB-SEC)		500,000
	RESUPPLY	2.23×10^6	---
	EASTERLY LAUNCH	2.23×10^6	---
	SOUTH POLAR	2.15×10^6	---

		DESIGNED FOR ON ORBIT	DESIGNED FOR ABORT
OMS	NUMBER OF ENGINES	3	3
	ENGINE THRUST (LB)	TBD*	12,000
	SYSTEM THRUST (LB)	TBD*	24,000
	TOTAL IMPULSE (LB-SEC)		
	RESUPPLY	10.34×10^6	---
	EASTERLY LAUNCH	3.72×10^6	---
	SOUTH POLAR	12.87×10^6	---

* TO BE DETERMINED DURING STUDY FROM RCS/OMS OPTIMIZATION.

Figure 2-1

RCS MISSION TOTAL IMPULSE REQUIREMENTS

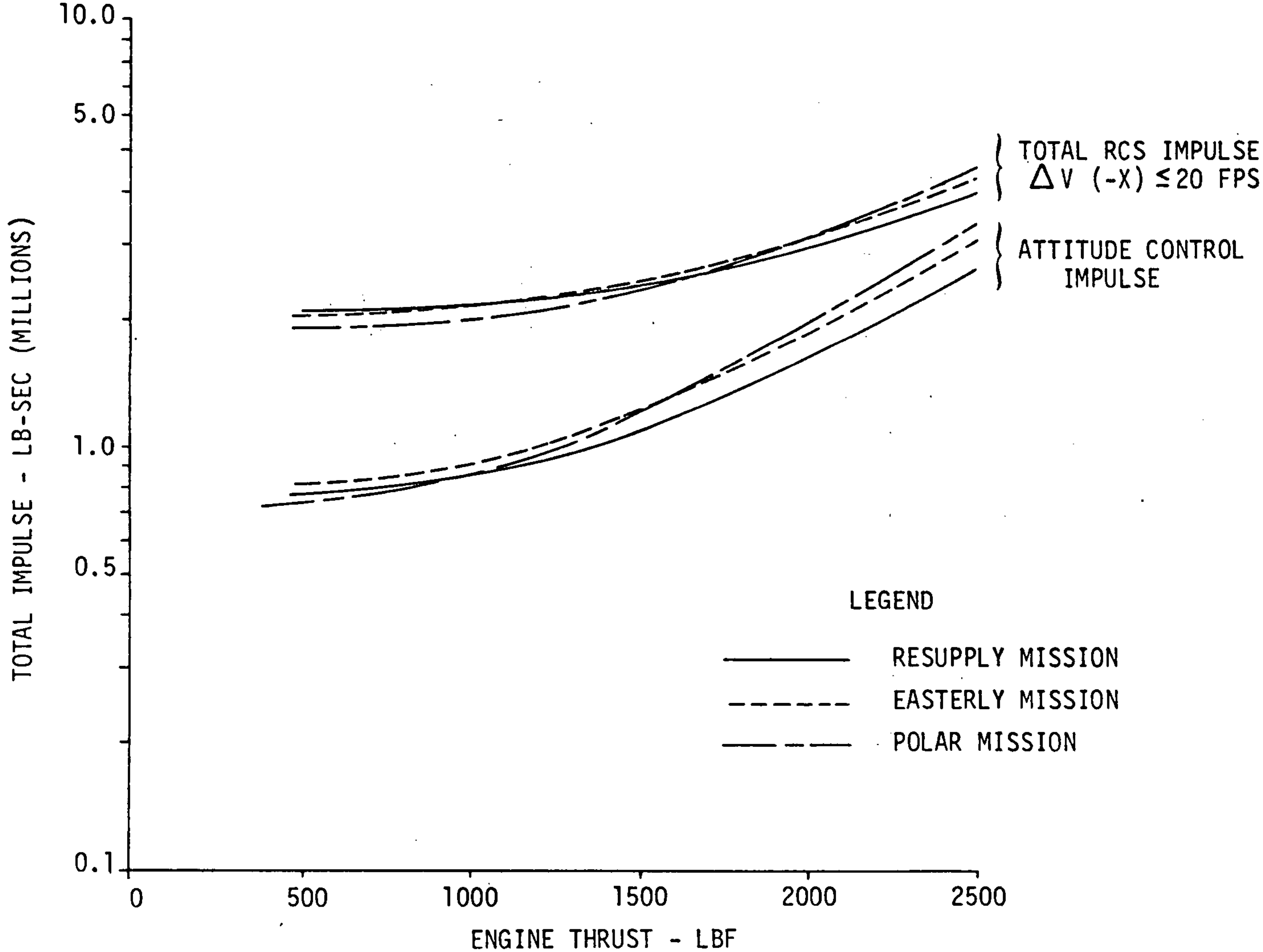


Figure 2-2

RCS MANEUVER REQUIREMENTS

MISSION	MANEUVER	NO. BURNS	ΔV (FPS)	THRUST (LBS)	BURN TIME (SEC)
RESUPPLY	COELLIPTIC BURN	1	18	4600	36
	BRAKING-1	4	45	4600	90
	DOCKING-1	PULSE	10	--	20
	SEPARATION-1	1	10	4600	20
	BRAKING-2	4	54	4600	107
	DOCKING-2	PULSE	10	--	20
	SEPARATION-2	1	10	4600	20
	TOTAL	11	157		
EASTERLY	SPACING BURN-1	1	10	3450	29
	SPACING BURN-2	1	10	3450	29
	ORBIT MAINTENANCE	12	54	4600	116
	BRAKING	4	44	4600	95
	DOCKING	PULSE	10		
	TOTAL	18	128		
SOUTH POLAR	PAYLOAD DEPLOYMENT	2	21	3450	55
	ORBIT MAINTENANCE	12	54	4600	106
	ON-ORBIT ACTIVITIES	5	55	4600	108
	TOTAL	19	130		

Figure 2-3

RCS TOTAL IMPULSE BREAKDOWN

o EASTERLY MISSION

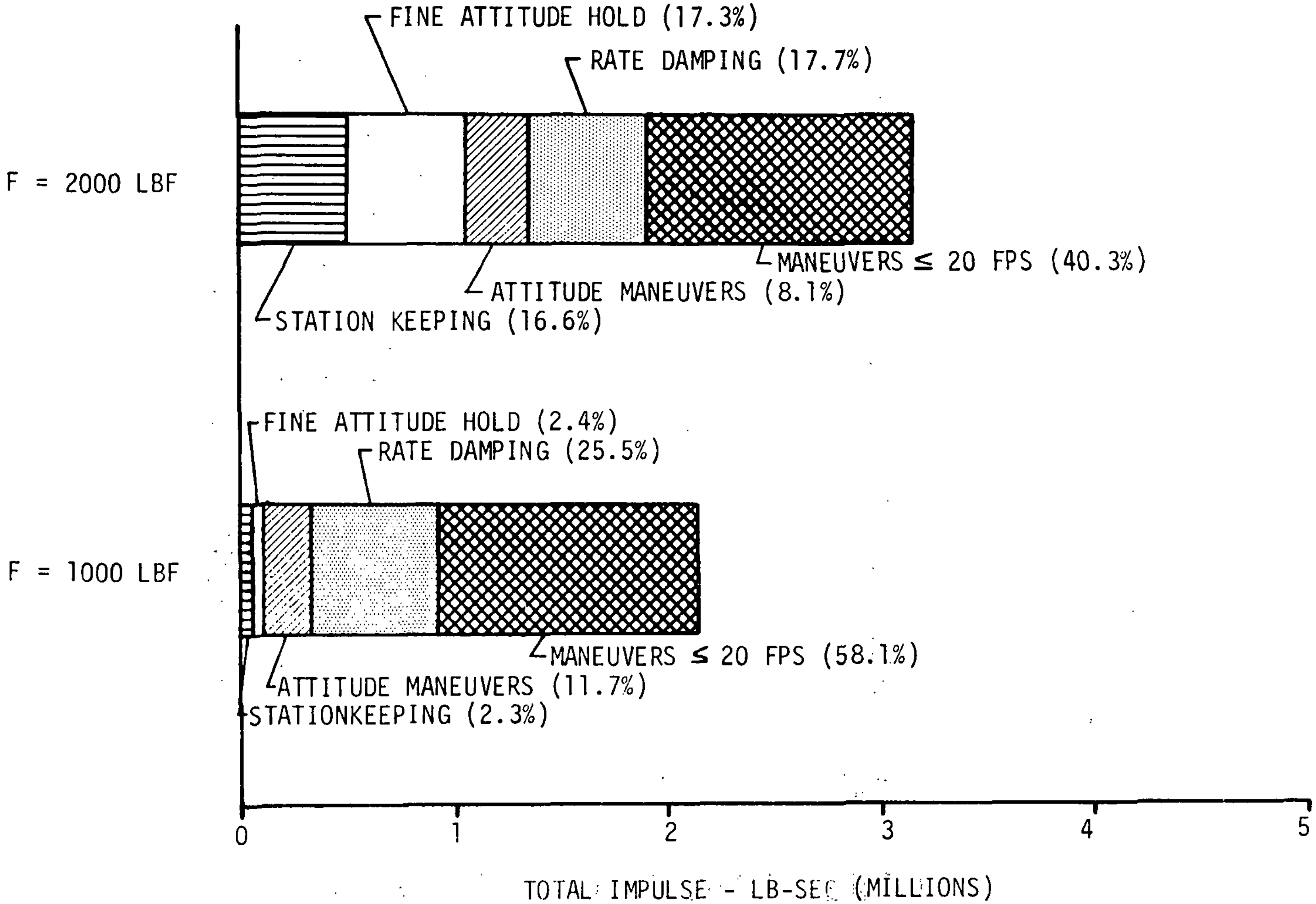


Figure 2-4

SUMMARY RCS DESCRIPTION

- o RCS DATA USED IN DEVELOPMENT OF PAYLOAD SENSITIVITY TO DESIGN PARAMETERS
- o SERIES GGA FLOW/TURBINE UPSTREAM

BOOSTER		ORBITER	
RCS DESIGN PARAMETER	PAYLOAD SENSITIVITY	RCS DESIGN PARAMETER	PAYLOAD SENSITIVITY
P_C = 500 LBF/IN^{2}A		P_C = 500 LBF/IN^{2}A	
F = 1150 LB	$\frac{\partial P}{\partial F}$ = +.16 LB_M/LB_F	F = 1150 LB	$\frac{\partial P}{\partial F}$ = -1.87 LB_M/LB_F
I_{TOT} = 500,000 LB-SEC		I_{TOT} = 2,210,000 LB-SEC	
$I_{SP_{SYS}}$ = 376 SEC	$\frac{\partial P}{\partial I_{SP}}$ = +.66 LB_M/SEC	$I_{SP_{SYS}}$ = 376/382 SEC	$\frac{\partial P}{\partial I_{SP}}$ = +15.4 LB_M/SEC
ε = 60		ε = 60/120	
O/F = 3.15		O/F = 3.15	
W_{INERT} = 5770	$\frac{\partial P}{\partial W_I}$ = -.16 LB_M/LB_M	W_{INERT} = 9320 LB	$\frac{\partial P}{\partial W_I}$ = -1.0 LB_M/LB_M
$T_{COND}\,H_2/O_2$ = 200/350°R		$T_{COND}\,H_2/O_2$ = 200/350°R	
P_{MAX}/P_{SW} = 2.0		P_{MAX}/P_{SW} = 2.0	
P_{SW}/P_{MIN} = 1.135		P_{SW}/P_{MIN} = 1.135	
ΔT_{COND} = 0.5 SEC		ΔT_{COND} = 0.5 SEC	

Figure 2-5

PAYLOAD PENALTY FOR RCS THRUST COMMONALITY

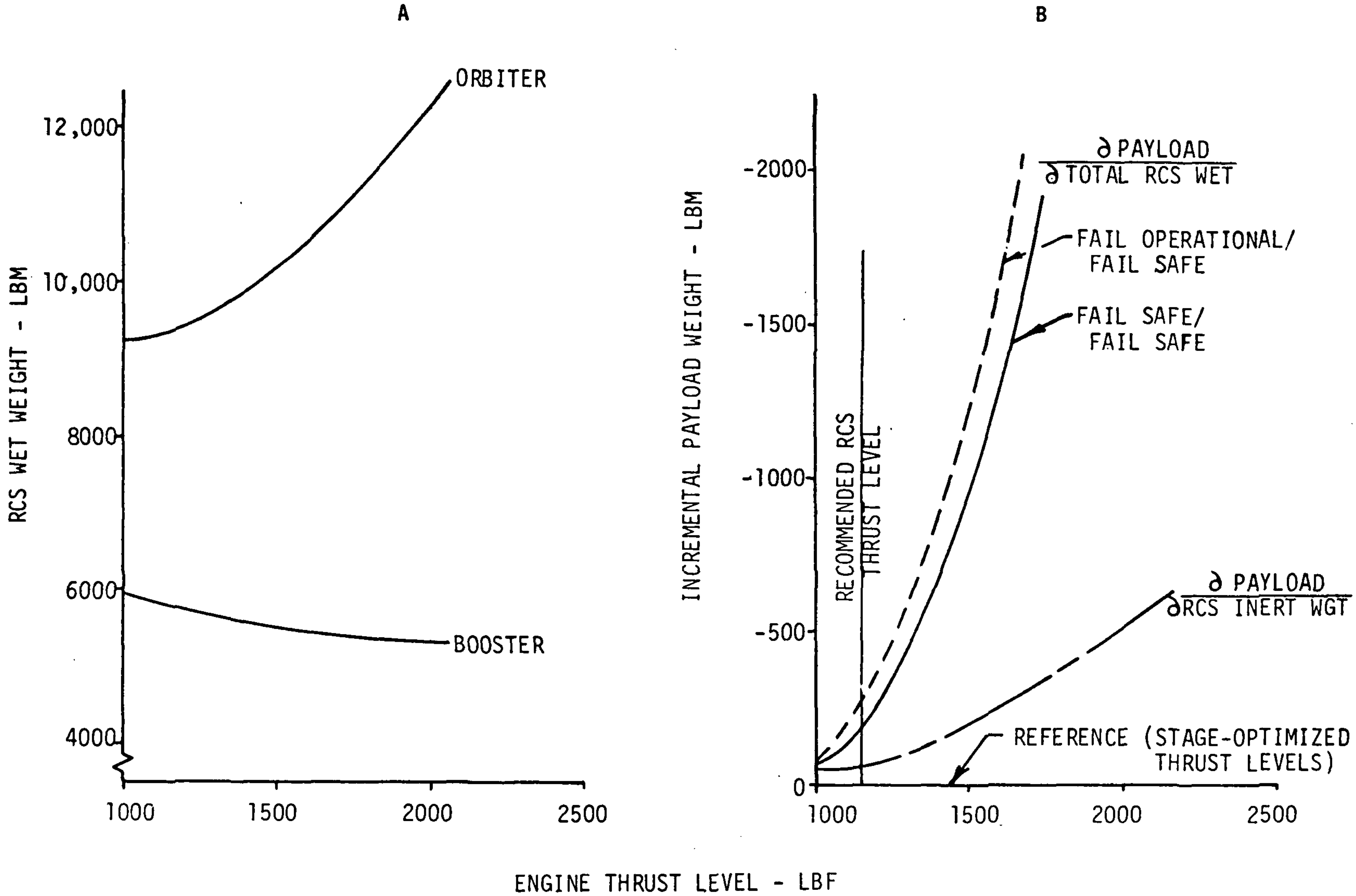


Figure 2-6

level required to produce acceleration above the design minimum under normal operating conditions, and safe acceleration after any single failure or any two failures. This is the SSVDRD requirement. To compare the effect of a fail operational/fail safe criterion, weights were also developed for systems designed to be capable of providing minimum design acceleration levels after one failure and safe acceleration levels after two failures. As shown in Figure 2-6B, the failure criteria has limited effect on the optimum thrust level. From these data, a common booster and orbiter RCS thrust level of 1150 lbf was selected as a baseline for the system study. A slightly lower thrust level provides a small increase in payload capability, but requires several additional thrusters on the booster. At a thrust level of 1150 lbf, 33 RCS thrusters are required on the orbiter and 24 on the booster.

Associated with the difference between payload sensitivity to total RCS weight and the sensitivity to only inert weight (Figure 2-6B),are certain assumptions involved in defining the mission total impulse requirements. The most influential of these assumptions were investigated to ascertain if they would affect the thrust level selection. These are shown in Figure 2-7. As shown, variation in the attitude hold time prior to a maneuver, the operating mode during station keeping (full thrust level or igniter thrust, only), and the number of thrusters firing during attitude control (coupled or uncoupled control) have essentially no effect on the payload weight-thrust trend. These data provided additional assurance that the thrust level of 1150 lbf selected for the study would be unaffected by later changes in the RCS design or operating philosophy.

