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**SPACE SHUTTLE HIGH PRESSURE
AUXILIARY PROPULSION SUBSYSTEM
DEFINITION STUDY
SUBTASK A REPORT**

Contract Number NAS 8-26248

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY - EAST

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SPACE SHUTTLE HIGH PRESSURE AUXILIARY PROPULSION SUBSYSTEM DEFINITION STUDY

12 FEBRUARY 1971

REPORT MDC E0297

SUBTASK A REPORT

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1. INTRODUCTION

Development of the NASA space shuttle vehicle system for future manned space operations required development of a number of subsystems which were either new, or significant extensions of current technology. Among these is the auxiliary propulsion subsystem (APS) used for shuttle control and maneuvering after main engine cutoff. The magnitude of APS control requirements was far higher than those of previous space vehicles. To provide a high performance APS and, in addition, to take advantage of benefits which can be derived in the areas of propellant logistics, safety, reuse, and performance, a gaseous hydrogen/oxygen auxiliary propulsion subsystem was identified as most desirable.

There are two basic means of implementing an APS of this type:

- (1) a high pressure APS in which the propellants are stored at, or conditioned to, the most desirable thruster operating pressures;
- (2) a low pressure APS in which propellants are supplied to control thrusters from main ascent propellant tanks at normal ullage pressures.

Within these broad categories, many APS alternatives or options were available. Typically, storage of propellants, conditioning assembly design, integration with other propulsion subsystems, and exact mode of APS usage during mission could be implemented in a variety of ways.

Each basic APS category and its alternate implementation scheme offered different advantages and disadvantages in terms of subsystem performance and required technology development. Thus, APS selection for the shuttle, and definition of advanced technology necessary for APS development, required in-depth studies.

To fulfill this need, NASA contracted for two-phase definition studies of both high and low pressure APS. The first phase, Subtask A, was a conceptual subsystem definition designed to provide NASA with sufficient data for selection of the best means of APS implementation in both high and low pressure categories. The second phase, Subtask B, involved a preliminary design of the particular concept(s) selected in each basic APS category. A high pressure APS study was conducted by McDonnell Douglas Astronautics Company-East under Contract No. NAS 8-26248. The Aerojet Liquid Rocket Company, under subcontract to MDAC-East, provided analyses and design support necessary to define the active components for APS evaluation.

Technical direction for this effort was provided by the NASA Marshall Space Flight Center (MSFC) at Huntsville, Alabama, through the office of Mr. John McCarty, Deputy Chief, Propulsion and Power Branch of the Astronautics Laboratory.

The problem addressed in Subtask A of the high pressure APS study was to provide sufficient comparative data on various APS concepts to allow selection of the best high pressure approach for Subtask B preliminary design. This required consideration of a large number of high pressure APS concepts. For this phase of study, the predominate concern was the relative merit of various APS concepts, rather than their absolute performance levels. Component and assembly optimizations, within a given subsystem concept, were limited to those areas which potentially could impact subsystem selection. For these reasons, the final data resulting from this study phase could not be considered as representative of a refined absolute performance level for any particular subsystem. This aspect of design was properly the result of the second phase of study, which provided component optimizations for the selected APS concept. The vehicles considered in Subtask A were the two orbiters and boosters defined in Reference (a). Mission and control requirements for the vehicles were also defined in Reference (a). First phase (conceptual subsystem definition) results of the high pressure APS study are summarized in this volume.

Subtask B was initiated using configuration concepts defined during Subtask A. Vehicles and requirements were redefined by NASA prior to Subtask B. Considered for Subtask B APS installation were Orbiter B, Orbiter C, and the Booster defined in Reference (b). Trade-off studies were then performed to determine thruster arrangement and thrust level which would best meet maneuvering requirements and provide minimum weight configuration. Other criteria were considered, such as no heat shield penetration during reentry and a common thruster for orbiters and booster. In-depth component and assembly trade studies and design analyses, were performed in parallel with supporting subsystem design and operating analyses to define the recommended baseline APS. Final baseline APS installation and preliminary design, including component definition, were then accomplished. Results of the second phase (preliminary APS design) of the high pressure APS study are summarized in the Subtask B report (Reference (c)).

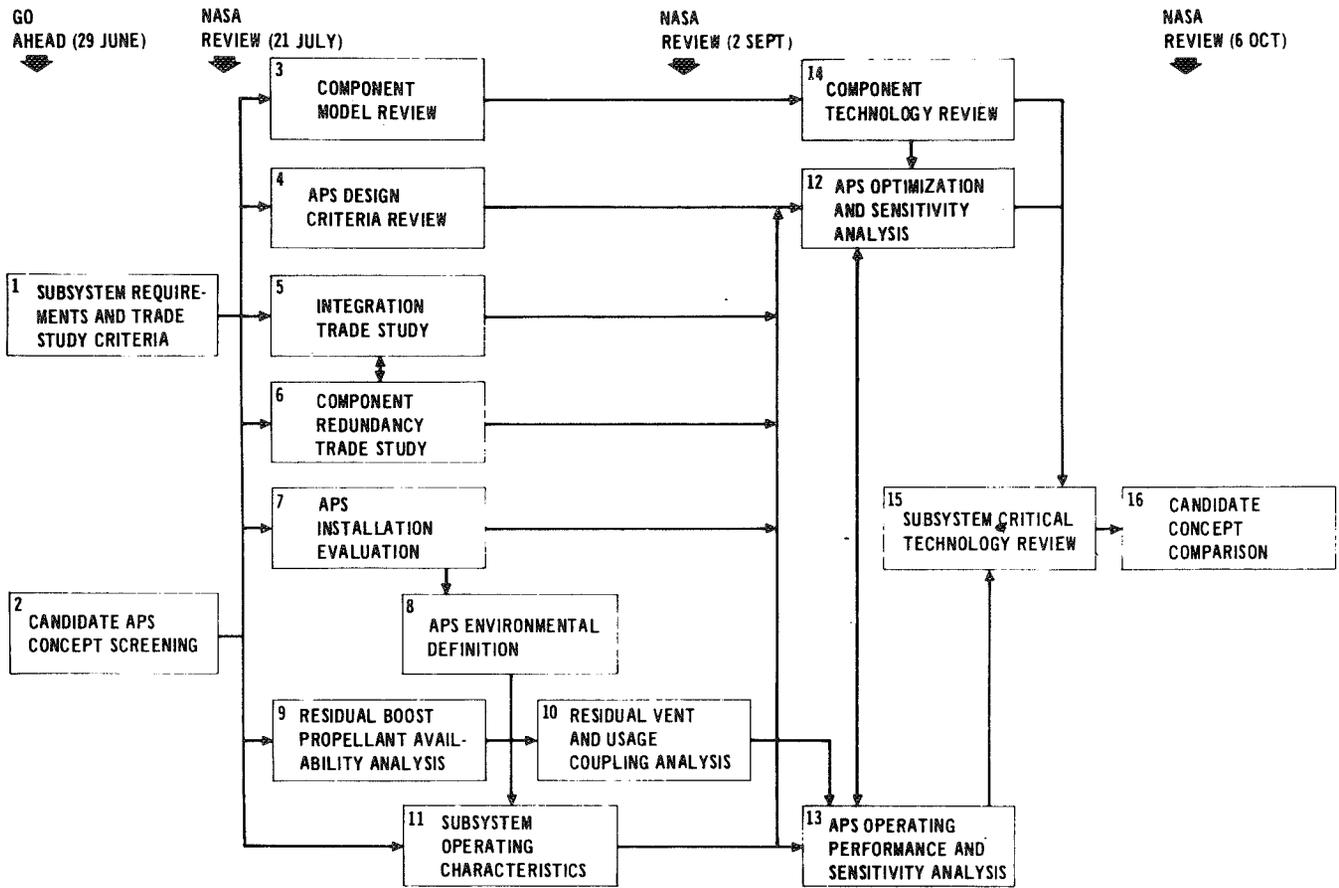
The High Pressure APS Description Handbook (Reference (d)) defines preliminary design, operating performance, and weight sensitivities for the selected APS for Orbiter B, Orbiter C, and the Booster defined in Reference (b).

The body of this report summarizes the concept trade studies, together with a description of study approach, requirements used in the study, and concepts considered. Appendices A through G provide background data for APS models used in the trade studies, while Appendix H supplies data and rationale used for initial screening of candidate APS concepts.

2. STUDY APPROACH

The purpose of this study phase was to establish the most attractive approach for high pressure APS based on defined selection criteria. Thus, the primary goal in this phase was to evaluate fairly, but in a timely manner, all possible APS candidates. Reference (e) provides a detailed program plan for the complete study and defines detailed task objectives and their relationship to the overall study. An overview of the Subtask A approach is presented below.

Figure 2-1 shows program tasks associated with Subtask A. The initial study effort was to establish specific APS requirements to be used for concept comparison and to define a matrix of all reasonable high pressure APS concepts. This latter required screening the many candidates to eliminate trite approaches, and to establish a reasonable number of candidates for consideration in trade studies. The next tasks were aimed at development of data needed to configure and evaluate candidates selected for trade studies. This required structuring of all component models and development of component performance over a broad parametric range. Also, intrasubsystem trades were performed to configure assemblies where they exhibited features which could impact APS concept selection. Among these were integration of APS and OMS propellant supplies, component redundancy required to meet failure criteria, availability of residual boost propellants for those concepts which could utilize booster residuals, and subsystem operation or installation features. Tasks 3 through 11 (Figure 2-1) allowed definition of baseline subsystem schematics and design criteria for trade studies. Using these, design analyses were then conducted to define subsystem design operating points which would provide minimum weight for each APS concept. Since selection criteria for this study included factors other than weight, the minimum weight version of a concept may not have resulted in a fair comparison. To counteract this, and to show each subsystem concept to best advantage in the comparison, minimum weight designs were iterated to achieve the best balance between subsystem weight, technology, flexibility, and simplicity for each APS concept. Designs were then compared on defined study selection criteria of weight, technology, flexibility, and simplicity.



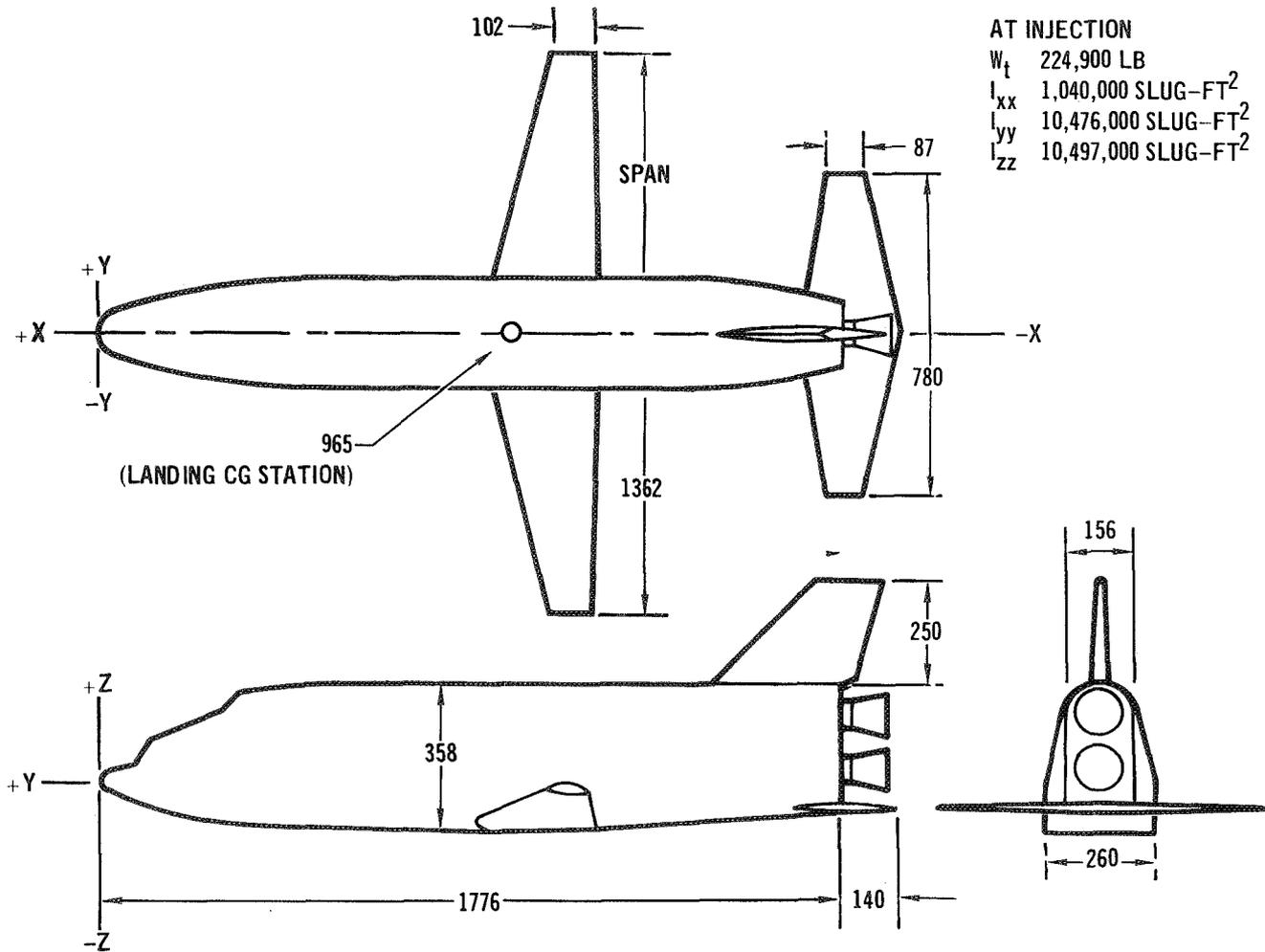
SUBTASK A – TASK DESCRIPTION FLOW CHART

FIGURE 2-1

3. APS REQUIREMENTS

Reference (a), which provides a summary description of space shuttle vehicles and missions, was issued by NASA to guide APS design. Four space shuttle vehicles were evaluated during this phase of study, high and low crossrange boosters and orbiters. These are illustrated in Figures 3-1 through 3-4. Included in Reference (a) were preliminary control and translation acceleration requirements which are summarized in Figures 3-5 and 3-6. For the study, a shuttle mission time line corresponding to the space station resupply/logistics mission was also provided as a baseline mission for Subtask A comparisons. Appendix G of this report summarizes various thruster sizing options capable of satisfying these acceleration requirements. Based on data presented in Appendix G, control thrust levels, and number of control thrusters required, were established for each orbiter and booster. These are summarized in Figure 3-7.

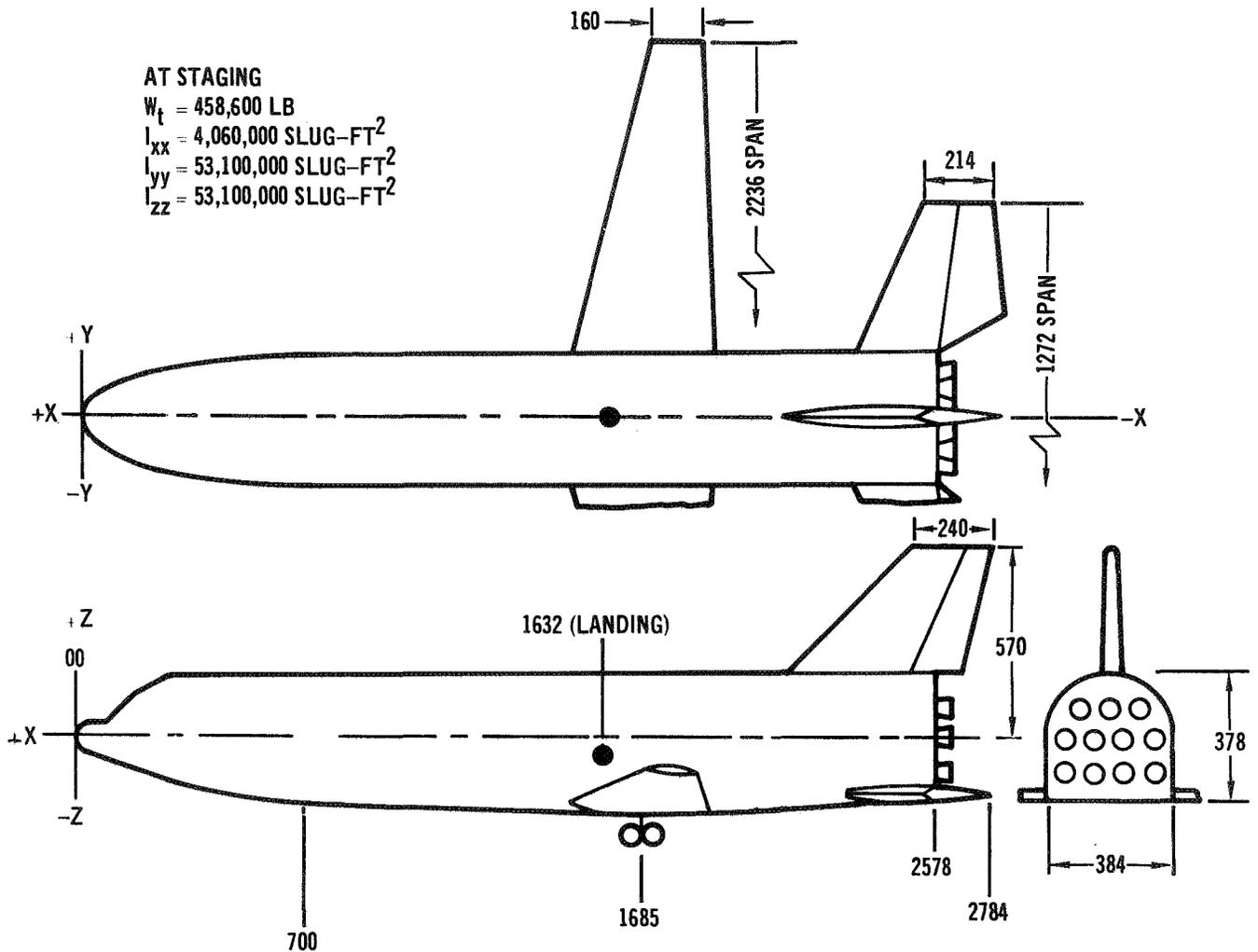
As a part of this effort, several alternate means of performing shuttle on-orbit control and maneuver functions were considered. Two basic cases were considered: (1) an auxiliary propulsion subsystem designed to perform all post-separation maneuver and control functions, and (2) an auxiliary propulsion subsystem designed to operate in conjunction with an orbit maneuvering subsystem (OMS). In this latter case, the APS would perform only control functions and vernier translation maneuvers. Two levels of APS translation maneuvers were considered: (1) translation maneuvers ≤ 10 ft/sec, and (2) translation maneuvers ≤ 50 ft/sec. A basic premise used for this study was that when an OMS system was used, the APS would provide propellant settling prior to all OMS firings. The amount of impulse allowed for settling was 30K lb-sec for each OMS firing. Using the above maneuvering velocity allocations, total impulse requirements were determined for each maneuvering velocity level (Figure 3-7). As shown, APS requirements varied from 1.5M lb-sec to approximately 16M lb-sec, depending on number of APS translation maneuvers to be performed.