The other major requirement affecting system design is the maximum system thrust demanded from the RCS. Figure 2-3 identifies the thrust level used for the various maneuvers in each of the three reference missions. These, together with limit cycle and calculated entry requirements are summarized in Figure 2-8. As shown, maximum system thrust requirements occur during reentry where thrust level is dictated by a requirement for a 1.5 deg/sec^2 continuous yaw-roll coordinated maneuver capability. For the orbiter, an equivalent thrust of 5 thrusters is required from the system; for the booster, a continuous thrust equivalent to 8 thrusters is required. For design purposes, a common conditioner with a flow or system thrust capability of 5750 lbf was selected for both the orbiter and booster. An extra conditioner would be provided on the booster to satisfy its higher flow requirements. This avoids large orbiter weight penalties that would

EFFECT OF ALTERNATE RCS CONTROL MODES ON OPTIMUM THRUST LEVEL

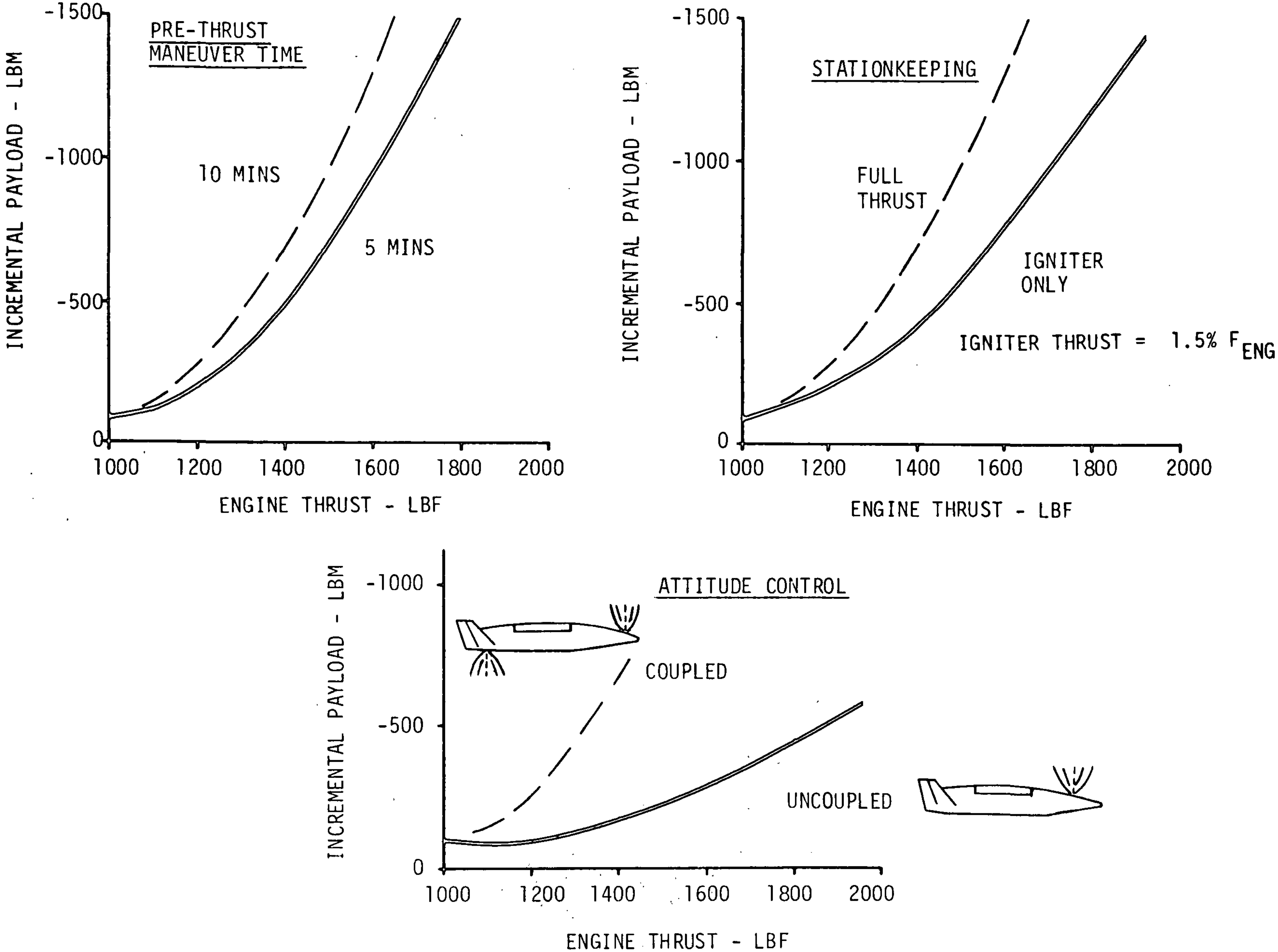


Figure 2-7

SUMMARY OF SYSTEM THRUST REQUIREMENTS

o 1150 LB THRUST ENGINES

OPERATING CONDITION	SYSTEM THRUST, LB BOOSTER	ORBITER
LIMIT CYCLE	.13 - 5.25	.15 - 5.97
ORBIT MANEUVERS	+N/R	2300 - 4600
DEORBIT (BACKUP)	+N/R	4600
REENTRY	9200	5750

+ NO REQUIREMENT

DESIGN THRUST LEVEL - 1.5°/SEC^2 CONTINUOUS YAW-ROLL COORDINATED MANEUVER

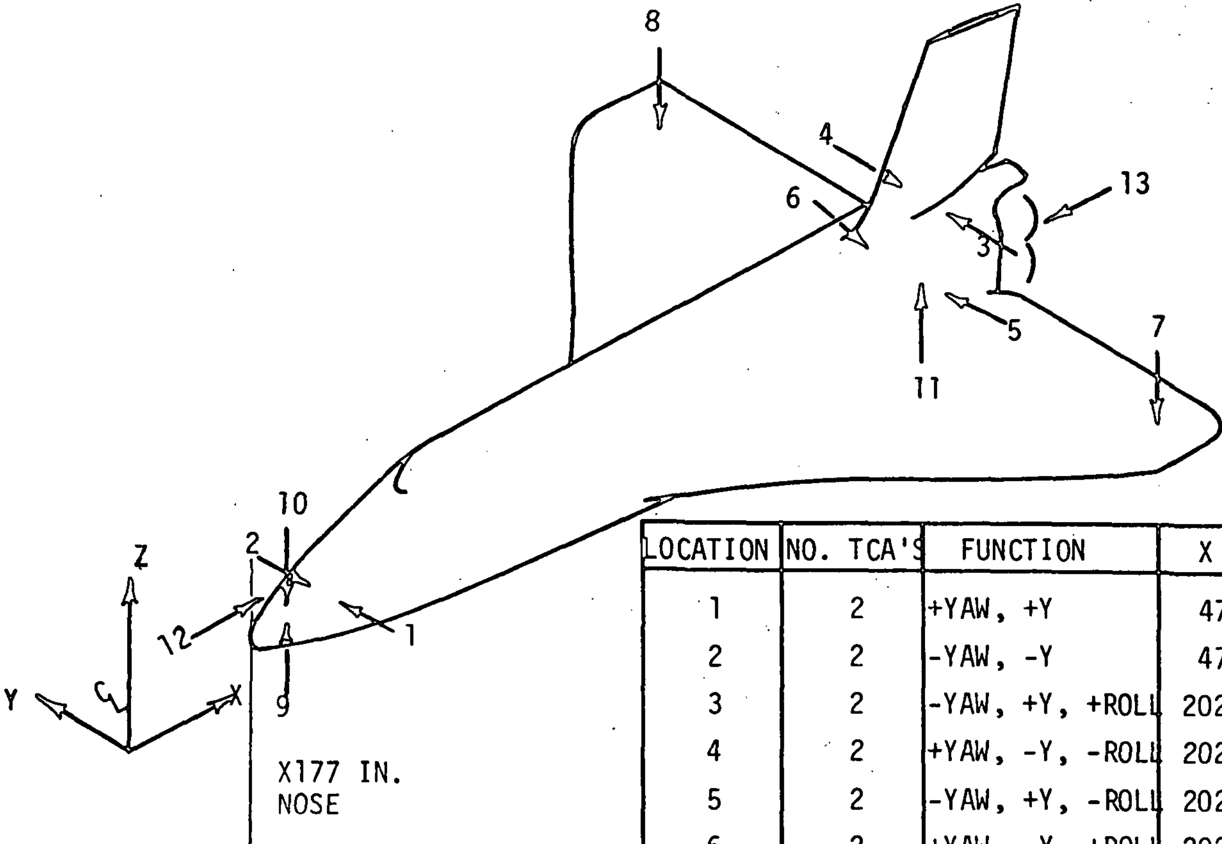
Figure 2-8

be associated with use of a conditioner sized for the booster or the increased development cost for two different conditioners.

Figures 2-9 and 2-10 provide descriptions of orbiter and booster thruster locations and the number of thrusters employed. Figures 2-11, 2-12, and 2-13 show the capability of this design during each mode of operation (i.e., entry and on-orbit control and orbit maneuvers). For the orbiter, aft mounted yaw thrusters are used to provide on-orbit roll control while wing mounted thrusters are used to provide entry roll control. Figures 2-14, 2-15, and 2-16 define the impulse expenditure histories for the three reference missions. In these figures, the RCS maneuvers listed in Figure 2-3 are included in the maneuver impulse requirements.

2.2 Orbit Maneuvering System Requirements - Reference K specifies that -X axis translation maneuvers requiring a velocity change equal to or greater than 20 fps should be performed by the OMS. One of the initial study efforts required was confirmation of this velocity allocation. To accomplish this, OMS mission requirements (number of burns and velocity increments) were defined for each of the three reference missions. Then, incremental RCS/OMS system weight savings, associated with the higher OMS performance, were determined for each mission. A typical liquid propellant OMS engine operating at 8000 lbf thrust, 800 lbf/in^2 chamber pressure and a mixture ratio of 6, was assumed in the analysis. OMS engine specific impulse was 449 sec compared to 387 sec for the RCS. OMS weight was based on the use of three engines, and allocations for feed lines and start/shutdown propellant losses were included (start/shutdown losses were varied from 50 to 150 lbm of propellant per start). Results of this analysis are presented in Figures 2-17, 2-18 and 2-19 for the easterly, south polar, and resupply missions, respectively. Shown are incremental weight savings as a function of the total velocity increment allocated to the OMS. Initially the system weight decreases sharply, reflecting high OMS performance for the large mission maneuvers such as ascent, circularization, phasing, and deorbit, where start/shutdown losses are a negligible portion of the total propellant consumed during the burn(s). After these major maneuvers the OMS burns are for much lower ΔV, and start/shutdown losses reduce overall performance, resulting in reduced system weight savings. For both the easterly and resupply missions, system weight is minimized by the defined velocity allocation of 20 fps (ΔV). However, in the south polar mission no minimum is observed.

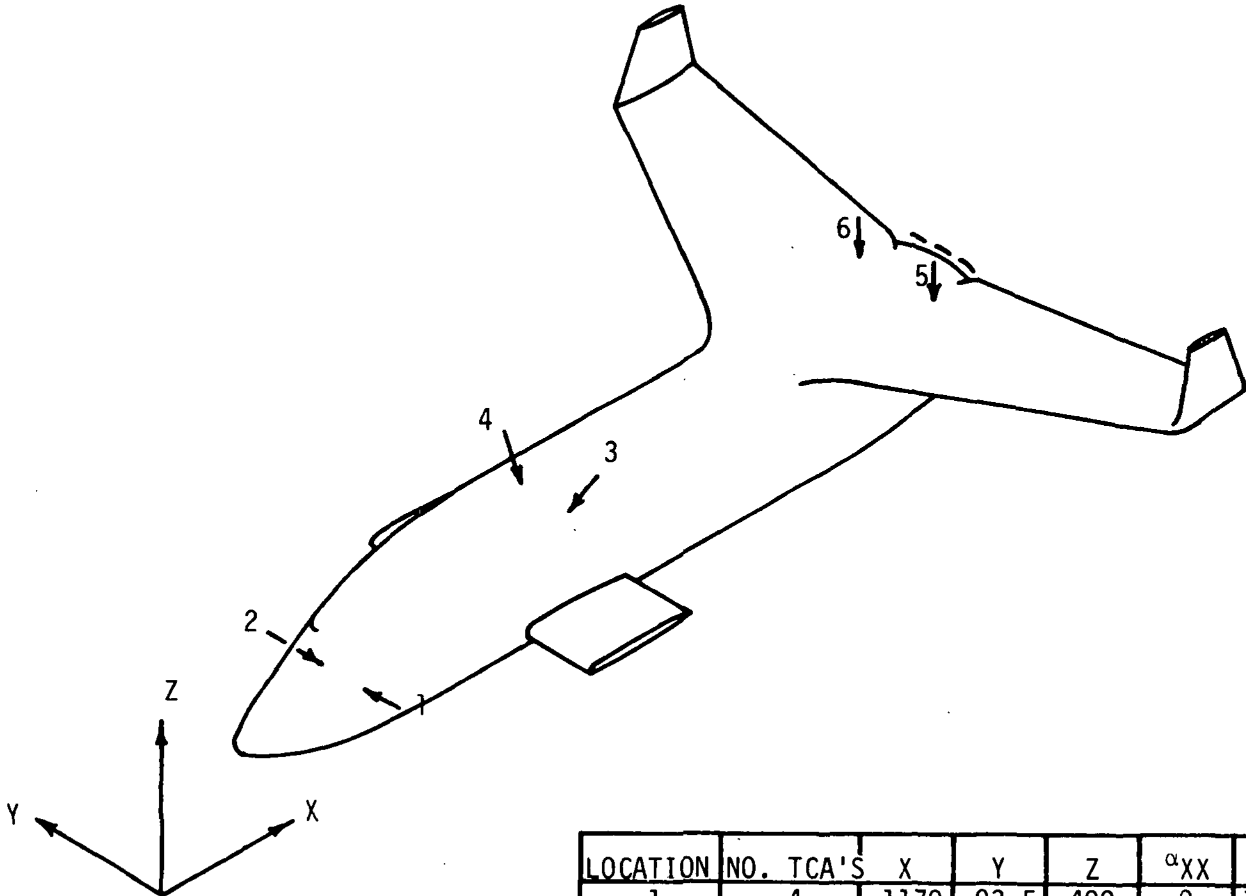
ORBITER THRUSTER LOCATIONS



LOCATION	NO. TCA'S	FUNCTION	X	Y	Z	αXX	αYY	αZZ
1	2	+YAW, +Y	474	-93	281	0	+1.0	0
2	2	-YAW, -Y	474	+93	281	0	-1.0	0
3	2	-YAW, +Y, +ROLL	2029	-106	400	0	+1.0	0
4	2	+YAW, -Y, -ROLL	2029	+106	400	0	-1.0	0
5	2	-YAW, +Y, -ROLL	2029	-142	226	0	+.985	-.174
6	2	+YAW, -Y, +ROLL	2029	+142	226	0	-.985	-.174
7	3	+PITCH,-Z,-ROLL	1965	-530	235	0	0	-1.0
8	3	+PITCH,-Z,+ROLL	1965	+530	235	0	0	-1.0
9	2	+PITCH, +Z	368	0	175	0	0	+1.0
10	3	-PITCH, -Z	368	0	294	0	0	-1.0
11	2	-PITCH, +Z	1954	0	140	0	0	+1.0
12	4	+X	474	0	307	+1.0	0	0
13	4	-X	2100	0	307	-1.0	0	0

Figure 2-9

BOOSTER THRUSTER LOCATIONS



LOCATION	NO. TCA'S	X	Y	Z	α_{XX}	α_{YY}	α_{ZZ}
1	4	1170	-93.5	400	0	1.0	0
2	4	1170	93.5	400	0	-1.0	0
3	4	2020	-151	549	0	.309	-.95
4	4	2020	151	549	0	-.309	-.95
5	4	3833	-200	604	0	0	-1.0
6	4	3833	200	604	0	0	-1.0