NOTE: ALL DIMENSIONS IN INCHES

ORBITER A - LOW CROSS RANGE

FIGURE 3-1



NOTE: ALL DIMENSIONS IN INCHES

BOOSTER A - LOW CROSS RANGE

FIGURE 3-2

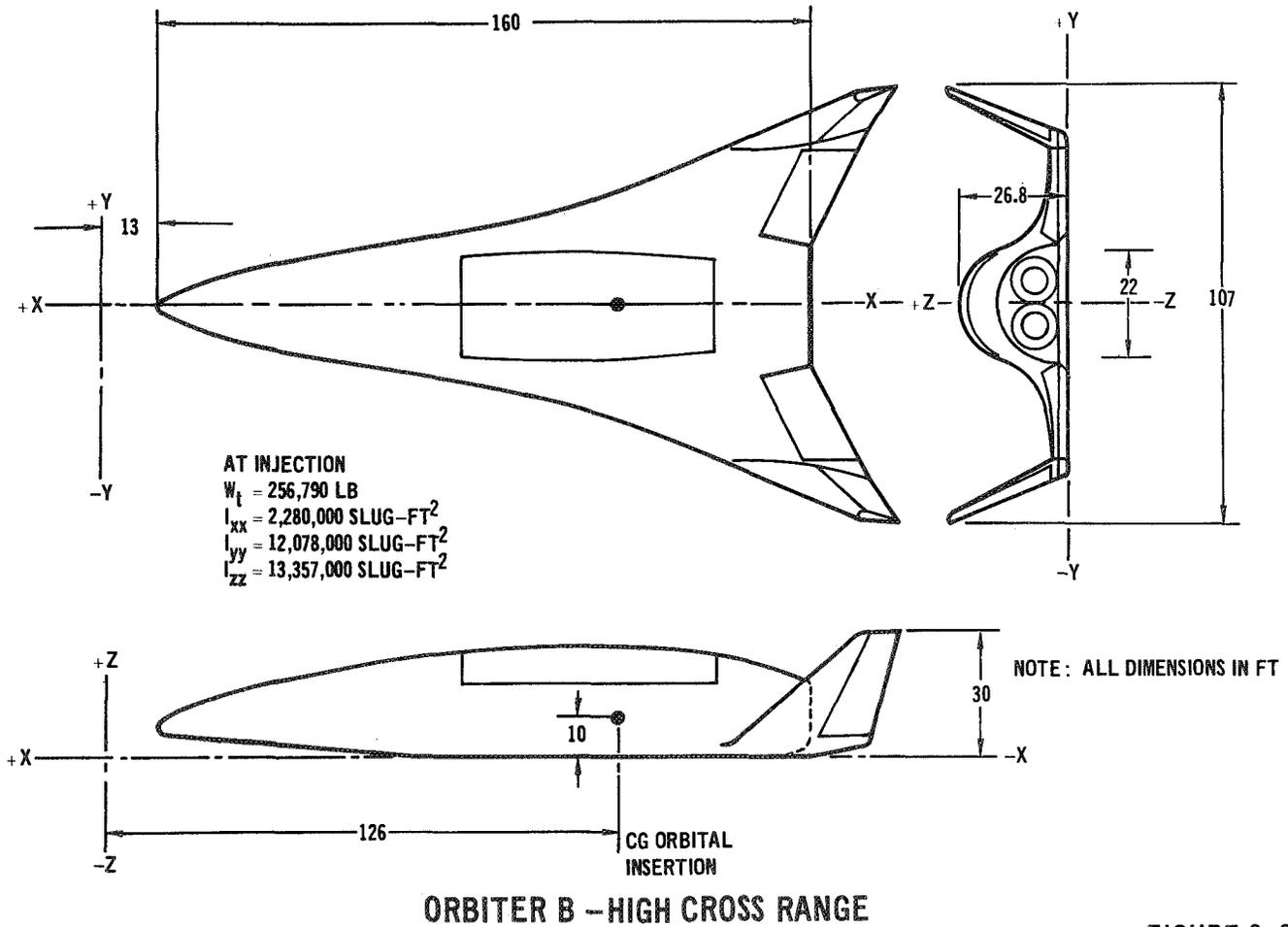


FIGURE 3-3

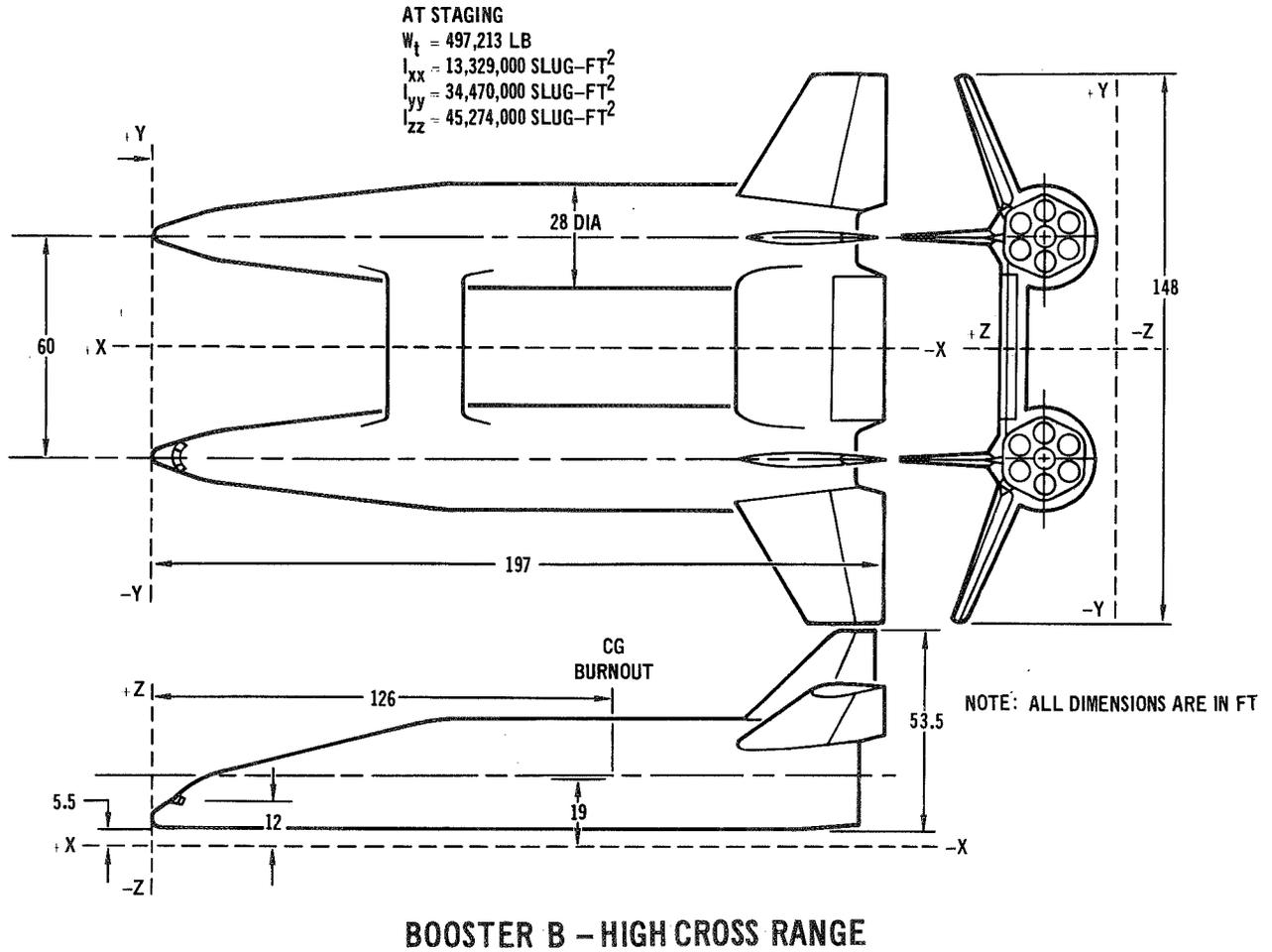


FIGURE 3-4

EVENT		2ND STAGE BOOST ENGINE OUT			1 TO 28 46 TO 53			29 TO 45			54		
		X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
TRANSLATION ACCELERATION FT/SEC ²	MIN	NO			0.07	0.07	0.07	SAME AS			NO		
	NOM MIN	REQUIREMENT			0.1	0.1	0.1	EVENT 1			REQUIREMENT		
	NOM MAX				0.5	0.25	0.25						
	MAX				1.0	1.0	1.0						
ANGULAR ACCELERATION DEG/SEC ²	MIN NOM MIN NOM MAX MAX	R	P	Y	R	P	Y	R	P	Y	R	P	Y
		NO			0.3	0.3	0.3	SAME AS			0.3	0.3	0.3
		REQUIREMENT			0.5	0.5	0.5	EVENT 1			1.0	0.5	1.00
					2.0	2.0	2.0				1.75	1.0	1.75
					4.0	4.0	4.0				4.0	4.0	4.0
FINE ATTITUDE LIMITS - DEG		NO			0.5	0.5	0.5	0.5	0.5	0.5	2.0	2.0	2.0
COARSE ATTITUDE LIMITS - DEG		NO			45	45	45	5.0	5.0	5.0			
		REQUIREMENT											

SPACE STATION/BASE LOGISTICS MISSION - ORBITER
MANEUVERING CAPABILITY REQUIREMENTS

FIGURE 3-5

EVENT		2			3			4			5		
		X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
TRANSLATION ACCELERATION FT/SEC ²	MIN	NO						NO					
	NOM MIN	REQUIREMENT						REQUIREMENT					
	NOM MAX												
	MAX												
ANGULAR ACCELERATION DEG/SEC ²	MIN NOM MIN NOM MAX MAX	R	P	Y	R	P	Y	R	P	Y	R	P	Y
		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
		1.0	0.5	1.0	0.5	0.5	0.5	0.5	0.5	0.5	1.0	0.5	1.0
		1.75	1.0	1.75	1.0	1.0	1.0	1.0	1.0	1.0	1.75	1.0	1.75
		2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
ANGULAR RATE DEG/SEC	MIN NOM MIN NOM MAX MAX				2.0	2.0							
ATTITUDE LIMITS - DEG		2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

SPACE STATION/BASE LOGISTICS MISSION - BOOSTER
MANEUVERING CAPABILITY REQUIREMENTS

FIGURE 3-6

VEHICLE	THRUST LEVEL (LB)	NUMBER OF THRUSTERS	TOTAL IMPULSE *			
			BOOSTER	ORBITER		
				≤ 10 FPS	≤ 50 FPS	ALL
BOOSTER A	2600	18	0.475	-	-	-
ORBITER A	500	32		1.485	2.968	13.912
BOOSTER B	2000	16	0.475	-	-	-
ORBITER B	1000	28		1.707	3.449	15.989

* USAGE DUE TO ERRORS IN ATTITUDE SENSORS NOT INCLUDED

REQUIREMENTS SUMMARY

Subtask A

FIGURE 3-7

4. TRADE STUDY CONCEPTS

Appendix H of this report describes the rationale and provides preliminary screening data which allowed definition of concepts to be considered. Based on the data provided in Appendix H, orbiter and booster concept matrices of Figures 4-1 and 4-2 were established. A total of 50 possible APS options are identified; however, many of these are associated with vehicle requirements. The principal variations to be observed are in the basic APS concept definition. As shown in Figure 4-1, there are three basic APS concepts to be considered for orbiters. Similarly, Figure 4-2 identifies four basic APS concepts for boosters. For both boosters and orbiters, alternate means of thermal conditioning are identified. For purposes of clarity, thermal conditioning can be separated as an independent trade study because alternate conditioner concepts have similar effects on performance of the different APS concepts.

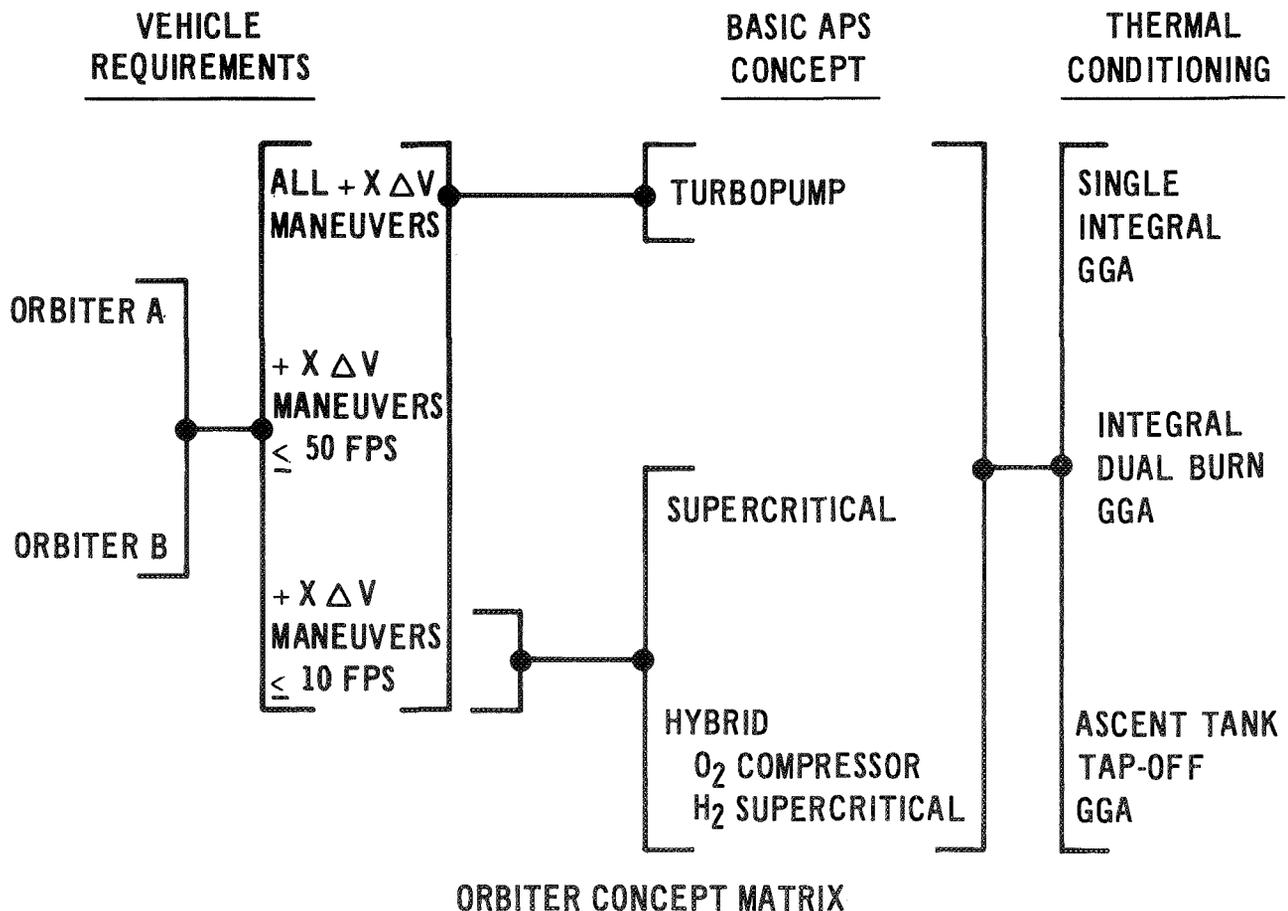
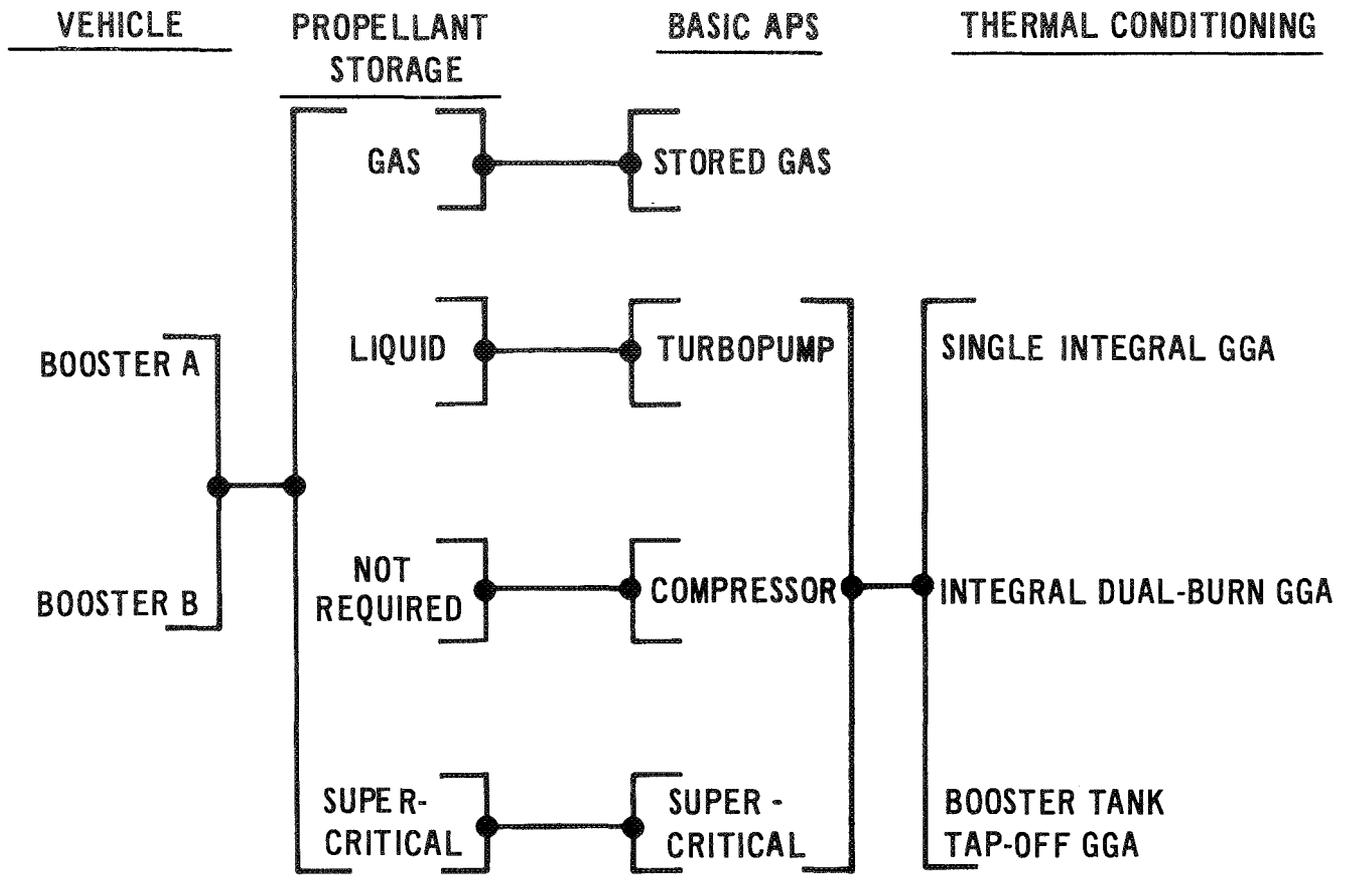


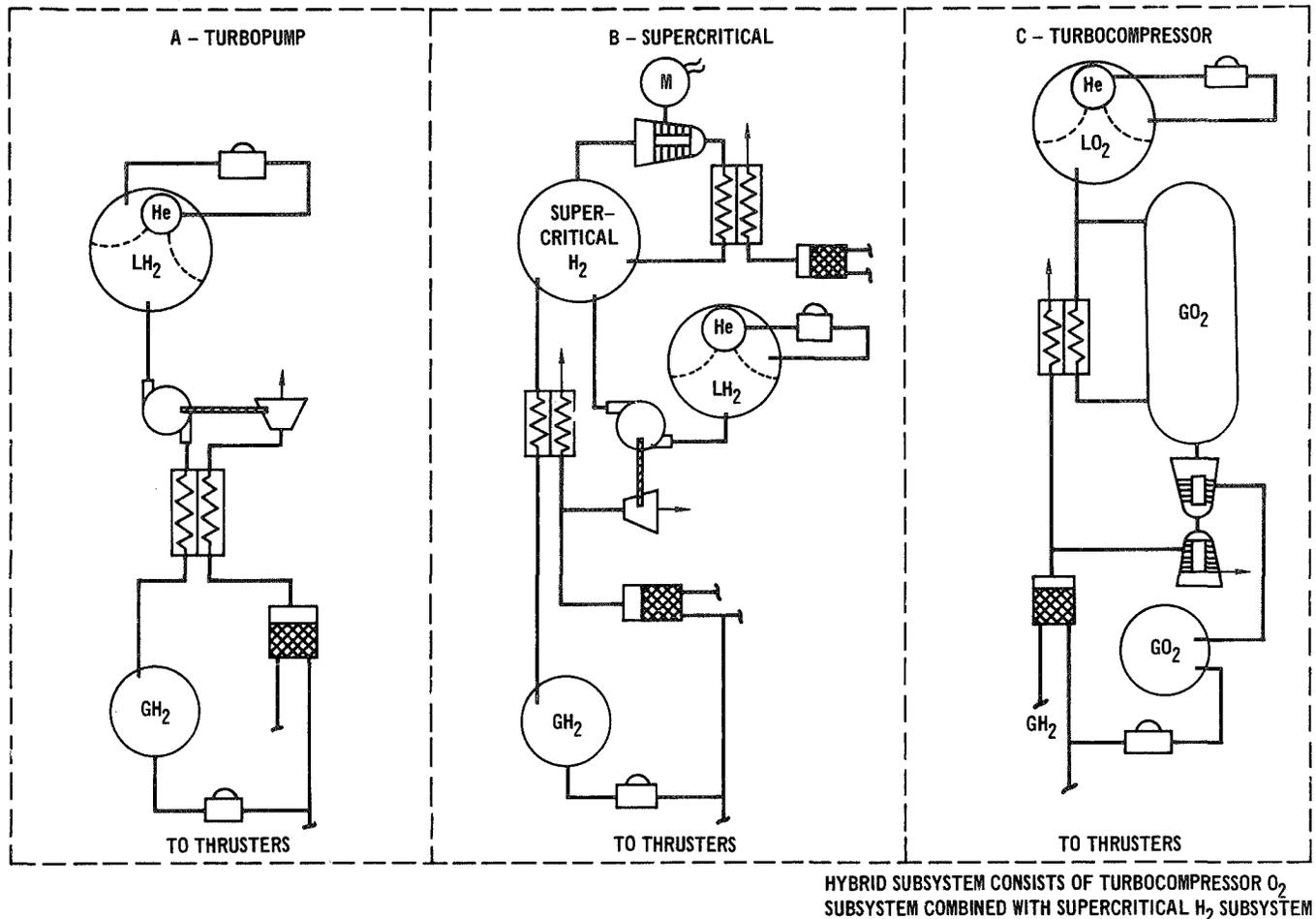
FIGURE 4-1



BOOSTER CONCEPT MATRIX

FIGURE 4-2

Candidate orbiter concepts are illustrated in simplified schematics in Figure 4-3. For clarity, schematics of Figure 4-3 have eliminated propellant control components (such as valves) and redundant components provided to satisfy failure criteria. Only one of two similarly configured propellant sides is shown for clarity. A brief description of candidate orbiter and booster concepts follows. Appendix A provides a more detailed description of their design and operation.



ORBITER APS CANDIDATE CONCEPTS

FIGURE 4-3

4.1 Turbopump APS Concept - The basic turbopump APS concept is illustrated in Figure 4-3A. Propellant is stored as a liquid in a single tank containing both OMS and APS propellant supplies. Turbopump suction head requirements are provided by low pressure cold helium pressurization. The turbopump assembly increases propellant pressures to that required for subsystem operation, while the heat exchanger downstream of the turbopump provides thermal conditioning necessary to raise propellants to their operating temperatures. Conditioned propellant vapor is then stored in an accumulator. A pressure regulator downstream of the accumulator controls pressure for both control thrusters and gas generator assembly. Power for thermal conditioning and turbopump operation are provided by a low mixture ratio, bipropellant gas generator assembly.

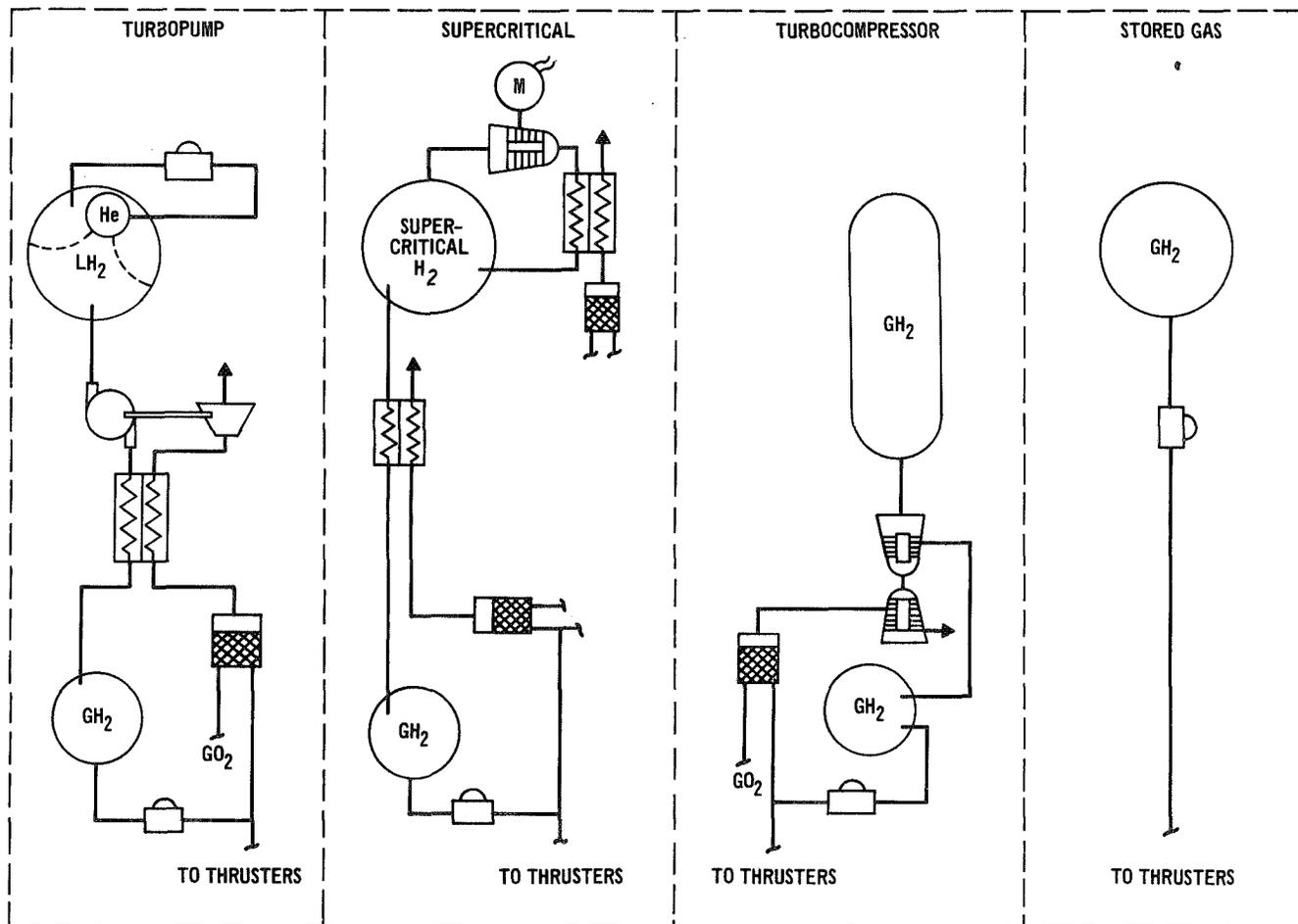
4.2 Supercritical APS Concept - In the supercritical concept, propellant is stored above critical pressures and/or at the pressure required for subsystem

operation. Thus, the propellant storage tank operates at relatively high pressures and constitutes an appreciable portion of subsystem weight. Storage tank pressures in this subsystem concept are maintained by heat addition provided by an external heat exchanger/circulation pump loop as illustrated in Figure 4-3B. To avoid excessive weight penalties associated with large capacity, high pressure tanks, two propellant tanks are provided. The APS propellant supply tank is sized to provide only the total impulse required between major orbit maneuvering subsystem operations. During OMS firings, the supercritical storage tank is refilled by a turbopump assembly from the low pressure liquid propellant storage tank. The subsystem incorporates a downstream heat exchanger to complete thermal conditioning of propellants to the temperatures required for thruster operation.

4.3 Hybrid APS Concept - For the orbiters, a complete turbocompressor concept was not considered because of excessive weight penalties associated with the hydrogen side. However, a concept using a supercritical hydrogen supply (similar to that described above) in conjunction with a compressor oxygen supply was included in the study. The oxygen supply assembly for this concept is illustrated in Figure 4-3C. Low pressure propellant vapor is extracted from main engine tanks and compressed in a turbocompressor assembly to the pressures required for subsystem operation. No thermal conditioning downstream of the compressor is required, since temperature rise due to compression is ample for thruster operation. Oxygen gas temperature for a pressure ratio of 3 is approximately 650°R with an initial gas temperature in the main engine tank of 379°R. The turbocompressor is powered by a gas generator assembly similar to the turbopump concept design. For even the lowest total impulse requirement, the main engine propellant tanks do not contain sufficient propellant vapor for the entire mission; therefore, a separate propellant resupply tank is required to replenish main engine tanks when pressure falls below a prescribed level. A heat exchanger supplied with energy by a gas generator preconditions oxygen to a vapor state prior to main engine tank replenishment.

4.4 Booster APS Concepts - APS concepts considered for the boosters are illustrated in Figure 4-4. These are similar to those described above for the orbiter, with the exception of the stored gas subsystem. Turbopump concepts are identical. The supercritical concept for the booster is similar to that described for the orbiters with one exception. That is, since booster total impulse requirements are relatively low, no resupply to the supercritical storage tank is required. In analyzing booster requirements, compressors were considered for both hydrogen and

turbocompressor concepts is that the booster requires no auxiliary resupply propellant assembly since there are ample residual propellant vapors after main engine cutoff to satisfy mission total impulse requirements. Also considered for the booster was a simple stored gas bipropellant APS concept, whose operation is similar to a conventional cold gas attitude control system, with the exception that hydrogen and oxygen are burned as bipropellants. Gaseous propellant is stored at high pressure and regulated to required thruster operation pressure.



BOOSTER APS CANDIDATE CONCEPTS

FIGURE 4-4

4.5 Conditioning Assembly Selection - As shown in Figures 4-1 and 4-2, there are a number of alternates available for conditioner implementation. Three thermal conditioning concepts are shown:

- (1) a single integral gas generator assembly
- (2) a dual burn or staged combustion gas generator assembly
- (3) a main ascent tank tap-off cycle.

In addition, each of these concepts can be implemented somewhat differently with

oxygen propellant supplies. The single difference between booster and orbiter regard both to their operating temperatures and to usage of vent gas from conditioners for additional useful impulse. Appendix D summarizes analyses conducted to identify the particular approach best suited to various APS concepts. From these, it was determined that total impulse required by the APS was the strongest influence on conditioner approach selection.

For those subsystems used in the all-maneuver case, a conditioning assembly tailored to provide maximum possible performance was desirable, since that approach yielded very significant weight advantages. For this reason, an assembly using a high temperature gas generator in conjunction with propulsive venting was selected for both orbiters in all-maneuver class. At the lower impulse levels, advantages of conditioner assembly high performance were less compelling. Since only a small fraction of the impulse could be provided by propulsive venting, it was not desirable. For the ≤ 50 ft/sec velocity allocation, a high temperature gas generator without propulsive venting was selected. For ≤ 10 ft/sec maneuvers, a single integral gas generator operating at 2000°R without propulsive venting was selected.

With conditioner concepts identified above, the APS concept matrices of Figures 4-1 and 4-2 reduce to a total of 18 alternate concepts. These alternates, together with their associated maneuver levels and vehicle elements, are tabulated in Figure 4-5. Figure 4-5 thus forms the complete list of subsystems compared in Subtask A, after all screening had been accomplished.

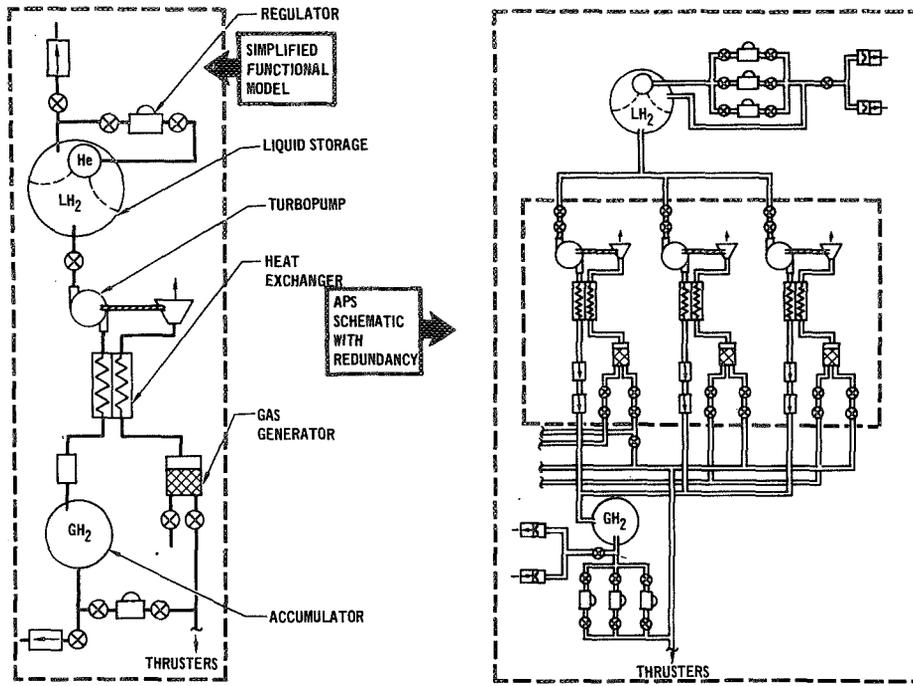
ORBITER	IMPULSE CLASS	SUPER-CRITICAL	TURBOPUMP	HYBRID	STORED GAS	TURBO-COMPRESSOR
A	ALL MANEUVER		✓			
	≤ 50 FPS		✓			
	≤ 10 FPS	✓	✓	✓		
B	ALL MANEUVER		✓			
	≤ 50 FPS		✓			
	≤ 10 FPS	✓	✓	✓		
		2	+	6	+	2 = 10
BOOSTER						
A		✓	✓		✓	✓
B		✓	✓		✓	✓
		2	+	2	+	2 + 2 = 8
<div style="border: 1px solid black; padding: 5px; display: inline-block;"> 10 ORBITER APS CANDIDATES 8 BOOSTER APS CANDIDATES </div>						

APS CONCEPT SUMMARY

FIGURE 4-5

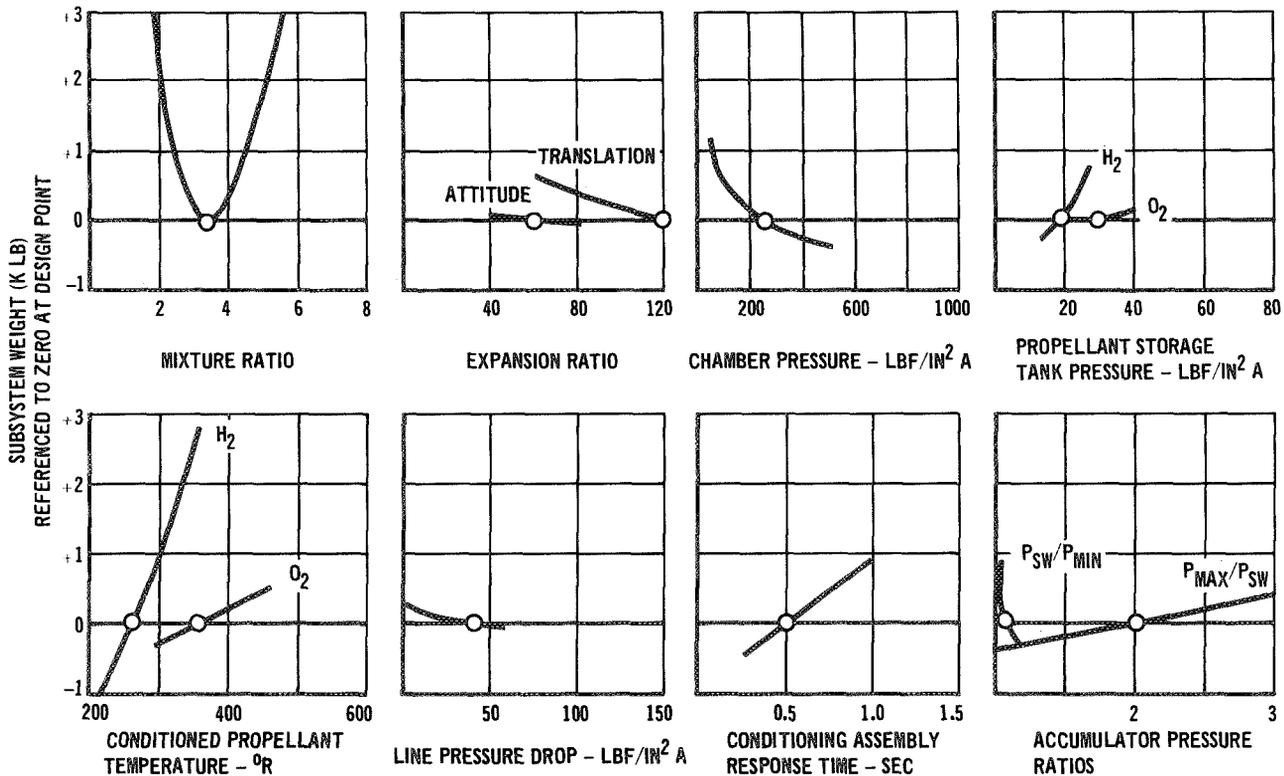
5. TRADE STUDY RESULTS

The 18 concepts identified in Figure 4-5 were compared on the basis of subsystem weight, technology, simplicity, and flexibility to changes in requirements. To do this, detailed subsystem schematics were developed to identify number of components within each subsystem, and to establish overall subsystem weight. The simple line schematics describing the concepts were expanded to incorporate the component redundancy necessary to satisfy space shuttle failure criteria. A typical example of this is shown in Figure 5-1 for a portion of a turbopump subsystem. Weight and performance models were developed over a parametric range for each component and assembly. Appendix E provides a summary description of component and assembly models used for APS synthesis. Using these parametric data, analyses were conducted to define APS weight and the most desirable design operating points. Appendix B provides a complete description of design optimization and sensitivity analysis conducted on each of the 18 candidate subsystems. In addition, Appendix B provides the rationale/data used to establish subsystem design points when it was not valid to design at minimum weight. Figure 5-2 provides an example of weight sensitivity to design variables and Figure 5-3 provides an example of weight sensitivity to APS requirements. Figure 5-4 provides a summary of APS design points and weights as developed by these analyses and Appendix B provides a complete compilation of the optimization of all subsystems. When optimum or desired design points were established, subsystems were judged according to study selection criteria. These criteria are identified in Figure 5-5, together with weighting applied to each criterion and the rationale used for assessment.



TYPICAL TURBOPUMP APS SCHEMATIC
(Hydrogen Side)

FIGURE 5-1



○ DESIGN POINT FOR TRADE STUDIES

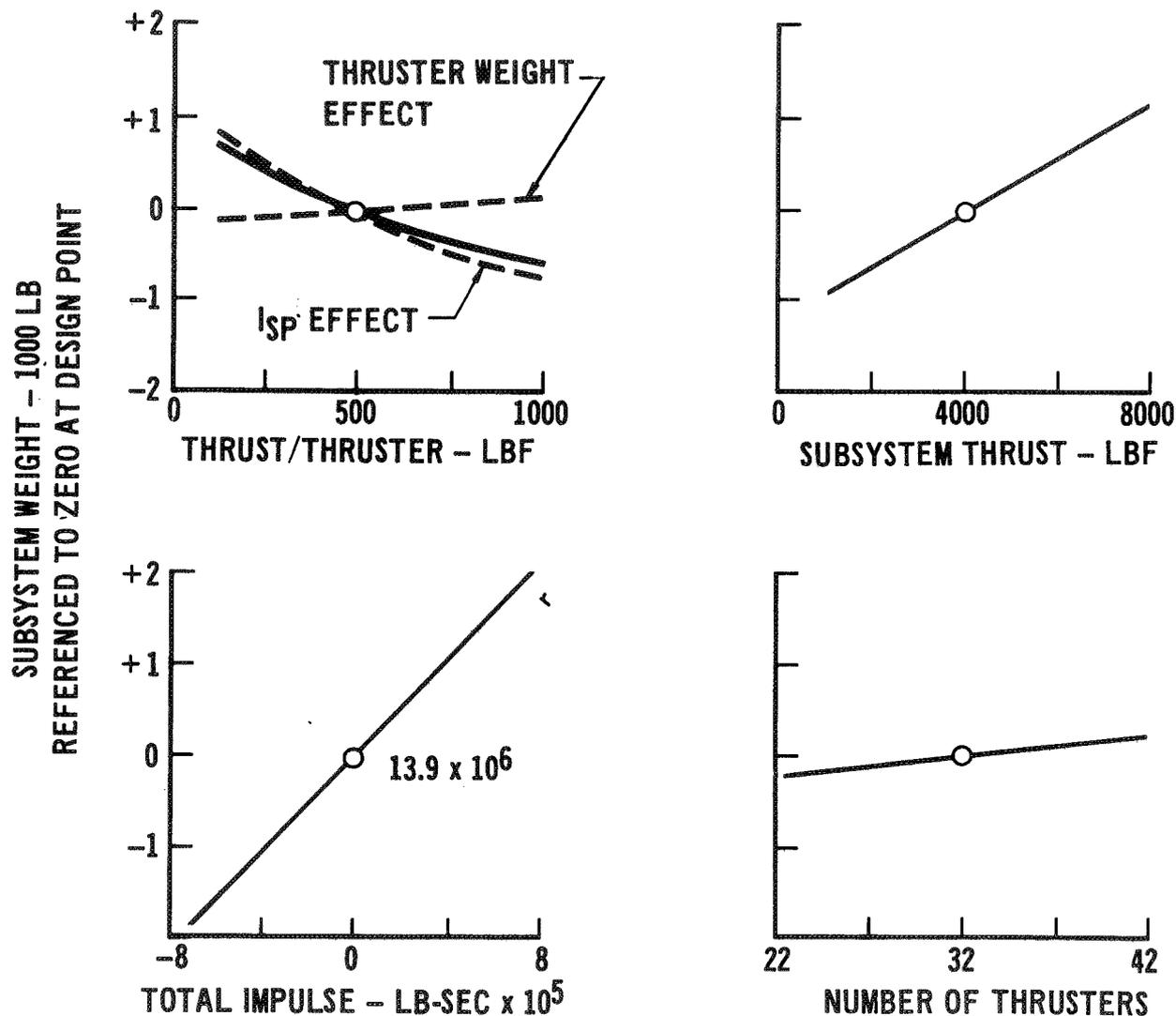
WEIGHT SENSITIVITY TO DESIGN VARIABLES

VEHICLE:
ORBITER A

SUBSYSTEM:
TURBOPUMP

IMPULSE CLASS:
ALL MANEUVER

FIGURE 5-2



VEHICLE: ORBITER A
SUBSYSTEM: TURBOPUMP
IMPULSE CLASS: ALL MANEUVERS

WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

FIGURE 5-3

THRUSTER M _r P _c	ε	FEED ASSEMBLY ΔP _{LINE} P _{T₁} /P _{T₂}	CONDITIONER T _{H₂} /T _{O₂} ΔT	NO. OF CYCLES	ACCUMULATOR P _{MAX} P _S P _{MIN} O ₂ /H ₂	WEIGHT	
ORBITER A: (32 THRUSTERS - 500 LB THRUST) ALL MANEUVERS - TURBOPUMP (13,912,000 LB-SEC) ≤ 50 FPS - TURBOPUMP (2,968,000 LB-SEC) ≤ 10 FPS - TURBOPUMP (1,485,000 LB-SEC) - SUPERCRITICAL - HYBRID	3.5 250	60/120 40	260/360 0.5	35 + 15 = 50	2 1.09/1.11	38,157	
	3.8 250	40	260/360 0.5	50	2 1.09/1.11	10,511	
	4.0 250	40	260/360 0.5	50	2 1.09/1.11	6,915	
	4.0 200	25	260/360 0.5	120 + 15 = 135	1.5/1.4 1.3	8,164	
	4.0 100	35	260/NA H ₂ 0.5 O ₂ 1.5		-/1.4 1.3	8,434	
	ORBITER B: (28 THRUSTERS - 1000 LB THRUST) ALL MANEUVERS - TURBOPUMP (15,989,000 LB-SEC) ≤ 50 FPS - TURBOPUMP (3,449,000 LB-SEC) ≤ 10 FPS - TURBOPUMP (1,707,000 LB-SEC) - SUPERCRITICAL - HYBRID	3.5 500	60/120 50	260/360 0.5	50	2 1.15/1.21	42,782
		3.8 500	50	260/360 0.5	50	2 1.15/1.21	11,771
		4.0 500	50	260/360 0.5	50	2 1.15/1.21	7,670
		4.0 200	25	260/360 0.5	120 + 15 = 135	1.5/1.4 1.3	9,918
		4.0 100	35	260/NA H ₂ 0.5 O ₂ 1.5		1.5/1.4 1.3	10,788
BOOSTER A: (18 THRUSTERS - 2600 LB THRUST 475,000 LB-SEC) - TURBOPUMP - SUPERCRITICAL - TURBO-COMPRESSOR - STORED GAS		5.0 500	40	260/360 0.5	50	2 1.6	3,929
	5.5 200	25	260/360 0.5		1.5/1.4 1.3	6,696	
	6.0 17.5	3	N/A 1.5		1.2 2.2	5,000	
	6.0 100	30	210/350 N/A (FINAL TEMP AFTER BLOWDOWN)	N/A	5 N/A	11,541	
	BOOSTER B: (16 THRUSTERS - 2000 LB THRUST 475,000 LB-SEC) - TURBOPUMP - SUPERCRITICAL - TURBO-COMPRESSOR - STORED GAS	5.0 500	40	260/360 0.5	50	2 1.6	3,316
5.5 200		25	260/360 0.5		1.5/1.4 1.3	5,543	
6.0 13.5		3	N/A 1.5		1.2 2.2	6,100	
6.0 125		30	210/350 N/A	N/A	6 N/A	10,248	