Figure 2-10

ENTRY CONTROL CAPABILITY

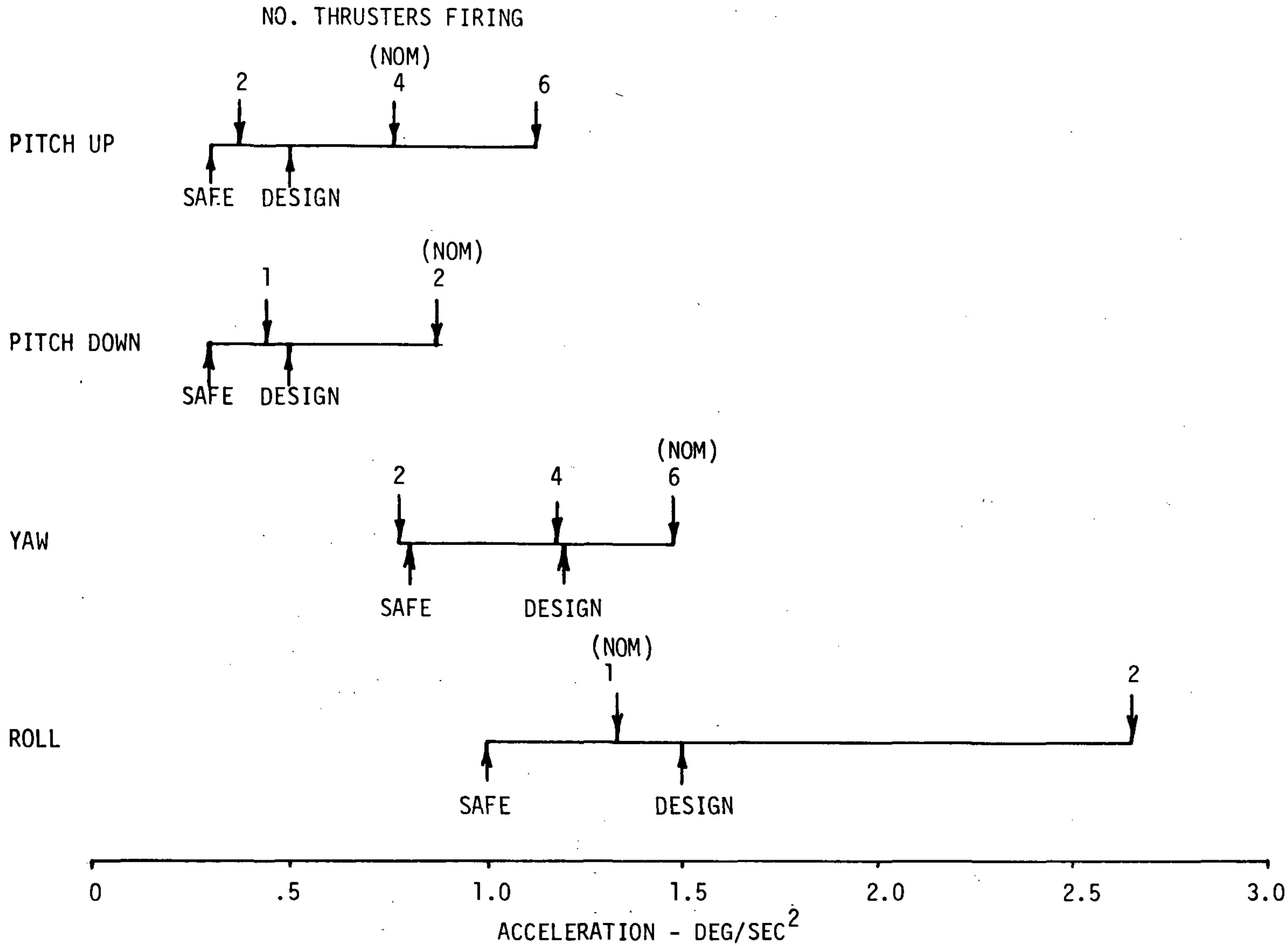


Figure 2-11

ORBIT MANEUVER CAPABILITY

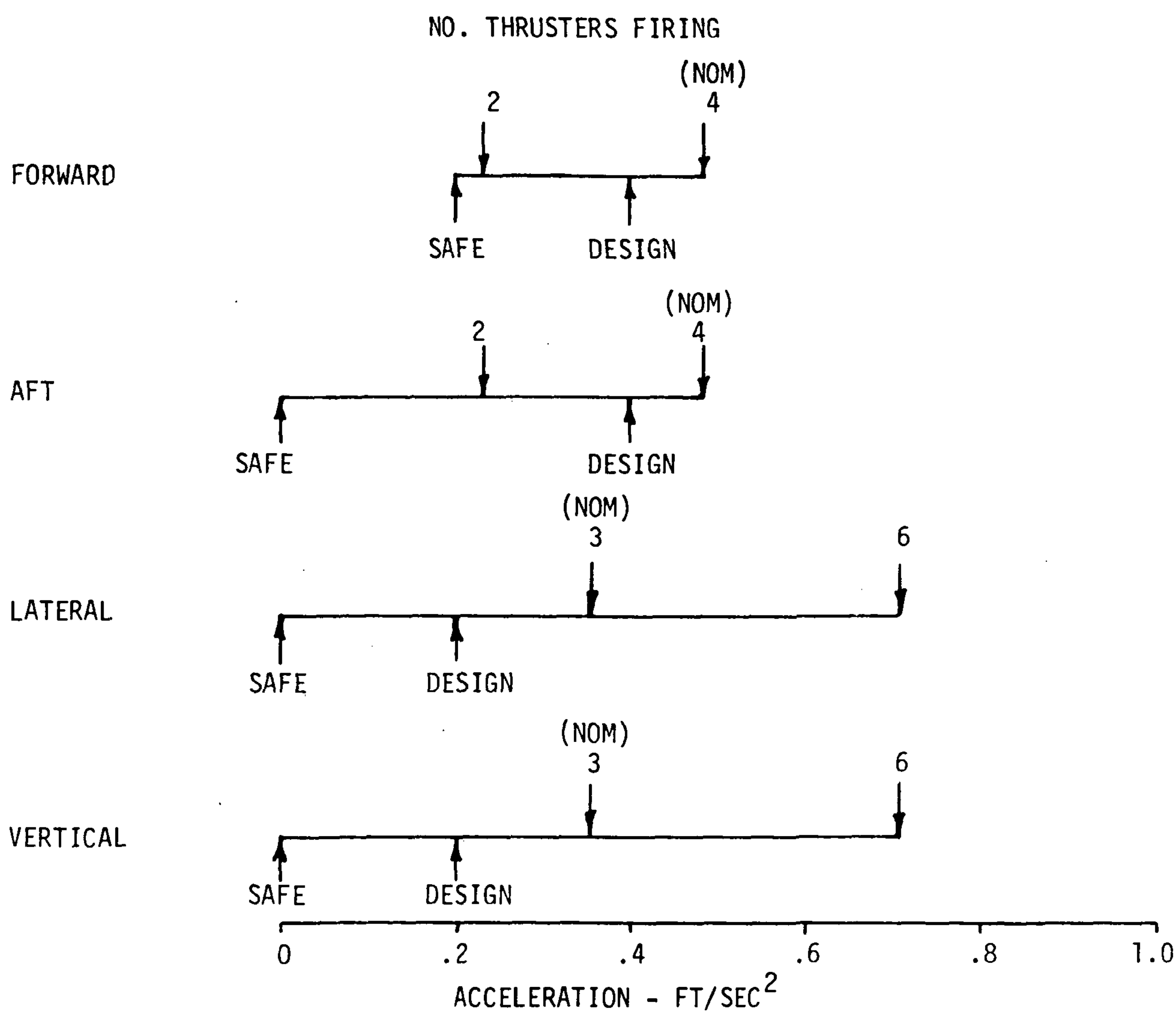


Figure 2-12

ON ORBIT CONTROL CAPABILITY

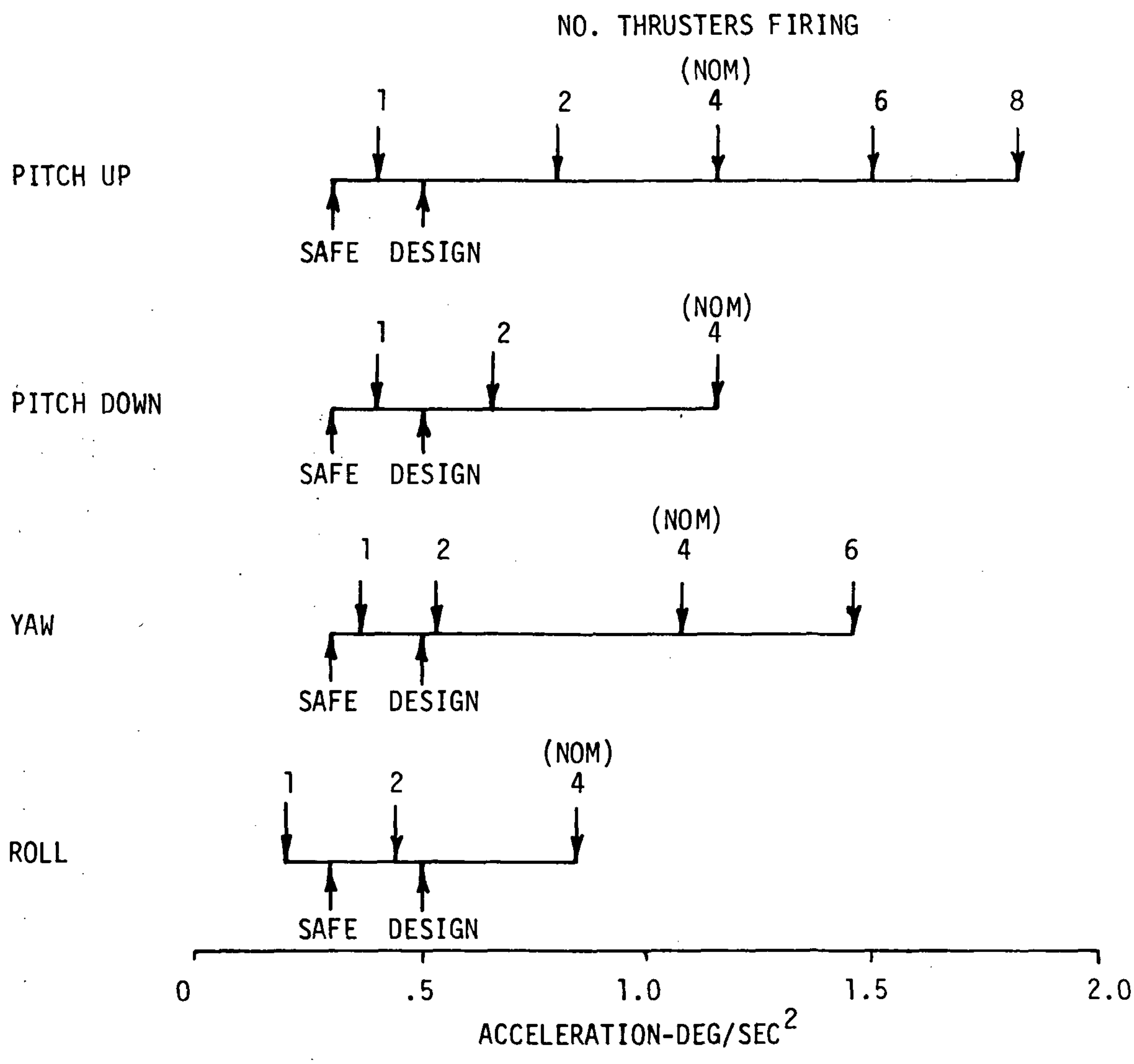


Figure 2-13

EASTERLY MISSION - APS IMPULSE REQUIREMENTS

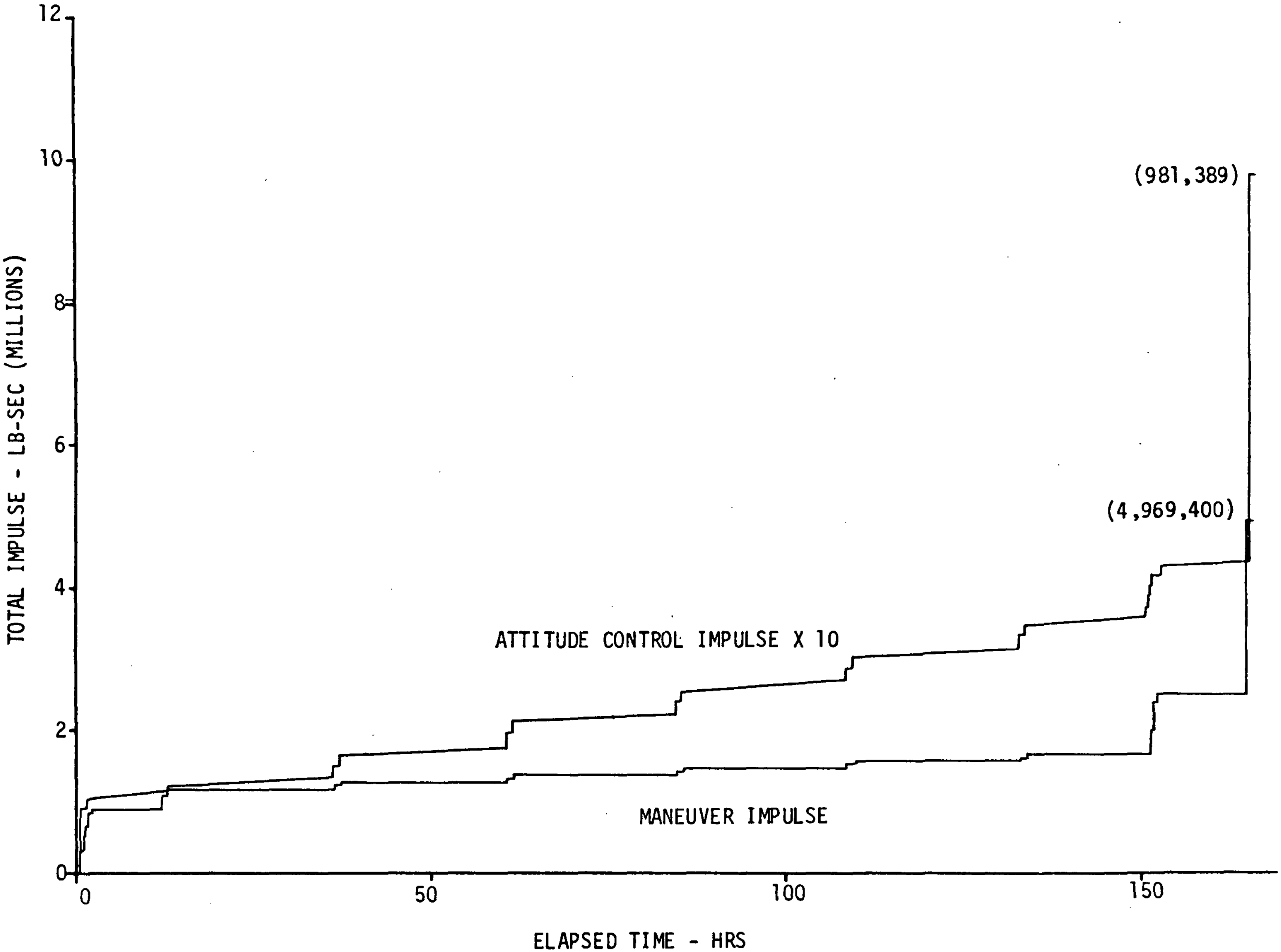


Figure 2-14

POLAR MISSION - APS IMPULSE REQUIREMENTS

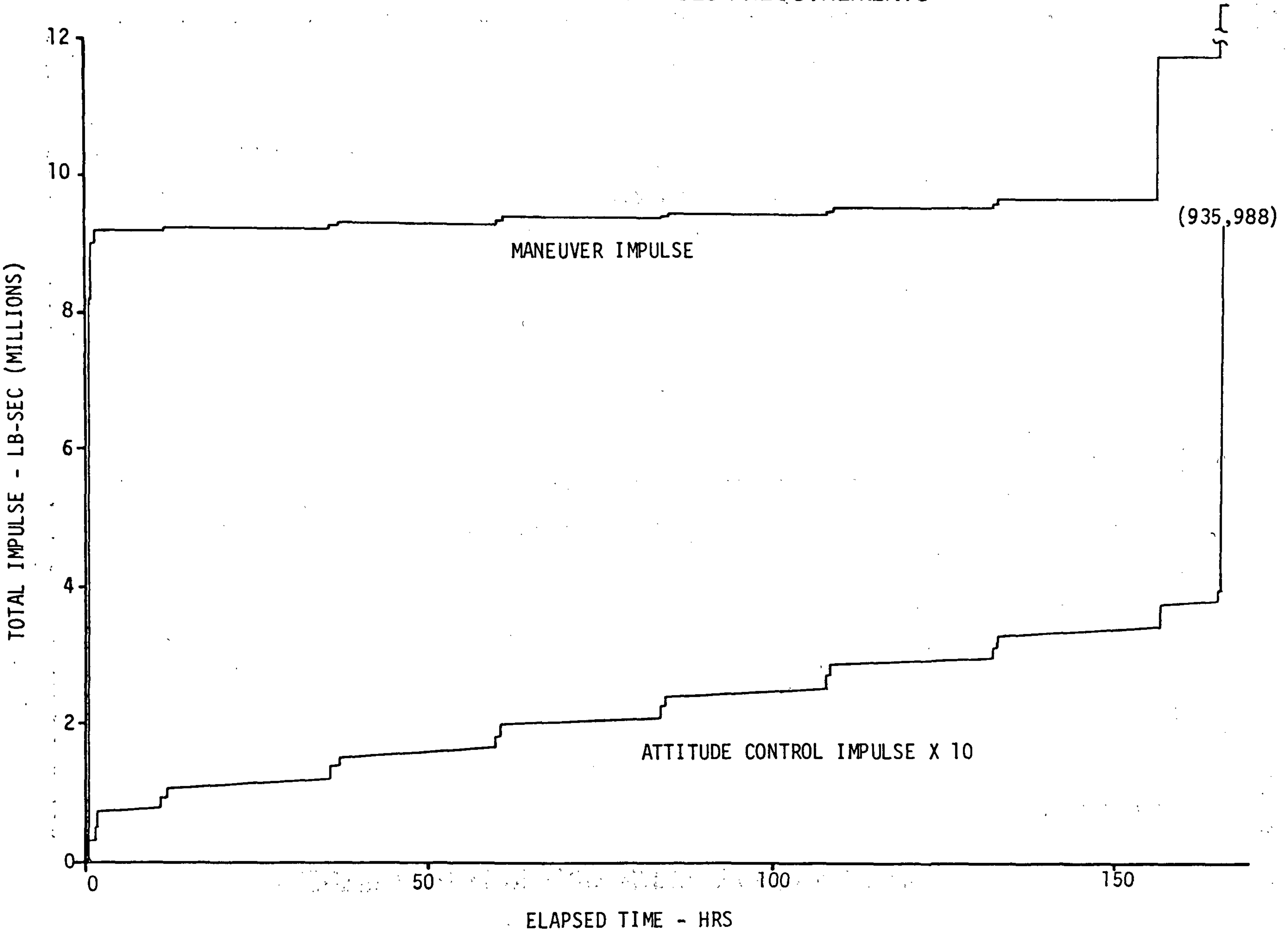


Figure 2-15

RESUPPLY MISSION - APS IMPULSE REQUIREMENTS

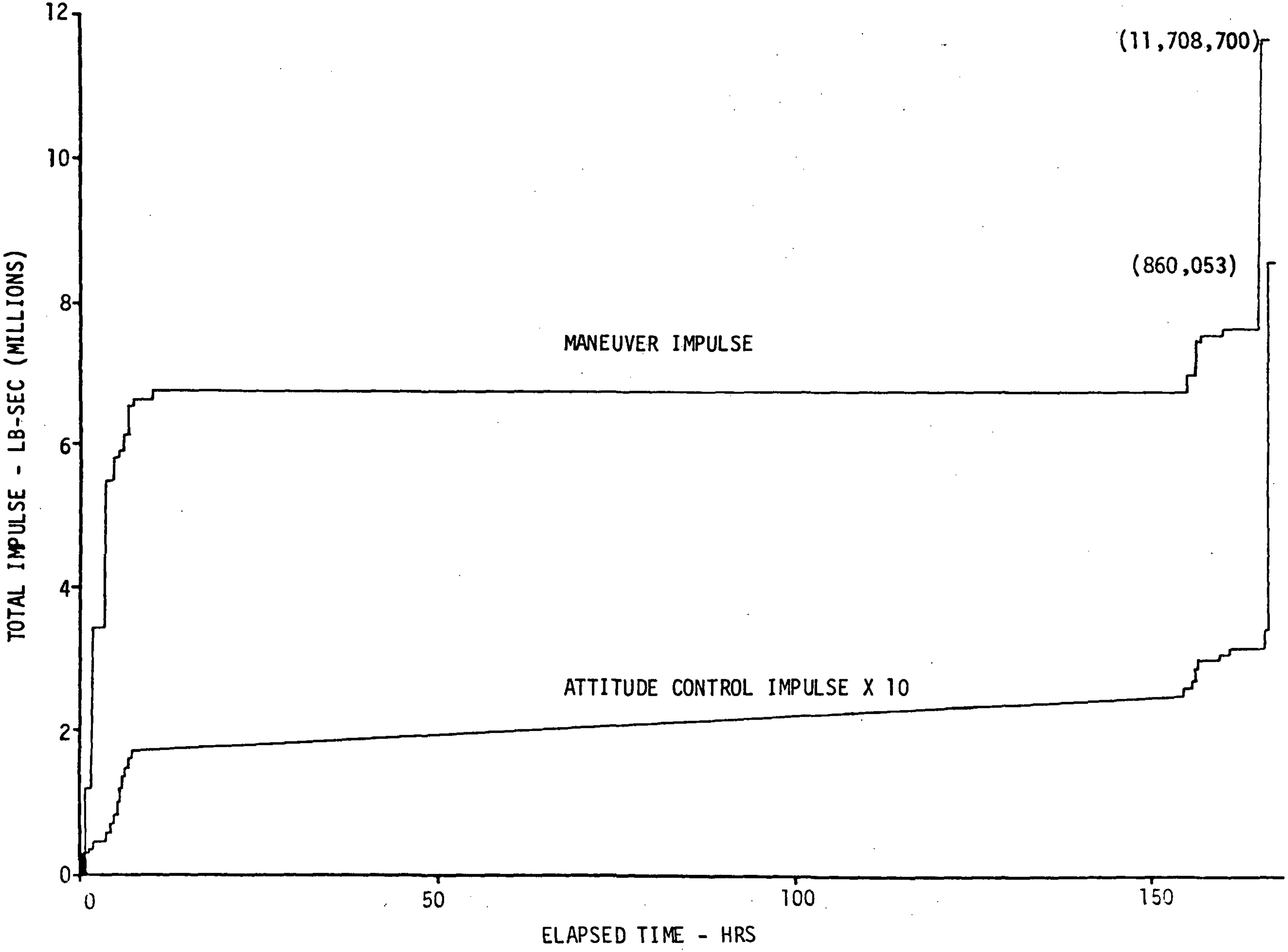


Figure 2-16

WEIGHT SENSITIVITY TO RCS/OMS VELOCITY ALLOCATION

- o EASTERLY LAUNCH
- o DELIVERY/RETRIEVAL OF OOS

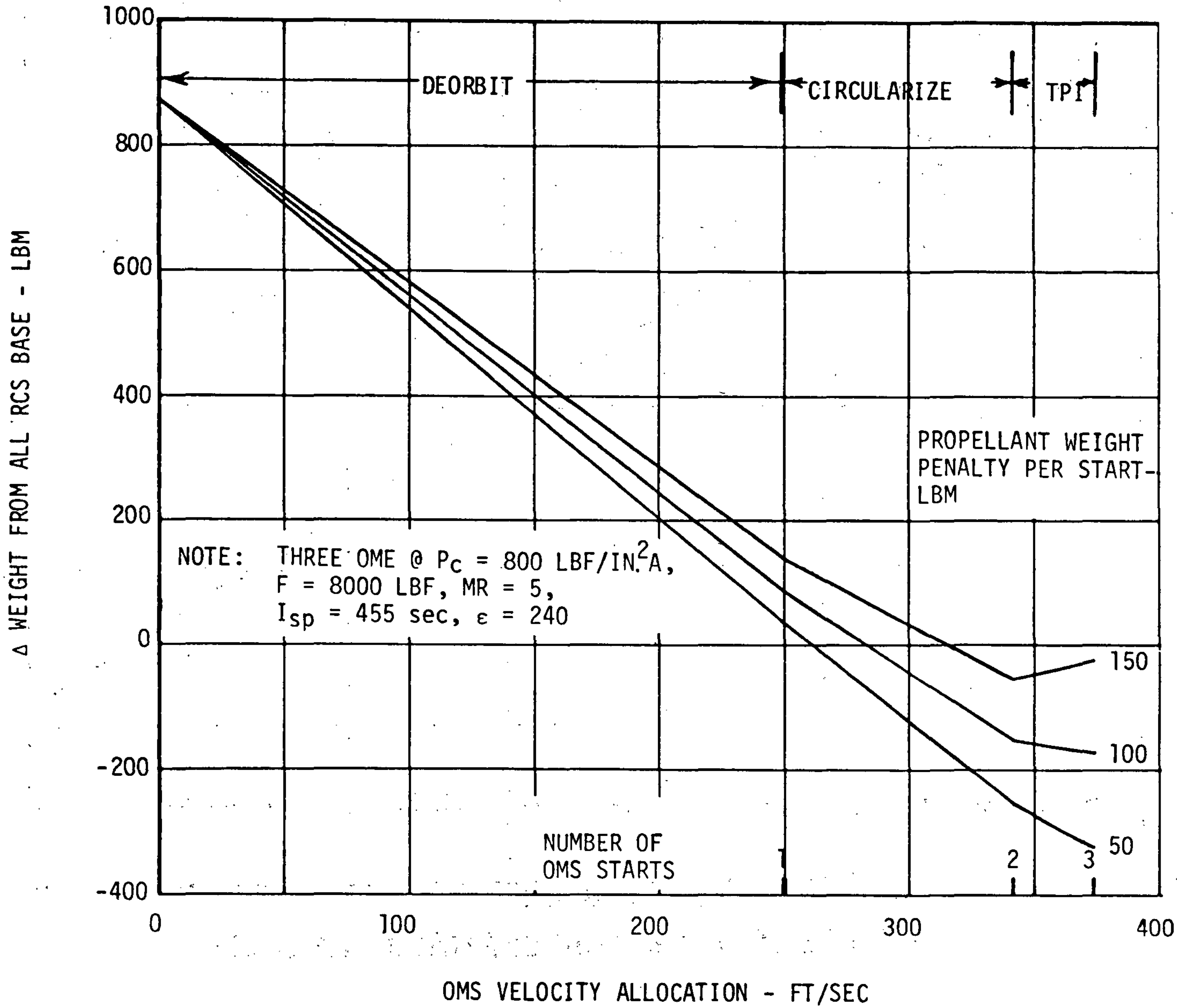


Figure 2-17

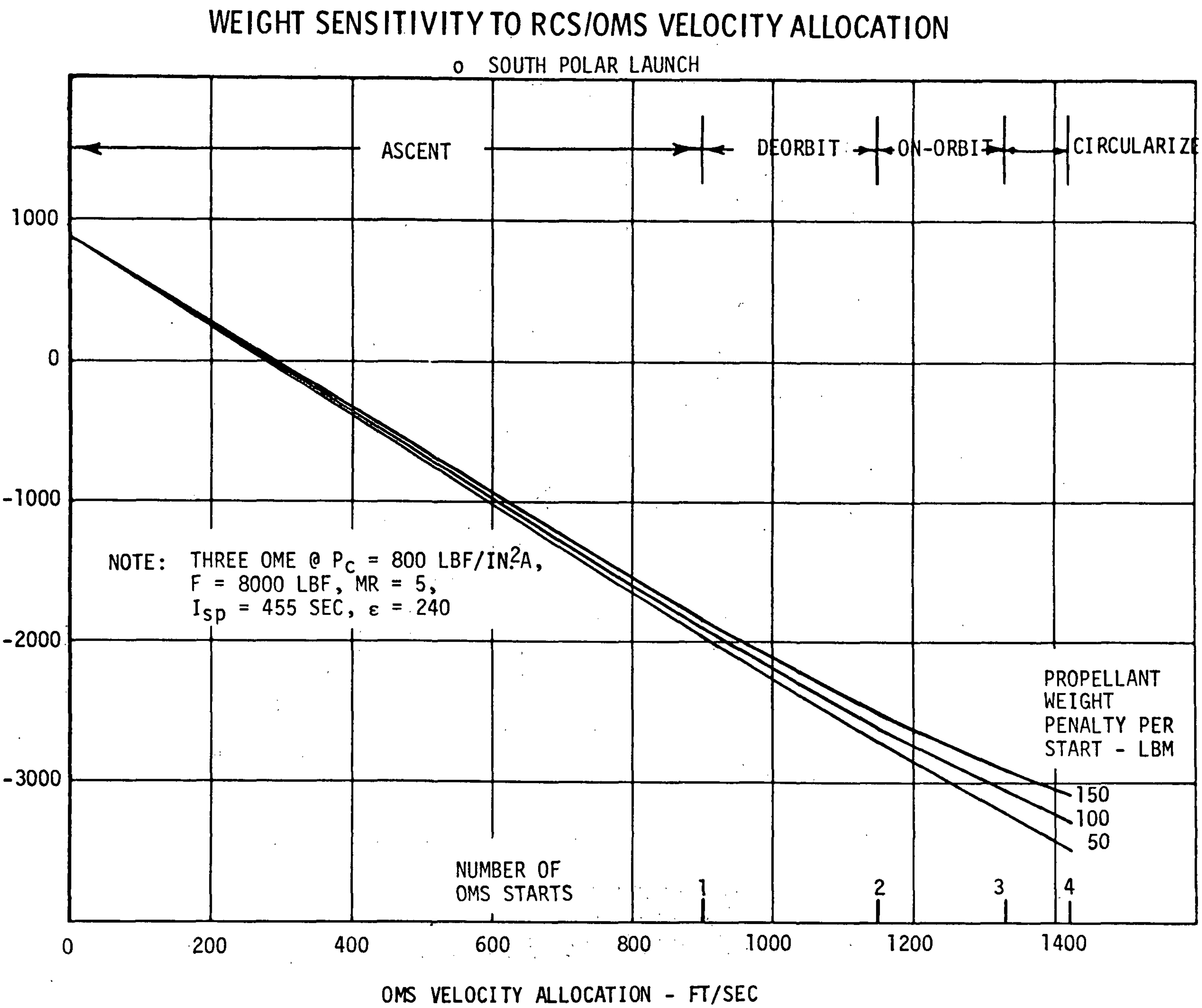

WEIGHT SENSITIVITY TO RCS/OMS VELOCITY ALLOCATION
o SOUTH POLAR LAUNCH
ASCENT
DEORBIT
ON-ORBIT
CIRCULARIZE
Δ WEIGHT FROM ALL RCS BASE - LBM
1000
0
-1000
-2000
-3000
NOTE: THREE OME @ P_C = 800 LBF/IN.^{2}A,