HIGH PRESSURE APS SUMMARY

FIGURE 5-4

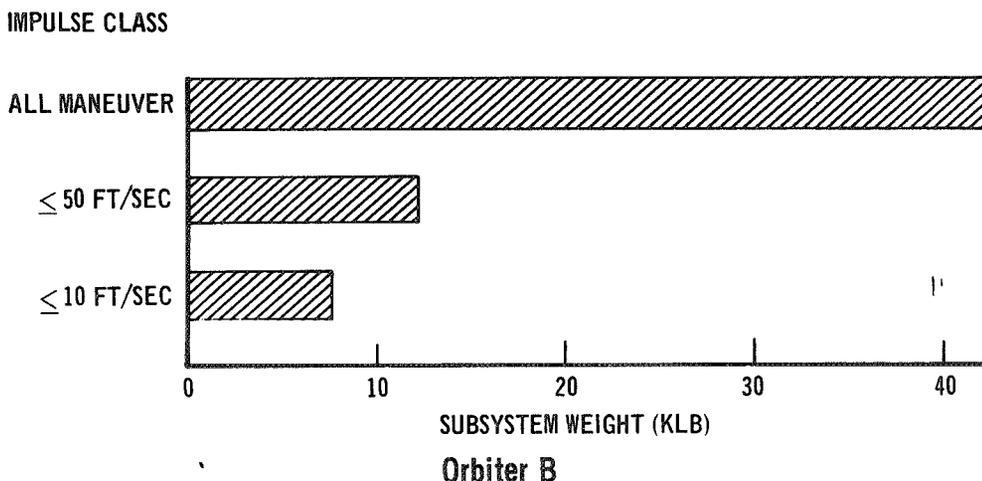
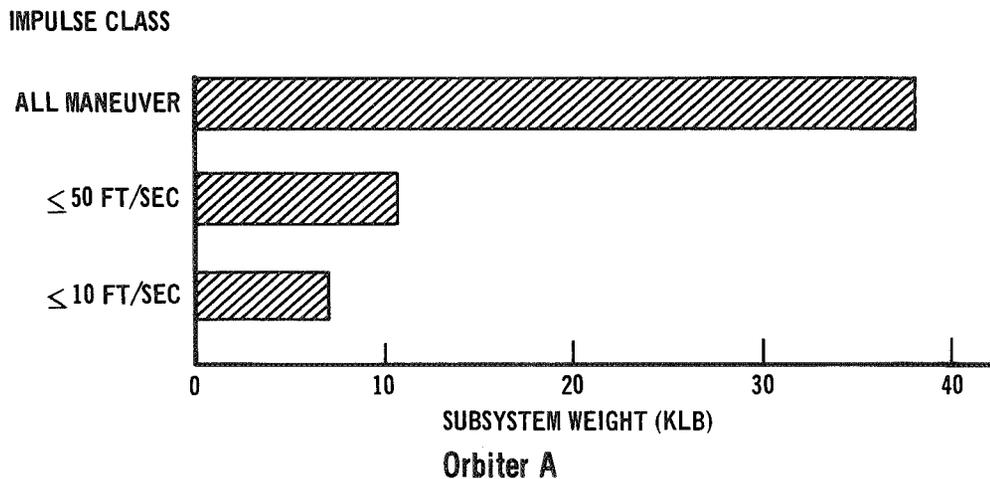
SELECTION CRITERIA	WEIGHTING (% OF TOTAL)	RATIONALE TO BE USED FOR WEIGHTING
TECHNOLOGY REQUIRED	0 - 25	WEIGHTING BASED ON ENGINEERING JUDGMENT OF DEVELOPMENT RISK, SCALING FROM STATE-OF-THE-ART THROUGH EXTENSION OF AN EXISTING TECHNOLOGY BASE TO COMPLETELY NEW CONCEPTS OR APPROACHES, AND ON DEVELOPMENT TEST REQUIREMENTS, CONSIDERING FACTORS SUCH AS NEED FOR ENVIRONMENT SIMULATION (ZERO g, VACUUM, ETC.) AND FACILITY AVAILABILITY FOR TEST.
SUBSYSTEM SIMPLICITY	0 - 20	WEIGHTING BASED ON CONSIDERATION OF: 1) THE NUMBER OF COMPONENTS AND INTEGRATION COMPLEXITY, 2) ASSEMBLY AND SUBSYSTEM CONTROL REQUIREMENTS, 3) COMPLEXITY OF SUBSYSTEM INTERFACES AND OPERATION, AND 4) DEVELOPMENT COMPLEXITY IN TERMS OF MANAGEMENT OF DEVELOPMENT.
SUBSYSTEM WEIGHT AND VOLUME	0 - 25	WEIGHTING BASED ON ABSOLUTE WEIGHT AND VOLUME CONSIDERING LOWEST WEIGHT SYSTEM AS REFERENCE AND A 10% ORBITER PAYLOAD LOSS (APPROXIMATELY 2500 LB) AS UNACCEPTABLE.
FLEXIBILITY TO MISSION CHANGES	0 - 30	WEIGHTING BASED ON SENSITIVITY OF SUBSYSTEM TO CHANGES IN: 1) MISSION IMPULSE USAGE RATES AND TOTAL IMPULSE, 2) TEMPERATURE ENVIRONMENT, 3) CONTROL ACCELERATION REQUIREMENTS AND, 4) COMPONENT LOCATION CHANGES.

APS STUDY CONCEPT SELECTION
Selection Criteria and Weighting Factors

FIGURE 5-5

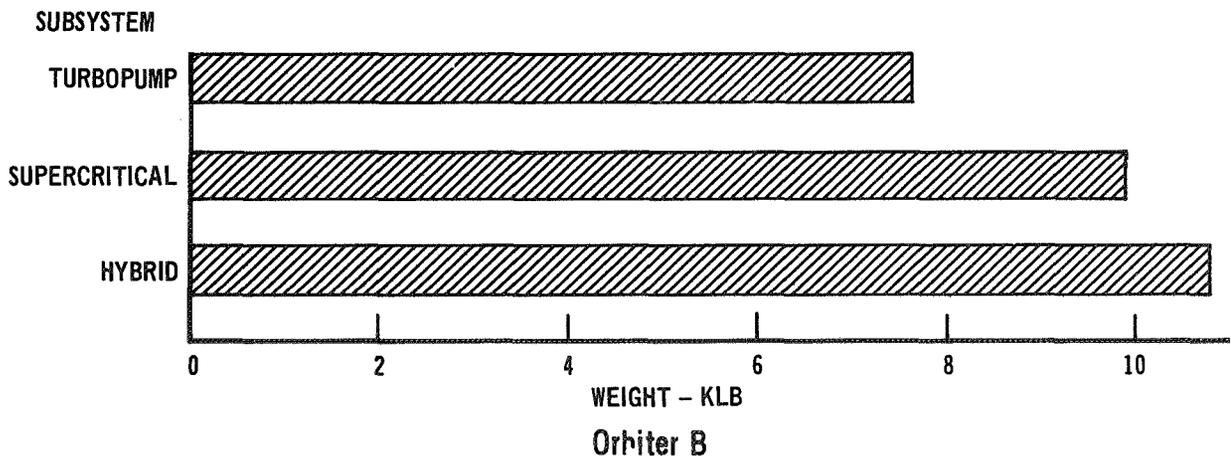
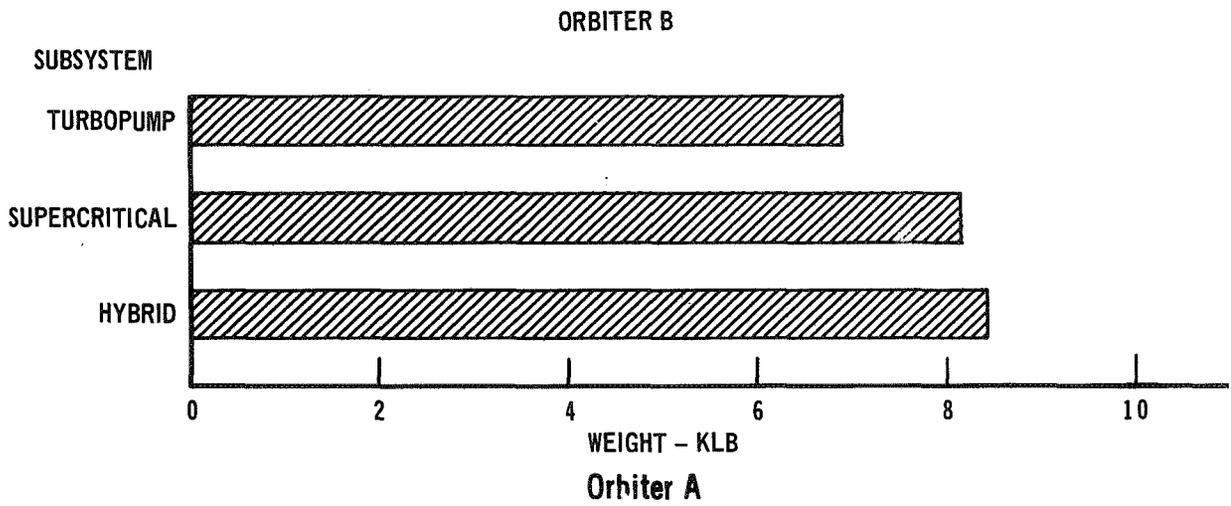
5.1 APS Weight Comparison - Figures 5-6, 5-7 and 5-8 summarize weights developed for each APS concept at design points listed in Figure 5-4. Figure 5-6 compares turbopump subsystems at various maneuver levels for both orbiters. Obviously, additional weight (to account for an OMS subsystem) must be included before a rational decision based on weight could be made regarding best maneuver velocity allocation for the APS. Evaluation of OMS weight was not a part of this contract effort; comparison of APS for different velocity levels is made exclusive of weight, with only technology, simplicity, and flexibility under comparison. Figure 5-7 provides a comparison of the three alternate orbiter concepts at a common maneuver level. Thus, data of Figure 5-7 form a valid weight comparison for alternate APS concepts. As shown, the turbopump subsystem is the lightest weight for both orbiters. Figure 5-8 compares four alternate APS concepts for both boosters. Again, as with the orbiters, the turbopump subsystem weighs

the least. Figure 5-9 summarizes the absolute weights for each of the concepts and shows a point rating on the basis of weight for each vehicle and each APS concept. As noted previously, no valid point rating can be made between impulse levels as no OMS weight is included.



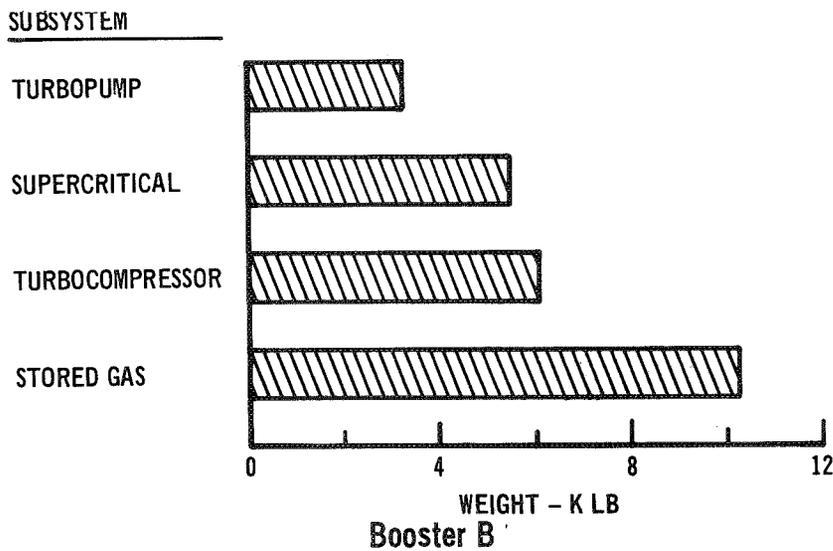
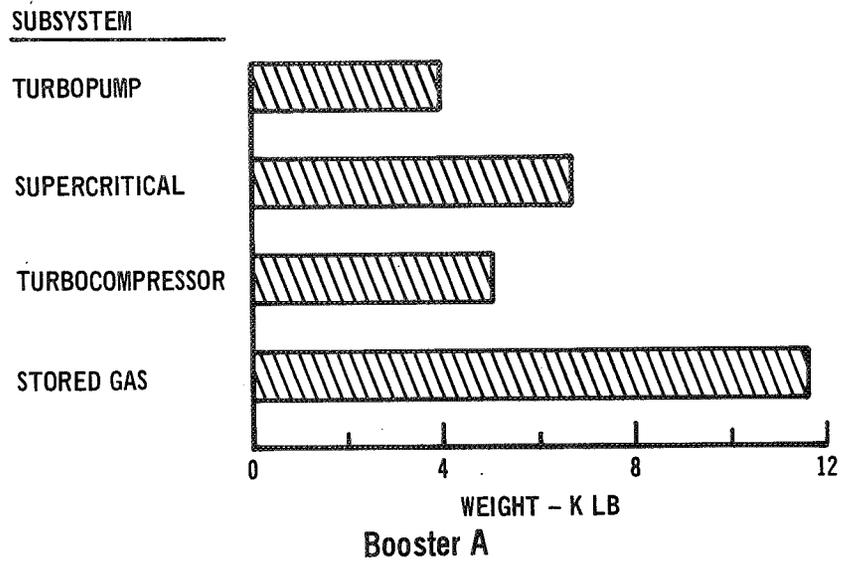
TURBOPUMP APS WEIGHT COMPARISON

FIGURE 5-6



APS WEIGHT COMPARISON (≤ 10 FT/SEC)

FIGURE 5-7



APS WEIGHT COMPARISON

FIGURE 5-8

SUBSYSTEM	ORBITER A		ORBITER B	
	WEIGHT-LB	POINTS	WEIGHT-LB	POINTS
TURBOPUMP				
ALL MANEUVER	38,157	*	42,782	*
≤ 50 FT/SEC	10,511	*	11,771	*
≤ 10 FT/SEC	6,935	25	7,670	25
SUPERCRITICAL (≤ 10 FT/SEC)	8,164	13	9,918	9
HYBRID (≤ 10 FT/SEC)	8,434	10	10,788	X

SUBSYSTEM	BOOSTER A		BOOSTER B	
	WEIGHT-LB	POINTS	WEIGHT-LB	POINTS
TURBOPUMP	3,929	25	3,316	25
SUPERCRITICAL	6,696	18	5,543	20
TURBOCOMPRESSOR	5,000	23	6,100	18
STORED GAS	11,541	6	10,248	8

*WEIGHT/POINT COMPARISON APPLICABLE ONLY TO SUBSYSTEMS AT THE ≤ 10 FT/SEC IMPULSE CLASS
X UNACCEPTABLE (ΔW > 2500 LB)

APS WEIGHT SUMMARY

FIGURE 5-9

5.2 APS Technology Critique - Each candidate APS concept was evaluated to provide an assessment of the technology considerations which would influence concept selection. Unlike weight, a valid assessment of technology requirements could be made between maneuver velocity allocations. This comparison is shown in Figure 5-10, which identifies the common technology considerations, applicable to all maneuver levels, associated with a turbopump subsystem, and those factors which impact concept selection at various maneuver levels. The principal difference between turbopump subsystem designs at different maneuver levels resides in conditioner assembly design. At high maneuver velocity levels, performance advantages are quite pronounced, and certain technology extensions or risks are warranted.

ALL MANEUVERS	≤ 50 FPS	≤ 10 FPS
<u>FACTORS WHICH IMPACT CONCEPT SELECTION</u>		
<ul style="list-style-type: none"> • HIGH TEMPERATURE - COOLED GAS GENERATOR DESIGN • HEAT EXCHANGER SHELL AND TUBE SUPPORT COOLING DESIGN • GG PROPELLANT SEQUENCING AND CONTROL DURING CONDITIONER TRANSIENTS • WARM GAS VENT VALVE DESIGN • THRUSTER DESIGN FOR LONG STEADY STATE DURABILITY 	<ul style="list-style-type: none"> • HIGH TEMPERATURE - COOLED GAS GENERATOR DESIGN • HEAT EXCHANGER SHELL AND TUBE SUPPORT COOLING DESIGN • GG PROPELLANT SEQUENCING AND CONTROL DURING CONDITIONER TRANSIENTS 	
<u>COMMON TECHNOLOGY CONSIDERATIONS</u>		
<ul style="list-style-type: none"> • RAPID SPIN-UP, CRYOGENIC COOLED/LUBED BEARING LIFE FOR TURBOPUMP • TURBOPUMP DYNAMIC SEAL LIFE • TURBINE PUMP THERMAL ISOLATION • DESIGN AND TEST OF LARGE, LOW G POSITIVE PROPELLANT POSITIONING DEVICE • ACCURATE-HIGH FLOW-LOW PRESSURE DROP PRESSURE REGULATORS • ACCUMULATOR MATERIALS FOR HIGH CYCLE LIFE • REUSABLE-HIGH PERFORMANCE TANK INSULATION ASSEMBLY DESIGN • THRUSTER DESIGN FOR OPERATION WITH MINIMUM PROPELLANT INLET TEMPERATURES • TUBE WALL HOT-SIDE ICING IN HEAT EXCHANGER • PERFORMANCE AND LIFE CAPABILITY OF THRUSTERS (COOLING AND VALVES) 		

TECHNOLOGY CRITIQUE
Orbiters/Turbopump

FIGURE 5-10

Figure 5-11 compares different APS concepts at a fixed maneuver velocity level. Again, technology is separated into common technology considerations and factors which impact APS concept selections. For the turbopump, primary technology differences are associated with design of a rapid spin-up, multicycle turbopump, and of the liquid positive propellant positioning device. For the supercritical subsystem, no propellant positioning is required, but this subsystem requires a more complex conditioner assembly design. Conditioner inlet temperatures vary markedly and the conditioner must be highly throttleable to accommodate varying conditioning requirements. The hybrid concept has a number of disadvantages in the realm of technology. All considerations applicable to the supercritical concept apply to the hybrid. In addition, it requires marked technology improvements in turbocompressor design and performance, plus additional technology associated with the propellant resupply assembly.