F = 8000 LBF, MR = 5,
I_{sp} = 455 SEC, ε = 240
PROPELLANT
WEIGHT
PENALTY PER
START - LBM
150
100
50
NUMBER OF
OMS STARTS
1
2
3
4
0
200
400
600
800
1000
1200
1400
OMS VELOCITY ALLOCATION - FT/SEC

Figure 2-18

WEIGHT SENSITIVITY TO RCS/OMS VELOCITY ALLOCATION

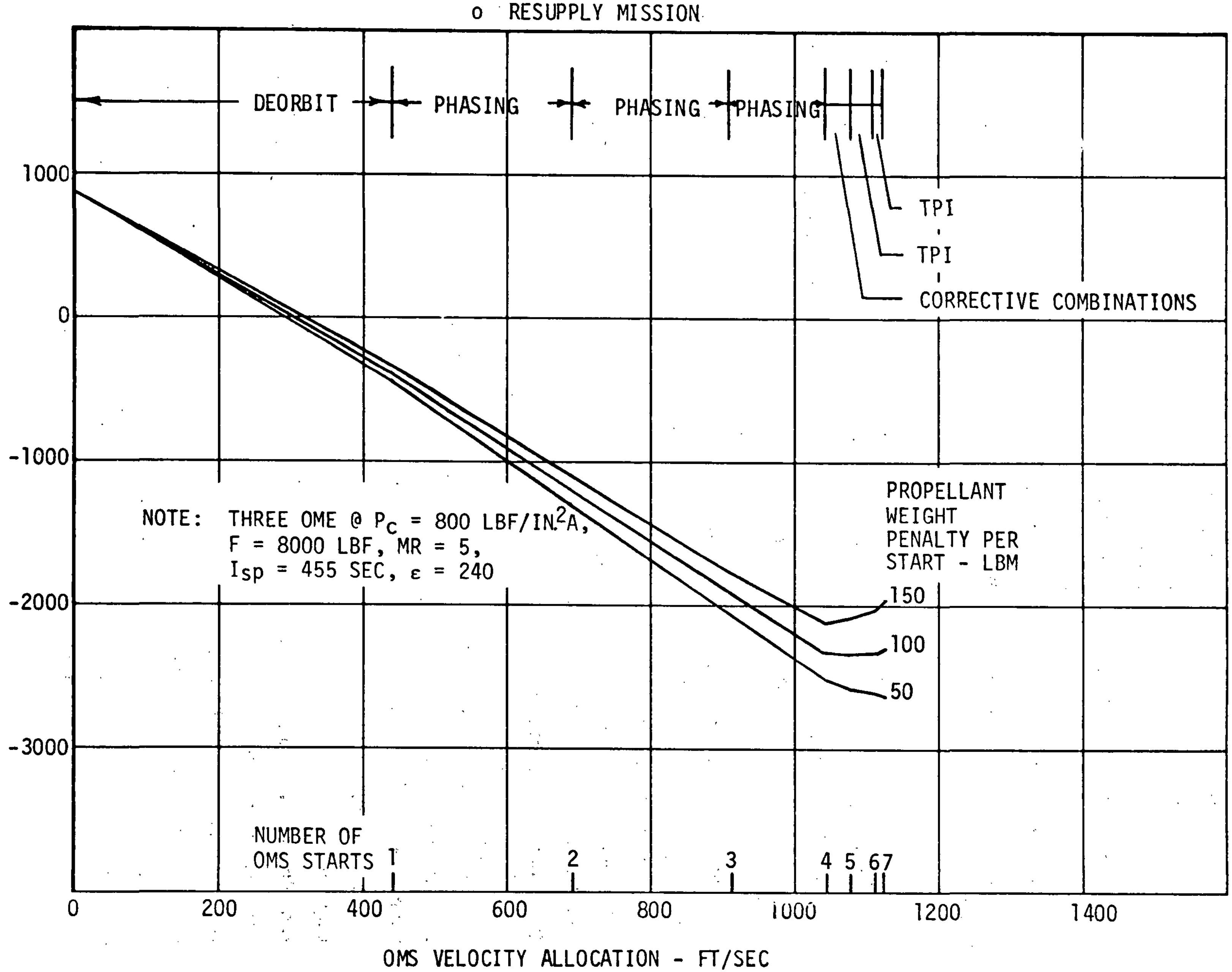


Figure 2-19

An alternate approach to confirmation of the optimum RCS velocity increment, which eliminated mission considerations, was also undertaken. This is illustrated in Figure 2-20 which shows specific impulse as a function of OMS velocity increment. The most desirable velocity allocation is determined at the point where OMS effective specific impulse (with start losses) equals that of the RCS. This point is identified in Figure 2-20 and occurs at a velocity increment of approximately 15 to 20 fps, depending on the assumed OMS start loss, again confirming the Reference K velocity allocation of 20 fps (ΔV) as most desirable for RCS/OMS design study purposes.