TURBOPUMP	SUPERCRITICAL	HYBRID
<ul style="list-style-type: none"> • RAPID SPIN-UP, CRYOGENIC COOLED/LUBED BEARING LIFE FOR TURBOPUMP • TURBOPUMP DYNAMIC SEAL LIFE • TURBINE-PUMP THERMAL ISOLATION • DESIGN AND TEST OF LARGE-LOW G POSITIVE PROPELLANT POSITIONING DEVICE 	<p>FACTORS WHICH IMPACT CONCEPT SELECTION</p> <ul style="list-style-type: none"> • CONDITIONER CONTROL AND SENSORS TO MAINTAIN ACCUMULATOR INLET TEMPERATURE • HIGHLY THROTTABLE GG • HOT GAS VALVE DESIGN FOR MULTI-CYCLE OPERATION 	
<p>COMMON TECHNOLOGY CONSIDERATIONS</p> <ul style="list-style-type: none"> • ACCURATE, HIGH FLOW, LOW PRESSURE DROP PRESSURE REGULATORS • ACCUMULATOR MATERIALS FOR HIGH CYCLE LIFE • REUSABLE , HIGH PERFORMANCE TANK INSULATION ASSEMBLY DESIGN • THRUSTER DESIGN FOR OPERATION WITH MINIMUM PROPELLANT INLET TEMPERATURE • TUBE WALL HOT-SIDE ICING IN HEAT EXCHANGER • PERFORMANCE AND LIFE CAPABILITY OF THRUSTERS (COOLING AND VALVES) 		

**TECHNOLOGY CRITIQUE
Orbiter < 10 FPS**

FIGURE 5-11

Figure 5-12 provides a comparison of the various booster APS concepts. In all instances, technology requirements are relaxed for the boosters. Turbopump cycle life is significantly reduced, as is the size of the propellant tank (hence the size of the propellant positioning device). With the supercritical concept, no resupply is required; therefore, technology requirements are relaxed. In the case of the turbocompressor, the compressors for the boosters are much larger and inlet design is more critical because of higher power requirements. The stored gas subsystem is ideal from a technology standpoint, since all components are basically state-of-the-art.

TURBOPUMP	SUPERCRITICAL	TURBOCOMPRESSOR	STORED GAS
<u>FACTORS WHICH IMPACT CONCEPT SELECTION</u>			
<ul style="list-style-type: none"> • RAPID SPIN-UP CRYOGENIC COOLED/LUBED BEARING LIFE • TURBOPUMP DYNAMIC SEAL LIFE • DESIGN AND TEST OF MODERATE SIZE, LOW G POSITIVE PROPELLANT POSITIONING DEVICE 	<ul style="list-style-type: none"> • CONDITIONER CONTROLS AND SENSORS TO MAINTAIN ACCUMULATOR INLET TEMPERATURE • HIGHLY THROTTABLE GAS GENERATOR 	<ul style="list-style-type: none"> • LARGE TURBOCOMPRESSOR DESIGN FOR FAST RESPONSE • TURBOCOMPRESSOR INLET DESIGN 	
<u>COMMON TECHNOLOGY CONSIDERATIONS</u> • ACCURATE, HIGH FLOW, LOW PRESSURE DROP PRESSURE REGULATORS			

BOOSTER TECHNOLOGY CRITIQUE

FIGURE 5-12

Figure 5-13 reviews point ratings assigned to each subsystem on the basis of the technology considerations just given. It should be noted that the point ratings identified in Figure 5-13 apply only to a specific vehicle. That is, point ratings between boosters and orbiters cannot be compared.

Orbiters

SUBSYSTEM	POINTS
TURBOPUMP (ALL)	18
TURBOPUMP (≤ 50 FPS)	19
TURBOPUMP (≤ 10 FPS)	20
SUPERCritical (≤ 10 FPS)	20
HYBRID (≤ 10 FPS)	14

Boosters

SUBSYSTEM	POINTS
TURBOPUMP	17
SUPERCritical	17
TURBOCOMPRESSOR	13
STORED GAS	25

TECHNOLOGY SUMMARY

FIGURE 5-13

5.3 APS Simplicity Critique - Figures 5-14 and 5-15 summarize unique advantages and disadvantages of various APS concepts, with regard to inherent subsystem simplicity and management of subsystem development. Comparing turbopump subsystem simplicity (Figure 5-14) across maneuver levels shows that there are only minimal differences. Figure 5-14 also compares three orbiter concepts at a fixed maneuver velocity level. Relative to other APS concepts, the turbopump concept is appreciably simpler, and offers greatest potential in terms of development management. The supercritical subsystem is complex, both from an operational and a design standpoint, and, since tankage development is totally constrained by development of other subsystem components, is by far the most complex in terms of subsystem management during development. The supercritical subsystem does offer, however, significant advantages in its lack of rotating machinery and propellant positioning requirement. Figure 5-15 provides a critique of simplicity considerations for the boosters. The stored gas subsystem is clearly simplest, and has an appreciable number of advantages relative to other subsystems. Figure 5-16 summarizes point ratings for simplicity criteria and (as is true also for technology) cannot be compared across vehicle element lines.

SUBSYSTEM	UNIQUE DISADVANTAGES	UNIQUE ADVANTAGES
TURBOPUMP ALL MANEUVER	<ul style="list-style-type: none"> • CONTROL AND SEQUENCING OF GG DURING CONDITIONER TRANSIENTS • CONTROL OF PROPULSIVE VENT FOR +X MANEUVERS 	<ul style="list-style-type: none"> • -
≤ 50 FPS	<ul style="list-style-type: none"> • CONTROL AND SEQUENCING OF GG DURING CONDITIONER TRANSIENTS 	<ul style="list-style-type: none"> • -
≤ 10 FPS	<ul style="list-style-type: none"> • - 	<ul style="list-style-type: none"> • -
≤ 10 FPS TURBOPUMP	<ul style="list-style-type: none"> • CONTROL AND SEQUENCING DURING PUMP STARTUP • COMPLEXITY ASSOCIATED WITH PUMP COOLING DURING SHUTDOWN AND NON-USE PERIODS 	<ul style="list-style-type: none"> • MINIMUM NUMBER OF SUBSYSTEM COMPONENTS • MOST STRAIGHT FORWARD COMPONENT INTEGRATION AND MANAGEMENT OF DEVELOPMENT • SIMPLEST CONTROL REQUIREMENT
SUPERCritical	<ul style="list-style-type: none"> • MAXIMUM NUMBER OF SUBSYSTEM COMPONENTS • MAXIMUM CONDITIONER ASSEMBLY CONTROL COMPLEXITY • MOST COMPLEX COMPONENT INTEGRATION • INCREASED OPERATIONAL AND INTEGRATION COMPLEXITY WITH REFILLS • VERY COMPLEX IN TERMS OF DEVELOPMENT MANAGEMENT 	<ul style="list-style-type: none"> • NO PROPELLANT POSITIONING • SIMPLIFIED DYNAMIC COMPONENT OPERATION
HYBRID SUPERCritical H ₂ TURBOCOMPRESSOR O ₂	<ul style="list-style-type: none"> • SAME AS ABOVE SUPERCritical • PROPELLANT POSITIONING REQUIRED • COMPLEX VEHICLE INTERFACE • PRECONDITIONING OF PROPELLANT RESUPPLY INCREASES CONTROL AND OPERATIONAL COMPLEXITY 	<ul style="list-style-type: none"> • SAME AS ABOVE SUPERCritical

ORBITER SIMPLICITY CRITIQUE

FIGURE 5-14

SUBSYSTEM	DISADVANTAGES	ADVANTAGES
TURBOPUMP	<ul style="list-style-type: none"> • CONTROL AND SEQUENCING DURING PUMP STARTUP 	<ul style="list-style-type: none"> • STRAIGHTFORWARD COMPONENT INTEGRATION AND MANAGEMENT OF DEVELOPMENT
SUPERCritical	<ul style="list-style-type: none"> • MAXIMUM NUMBER OF SUBSYSTEM COMPONENTS • MAXIMUM CONDITIONER ASSEMBLY CONTROL COMPLEXITY • MOST COMPLEX COMPONENT INTEGRATION • VERY COMPLEX IN TERMS OF DEVELOPMENT MANAGEMENT 	<ul style="list-style-type: none"> • NO PROPELLANT POSITIONING • SIMPLIFIED DYNAMIC COMPONENT OPERATION
TURBOCOMPRESSOR	<ul style="list-style-type: none"> • PROPELLANT POSITIONING REQUIRED • COMPLEX VEHICLE INTERFACE 	<ul style="list-style-type: none"> • PROPELLANT STORAGE NOT REQUIRED
STORED GAS		<ul style="list-style-type: none"> • MINIMUM NUMBER OF SUBSYSTEM COMPONENTS • MINIMUM OF COMPONENT INTEGRATION • SIMPLEST CONTROL REQUIREMENT

BOOSTER SIMPLICITY CRITIQUE

FIGURE 5-15

Orbiters

SUBSYSTEM	POINTS
TURBOPUMP (ALL)	20
TURBOPUMP (≤ 50 FT/SEC)	20
TURBOPUMP (≤ 10 FT/SEC)	20
SUPERCRITICAL (≤ 10 FT/SEC)	12
HYBRID (≤ 10 FT/SEC)	11

Boosters

SUBSYSTEM	POINTS
TURBOPUMP	14
SUPERCRITICAL	11
TURBOCOMPRESSOR	15
STORED GAS	20

SIMPLICITY SUMMARY

FIGURE 5-16

5.4 APS Flexibility Critique - APS flexibility to requirements changes was judged on the basis of data similar to those shown in Figure 5-3. Point weighting for flexibility was further subdivided for each requirement of interest. Considered were changes in subsystem weight associated with changes in thruster thrust, total subsystem thrust, total impulse, and number of APS thrusters. Ratings were based on quantitative sensitivities for each APS concept. Results are summarized in Figures 5-17, 5-18 and 5-19, and total point ratings are provided. Inspection of data in these figures shows that turbopump subsystems are the least sensitive to changes in requirements, thus providing the greatest potential from the standpoint of flexibility.

SUBSYSTEM	MISSION USAGE RATES SUBSYSTEM TOTAL THRUST		TOTAL IMPULSE		CONTROL ACCEL REQMT-THRUST PER ENGINE		COMPONENT LOCATION CHARGE NO. OF ENGINES		TOTAL POINTS
	$\Delta W/\Delta F_T$	POINTS	$\Delta W/\Delta I_T$	POINTS	$\Delta W/\Delta F$	POINTS	$\Delta W/\Delta N$	POINTS	
ORBITER A TURBOPUMP		(8) MAX		(8) MAX		(7) MAX		(7) MAX	
ALL MANEUVER	0.3	8	0.0026	8	-1.4	7	26.75	7	30
≤ 50 FPS	0.3	8	0.0027	7	-0.1	5	26.75	7	27
≤ 10 FPS	0.3	8	0.0030	5	0	5	26.75	7	25
ORBITER B TURBOPUMP									
ALL MANEUVER	0.2	8	0.0025	8	-1.0	7	24.2	7	30
≤ 50 FPS	0.2	8	0.0026	7	-0.125	5	24.2	7	27
≤ 10 FPS	0.2	8	0.0029	5	0	5	24.2	7	25

FLEXIBILITY CRITIQUE
Orbiter - Turbopump

FIGURE 5-17

SUBSYSTEM	MISSION USAGE RATE SUBSYSTEM TOTAL THRUST		TOTAL IMPULSE		CONTROL ACCEL REQMT-THRUST PER ENGINE		COMPONENT LOCATION CHARGE NO. OF ENGINE		TOTAL POINTS
	$\Delta W/\Delta F_T$	POINTS	$\Delta W/\Delta I_T$	POINTS	$\Delta W/\Delta F$	POINTS	$\Delta W/\Delta N$	POINTS	
ORBITER A TURBOPUMP		(8) MAX		(8) MAX		(7) MAX		(7) MAX	
ALL MANEUVER	0.3	8	0.0026	8	-1.4	7	26.75	7	30
≤ 50 FPS	0.3	8	0.0027	7	-0.1	5	26.75	7	27
≤ 10 FPS	0.3	8	0.0030	5	0	5	26.75	7	25
SUPERCritical, ≤ 10 FPS	0.3	8	0.0029	6	0.25	3	29.0	7	24
HYBRID, ≤ 10 FPS	0.3	8	0.0029	6	0.25	3	37.9	5	22
ORBITER B TURBOPUMP									
ALL MANEUVER	0.2	8	0.0025	8	-1.0	7	24.2	7	30
≤ 50 FPS	0.2	8	0.0026	7	-0.125	5	24.2	7	27
≤ 10 FPS	0.2	8	0.0029	5	0	5	24.2	7	25
SUPERCritical, ≤ 10 FPS	0.2	8	0.0028	6	0.4	3	34.5	6	23
HYBRID, ≤ 10 FPS	0.2	8	0.0028	6	0.4	3	46.5	5	22

FLEXIBILITY CRITIQUE
Orbiters

FIGURE 5-18

SUBSYSTEM	MISSION USAGE RATES SUBSYSTEM TOTAL THRUST		TOTAL IMPULSE		CONTROL ACCEL REQMT-THRUST PER ENGINE		COMPONENT LOCATION CHANGE NO. OF ENGINES		TOTAL POINTS
	$\Delta W/\Delta F_T$	POINTS	$\Delta W/\Delta I_T$	POINTS	$\Delta W/\Delta F$	POINTS	$\Delta W/\Delta N$	POINTS	
BOOSTER A		(8) MAX		(8) MAX		(7) MAX		(7) MAX	30
TURBOPUMP	0.1	5	0.004	7	0.2	7	40	7	26
TURBOCOMPRESSOR	0.1	5	0	8	0.3	6	54	6	25
SUPERCritical	0.2	4	0.004	7	0.6	4	58	58	20
STORED GAS	0.03	8	0.020	4	0.5	5	92	4	21
BOOSTER B									
TURBOPUMP	0.1	5	0.004	7	0.10	7	28	7	26
TURBOCOMPRESSOR	0.2	4	0	8	0.3	4	52	5	21
SUPERCritical	0.2	4	0.004	7	0.3	4	40	6	21
STORED GAS	0.03	8	0.020	4	0.3	4	60	4	20

FLEXIBILITY CRITIQUE
Boosters

FIGURE 5-19

6. CONCEPT COMPARISONS AND SELECTIONS

Using data provided in Section 5, total point ratings were established for each of 18 candidate concepts. Results are summarized in Figures 6-1, 6-2 and 6-3. Figure 6-1 compares turbopump subsystems at three maneuver velocity levels. Weight is not considered for reasons noted in 5.1. As shown, based on the other selection criteria, the all-maneuver class APS provides highest total point rating and (since other criterion would only be degraded by addition of an OMS system) is the best maneuver velocity application from the standpoints of technology, simplicity, and flexibility. Figure 6-2 provides a comparison of turbopump, supercritical, and hybrid subsystems for the two orbiters. As shown, the turbopump is clearly the best overall subsystem selection. Identical results were obtained for boosters (shown in Figure 6-3). Thus, on the basis of all selection criteria, the turbopump subsystem was demonstrably the best candidate for Subtask B preliminary design.

VEHICLE	IMPULSE CLASS	WEIGHT* 0-25%	TECHNOLOGY 0-25%	SIMPLICITY 0-25%	FLEXIBILITY 0-30%	TOTAL
ORBITER A	ALL MANEUVER	N/A	18	20	30	68 ✓
	≤ 50 FPS	N/A	19	20	27	66
	≤ 10 FPS	N/A	20	20	25	65
ORBITER B	ALL MANEUVER	N/A	18	20	30	68 ✓
	≤ 50 FPS	N/A	19	20	27	66
	≤ 10 FPS	N/A	20	20	25	65

✓ HIGHEST RATING

* WEIGHT COMPARISON NOT APPLICABLE DUE TO THE REQUIREMENT OF AN OMS AT ≤ 10 AND ≤ 50 FT/SEC

APS CONCEPT COMPARISON
Orbiter A & B Turbopump Subsystem

FIGURE 6-1

VEHICLE	SUBSYSTEM	WEIGHT 0-25%	TECHNOLOGY 0-25%	SIMPLICITY 0-20%	FLEXIBILITY 0-30%	TOTAL
ORBITER A	TURBOPUMP	25	20	20	25	90 ✓
	SUPERCRITICAL	13	20	12	24	69
	HYBRID	10	14	11	22	57
ORBITER B	TURBOPUMP	25	20	20	25	90 ✓
	SUPERCRITICAL	9	20	12	23	64
	HYBRID	X	14	11	22	X

✓ HIGHEST RATING

X UNACCEPTABLE ($\Delta W > 2500$ LB)

APS CONCEPT COMPARISON
Orbiter - ≤ 10 FPS Impulse Class

FIGURE 6-2

VEHICLE	SUBSYSTEM	WEIGHT 0-25%	TECHNOLOGY 0-25%	SIMPLICITY 0-20%	FLEXIBILITY 0-30%	TOTAL
BOOSTER A	TURBOPUMP	25	17	14	26	82 ✓
	SUPERCRITICAL	18	17	11	20	66
	STORED GAS	6	25	20	21	72
	TURBOCOMPRESSOR	23	13	15	25	76
BOOSTER B	TURBOPUMP	25	17	14	26	82 ✓
	SUPERCRITICAL	20	17	11	21	69
	STORED GAS	8	25	20	20	73
	TURBOCOMPRESSOR	18	13	15	21	67

✓ HIGHEST RATING

APS CONCEPT COMPARISON
Booster

FIGURE 6-3

7. REFERENCES

- (a) Space Shuttle Vehicle Description and Requirement Document: NASA-MSFC, dated 15 July 1970.
- (b) Space Shuttle Vehicle Description and Requirement Document: NASA-MSFC, dated 1 October 1970.
- (c) Gaines, R. D., Goldford, A. I., Kaemming, T. A., High Pressure Auxiliary Propulsion Subsystem Definition Study Subtask B Report: McDonnell Douglas Report MDC E0298, dated 12 February 1971.
- (d) Herm, T. S., Houte, F. W., High Pressure Auxiliary Propulsion Subsystem Definition Study Design Handbook: McDonnell Douglas Report No. MDC E0300, dated 12 February 1971.
- (e) Space Shuttle High Pressure Auxiliary Propulsion Subsystem Definition, Program Plan: MDAC-East Report E0201, dated 15 July 1970.

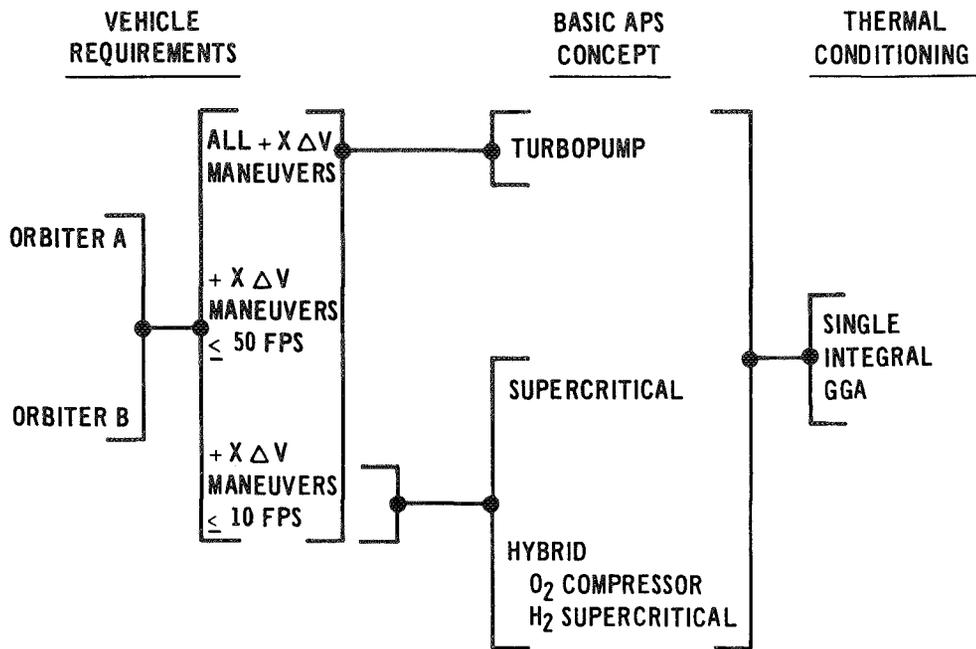
APPENDIX A
TRADE STUDY MODELS

A-1. INTRODUCTION

The trade study objective was to compare basic APS subsystem concepts for each set of APS requirements (i.e., for each booster and each impulse allocation for each orbiter). Subsystem concepts selected for comparison are identified by the booster and orbiter matrices of Figures A-1 and A-2. The trade study models were selected from preliminary screening, and from component and assembly trade studies. They represent the best method of implementing a concept for an APS requirement.

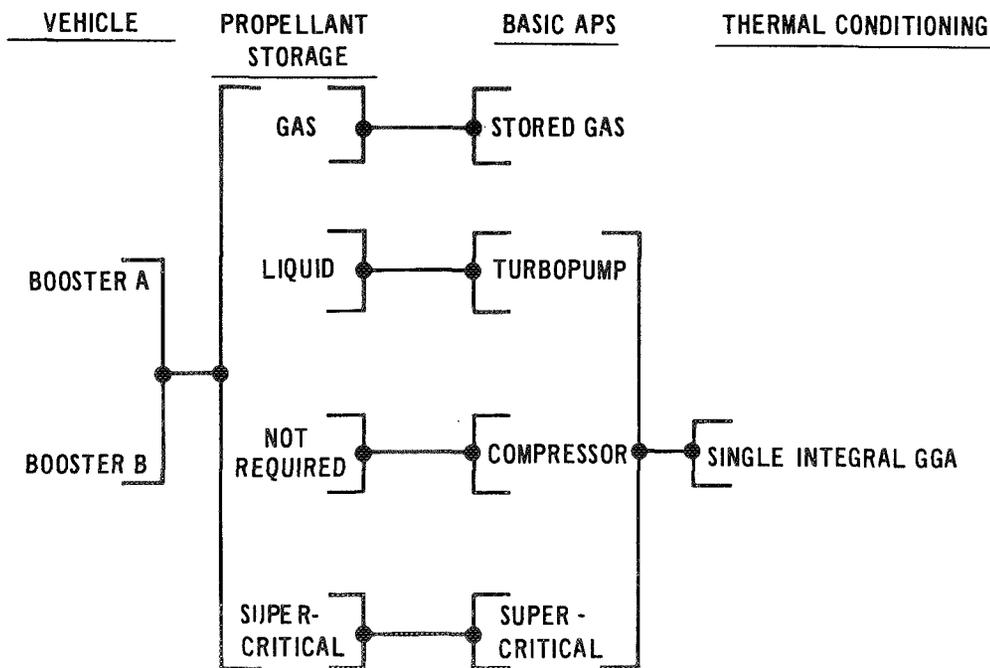
This appendix describes the configuration and operation of the trade study models. The models were evaluated to the extent that they represented workable subsystems, and components were defined in detail sufficient to allow valid concept comparisons. These models allowed a valid assessment of subsystem weight, technology requirements, flexibility, and operational complexity of each concept. Figure A-3 is a summary of the APS design points.

Subsystem concepts differ by their basic approach (i.e., turbopump, supercritical, trubocompressor, hybrid, and stored gas). Except for stored gas,



ORBITER CONCEPT MATRIX

FIGURE A-1



BOOSTER CONCEPT MATRIX

FIGURE A-2

THRUSTER M _r P _c	ε	FEED ASSEMBLY ΔP _{LINE} P _T /P _{H₂} /P _{T_{O₂}}	CONDITIONER T _{H₂} /T _{O₂} ΔT	NO. OF CYCLES	ACCUMULATOR P _{MAX} P _S P _S P _{MIN} O ₂ /H ₂ O ₂ /H ₂	WEIGHT
ORBITER A: (32 THRUSTERS - 500 LB THRUST) ALL MANEUVERS - TURBOPUMP (13,912,000 LB-SEC) ≤ 50 FPS - TURBOPUMP (2,968,000 LB-SEC) ≤ 10 FPS - TURBOPUMP (1,485,000 LB-SEC) - SUPERCRITICAL - HYBRID	60/120 60 60 60 60 60	40 19/30 40 19/30 40 19/30 25 25/30 35 19/45	260/360 0.5 260/360 0.5 260/360 0.5 260/360 0.5 260/NA H ₂ 0.5 O ₂ 1.5	35 + 15 = 50 50 50 120 + 15 = 135	2 1.09/1.11 2 1.09/1.11 2 1.09/1.11 1.5/1.4 1.3 -1.4 1.3	38,157 10,511 6,915 8,164 8,434
ORBITER B: (28 THRUSTERS - 1000 LB THRUST) ALL MANEUVERS - TURBOPUMP (15,989,000 LB-SEC) ≤ 50 FPS - TURBOPUMP (3,449,000 LB-SEC) ≤ 10 FPS - TURBOPUMP (1,707,000 LB-SEC) - SUPERCRITICAL - HYBRID	60/120 60 60 60 60	50 19/35 50 19/35 50 19/35 25 25/30 35 19/40	260/360 0.5 260/360 0.5 260/360 0.5 260/360 0.5 260/NA H ₂ 0.5 O ₂ 1.5	50 50 50 120 + 15 = 135	2 1.15/1.21 2 1.15/1.21 2 1.15/1.21 1.5/1.4 1.3 1.5/1.4 1.3	42,782 11,771 7,670 9,918 10,788
BOOSTER A: (18 THRUSTERS - 2600 LB THRUST 475,000 LB-SEC) - TURBOPUMP - SUPERCRITICAL - TURBO-COMPRESSOR - STORED GAS	40 40 10 60	40 25/35 25 N/A 3 N/A 30 N/A	260/360 0.5 260/360 0.5 N/A 1.5 210/350 N/A (FINAL TEMP AFTER BLOWDOWN)	50 N/A	2 1.6 1.5/1.4 1.3 1.2 2.2 5 N/A	3,929 6,696 5,000 11,541
BOOSTER B: (16 THRUSTERS - 2000 LB THRUST 475,000 LB-SEC) - TURBOPUMP - SUPERCRITICAL - TURBO-COMPRESSOR - STORED GAS	40 40 10 60	40 25/35 25 N/A 3 N/A 30 N/A	260/360 0.5 260/360 0.5 N/A 1.5 210/350 N/A	50 N/A	2 1.6 1.5/1.4 1.3 1.2 2.2 6 N/A	3,316 5,543 6,100 10,248

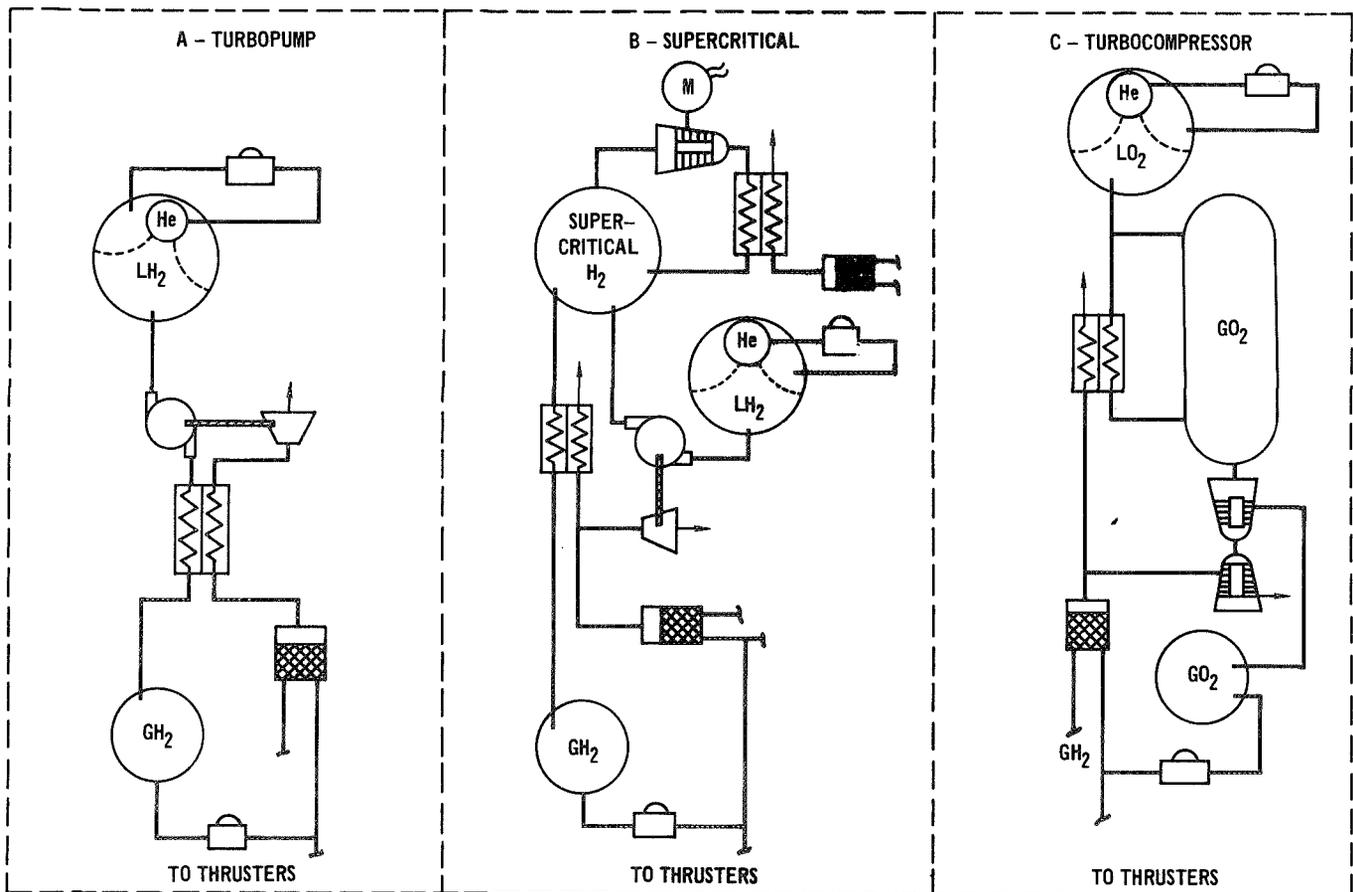
HIGH PRESSURE APS SUMMARY

FIGURE A-3

each concept is made of four primary assemblies. These are:

- (1) propellant storage assembly
- (2) conditioning assembly
- (3) accumulators
- (4) thruster assemblies

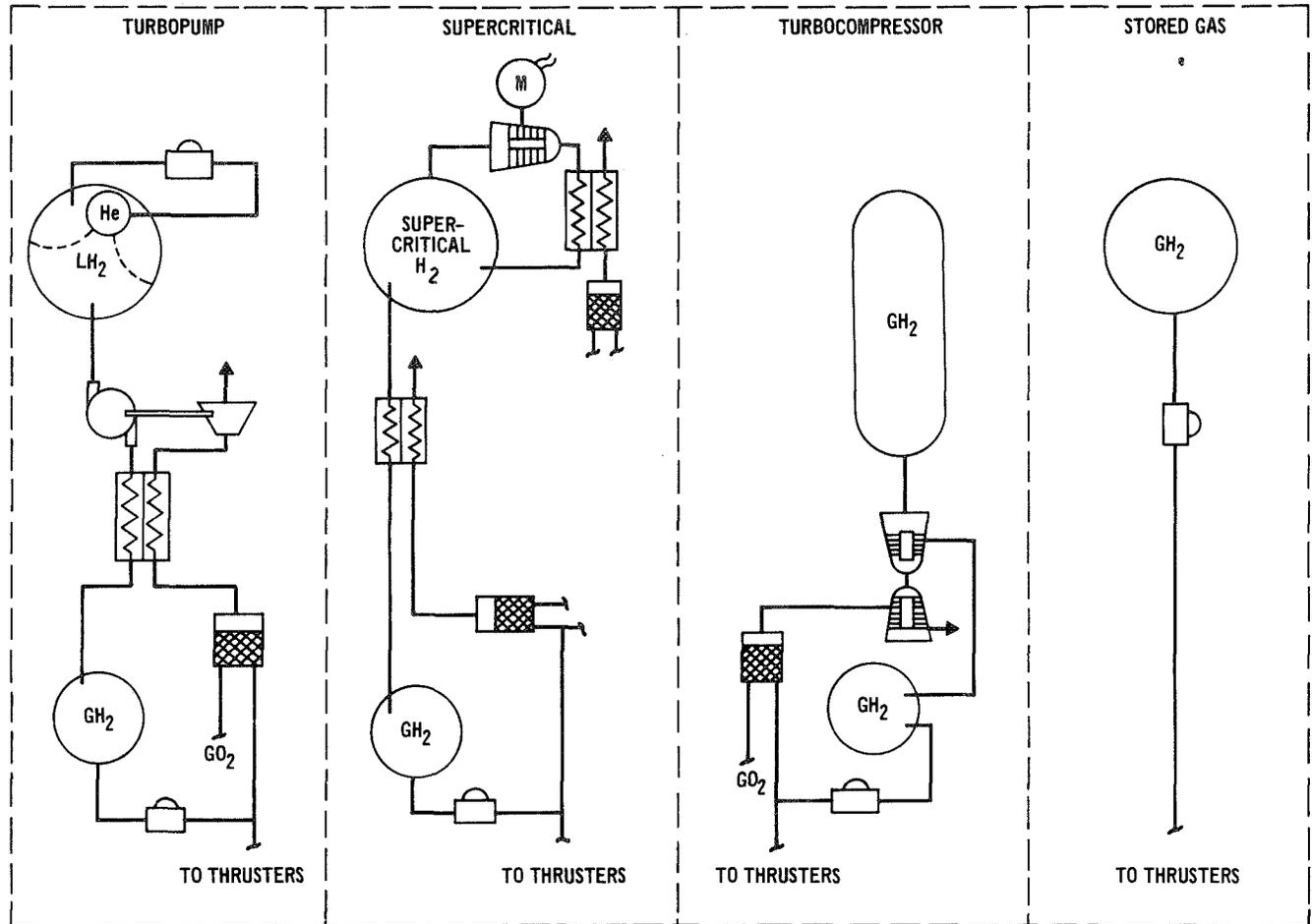
The stored gas concept uses only propellant storage assembly and thruster assemblies. Schematics of the different concepts are shown in Figures A-4 and A-5. A common thruster assembly model and a common accumulator assembly model were used for all trade study models. In every case thruster assemblies use gaseous H_2 and O_2 propellants, supplied at a regulated pressure from the accumulators in all concepts but stored gas, in which gaseous propellant comes directly from propellant storage assemblies. The operating mode of accumulators and thrusters is essentially that of a stored gas bipropellant propulsion subsystem. Models for design and operation of the remainder of assemblies (i.e., storage and conditioner assemblies) are not common. The following paragraphs provide a summary description of the design and operation of the trade study models.



HYBRID SUBSYSTEM CONSISTS OF TURBOCOMPRESSOR O_2 SUBSYSTEM COMBINED WITH SUPERCRITICAL H_2 SUBSYSTEM

ORBITER APS CANDIDATE CONCEPTS

FIGURE A-4



BOOSTER APS CANDIDATE CONCEPTS

FIGURE A-5

A-2 COMPONENTS COMMON TO ALL SUBSYSTEMS

A-2.1 Thruster Assemblies - Thruster assemblies were modeled as film cooled gaseous bipropellant thrusters. Each thruster is equipped with an igniter assembly using small, independent igniter valving and larger, high response valves for primary propellant supply. Thruster supply lines are sized primarily for maintaining constant thruster inlet pressures independent of number of thruster assemblies operating. They are insulated to reduce propellant heating.

A-2.2 Accumulators - Accumulators are modeled as insulated pressure vessels. In all subsystems they are used to decouple thruster assemblies from conditioning assemblies and are sized by conditioning assembly considerations. Conditioner assemblies operate between accumulator pressure switches, which signal the assembly on or off. At the lower switch level, the conditioner assembly is signalled to initiate operation. The upper switch level signals maximum accumulator pressure and shutdown of conditioner assembly. The accumulator is sized to provide sufficient total impulse to allow the subsystem to deliver maximum thrust over the time interval between the point where the conditioning assembly is switched on and where the conditioner assembly comes "on-line". The maximum operating pressure is a consideration of the desired number of conditioner cycles. The accumulators are equipped with relief valves to protect against overpressure.

A-3. SUBSYSTEM DESIGN DESCRIPTION

A-3.1 Turbopump APS - Four turbopump subsystem trade study models were defined, one for boosters and one for each of three APS +X maneuver levels for orbiters. The propellant storage assembly model for each of these is the same. For the combined APS/OMS subsystems, propellants are stored in common tanks.

The propellant storage assembly is composed of a primary structural shell (or pressure vessel), insulation, active cooling device, outer protective jacket, propellant pressurization subassembly, and propellant positioning screen. The primary structural shell is fabricated of aluminum. A tube-type heat exchanger is brazed to a thin metal foil surrounding the tank and propellant is allowed to vaporize in the tubing to absorb incoming heat flux. Insulation is the high performance type (HPI) and is modeled as multilayer aluminized mylar. An outer jacket of fiberglass protects the insulation from crushing loads, and is pressurized with an inert gas in the earth's atmosphere to prevent moisture contamination. The propellant positioning device is modeled as a double layer screen. This surface tension device provides propellant at the tank outlet under zero g conditions. Helium stored inside the propellant tank pressurizes propellant to provide the net positive suction pressure required by the pump.

The propellant conditioning assembly provides propellants to accumulators at required temperatures and pressures. This assembly consists of a conventional turbopump, crossflow heat exchanger, and a bipropellant gas generator which is supplied with propellants by the accumulators in the same manner as the thruster assemblies. Gas generator products are first passed through the heat exchanger, then through the turbopump turbine. Liquid propellant is pumped to the desired pressure by the turbopump and passed through the heat exchanger (where it is thermally conditioned) into the accumulator. The difference in the turbopump models is in the temperature at which the gas generators operate and the propulsive or nonpropulsive use of the hot gas exhaust. The trade study conditioner models for the booster and for the orbiter APS allocation of ≤ 10 ft/sec +X maneuvers are the same. The gas generator combustion temperature is 2000°R (considered state-of-the-art) and the conditioning flow is vented from the vehicle nonpropulsively. The orbiter trade study model for the APS allocation of ≤ 50 ft/sec +X maneuvers combusts gas generator propellants at 3500°R , and vents conditioning

flow nonpropulsively. The orbiter trade study model for the all +X maneuvers allocation combusts gas generator propellants at 3500°R, and vents conditioning flow propulsively during +X maneuvers.

A-3.2 Supercritical APS - Two supercritical subsystem trade study models were defined, one applicable to booster APS and one applicable to orbiter APS +X maneuver allocation of ≤ 10 ft/sec. The two models differ only in the propellant storage assembly. The orbiter APS propellant tank is refilled from the OMS propellant tank whereas the booster APS propellant tank contains the total propellant requirement.

The supercritical propellant storage tank is an aluminum pressure vessel covered with high performance insulation. The propellants are stored in a supercritical state at a pressure above the accumulator pressure. The high pressure of the propellant tanks allows for regulated flow to the accumulators. Since tank pressure falls as propellant leaves the tank the propellants must be heated to maintain tank pressure. The heat source is a gas generator which supplies energy to an external, tube-in-shell heat exchanger through which the propellant is circulated. A pump at the outlet of the heat exchanger circulates the propellant from the tank through the heat exchanger and back into the tank.

Due to excessive tank weight (caused by storing all propellant in the high pressure tank), the orbiter tank model is sized to hold only the propellant required between OMS burns, with the supercritical tank being refilled from the OMS tank during OMS burns. A conventional turbopump, powered by a gas generator, is used to transfer propellant. Due to small booster APS propellant requirements, all propellant is initially stored in the booster supercritical tank.

The conditioning assembly for both booster and orbiter models consists of a heat exchanger, heated by a gas generator, which thermally conditions the propellant before it reaches the accumulators. Gas generators in the subsystems use propellants from the accumulators, operate at 2000°R, and are vented non-propulsively from the vehicle.

A-3.3 Turbocompressor APS - Two turbocompressor subsystem trade study models are presented, one booster model and one model for an orbiter APS requirement of

+X maneuver ≤ 10 ft/sec. The booster model is used to provide both O_2 and H_2 propellants. The orbiter model provides only O_2 propellant, and is used in a hybrid subsystem where H_2 propellant is provided by a supercritical subsystem.

In the booster model, a propellant storage tank assembly is not required, as ample pressurized gaseous propellants are available from booster tanks. For the orbiter model, a subcooled liquid O_2 propellant storage tank similar to that for the turbopump concept is used to resupply the orbiter main O_2 tank, as sufficient residuals are not available.

The booster model conditioning assembly consists of a turbocompressor pumping gaseous propellants from boost tanks to accumulators. No thermal conditioning is required, since even at low compressor pressure ratios propellant temperature rise across the compressor is sufficient to satisfy thruster temperature requirements. The orbiter model conditioner assembly uses a heat exchanger between resupply tank and main engine tank. Liquid resupply propellant is heated to ensure a gaseous propellant supply in the main engine tank. The rest of the conditioning assembly is similar to that of the booster model. The gas generator which powers the turbocompressor is also used to heat the resupply heat exchanger. Gas generators in each model are combusted at $2000^\circ R$, and are vented nonpropulsively.

A-3.4 Stored Gas - A stored gas trade study model is presented for the boosters. The H_2 and O_2 propellants are stored in the gaseous state providing regulated flow to the thrusters.

A-4. DESCRIPTION OF OPERATION

A-4.1 Turbopump Subsystem - The propellant tankage assembly operates similarly to conventional storage propellant tankage. Pressure within the tank is maintained by mechanical regulation of a helium pressure supply. Propellants are maintained in a liquid state by a combination of high performance insulation and propellant vaporization. Normal on-orbit heating is absorbed by a coolant loop, in which propellant is extracted from the tank, and passed over the outer shell, where it absorbs heat leak by heat of vaporization. Propellants are maintained at the tank outlet by a surface tension screen device. This device provides positive propellant positioning in zero g or during low-level g operation in any vehicle direction.

Accumulators are precharged before flight. The conditioner assembly operates in the following manner. When accumulator pressure decays because of propellant usage, pressure sensors command the conditioner to initiate operation. Gas generator valves are then opened and the generator ignited. Products are passed through the heat exchanger, initiating tube warm up, and through the turbopump turbine, initiating turbine spinup. When both the turbopump and the heat exchanger have reached desired operating conditions, propellant is admitted to the heat exchanger. Conditioner flow and operation continue until the accumulator has reached its maximum operation pressure; the conditioner is then signaled off and the gas generator valve are closed. Assembly sequencing is dictated by the relative response times of the various components. For trade study purpose typical response times were used for analysis. Overall conditioner assembly response is dictated by the longest event sequence, (i.e., heat exchanger warm up or turbopump response). Propellant boiloff for tank cooling includes sufficient additional boiloff to absorb turbine-to-pump heat leak in order to maintain the pumps in a "chilled" condition.