The OMS mission velocity requirements based on the optimum velocity split of 20 fps are shown in Figure 2-21. Shown are on-orbit and once-around abort requirements for the three missions. The south polar mission demands are the most severe in both on-orbit and abort requirements, while the easterly and resupply missions have much reduced demands. The south polar mission requires an on-orbit ΔV of 1420 fps, of which 900 fps is for boost augmentation. The easterly and resupply missions require on-orbit ΔV's of 373 and 1126 fps, respectively, in which no additional boost augmentation is required. The OMS propellant tank volume is established by the Space Shuttle Phase B study requirement to store sufficient propellant to satisfy the south polar mission abort velocity increment of 2000 fps.

It is also desirable that the OMS design thrust satisfies the once-around abort requirements. Figure 2-22 shows the thrust and velocity requirements from the SSVDRD where the OMS is designed to provide abort assistance in the event of a main engine failure during ascent. The south polar mission imposes the most severe requirement on OMS thrust level; i.e., a thrust level of 24,000 lb is required at the OMS design tank capability of 2000 fps. As an alternative to designing the OMS for the abort capability, in which the 24,000 lbf of system thrust would be a firm requirement, the OMS thrust was varied parametrically to determine the on-orbit thrust level which provided the most desirable integration between the OMS and RCS. An on-orbit thrust level of 6000 lbf (one engine firing) was selected as the lowest value to be investigated, since above this value velocity losses associated with low thrust to weight ratio maneuvers can be neglected.

BREAK POINT - RCS VS OMS

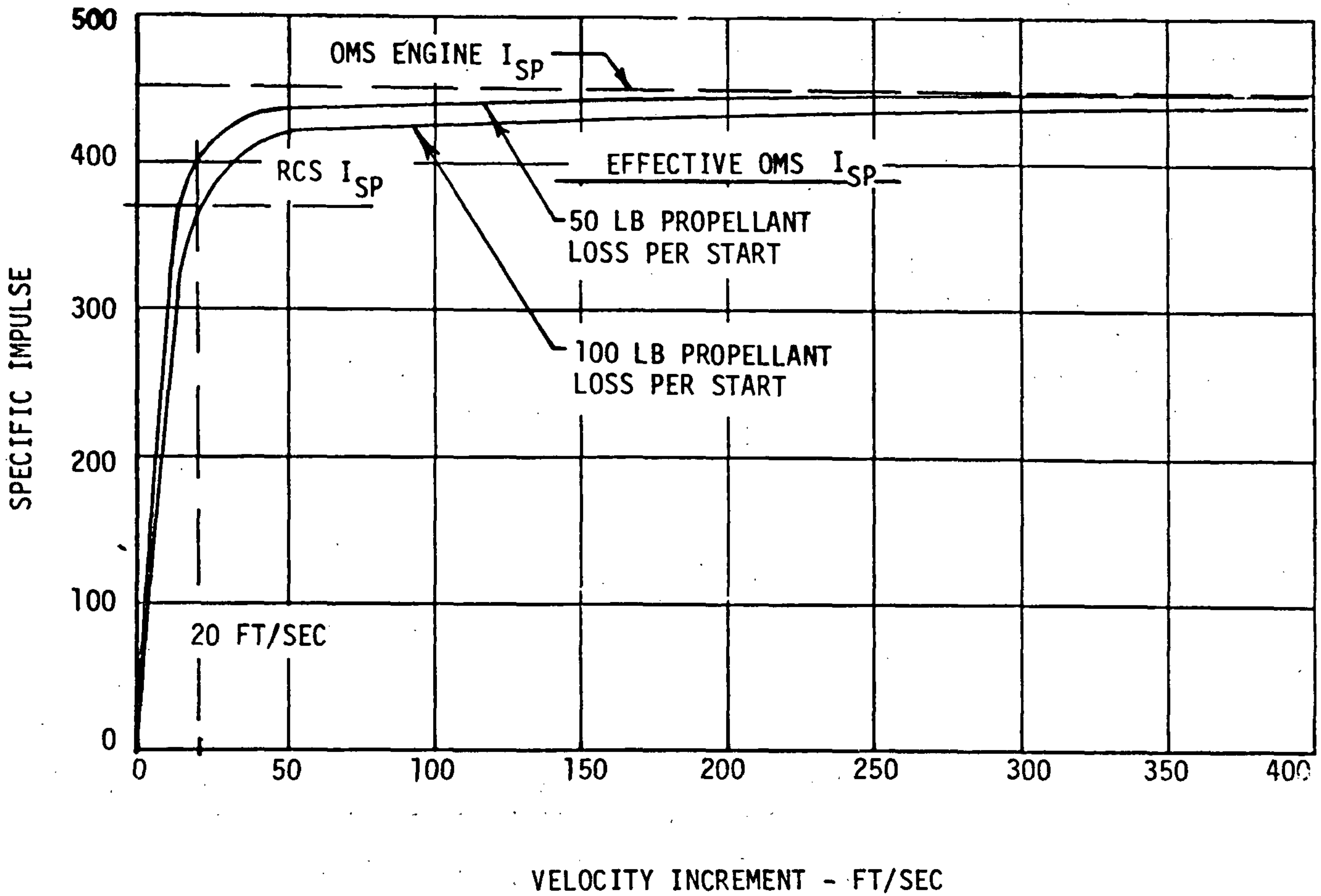


Figure 2-20

OMS MISSION REQUIREMENTS

DESIGN-EASTERLY LAUNCH 65,000 LB PAYLOAD (REQ'D) 100 N MI 7 DAYS		REFERENCE - SOUTH POLAR 40,000 LB PAYLOAD (MIN.) 100 N MI 7 DAYS		REFERENCE - RESUPPLY 25,000 LB PAYLOAD (MIN.) 270 N MI 7 DAYS	
FUNCTION	ΔV FT/SEC	FUNCTION	ΔV FT/SEC	FUNCTION	ΔV FT/SEC
CIRCULARIZATION	91	OMS BOOST AUGMENTATION	900	PHASING BURN	133
TERMINAL PHASE INITIATION	32	CIRCULARIZATION	90	PHASING BURN	248
DEORBIT BURN	250	ON ORBIT	180	PHASING BURN	224
		DEORBIT BURN	250	POSIGRADE MANEUVER	33
				TERMINAL PHASE	22
				TERMINAL PHASE	26
				DEORBIT BURN	440
TOTAL	373	TOTAL	1420	TOTAL	1126
ONCE-AROUND ABORT REQUIREMENT	800[1]	ONCE-AROUND ABORT REQUIREMENT	2000[1,2]	ONCE-AROUND ABORT REQUIREMENT	800[1]

1. ABORT REQUIREMENTS FOR OMS THRUST = 24,000 LBF
2. INCLUDES 900 FPS OMS BOOST AUGMENTATION

Figure 2-21

ORBITER OMS ABORT TO ORBIT REQUIREMENTS

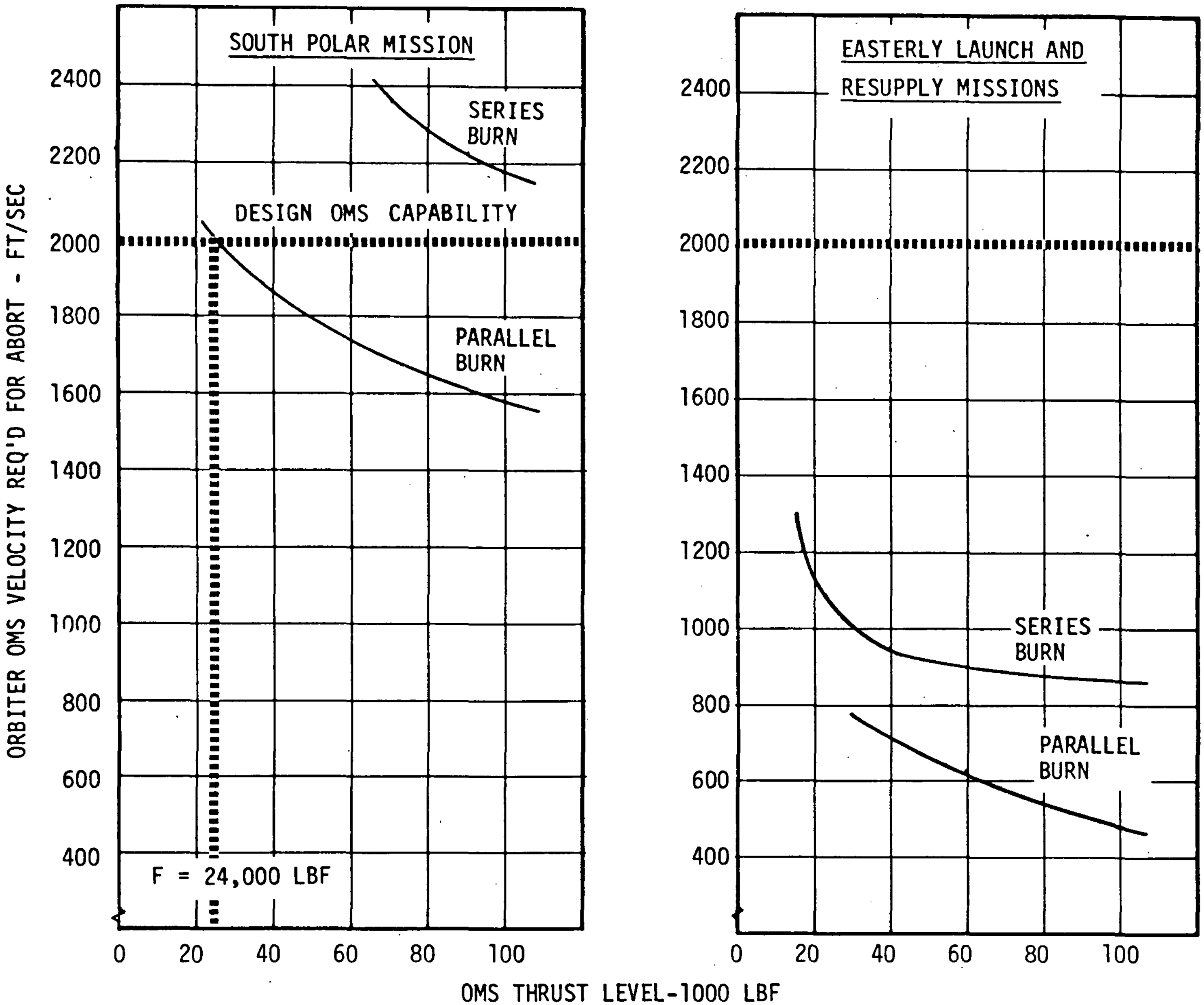


Figure 2-22

Three OMS engines are required to meet the fail-safe/fail-safe operating requirement of the SSVDRD but the number can be reduced to two if the X axis RCS thrusters are used as OMS backup.

3. REFERENCES

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APPENDIX A

SPACE SHUTTLE VEHICLE DESCRIPTION AND REQUIREMENTS

A1. Introduction - The vehicle requirements and characteristics which formed the basis for RCS/OMS design were part of the original contract definition and were issued by the NASA as a "Space Shuttle Vehicle Description and Requirements Document (SSVDRD)." This appendix summarizes the NASA SSVDRD and includes general RCS/OMS design requirements, mission requirements, system and component design criteria, and both orbiter and booster vehicle characteristics.

A2. General Requirements - The following general requirements shall be applied for RCS/OMS design.

1. The vehicle trajectory design load factors shall be 3-g maximum along the vehicle longitudinal axis.
2. Systems shall be designed for a minimum of maintenance with ease of removal and replacement; maximum use of aircraft design practice will be used.
3. The Reaction Control System shall provide three-axis translation and three-axis attitude control capability for orbiter stages with three-axis attitude control for booster stages and will be designed to minimize cross coupling which may result from normal operational modes or potential failure modes.
4. The Space Shuttle design shall include proper onboard provisions to quickly and easily place the Space Shuttle vehicle in a safe condition following landing.
5. Maximum use of existing standards for the selection, design, packaging, and integration of hardware should be employed, consistent with program operational requirements.
6. The RCS shall be capable of operating satisfactorily when subjected to normal-g, reduced-g, zero-g, or reversed-g environments, with no time limitation imposed for any of these conditions.
7. The RCS shall permit propellant fill and drain and pressurization and venting in either a vertical or horizontal booster orientation.
8. The Reaction Control System shall function independent of gravity field and vehicle attitude orientation.

9. The vehicle should be capable of loading fluid consumables within the two hour period immediately prior to launch.
10. The Auxiliary Propulsion System shall be designed to function for a minimum service life of 100 mission cycles over a 10-year period with cost effective refurbishment.
11. At least seven days of self-sustaining lifetime shall be provided for the mission duration.
12. The APS shall be designed to fail-safe after the failure of any two critical components. An exception to this will be the OMS operation in the abort mode. In this case, the OMS shall be designed for fail-safe operation after a single failure; i.e., assuming that the main engine failure constitutes the first system failure. Pressure vessels and fluid lines shall be considered exempt from the fail-safe criteria, but shall be appropriately designed for the necessary reliable operation. Redundant paths, such as fluid lines, electrical wiring, connectors, and explosive trains, shall be located to ensure that an event which damages one line is not likely to damage the other.

A3. Mission Requirements - The Space Shuttle is designed to perform three missions. The easterly launch mission is designated the design mission by virtue of the fact that it has the maximum payload; however, the reference south polar mission is primarily responsible for sizing both Shuttle stages. The requirement to provide sufficient capability for a one pass orbiter abort following an engine failure and/or after orbiter/booster separation is also imposed for each of the three missions. Nominal insertion orbit for all missions is 50 nautical miles perigee by 100 nautical miles apogee. Figure A-1 provides summary data for the three missions.

FIGURE A-1

MISSION REQUIREMENTS SUMMARY

Requirement	Design	Reference	
	Easterly	Polar	Resupply
Inclination (°)	28.5	90	55
Orbit Altitude (nm)	100	100	270
OMS Capability (fps)	900	650	1500
Required Payload (lb)	65,000	---	---
Assumed Minimum Payload (lb)	---	40,000	25,000
Mission Duration (Days)	7	7	7

A3.1 Design Mission (Easterly Launch) - The Space Shuttle design mission consists of delivering and retrieving payloads in a 100 nautical mile circular orbit with an inclination of 28.5 degrees, remaining in orbit up to seven days, and returning to the launch site. The orbiter has the capability to deploy the payload and, if required, retrieve it. Payloads requiring insertion into orbits much higher than the nominal delivery altitude will use an orbit-to-orbit shuttle (OOS) which is also carried by the orbiter. The sequence of mission events, from lift-off to landing, is shown for the easterly mission in Figures A-2 and A-3 for the orbiter and booster, respectively. The orbiter is inserted into a 50 x 100 nautical mile orbit which is circularized at apogee. After payload deployment, the orbiter remains on station for about six days and operates in a ±20 degree deadband until payload retrieval. Twelve orbit maintenance burns are made to retain the 100 nautical mile parking orbit. The cross range capability of the delta wing orbiter eliminates the need for pre-deorbit phasing and at the appropriate time the orbiter makes a retrograde maneuver and returns to the launch site. The anticipated on-orbit maneuvering ΔV requirement for this mission is 491 fps nominal. Additional propellant must be provided for on-orbit attitude control.