The preferred starting sequence for conditioner considers pump spinup (without bypass) until sufficient pressure unbalance exists to open downstream check valves, when accumulator recharge commences. An alternate approach is to allow no flow through the heat exchanger cold side during initial start transient. This

enhances heat exchanger response as only dry tubes are being heated. During pump start up, propellant would be bypassed (to prevent pump dead heading) back to the propellant tank or, potentially, to another propellant supply.

In those cases where the APS provides a long steady state burn the conditioner is designed to operate throughout the single burn period (i.e., the conditioner is sized to provide the maximum total subsystem thrust which can occur during a major translation maneuver).

A-4.2 Supercritical Subsystem - The storage assembly operates in the following manner. At lift-off, the propellant storage tank is fully charged to the desired operating pressure with cold propellants. Nominally, these propellants are near normal ambient saturation temperatures; thus, the propellant state within storage tanks is that of a compressed liquid. The storage tank is equipped with an external heat exchanger assembly. On demand, propellants are circulated through the external heat exchanger, heated, and pumped back into the storage tank. The hot side of this heat exchanger is supplied with products from a bipropellant gas generator. Control of this assembly is accomplished by a tank pressure sensor. When, due to propellant extraction, tank pressure falls below a defined pressure level, propellant circulation is initiated, the gas generator is signaled on, and combustion products are routed to heat exchanger hot side. Heat transfer to the circulated propellant provides the energy necessary to maintain propellant tank pressure. Propellant tank design pressure level is dictated by response time of this heat exchanger and maximum propellant extraction rate. Storage pressure is fixed to allow maximum extraction rate during time required for heat exchanger warmup. During normal operation, the amount of heat addition required to maintain tank pressure varies due to inherent thermodynamic variations in fluid properties. Thus, the storage tank heat exchanger must provide a throttling capability. This throttling requirement varies somewhat with the amount of residual permitted at mission completion; however, a throttling requirement in the order of six will likely be required for the storage tank gas generator.

The downstream heat exchanger operates open loop in relation to accumulator pressure. When accumulator pressure falls below a predetermined level, the gas generator is signaled on. When heat exchanger warmup has been accomplished, the

main propellant valve on the cold side inlet is signaled open and propellant flow is initiated. Temperature measurements on the cold side outlet will be required as intelligence for control of gas generator flow rate and/or propellant flow rate. Maximum heat addition, and thus maximum gas generator flow, in this heat exchanger will occur at initial phases of mission and/or after every storage tank recharge. Near the end of storage tank operation and/or just prior to each recharge, gas generators will be operating at minimum flow rate, since the heat addition required is minimal because propellant storage state is approaching that required in the accumulators.

A-4.3 Turbocompressor Subsystem - In the turbocompressor concept, propellant is extracted as a gas from main engine propellant tanks. In the case of the boosters, ample APS propellant is available as residual gas in the booster tanks and no additional propellant supply is required. In the case of the orbiters, however, resupply is necessary to satisfy APS impulse requirements. The subsystem is equipped with controls which sense main engine tank pressure. When this pressure falls below a prescribed level, gas generator flow is initiated to the intermediate heat exchanger. Flow of resupply propellant is then initiated through the warm heat exchanger and into the tank.

The conditioner assembly operates similarly to all other APS concepts; that is, the assembly operates open loop about accumulator pressure. When pressure falls below a predetermined level, the gas generator is started and its exhaust products provide the turbocompressor power. When pressure exceeds minimum accumulator pressure and downstream check valves open, accumulator recharge is initiated.

A-4.4 Stored Gas Subsystem - The propellant storage assembly is passive and no conditioning assembly exists. Gaseous H_2 and O_2 propellants are supplied directly from the storage tanks to the thrusters on demand, under conditions of regulated flow.

**APPENDIX B
APS DESIGN AND
WEIGHT SENSITIVITY**

B-1. INTRODUCTION

This appendix provides a description of the methods employed to determine design conditions for each candidate APS concept. Shown are concept weight sensitivity to various design parameters, such as mixture ratio, chamber pressure, and line pressure drop. Under ideal conditions, APS design points would have been selected to provide minimum subsystem weight; however, APS weight was only one of four selection criteria, and, for this reason, minimum weight did not necessarily show each subsystem to its best advantage. Minimum weight designs were compromised to provide each APS concept with its highest rating as regards all selection criteria. This appendix provides weight sensitivity data for all design features and for all APS requirements. In those cases where APS designs were shifted from a minimum weight condition, the rationale for design point selection is provided.

B-2. CANDIDATE APS CONCEPTS

Figure B-1 lists all candidate APS approaches for both boosters and orbiters. A total of ten orbiter candidates and eight booster candidates were evaluated. Figure B-2 summarizes the selected design points. In general, design points and sensitivities are quite similar for the various concepts. For this reason, particular emphasis is given to a single turbopump concept, and, for the remaining subsystem types, design features are discussed only if they are unique or if a different philosophy had been applied to determine the design point. The final paragraph in this appendix provides APS weight sensitivity to design requirements such as thrust level, number of thrusters, and total impulse. Here a similar approach is followed. A typical turbopump subsystem is discussed in detail and the remaining concepts or candidates are discussed only if their features are different. For all analyses presented in the following paragraphs, the APS schematics of Appendix C were used to define number and type of components used in weight accounting. The conditioner concepts applied were those defined in Appendix D, while the component models of Appendix E were used throughout this study phase.

IDENTIFIER:	VEHICLE/APS TYPE/VELOCITY LEVEL		
VEHICLE	APS TYPE	VELOCITY LEVEL	IDENTIFICATION
ORBITER A	TURBOPUMP	ALL + X MANEUVERS + X MANEUVERS \leq 50 FPS + X MANEUVERS \leq 10 FPS	OA/TP/ALL OA/TP/50 FPS OA/TP/10 FPS
	SUPERCRITICAL HYBRID		OA/SC/10 FPS OA/HY/10 FPS
ORBITER B	TURBOPUMP	ALL + X MANEUVERS + X MANEUVERS \leq 50 FPS + X MANEUVERS \leq 10 FPS	OB/TP/ALL OB/TP/50 FPS OB/TP/10 FPS
	SUPERCRITICAL HYBRID		OB/SC/10 FPS OB/HY/10 FPS
BOOSTER A	TURBOPUMP	NOT APPLICABLE	BA/TP
	SUPERCRITICAL		BA/SC
	TURBOCOMPRESSOR		BA/TC
	STORED GAS		BA/SG
BOOSTER B	TURBOPUMP	NOT APPLICABLE	BB/TP
	SUPERCRITICAL		BB/SC
	TURBOCOMPRESSOR		BB/TC
	STORED GAS		BB/SG

APS CONCEPT IDENTIFICATION

FIGURE B-1

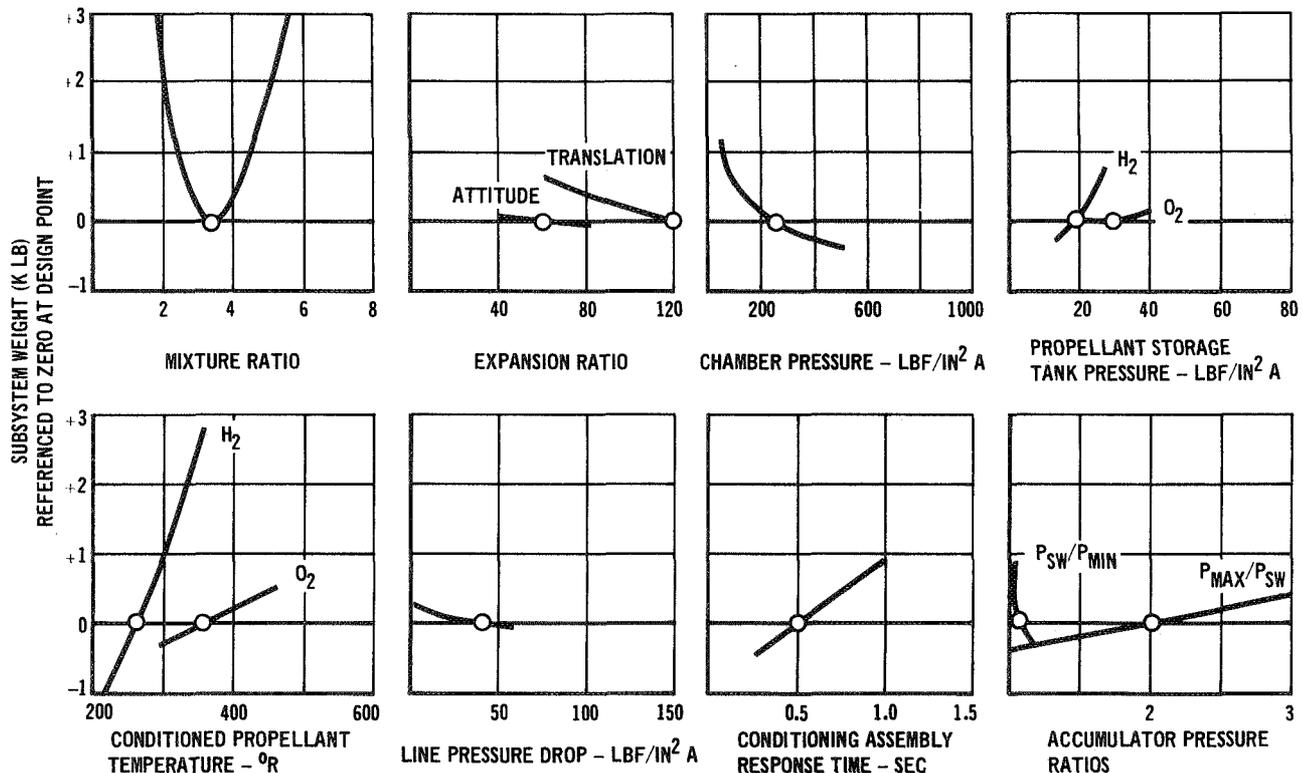
THRUSTER MR PC	ϵ	FEED ASSEMBLY $\Delta P_{LINE} \frac{P_{H_2}}{P_{O_2}}$	CONDITIONER $\frac{T_{H_2}}{T_{O_2}} \Delta T$	NO. OF CYCLES	ACCUMULATOR $\frac{P_{MAX}}{P_S} \frac{P_S}{O_2/H_2}$ $\frac{P_S}{O_2/H_2}$ P MIN O ₂ /H ₂	WEIGHT	
ORBITER A: (32 THRUSTERS - 500 LB THRUST) ALL MANEUVERS - TURBOPUMP (13,912,000 LB-SEC) ≤ 50 FPS - TURBOPUMP (2,968,000 LB-SEC) ≤ 10 FPS - TURBOPUMP (1,485,000 LB-SEC) - SUPERCRITICAL - HYBRID	3.5 250	40 19/30	260/360 0.5	35 + 15 = 50	2 1.09/1.11	38,157	
	3.8 250	40 19/30	260/360 0.5	50	2 1.09/1.11	10,511	
	4.0 250	40 19/30	260/360 0.5	50	2 1.09/1.11	6,915	
	4.0 200	25 25/30	260/360 0.5	120 + 15 = 135	1.5/1.4 1.3	8,164	
	4.0 100	35 19/45	260/NA H ₂ 0.5 O ₂ 1.5		-/1.4 1.3	8,434	
		60/120					
ORBITER B: (28 THRUSTERS - 1000 LB THRUST) ALL MANEUVERS - TURBOPUMP (15,989,000 LB-SEC) ≤ 50 FPS - TURBOPUMP (3,449,000 LB-SEC) ≤ 10 FPS - TURBOPUMP (1,707,000 LB-SEC) - SUPERCRITICAL - HYBRID	3.5 500	50 19/35	260/360 0.5	50	2 1.15/1.21	42,782	
	3.8 500	50 19/35	260/360 0.5	50	2 1.15/1.21	11,771	
	4.0 500	50 19/35	260/360 0.5	50	2 1.15/1.21	7,670	
	4.0 200	25 25/30	260/360 0.5	120 + 15 = 135	1.5/1.4 1.3	9,918	
	4.0 100	35 19/40	260/NA H ₂ 0.5 O ₂ 1.5		1.5/1.4 1.3	10,788	
		60/120					
BOOSTER A: (18 THRUSTERS - 2600 LB THRUST 475,000 LB-SEC) - TURBOPUMP - SUPERCRITICAL - TURBO-COMPRESSOR - STORED GAS	5.0 500	40 25/35	260/360 0.5	50	2 1.6	3,929	
	5.5 200	25 N/A	260/360 0.5		1.5/1.4 1.3	6,696	
	6.0 17.5	3 N/A	N/A 1.5		1.2 2.2	5,000	
	6.0 100	30 N/A	210/350 N/A (FINAL TEMP AFTER BLOWDOWN)	N/A	5 N/A	11,541	
		40					
		40					
BOOSTER B: (16 THRUSTERS - 2000 LB THRUST 475,000 LB-SEC) - TURBOPUMP - SUPERCRITICAL - TURBO-COMPRESSOR - STORED GAS	5.0 500	40 25/35	260/360 0.5	50	2 1.6	3,316	
	5.5 200	25 N/A	260/360 0.5		1.5/1.4 1.3	5,143	
	6.0 13.5	3 N/A	N/A 1.5		1.2 2.2	6,100	
	6.0 125	30 N/A	210/350 N/A	N/A	6 N/A	10,248	
		40					
		40					

HIGH PRESSURE APS SUMMARY

FIGURE B-2

B-3. APS DESIGN POINTS

Figure B-3 shows weight sensitivity to different design variables for the Orbiter A turbopump subsystem (OA/TP/ALL) for all maneuvers. Shown is APS sensitivity to: mixture ratio, expansion ratio, chamber pressure, propellant tank pressure, propellant conditioning temperature, line pressure drop, conditioning assembly response time, and accumulator pressure ratios. The following paragraphs discuss each design feature.



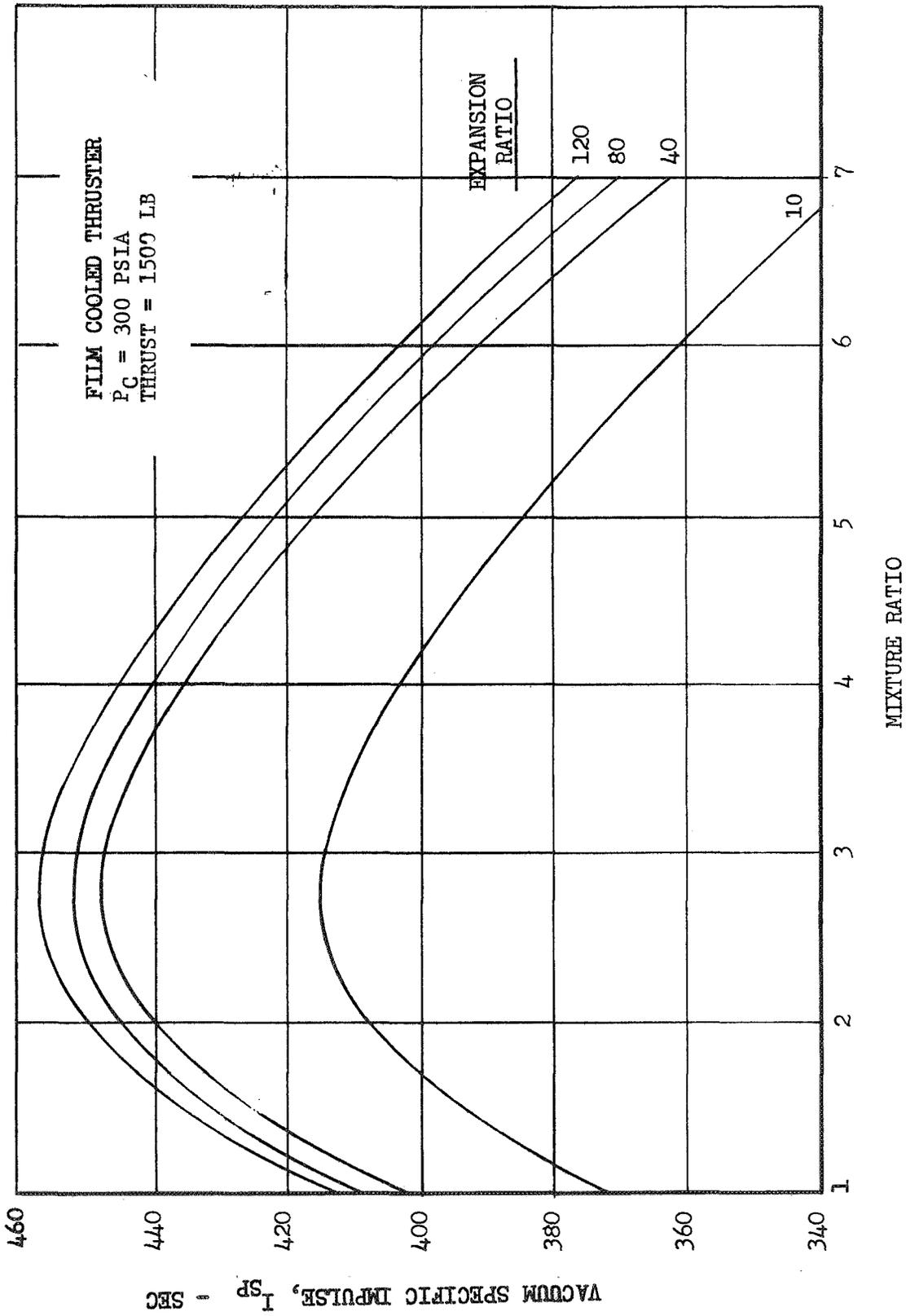
○ DESIGN POINT FOR TRADE STUDIES

WEIGHT SENSITIVITY TO DESIGN VARIABLES

VEHICLE: ORBITER A SUBSYSTEM: TURBOPUMP IMPULSE CLASS: ALL MANEUVER

FIGURE B-3

B-3.1 Mixture Ratio - The mixture ratio selected for the OA/TP/ALL APS is shown by Figure B-3 to be sharply defined by a minimum subsystem weight at a thruster mixture ratio of 3.5. The pronounced minimum in the mixture ratio sensitivity curve occurs principally because, in the all-maneuver impulse class, subsystem weight is extremely sensitive to propellant specific impulse. Even very minor specific impulse losses result in high weight penalties; therefore, subsystem weight becomes minimum very near the optimum specific impulse point. The effect of mixture ratio on specific impulse is illustrated by Figure B-4 which shows that



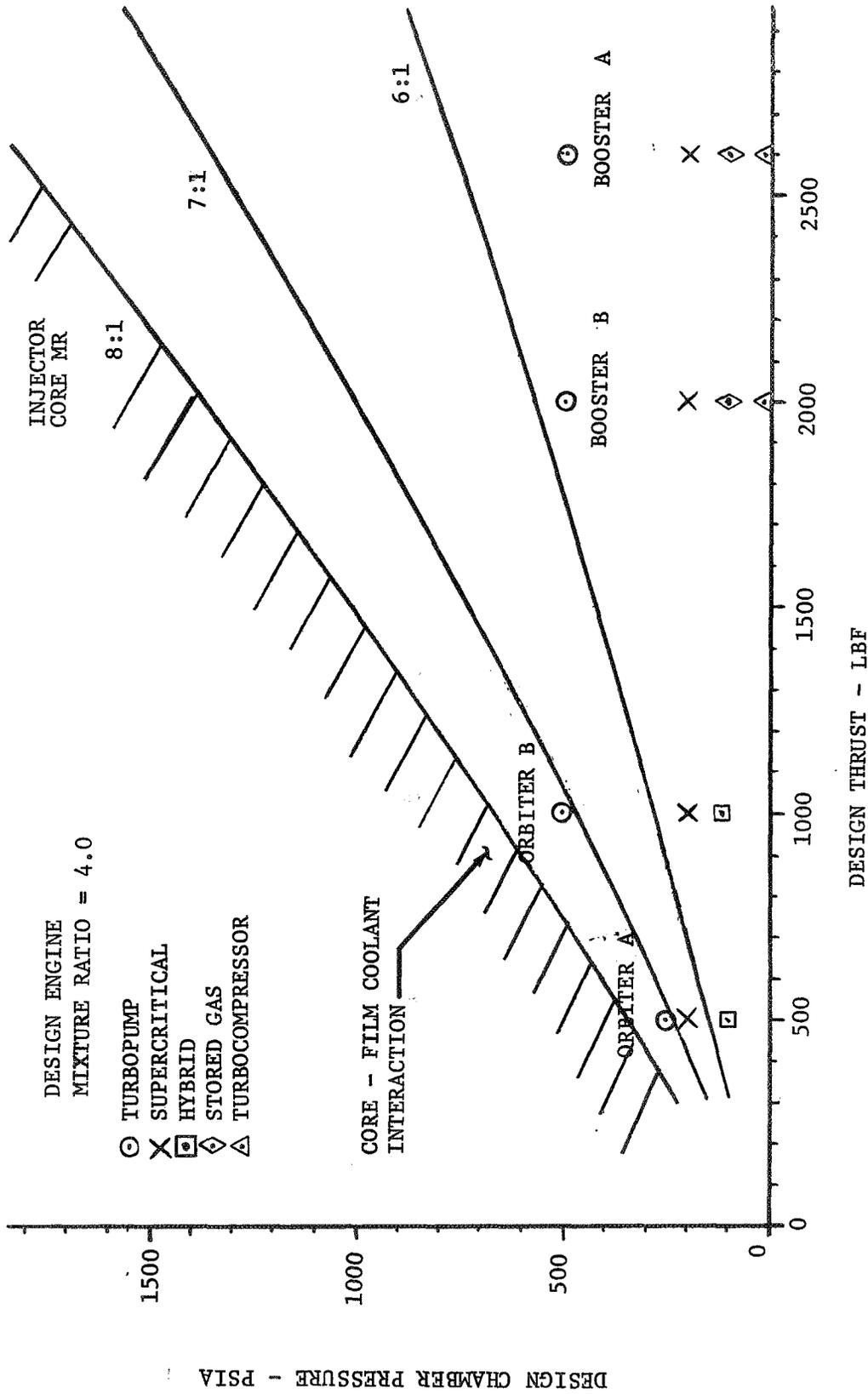
MIXTURE RATIO INFLUENCE ON SPECIFIC IMPULSE

FIGURE B-4

the optimum occurs at a mixture ratio of approximately 3.0. The slight increase to 3.5 results from the small subsystem mass fraction advantage afforded by higher mixture ratios.