A3.2 Reference Mission (South Polar) - The south polar mission consists of launching the orbiter into an injection orbit of 50 x 100 nautical miles, with a 90 degree inclination and circularizing at apogee utilizing the Orbital Maneuvering Propulsion System. A variety of payloads will be delivered, serviced, and/or retrieved. The orbiter remains in orbit for seven days and operates in a ±20 degree

EASTERLY MISSION TIMELINE

EVENT	INITIATION TIME (DAYS:HRS:MIN:SEC)	Δt BETWEEN EVENTS (DAYS:HRS:MIN:SEC)	APS REQUIREMENTS
1. LIFT-OFF	00:00:00:00	00:00:03:17.1	NO APS REQUIREMENT
2. ORBITER ENGINE IGNITION	00:00:03:17.1	00:00:03:15.3	DAMP SEPARATION RATES. PROVIDE ROLL CONTROL & ABORT ΔV FOR ORBITER MAIN ENGINE-OUT CONDITION
3. INSERTION INTO 50 x 100 N.M. ORBIT	00:00:06:32.4	00:00:33:44.6	DAMP MAIN ENGINE CUT-OFF TRANSIENTS. DEADBAND ±20°
4. PRETHRUST ATTITUDE	00:00:40:17	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° DEADBAND
5. CIRCULARIZE ORBIT	00:00:50:17	00:00:00:16	HORIZONTAL, IN-PLANE POSIGRADE MANEUVER, 91 fps ΔV.
6. ATTITUDE HOLD	00:00:51:33	00:00:19:27	DEADBAND ±20°
7. OOS DEPLOYMENT	00:01:11:00	00:00:10:00	MANEUVER TO DEPLOYMENT ATTITUDE AND HOLD AT ±0.5° DEADBAND
8. DEPLOY OOS	00:01:21:00	00:00:13:00	ROTATE OOS FROM CARGO BAY, 1 fps MULTIAXIS ΔV. DEADBAND ±0.5°
9. SEPARATE OOS	00:01:34:00	00:00:06:00	DEADBAND ±0.5°
10. SPACING BURN – 1	00:01:40:00	00:00:00:08	RADIAL IN-PLANE, DOWNWARD MANEUVER, 10 fps ΔV
11. ATTITUDE HOLD	00:01:40:08	00:00:44:44	DEADBAND ±0.5°
12. SPACING BURN – 2	00:02:24:52	00:00:00:08	RADIAL IN-PLANE, UPWARD MANEUVER 10 fps ΔV.
13. ATTITUDE HOLD	00:02:25:00	00:09:45:00	DEADBAND ±20°
* 14. PRETHRUST ATTITUDE MANEUVER	00:12:00:00	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° DEADBAND.

FIGURE A–2

EASTERLY MISSION TIMELINE (Cont'd)

EVENT	INITIATION TIME (DAYS: HRS:MIN:SEC)	Δt BETWEEN EVENTS (DAYS:HRS:MIN:SEC)	APS REQUIREMENTS
* 15. ORBIT MAINTENANCE BURN - 1	00:12:10:00		HORIZONTAL, IN-PLANE, POSIGRADE MANEUVER, 4.5 fps ΔV
		00:00:00:04	
16. ATTITUDE HOLD	00:12:10:04		DEADBAND ±20°
		00:00:34:56	
17. PRETHRUST ATTITUDE MANEUVER	00:12:45:00		MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° DEADBAND
		00:00:10:00	
18. ORBIT MAINTENANCE BURN -2	00:12:55:00		HORIZONTAL, IN-PLANE, POSIGRADE MANEUVER, 4.5 fps ΔV
		00:00:00:08	
19. ATTITUDE HOLD	00:12:55:08		DEADBAND ±20°
		00:23:04:52 (00:16:57:52-Last Day)	
20. RELATIVE TRACKING OF OOS AND PRETHRUST TARGETING	06:05:53:00		MANEUVER TO LINE-OF-SIGHT ATTITUDE TO OOS. MAINTAIN ±5° DEADBAND
		00:00:10:00	
21. PRETHRUST ATTITUDE MANEUVER	06:06:03:00		MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° DEADBAND
		00:00:10:00	
22. TERMINAL PHASE INITIATION (TPI)	06:06:13:00		IN-PLANE POSIGRADE MANEUVER 32 fps ΔV.
		00:00:00:27	
23. RELATIVE TRACKING OF OOS AND PRETHRUST	06:06:13:27		MANEUVER TO LINE-OF-SIGHT ATTITUDE TO OOS. MAINTAIN ±5° DEADBAND.
		00:00:20:33	
24. PRETHRUST ATTITUDE MANEUVER	06:06:34:00		MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° DEADBAND
		00:00:10:00	
25. BRAKING BURNS	06:06:44:00		44 fps OVER SERIES OF RANGE/RANGE-RATE GATES
		00:00:23:00	

*EVENTS 14 THROUGH 19 REPREATED FOR TOTAL OF SIX (6) DAYS.

FIGURE A-2

EASTERLY MISSION TIMELINE (Cont'd)

EVENT	INITIATION TIME (DAYS:HRS:MIN:SEC)	Δt BETWEEN EVENTS (DAYS:HRS:MIN:SEC)	APS REQUIREMENTS
26. DOCKING	06:07:07:00	00:00:02:00	10 fps MULTIAXIS ΔV, $\pm 0.5°$ DEADBAND
27. OOS RETRIEVAL	06:07:09:00	00:00:15:00	1 fps MULTIAXIS ΔV. DEADBAND $\pm 0.5°$. STOW OOS IN CARGO BAY
28. POSITION UPDATE	06:07:24:00	00:00:10:00	DEADBAND $\pm 5°$
29. ATTITUDE HOLD	06.07:34:00	00:12:20:30	DEADBAND $\pm 20°$
30. PRETHRUST ATTITUDE MANEUVER	06:19:54:30	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT $\pm 0.5°$ DEADBAND
31. DEORBIT BURN	06:20:04:30	00:00:03:19	RETROGRADE, IN PLANE, 250 fps ΔV.
32. ENTRY ATTITUDE MANEUVER	06:20:07:49	00:00:11:40	ORIENT TO 30° α. DEADBAND $\pm$ 0.5°
33. ENTRY	06.20:19:29	00:00:29:55	MANEUVER AS REQ'D 60 fps ΔV DEADBAND $\pm 1°$ Pitch; $\pm 2°$ (yaw-roll)
34. TRANSITION MANEUVER	06:20:49:24	00:00:07:50	PITCH DOWN TO AIRPLANE FLIGHT MODE
35. DEACTIVATE APS	06:20:57:14		48,000 FT TERMINATION ALTITUDE

FIGURE A-2

SOUTH POLAR MISSION TIMELINE (BOOSTER)

	TIME OF INITIATION DAYS:HRS:MIN:SEC	Δt BETWEEN EVENTS DAYS:HRS:MIN:SEC
DESCENT BOOSTER		
o Initate Separation	00:03:15.7	
o Separation	00:03:18.2	00:00:02.5
o Orientate to $\alpha = 60°$ $\beta = 90°$	00:04:15	00:00:56.8
o Orientate to $\beta = 90°$	00:06:10	00:01:55
o Initiate α Modulation	00:06:12	00:00:02
o Initiate β Modulation	00:06:38	00:00:26
o Start ABES	00:08:48	00:02:10
o Orientate to $\beta = 0°$	00:09:28	00:00:40
o Orientate to $\alpha = 11°$	00:10:18	00:00:50
o Start Cruise Back (438 NM)	00:10:48	00:00:30
o Land	01:40:48	01:30:00

Figure A-3

deadband prior to returning to the launch site. Typical mission event sequences from lift-off to landing are shown in Figures A-4 and A-5 for the orbiter and booster. In addition to normal on-orbit maneuvering functions, the OMS provides 900 fps ΔV augmentation in the ascent operating mode. The OMS ΔV allocation of Figure A-4 for on-orbit maneuvers is 520 fps. Additional propellant is carried for attitude control.

A3.3 Reference Mission (Resupply) - The resupply mission consists of providing logistic support for a space station/space base in a 270 nautical mile, 55 degree circular orbit. Logistic support will consist of periodic transportation of expendable supplies, experiments, data and passengers to and from the space station. The duration of each mission is seven days. The resupply mission requires the orbiter to rendezvous and dock with the space station. Therefore, depending upon launch time, the orbiter may be required to perform a phasing burn(s) prior to rendezvous with the space station.

Typical resupply mission event sequences are shown in Figures A-6 and A-7 for the orbiter and booster. Approximately five hours of phasing, which are part of the transfer/gross rendezvous maneuver,are considered for the orbiter. Upon reaching apogee of the 50 x 100 nautical mile insertion, orbit perigee is raised to 123 nautical miles. Approximately 1/2 orbit later, the 100 nautical mile apogee is raised to 241 nautical miles and the orbiter remains in a 123 x 241 nautical mile orbit for 1-1/2 revolutions. At this time, the orbit is changed to 241 x 250 nautical miles and 1/2 orbit later, perigee is raised to 260 nautical miles. The orbit is circularized at 260 nautical miles at the appropriate time and the orbiter prepares for initiation of final rendezvous and docking maneuvers. After docking and cargo module transfer, the orbiter separates and remains in a 20 degree deadband until cargo is transferred to the station and the return cargo is loaded into a returning module. The orbiter then redocks with the cargo module, separates from the station, and returns to the launch site. A typical mission will expend, as shown in Figure A-6, approximately 1283 fps velocity increment. Approximately 100 to 160 fps is estimated for dispersion corrections. Additional propellant is provided for on-orbit attitude control.

A3.4 Ascent Abort Requirements - A major requirement for the Orbit Maneuvering Propulsion System will be to provide for safe entry in the event of a main engine

SOUTH POLAR MISSION TIMELINE

EVENT	INITIATION TIME (DAYS:HRS:MIN:SEC)	Δt BETWEEN EVENTS (DAYS:HRS:MIN:SEC)	APS REQUIREMENTS
1. LIFT-OFF	00:00:00:00	00:00:03:18.2	NO APS REQUIREMENT
2. ORBITER ENGINE & OMS IGNITION	00:00:03:18.2	00:00:03:18.6	DAMP SEPARATION RATES. OMS BOOST AUGMENTATION, 900 fps. PROVIDE ROLL CONTROL & ABORT ΔV FOR ORBITER MAIN ENGINE-OUT CONDITION.
3. ORBITER ENGINE SHUT-DOWN	00:00:06:36.8	00:00:02:14.8	DAMP MAIN ENGINE CUT-OFF TRANSIENTS. DEAD BAND ±0.5°
4. OMS SHUT-DOWN/INSERTION INTO 50 x 100 N.M. ORBIT	00:00:08:51.6	00:00:43:40.4	DEADBAND ±20°
5. PRETHRUST ATTITUDE MANEUVER	00:00:42:32	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.50
6. CIRCULARIZE ORBIT AT 100 x 100 N.M.	00:00:52:32	00:00:01:15	HORIZONTAL, IN-PLANE, POSIGRADE MANEUVER, 90 fps ΔV.
7. ATTITUDE HOLD	00:00:53:47	00:00:33:28	DEADBAND ±20°
8. PAYLOAD DEPLOYMENT ATTITUDE MANEUVER	00:01:26:15	00:00:10:00	MANEUVER TO PAYLOAD DEPLOYMENT ATTITUDE AND HOLD AT ±0.5° DEADBAND.
9. DEPLOY & SEPARATE PAYLOAD	00:01:36:15	00:01:00:00	21 fps MULTIAXIS ΔV. DEADBAND ±0.5°
10. ATTITUDE HOLD	00:02:36:15	00:08:36:17	DEADBAND ±20°

Figure A-4

SOUTH POLAR MISSION TIMELINE (Cont'd)

EVENT	INITIATION TIME (DAYS:HRS:MIN:SEC)	Δt BETWEEN EVENTS (DAYS:HRS:MIN:SEC)	APS REQUIREMENTS
* 11. PRETHRUST ATTITUDE MANEUVER	00:11:12:32	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5°
* 12. ORBIT MAINTENANCE BURN - 1	00:11:22:32	00:00:00:04	HORIZONTAL, IN-PLANE, POSIGRADE MANEUVER, 4.5 fps ΔV.
* 13. ATTITUDE HOLD	00:11:22:36	00:00:34:56	DEADBAND ±20°
* 14. PRETHRUST ATTITUDE MANEUVER	00:11:57:32	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° DEADBAND
* 15. ORBIT MAINTENANCE BURN - 2	00:12:07:32	00:00:00:04	HORIZONTAL, IN-PLANE, POSIGRADE MANEUVER, 4.5 fps ΔV.
* 16. ATTITUDE HOLD	00:12:07:36	00:23:04:56 (REPEATED FOR 6 DAYS)	DEADBAND ±20°
17. ON-ORBIT ACTIVITIES	06:11:12:32	00:01:30:00	ASSUME 55 fps MULTIAXIS ΔV & 180 fps POSIGRADE ΔV. DEADBAND ±0.5°
18. ATTITUDE HOLD	06:12:42:32	00:07:11:38	DEADBAND ±20°
19. PRETHRUST ATTITUDE MANEUVER	06:19:54:30	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° DEADBAND
20. DEORBIT BURN	06:20:04:30	00:00:03:19	RETROGRADE, IN-PLANE 250 fps ΔV
21. ENTRY ATTITUDE MANEUVER	06:20:07:49	00:00:09:40	ORIENT TO 30°αC DEADBAND ±0.5°
22. ENTRY	06:20:17:29	00:00:21:50	MANEUVER AS REQ'D. 60 fps MULTIAXIS ATTITUDE CONTROL
23. INITIATE TRANSITION MANEUVER	06:20:49:19	00:00:07:50	PITCH DOWN TO AIRPLANE FLIGHT MODE
24. DEACTIVATE APS	06:20:57:09		48,000 FT TERMINATION ALTITUDE

* EVENTS 11 THROUGH 16 REPEATED FOR TOTAL OF SIX (6) DAYS

Figure A-4

EASTERLY MISSION TIMELINE (BOOSTER)

	TIME OF INITIATION DAYS:HRS:MIN:SEC	TIME BETWEEN EVENTS DAYS:HRS:MIN:SEC
DESCENT BOOSTER		
o Initiate Separation	00:03:14.6	
		00:00:02.5
o Separation	00:03:17.1	
		00:00:57.9
o Orientate to $\alpha = 60°$ $\beta = 0°$	00:04:15	
		00:01:55
o Orientate to $\beta = 90°$	00:06:10	
		00:00:02
o Initiate α Modulation	00:06:12	
		00:00:26
o Initiate β Modulation	00:06:38	
		00:02:10
o Start ABES	00:08:48	
		00:00:40
o Orientate to $\beta = 0°$	00:09:28	
		00:00:50
o Orientate to $\alpha = 11°$	00:10:18	
		00:00:30
o Start Cruise Bank (438 NM)	00:10:48	
		01:30:00
o Land	01:40:48	

Figure A-5

RESUPPLY MISSION TIMELINE

EVENT	INITIATION TIME (DAYS:HRS:MIN:SEC)	Δt BETWEEN EVENTS (DAYS:HRS:MIN:SEC)	APS REQUIREMENTS
1. LIFT-OFF	00:00:00:00	00:00:03:17.7	NO APS REQUIREMENT
2. ORBITER ENGINE IGNITION	00:00:03:17.7	00:00:03:16.7	DAMP SEPARATION RATES. PROVIDE ROLL CONTROL AND ABORT ΔV FOR ORBITER MAIN ENGINE-OUT CONDITION
3. INSERTION INTO 50 x 100 N.M.	00:00:06:34.4	00:00:33:39.6	DAMP MAIN ENGINE CUT-OFF TRANSIENTS DEADBAND ± 20°
4. PRETHRUST ATTITUDE MANEUVER	00:00:40:14	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ± 0.5° DEADBAND.
5. PHASING BURN INTO 123 x 100 N.M. ORBIT	00:00:50:14	00:00:01:51	HORIZONTAL, IN-PLANE POSIGRADE MANEUVER, 133 fps ΔV
6. ATTITUDE HOLD	00:00:52:05	00:00:33:09	DEADBAND ±20°
7. PRETHRUST ATTITUDE MANEUVER	00:01:25:14	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° DEADBAND
8. PHASING BURN INTO 241 x 123 N.M. ORBIT	00:01:35:14	00:00:03:27	HORIZONTAL, IN-PLANE POSIGRADE MANEUVER, 248 fps ΔV
9. ATTITUDE HOLD	00:01:38:41	00:02:02:45	DEADBAND ± 20°
10. PRETHRUST ATTITUDE MANEUVER	00:03:41:26	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° ATTITUDE
11. PHASING BURN INTO 250 x 241 N.M. ORBIT	00:03:51:26	00:00:03:06	HORIZONTAL, IN-PLANE POSIGRADE MANEUVER, 224 fps ΔV

Figure A-6

RESUPPLY MISSION TIMELINE (Cont'd)

EVENT	INITIATION TIME (DAYS:HRS:MIN:SEC)	Δt BETWEEN EVENTS (DAYS: HRS:MIN:SEC)	APS REQUIREMENTS
12. ATTITUDE HOLD	00:03:54:32	00:00:21:54	DEADBAND ±20°
13. RELATIVE TRACKING OF SPACE STATION AND PRETHRUST TARGETING	00:04:16:26	00:00:10:00	MANEUVER TO LINE-OF-SIGHT ATTITUDE TO SPACE STATION, MAINTAIN ±5° DEADBAND
14. PRETHRUST ATTITUDE MANEUVER	00:04:26:26	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° DEADBAND
15. NCC	00:04:36:26	00:00:00:28	POSIGRADE MANEUVER, 33 fps ΔV
16. ATTITUDE HOLD	00:04:36:54	00:00:24:32	DEADBAND ±20°
17. RELATIVE TRACKING OF SPACE STATION AND PRETHRUST TARGETING	00:05:01:26	00:00:10:00	MANEUVER TO LINE-OF-SIGHT ATTITUDE TO SPACE STATION. MAINTAIN ±50° DEADBAND
18. PRETHRUST ATTITUDE	00:05:11:26	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° DEADBAND
19. COELLIPTIC BURN INTO 260 x 260 N.M. ORBIT	00:05:21:26	00:00:00:15	POSIGRADE MANEUVER, 18 fps ΔV
20. ATTITUDE HOLD	00:05:21:41	00:00:24:45	DEADBAND ±20°
21. RELATIVE TRACKING OF SPACE STATION AND PRETHRUST TARGETING	00:05:46:26	00:00:10:00	MANEUVER TO LINE-OF-SIGHT ATTITUDE TO SPACE STATION. MAINTAIN AT ±5° DEADBAND.
22. PRETHRUST ATTITUDE MANEUVER	00:05:56:26	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° DEADBAND
23. TERMINAL PHASE	00:06:06:26	00:00:00:18	IN-PLANE, POSIGRADE MANEUVER. 22 fps ΔV.

Figure A-6

RESUPPLY MISSION TIMELINE (Cont'd)

EVENT	INITIATION TIME (DAYS:HRS:MIN:SEC)	Δt BETWEEN EVENTS (DAYS:HRS:MIN:SEC)	APS REQUIREMENTS
24. RELATIVE TRACKING OF SPACE STATION AND PRETHRUST TARGETING	00:06:06:44	00:00:25:41	MANEUVER TO LINE-OF-SIGHT ATTITUDE TO SPACE STATION. MAINTAIN ±5° DEADBAND
25. PRETHRUST ATTITUDE MANEUVER	00:06:32:25	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD ±0.5° DEADBAND
26. BRAKING BURNS	00:06:42:25	00:00:12:04	45 fps OVER SERIES OF RANGE/ RANGE-RATE GATES
27. DEPLOY CARGO CONTAINER	00:06:54:29	00:00:25:00	1.0 fps MULTI-AXIS RATE DAMPING. ±0.5° DEADBAND
28. DOCKING	00:07:19:29	00:03:00:00	10 fps MULTI-AXIS ΔV, ±0.5° DEADBAND
29. SEPARATION	00:10:19:29	00:00:00:16	10 fps ΔV RETROGRADE .±0.5° DEADBAND
30. STATION KEEPING AND ATTITUDE HOLD	00:10:19:45	05:23:39:44	DEADBAND ±20°
31. RELATIVE TRACKING OF SPACE STATION AND PRETHRUST TARGETING	06:09:59:29	00:00:10:00	MANEUVER TO LINE-OF-SIGHT ATTITUDE TO SPACE STATION, MAINTAIN ATTITUDE AT ±5° DEADBAND
32. PRETHRUST ATTITUDE MANEUVER	06:10:09:29	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD AT ±0.5° DEADBAND.
33. TERMINAL PHASE INITIATION (TPI-2)	06:10:19:29	00:00:00:22	IN-PLANE, POSIGRADE MANEUVER 26 fps ΔV
34. ATTITUDE HOLD	06:10:19:51	00:00:30:56	DEADBAND ±20°.
35. RELATIVE TRACKING OF SPACE STATION AND PRETHRUST TARGETING	06:10:50:47	00:00:10:00	MANEUVER TO LINE-OF-SIGHT ATTITUDE TO SPACE STATION. MAINTAIN ±5° DEADBAND.

Figure A-6

RESUPPLY MISSION TIMELINE (Cont'd)

EVENT	INITIATION TIME (DAYS:HRS:MIN:SEC)	Δt BETWEEN EVENTS (DAYS:HRS:MIN:SEC)	APS REQUIREMENTS
36. PRETHRUST ATTITUDE MANEUVER	06:11:00:47	00:00:10:00	MANEUVER TO BURN ATTITUDE AND HOLD $\pm$0.5° DEADBAND
		00:00:10:00	
37. BRAKING BURNS	06:11:10:47		54 fps OVER SERIES OF RANGE/ RANGE-RATE GATES
		00:00:37:25	
38. DOCKING	06:11:48:02		10 fps MULTI-AXIS ΔV $\pm$0.5° DEADBAND
		00:03:00:00	
39. SEPARATION	06:14:48:02		10 fps ΔV. RETROGRADE $\pm$0.5° DEADBAND
		00:00:15:00	
40. STOW CARGO CONTAINER	06:15:03:02		1.0 fps MULTI-AXIS RATE DAMPING: $\pm$0.5° DEADBAND
		00.00:15:00	
41. POSITION UPDATE	06:15:18:02		DEADBAND $\pm$5°
		00:00:10:00	
42. ATTITUDE HOLD	06:15:28:02		DEADBAND $\pm$20°
		00:05:02:26	
43. PRETHRUST ATTITUDE	06:20:30:28		MANEUVER TO BURN ATTITUDE AND HOLD AT $\pm$0.5° DEADBAND
		00:00:10:00	
44. DEORBIT BURN	06.20:40:28		RETROGRADE: IN-PLANE. 440 fps ΔV.
		00:00:05:08	
45. ENTRY ATTITUDE MANEUVER	06:20:45:36		ORIENT TO 34° α DEADBAND $\pm$0.5°.
		00:00:28:00	
46. ENTRY	06:21:13:36		MANEUVER AS REQ'D. 60 fps ΔV. DEADBAND $\pm$1°(PITCH):$\pm$2°(YAW-ROLL)
		00:00:20:25	
47. TRANSITION MANEUVER	06:21:34:01		PITCH DOWN TO AIRPLANE FLIGHT MODE
		00:00:12:50	
48. DEACTIVATE APS	06:21:46:51		48,000 FT TERMINATION ALTITUDE

Figure A-6

RESUPPLY MISSION TIMELINE (BOOSTER)

EVENT	TIME OF INITIATION DAYS:HRS:MIN:SEC	Δt BETWEEN EVENTS DAYS:HRS:MIN:SEC
o Liftoff	00:00:00	
o Initiate Separation	00:03:15.2	00:03:15.2
o Separation	00:03:17.7	00:00:02.5
o Orientate to $\alpha = 60°$ $\beta = 0°$	00:04:15	00:00:57.3
o Orientate to $\beta = 90°$	00:06:10	00:01:55
o Initiate α Modulation	00:06:12	00:00:02
o Initiate β Modulation	00:06:38	00:00:26
o Start ABES	00:08:48	00:02:10
o Orientate to $\beta = 0°$	00:09:28	00:00:40
o Orientate to $\alpha = 11°$	00:10:18	00:10:18
o Start Cruise Back (438 NM)	00:10:48	00:00:30
o Land	01:40:48	00:30:00

Figure A-7

failure during ascent. In this mission abort situation, the remaining orbiter main engine will be operated at 109 percent of its nominal thrust level. However, total ascent thrust will still be appreciably reduced and the increased gravity losses incurred must be made up by the Orbit Maneuvering System. Two operating modes are feasible; i.e., the OMS can be burned after main engine shutdown (series) or during main engine firing (parallel). Figures A-8 and A-9 provide definition of the abort ΔV augmentation required of the OMS as a function of OMS thrust level for the three missions to be considered.

A3.5 Vehicle Acceleration Requirements - The translation and rotational acceleration requirements for the Shuttle orbiter and booster are provided in Figures A-10 and A-11, respectively. Also provided in these figures are the attitude limits during the various mission phases. The acceleration requirements are to be interpreted as follows for system design:

Fail-Safe - Systems shall provide in excess of the safe acceleration levels after any failure or any two failures

Design - Systems shall provide acceleration levels above the design minimum under normal operating conditions (i.e., no failure).

A4. System and Component Design Criteria - The APS system design shall reflect the 10 year, 100 mission vehicle life requirement with cost effective refurbishment. Systems shall be designed for a minimum of maintenance with ease of component removal and replacement. Additionally, the APS shall be designed to fail-safe after the failure of any two critical components. Specific criteria applied to APS design are summarized below.

A4.1 Factors of Safety - Safety factors should be based on limit loads and stress conditions and on material properties described in the "A" allowable values of MIL-HDBK-5A or equivalent values based on probability and confidence.

1. A material ultimate factor of 1.4 (prelaunch through entry transition) or 1.5 (entry transition to prelaunch) shall be applied to general structure loads resulting from inertia, dynamic response, engine thrust, thermal conditions, and other miscellaneous conditions.
2. A material proof factor of 1.5 and ultimate factor of 2.0 shall be applied to stresses resulting from pressure conditions.

ORBITER OMS ASCENT ABORT REQUIREMENTS

- EASTERLY LAUNCH MISSION
- RESUPPLY MISSION

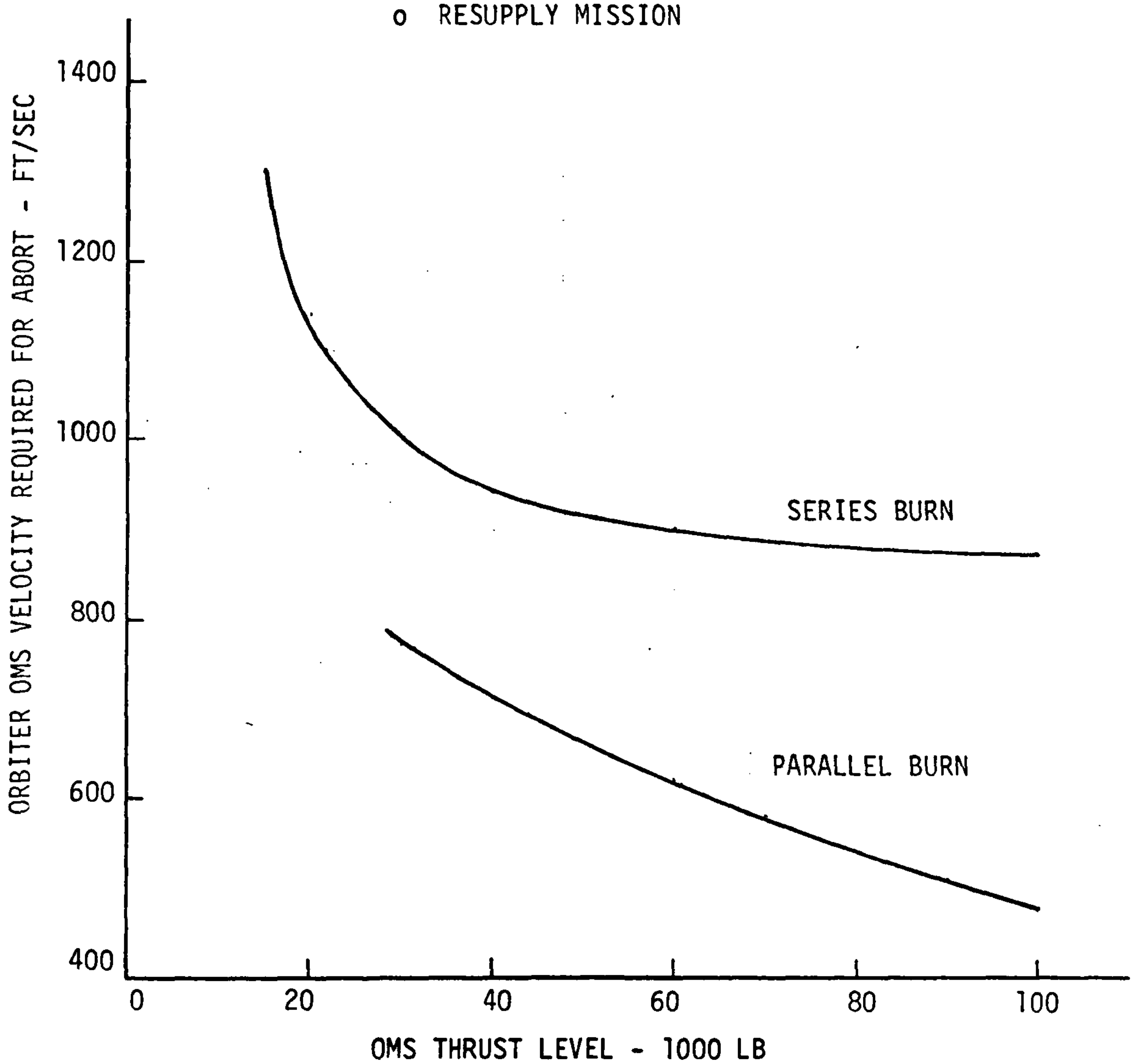

Figure A-8

ORBITER OMS ASCENT ABORT REQUIREMENTS

o SOUTH POLAR MISSION

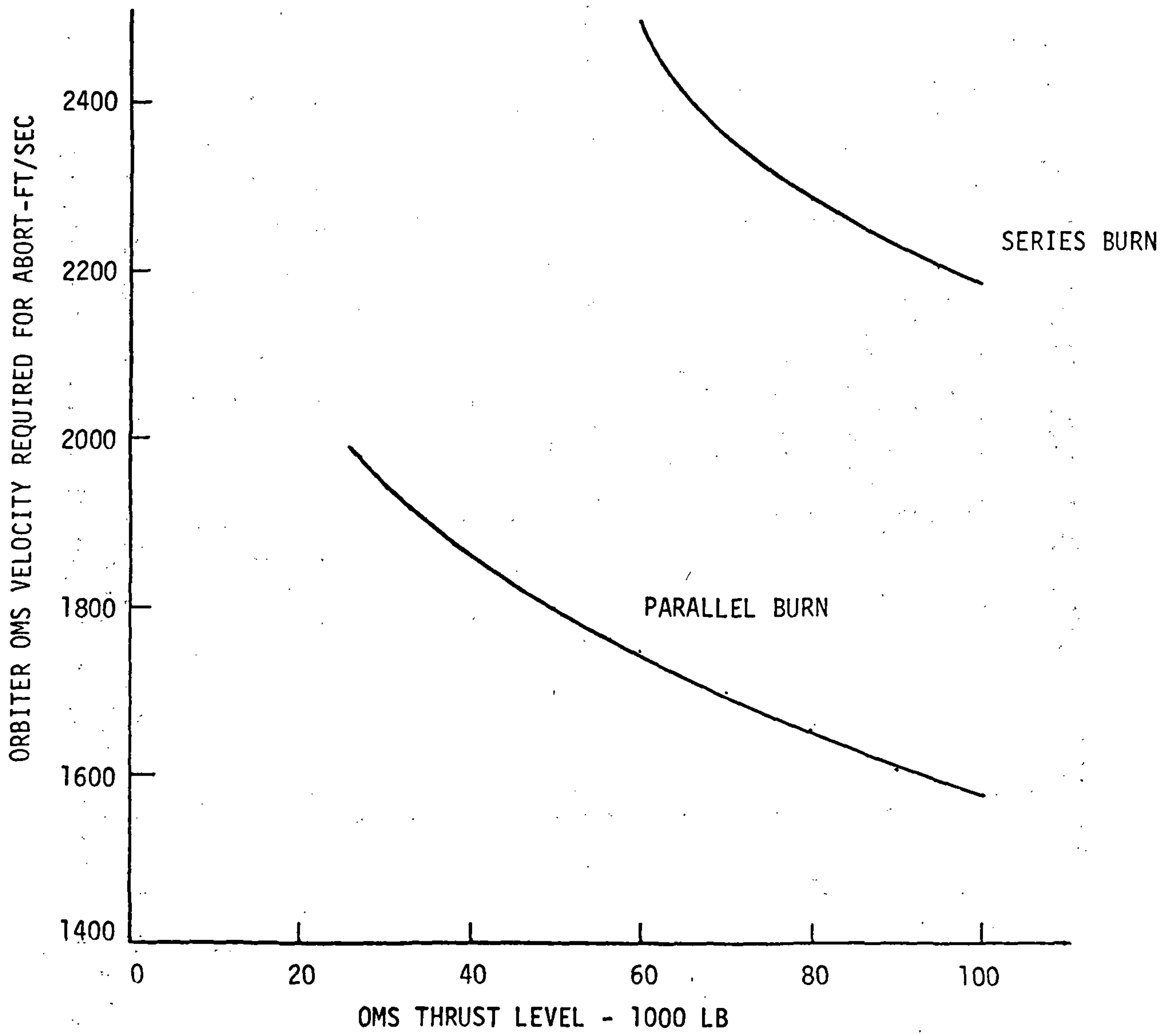

Figure A-9

ORBITER MANEUVERING ACCELERATION REQUIREMENTS

MISSION PHASE		ASCENT			ON-ORBIT			ENTRY			TRANSITION		
		-X	+X	±Y,Z	-X(a)	+X	±Y,Z	-X	+X	±Y,Z	-X	+X	±Y,Z
TRANSLATION ACCELERATION FT/SEC^2	SAFE MINIMUM	1.0(OMS)	N/R+		0.6(OMS) 0.2(OMS)	0.0	0.0	N/R+			N/R+		
	DESIGN	1.5(OMS)			1.2(OMS) 0.4(APS)	0.4	0.2						
		P	Y	R	P	Y	R	P	Y	R	P	Y	R
ANGULAR ACCELERATION DEG/SEC^2	SAFE MINIMUM	N/R+		(b)	0.3	0.3	0.3	0.3	0.8	1.0			
	DESIGN				0.5	0.5	0.5	0.5	1.2	1.5	TBD	TBD	TBD
ATTITUDE LIMITS DEG	FINE COURSE	N/R+ N/R+		1.0 N/R+	0.5 20.	0.5 20.	0.5 20.	1.0 N/R+	2.0 N/R+	2.0 N/R+			

\+ NO REQUIREMENT

(a) FAIL SAFE DEORBIT BACKUP SHALL BE PROVIDED BY APS; DEORBIT MANEUVER SHALL NOT EXCEED 5 MINUTES DURATION

(b) ROLL CONTROL TORQUE OF 40,000 FT-LB(MIN) REQUIRED FOR FAILED MAIN ENGINE

Figure A-10

BOOSTER MANEUVERING ACCELERATION REQUIREMENTS

MISSION PHASE		POST-SEPARATION			ORIENTATION			ENTRY(a)			TRANSITION(a)		
		X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
TRANSLATION ACCELERATION ft/sec^2	SAFE DES MIN	NO REQUIREMENT			NO REQUIREMENT			NO REQUIREMENT			NO REQUIREMENT		
		P	Y	R	P	Y	R	P	Y	R	P	Y	R
ANGULAR ACCELERATION deg/sec^2	SAFE DES MIN	0.12 0.30	0.12 0.30	0.12 0.30	0.12 0.30	0.12 0.30	0.12 0.30	NO REQUIREMENT			NO REQUIREMENT		
ATTITUDE LIMITS deg	FINE COURSE	2.0 N/R	2.0 N/R	2.0 N/R	2.0 N/R	2.0 N/R		NO REQUIREMENT			NO REQUIREMENT		

(a) CONTROL PROVIDED BY AERODYNAMIC SURFACES

Figure A-11

3. When only typical fatigue allowables are available, the component shall be capable of withstanding 10 times the predicted number of load cycles. When sufficient fatigue data are available to establish statistical minimum guaranteed fatigue allowables, the component shall be capable of withstanding three times the predicted number of load cycles.

A4.2 Materials - Materials used in the manufacture of the APS shall be of high quality suitable for the purpose and shall conform to applicable specifications. All materials employed must have proven capability to be fabricated to the shape and form (including weldability) to satisfy the design requirements.

Materials known to be susceptible to stress corrosion cracking shall not be used in a configuration/application conducive to stress corrosion cracking. Materials known to be susceptible to stress corrosion cracking shall not be used without prior approval by the procuring activity.

Materials recognized to be susceptible to embrittlement when exposed to gaseous hydrogen shall not be used in a configuration/application conducive to hydrogen embrittlement.

All material used shall be selected on the basis of having maximum compatibility with the environment with which it is used, with primary importance placed on material-propellant compability and the use of nonflammable materials whenever possible. Any material used internally in the oxidizer system shall be LOX compatible.

A4.2.1 Fluids and Mechanical Criteria

1. Fluid line sizes shall be selected on the basis of design velocities that will result in an acceptable compromise between the excessive pressure drop produced by too-small diameter tubings and the weight and cost of too-large diameter lines. Gas velocities shall be limited to Mach 0.3 or less, except where higher values are specifically justified and approved.
2. Mechanically separable seal connectors in tubing or ducting greater than 1 inch in diameter shall be bolted-type flanges, unless otherwise justified and approved. All flanges in tubing or ducting will incorporate redundant seals.

3. Flight components shall be limited to those required for flight operations, except for components required for onboard checkout and servicing. Components integration, packaging, and simplicity of checkout shall be considered where advantages in maintainability, serviceability, replaceability, weight, and cost could be realized.

A4.2.2 Thermal Conditioning and Control

1. Passive-type thermal control shall be employed to the maximum extent possible.
2. Thermal protection requirements identified shall be included in the system or component design and corresponding weights included in the overall system weight.

A4.3 Vehicle/System Exchange Ratios - Figure A-12 provides typical stage and gross lift-off weight exchanges for use in system design trade studies. The data presented are a compilation of results obtained from vehicle sizing studies and reflect all known penalties including factors such as landing engine fuel for cruise back range and changes to ascent and entry drag.

A5. Vehicle Characteristics - The orbiter stage of the Shuttle Phase B System is a delta wing, high crossrange configuration and the booster is a single body, swept wing, canard configuration. Figures A-13 and A-14 present mass properties for the two stages. Figures A-15 and A-16 show profile sketches of the orbiter and booster indicating general vehicle dimensions and RCS thruster locations.

PARAMETRIC VEHICLE SENSITIVITIES-FIXED PAYLOAD+

VARIABLE	EASTERLY LAUNCH INERT WGT BOOSTER	EASTERLY LAUNCH INERT WGT ORBITER	EASTERLY LAUNCH GROSS WGT (GLOW)	RESUPPLY MISSION INERT WGT BOOSTER	RESUPPLY MISSION INERT WGT ORBITER	RESUPPLY MISSION GROSS WGT (GLOW)	SOUTH POLAR MISSION INERT WGT BOOSTER	SOUTH POLAR MISSION INERT WGT ORBITER	SOUTH POLAR MISSION GROSS WGT (GLOW)	SENSITIVITY UNITS
APS INERT WGT										
- BOOSTER	1.5	0.07	6.1	1.6	0.07	6.4	1.6	0.07	6.5	LB/LB
- ORBITER	2.1	2.59	34.9	2.0	2.7	34.0	2.3	2.8	37.7	LB/LB
VEH. BASE AREA										
- ORBITER	30.6	37.8	510	28.0	37.8	476	31.2	37.8	510	LB/FT^2
APS TANK VOL.										
- BOOSTER	0.21	0.01	0.85	0.22	0.01	0.88	0.21	0.01	0.87	LB/FT^3
- ORBITER	1.69	2.1	28.1	2.0	2.7	34.1	2.2	2.6	35.4	LB/FT^3

\+ VEHICLE SYSTEM RESIZED TO MAINTAIN FIXED PAYLOAD

Figure A-12

FIGURE A-13

ORBITER MASS PROPERTIES

DESIGN EASTERLY LAUNCH		STAGING	INSERTION	ON-ORBIT	ENTRY
Weight (lb)		860,442	331,780	319,187	277,291
Center of Gravity (in.)	X	+1063	+1465	+1485	+1481
	Y	0	0	0	0
	Z	+ 257	+ 303	+ 306	+ 298
Moment of Inertia (Slug-ft^2 x 10^{-6})					
	I_{XX}	2.55	1.96	1.94	1.84
	I_{YY}	42.24	15.25	14.06	12.86
	I_{ZZ}	42.66	15.58	14.39	13.23
SOUTH POLAR					
Weight (lb)		853,407	302,075	290,012	278,376
Center of Gravity (in.)	X	+1067	+1470	+1491	+1486
	Y	0	0	0	0
	Z	+ 253	+ 295	+ 298	+ 298
Moment of Inertia (Slug-ft^2 x 10^{-6})					
	I_{XX}	2.45	1.88	1.86	1.84
	I_{YY}	43.77	14.77	13.60	12.99
	I_{ZZ}	44.32	15.16	13.99	13.37
RESUPPLY					
Weight (lb)		845,988	317,149	293,197	276,367
Center of Gravity (in.)	X	+1063	+1486	+1498	+1489
	Y	0	0	0	0
	Z	+ 250	+ 286	+ 289	+ 288
Moment of Inertia (Slug-ft^2 x 10^{-6})					
	I_{XX}	2.56	2.07	2.03	2.01
	I_{YY}	42.90	15.34	13.59	12.73
	I_{ZZ}	43.67	15.93	14.16	13.29

FIGURE A-14

BOOSTER MASS PROPERTIES

Design - Easterly Launch*		Mission Phase		
		Lift-Off	Staging	Start of Cruise
Weight (lb)		3,756,180	721,280	699,292
Center of Gravity (in.)	X	+2071	+3021	+3015
	Y	0	0	0
	Z	+ 404	+ 423	+ 424
Moment of Inertia (Slug $ft^2 \times 10^{-6}$)				
	I_{XX}	9.45	9.38	9.38
	I_{YY}	439.85	118.32	115.45
	I_{ZZ}	444.00	122.52	119.65

*Applicable to Resupply and South Polar Missions

ORBITER RCS THRUSTER LOCATIONS

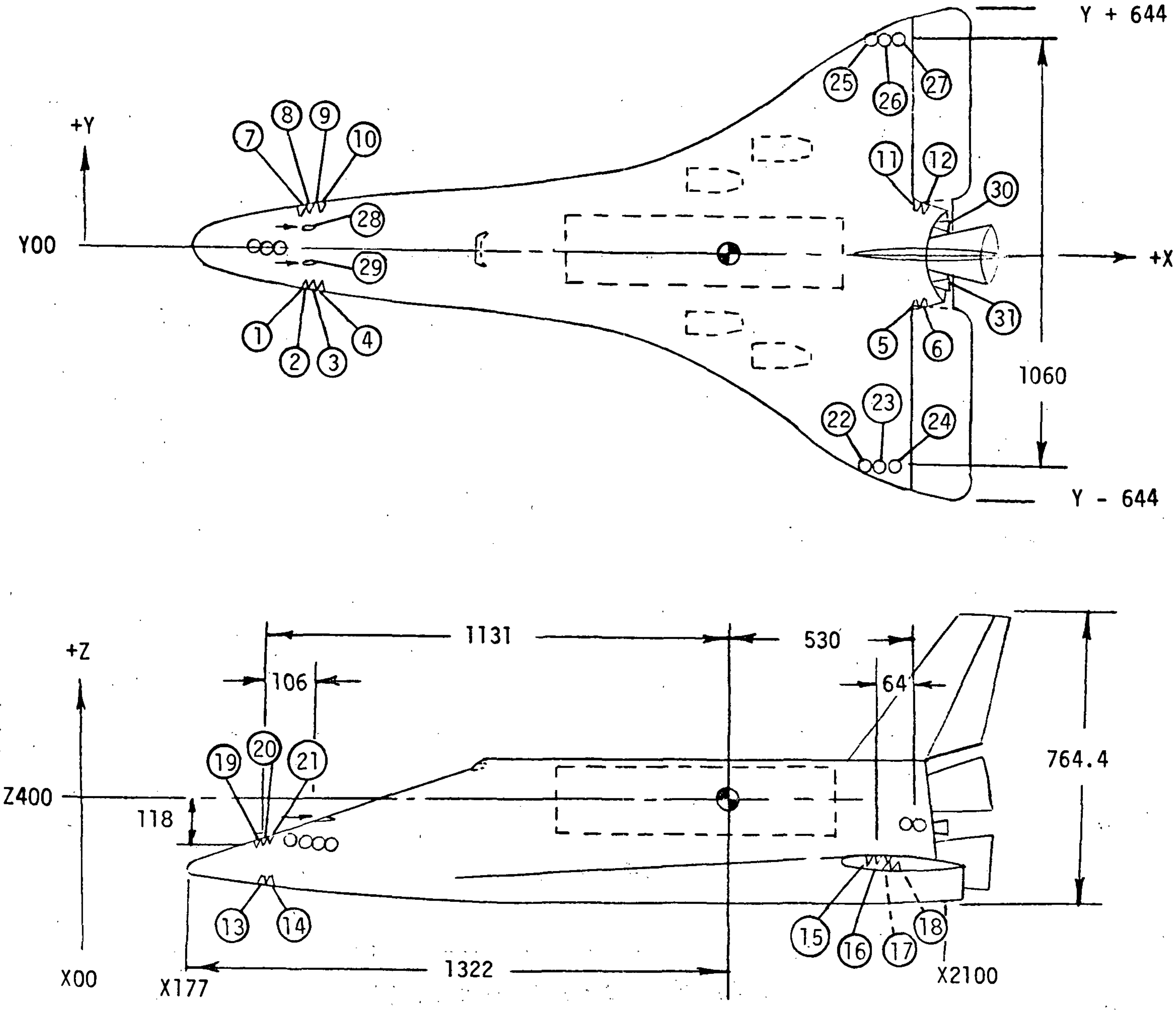

Figure A-15

BOOSTER RCS THRUSTER LOCATIONS

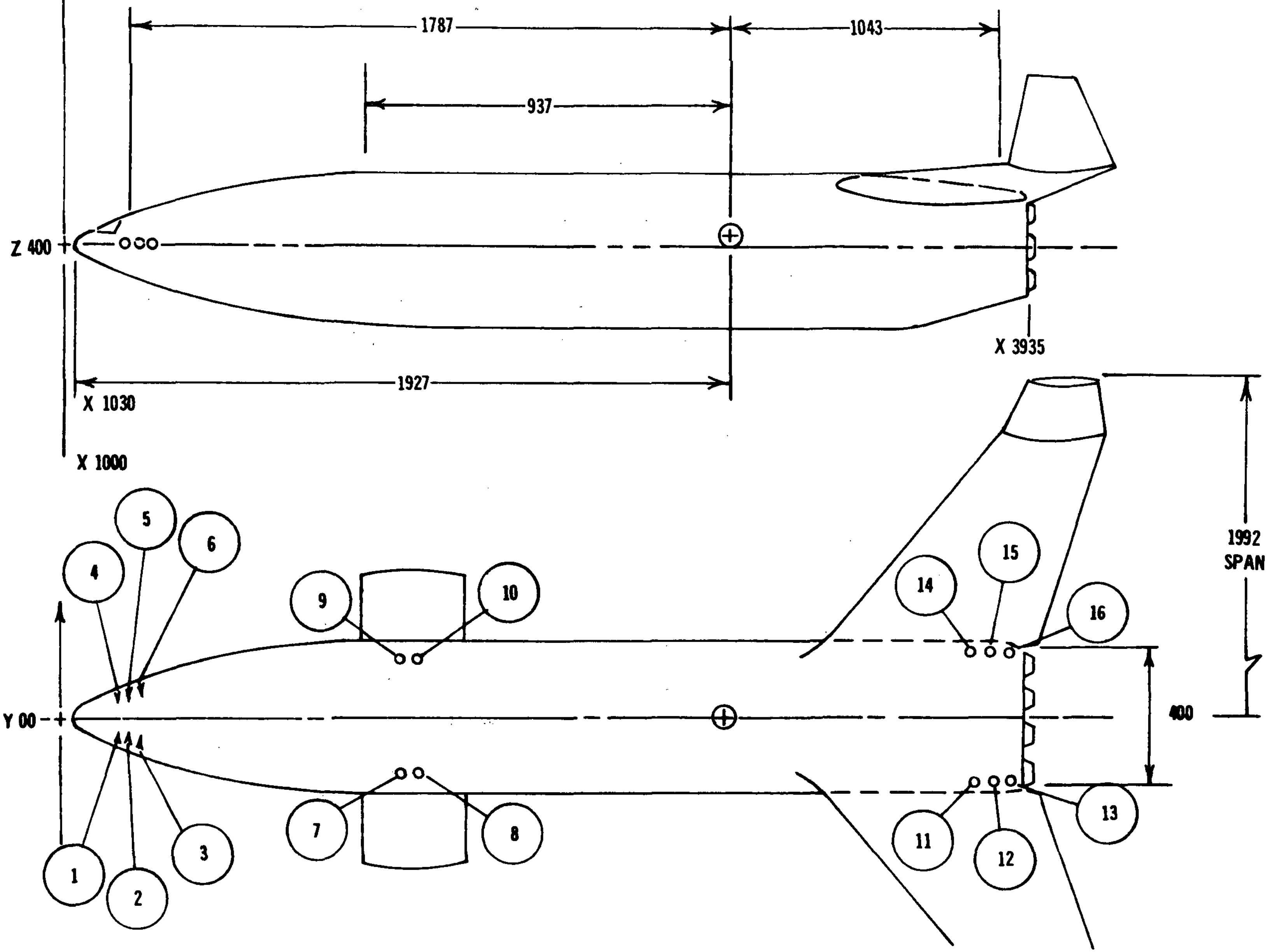

Figure A-16