B-3.2 Expansion Ratio - Figure B-3 shows the effect of expansion ratio on APS weight. Effects of varying the expansion ratio of both attitude control thrusters and translation (or +X) thruster nozzle expansion ratios are shown. Changes in attitude control thruster expansion ratio about the design value of 60 to 1 have little or no effect on subsystem weight. The 60:1 design point was selected for attitude control primarily because it was near minimum weight and no difficulty was foreseen in thruster installation. A somewhat different trend is seen for the +X translation thrusters. Here a design value of 120 was selected for the nozzle expansion ratio. If this expansion ratio is reduced, relatively large increases in subsystem weight occur. This result reflects the large fraction of APS impulse that is expended in the +X direction. As a result, small +X performance losses are reflected as large weight increases and increased nozzle weight can be easily absorbed through improved performance.

B-3.3 Thruster Chamber Pressure - Figure B-3 also shows the effect of chamber pressure on APS weight. The design value of 250 lbf/in² is, as shown, well below that which would provide a minimum weight. The design value was selected because of limitations in thruster cooling. The baseline thruster concept for Subtask A studies was a film cooled unit. In this thruster the amount of film cooling required is sensitive to the operating chamber pressure of the thruster. As chamber pressure is increased, the amount of hydrogen used for cooling must be increased, and, as this is done, the mixture ratio of the central or primary core of the thruster gets higher. When the amount of hydrogen for film cooling is increased to the point where the injector core mixture ratio reaches stoichometric, chemical reactions between the core and cooling film will be increased, and film effectiveness will be reduced. Thus, it is desirable to limit core mixture ratio to somewhat below stoichometric. Figure B-5 shows the design chamber pressure as a function of thrust for various injector core mixture ratios. Also shown in Figure B-5 are design points for the various APS concepts and for the different vehicles considered. For Orbiter A which operates at a relatively low thrust level, chamber pressures in excess of approximately 250 lbf/in² approach an injector core mixture ratio of 8 to 1. Hence, a chamber pressure of 250 lbf/in² was selected at the design thrust level for Orbiter A.



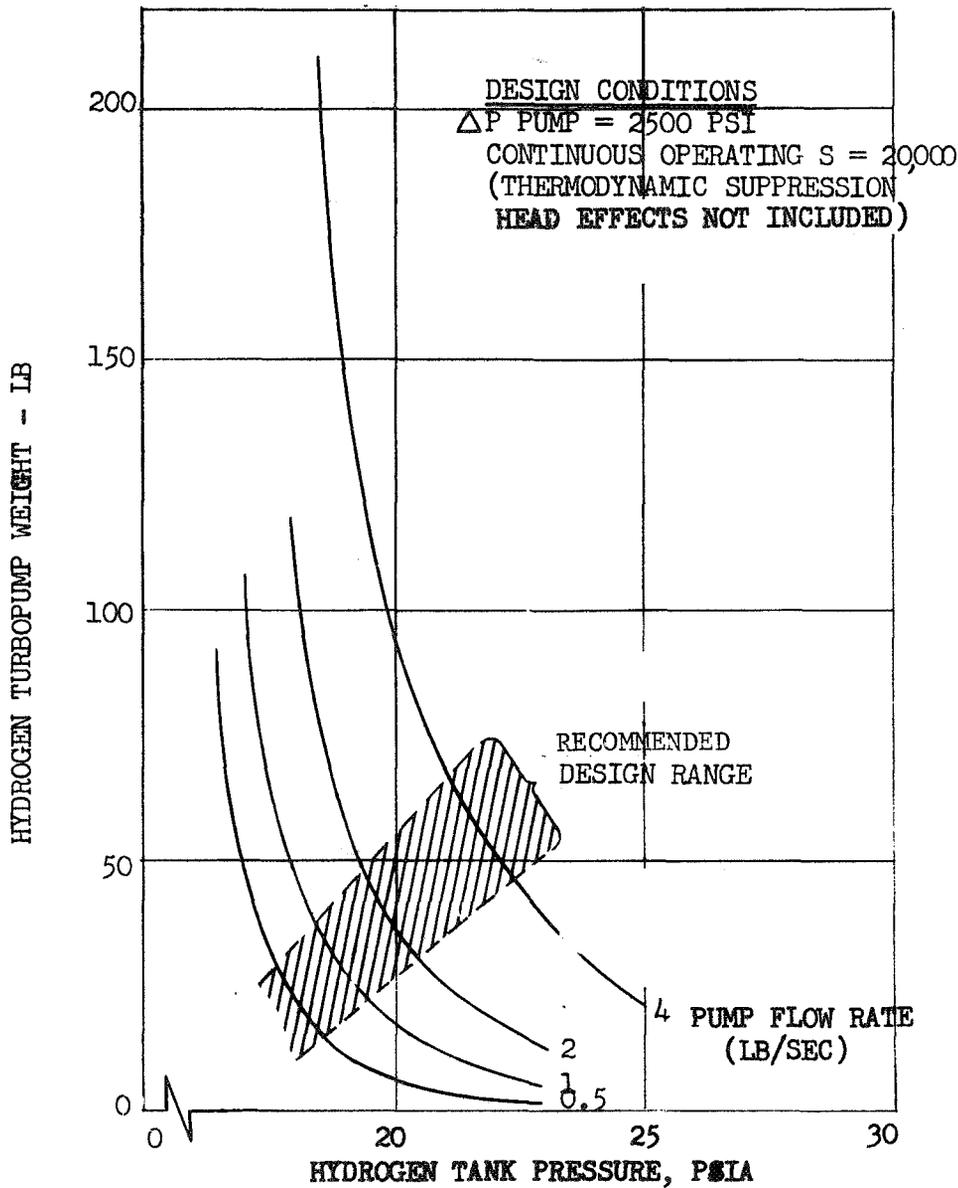
DESIGN CHAMBER PRESSURE LIMITATION

FIGURE B-5

B-3.4 Propellant Tank Pressure - Figure B-3 also illustrates APS weight sensitivity to variations in both hydrogen and oxygen storage tank pressure. This sensitivity reflects the tradeoff between increased turbopump weight at low tank pressures (low net positive suction head) and increased helium pressurization weights at higher tank pressures. For the oxygen tank, an optimum results at a propellant storage tank pressure of approximately 30 lbf/in²a or about 15 lbf/in² NPSP. The hydrogen design point is 20 lbf/in²a. Subsystem weight continues to decrease below this point, but, based on current technology, a hydrogen pump NPSP of at least 3 to 4 lbf/in² was desired. Figure B-6 illustrates the increases in turbopump weight that result from reductions in hydrogen tank pressure. The increases result primarily from an increase in overall pump diameter and, at very low NPSP, the potential need for inducers. The recommended design range shown on Figure B-6 reflects a design suited to continuous operation for the durations expected for the shuttle APS.

B-3.5 Propellant Conditioning Temperature - Figure B-3 illustrates APS weight sensitivity to hydrogen and oxygen conditioning temperature. Sensitivity to hydrogen temperature is comparable to that shown previously for overall mixture ratio. Design values of 260°R for the hydrogen and 360°R for the oxygen were selected for this APS. This selection was based largely on an engineering judgment that minimum acceptable propellant temperature at thruster inlet would be 200° and 300°R for hydrogen and oxygen, respectively. Little or no data were available at the time to define acceptability of low temperature hydrogen and oxygen for thruster ignition and/or operation. These thruster temperatures require propellant conditioning to stated design values when isenthalpic expansion through pressure regulators and lines downstream of accumulators is considered. Figure B-7 illustrates this throttling effect. Shown is an envelope of accumulator pressures and temperatures that can be achieved during the mission due to expansion and compression of the gas within the accumulators. From the accumulator pressures shown, pressure is reduced isenthalpically by throttling through the regulator and supply lines. Thruster inlet temperature is reduced to that corresponding to thruster inlet pressure.

B-3.6 Line Pressure Drop - Figure B-3 illustrates the sensitivity of APS weight to variations in supply line pressure losses. Here the basic trade effected was between increased supply line size at low pressure drop and increased pump and accumulator weights at high pressure loss. A value of approximately 40 lbf/in² offers a near-minimum subsystem weight and the gas velocities and line



TANK PRESSURE EFFECTS

FIGURE B-6

sizes present no unique difficulties in the design.

B-3.7 Conditioner Response Time - Figure B-3 shows APS weight sensitivity to increases in overall response time of the conditioners. In the case of the turbopump APS, this response time represents combined response of turbopump, gas generator and heat exchanger. Figure B-8A illustrates the simplified conditioner transient used in modeling the turbopump conditioning assembly. At conditioner switching pressure, the gas generator valve is actuated and, after a very brief ignition delay, gas generator pressure reaches an equilibrium value. After initiation of

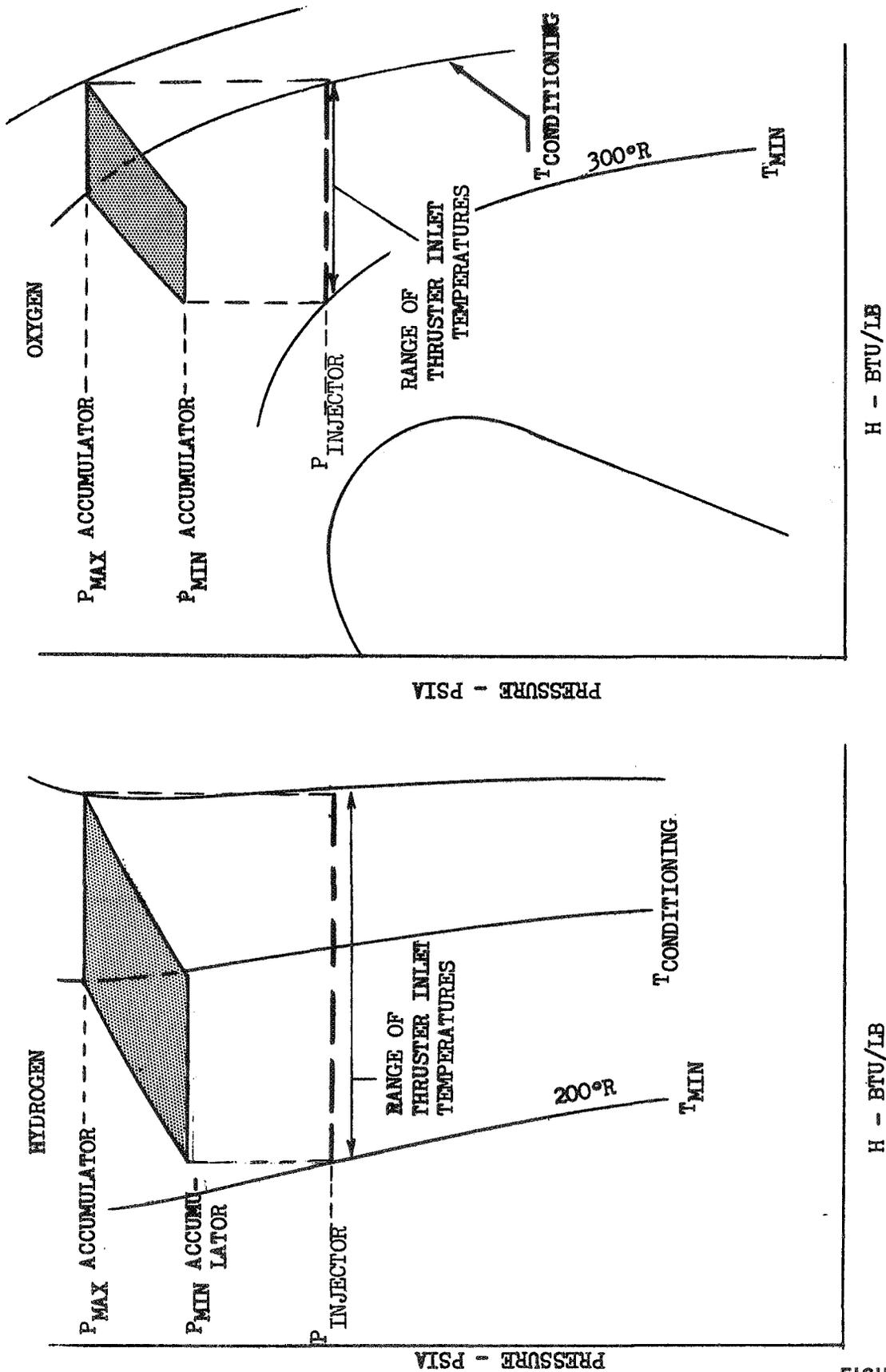
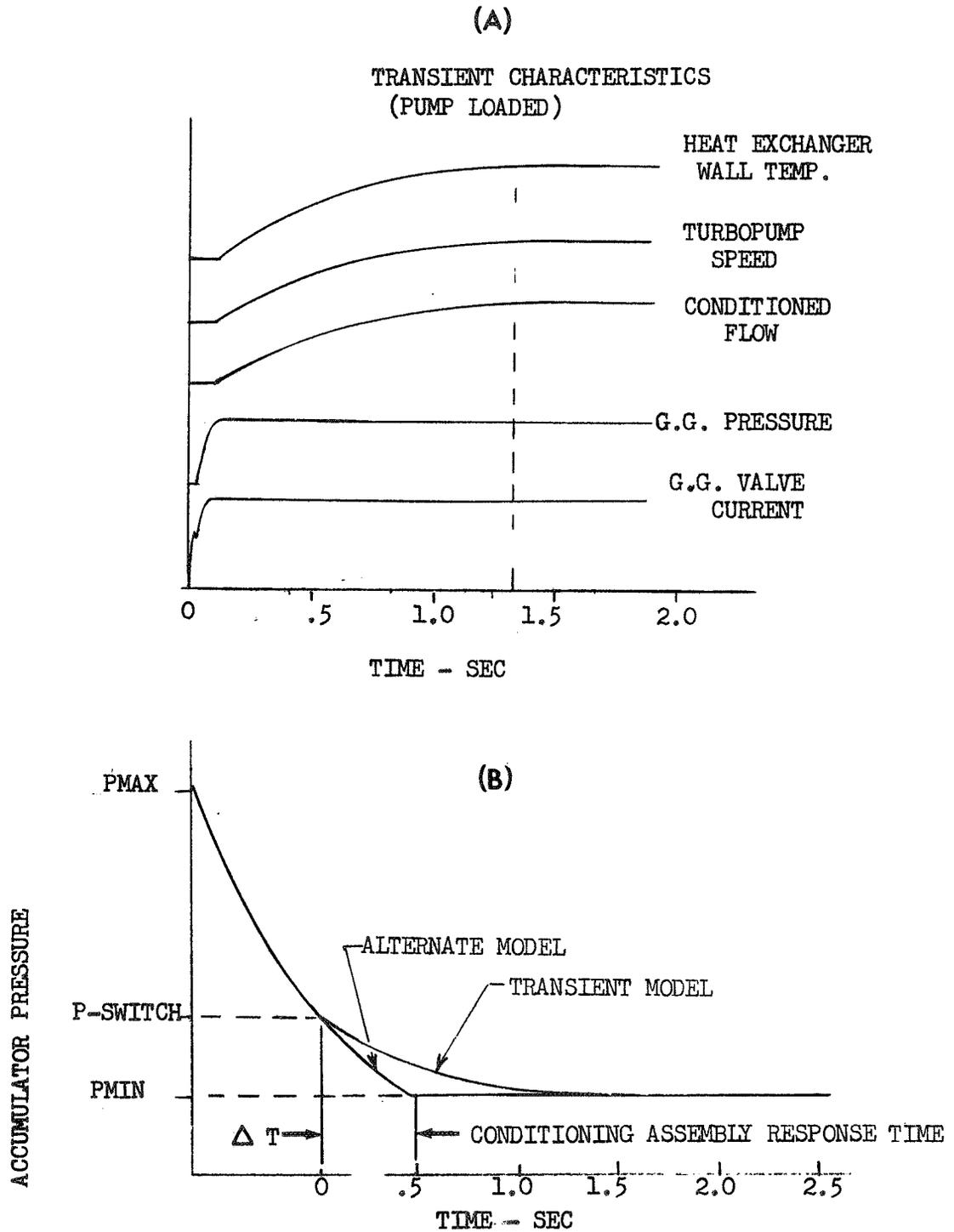


FIGURE B-7



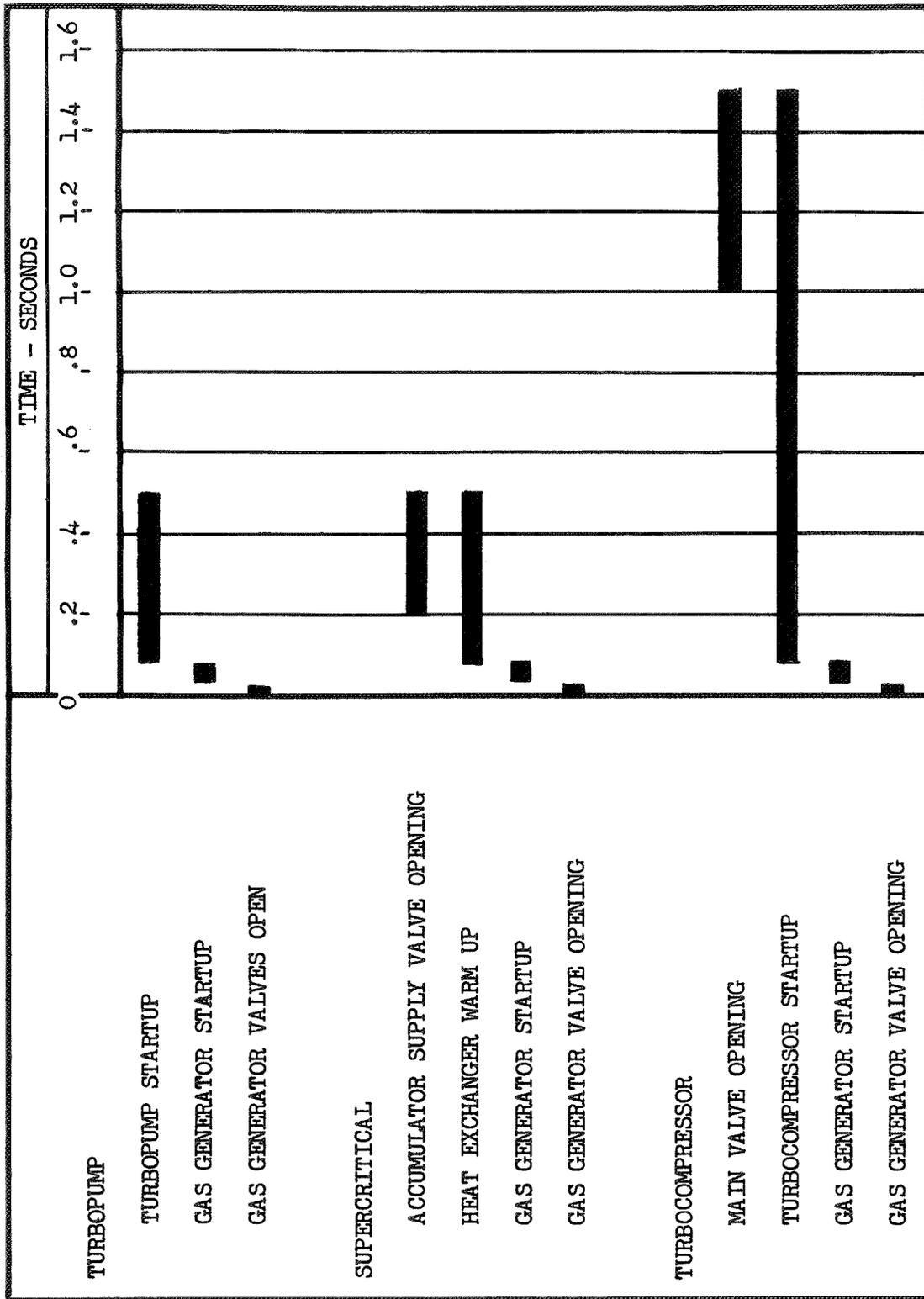
TURBOPUMP CONDITIONING ASSEMBLY RESPONSE MODEL

FIGURE B-8

gas generator flow, turbopump speed and heat exchanger wall temperature begin to rise and reach their equilibrium values in approximately 1.5 sec. In the accumulator, initiation of the conditioner transient at P_{switch} results in a P_{min} when the conditioner reaches steady state, in about 1.5 sec, shown in Figure 8B.

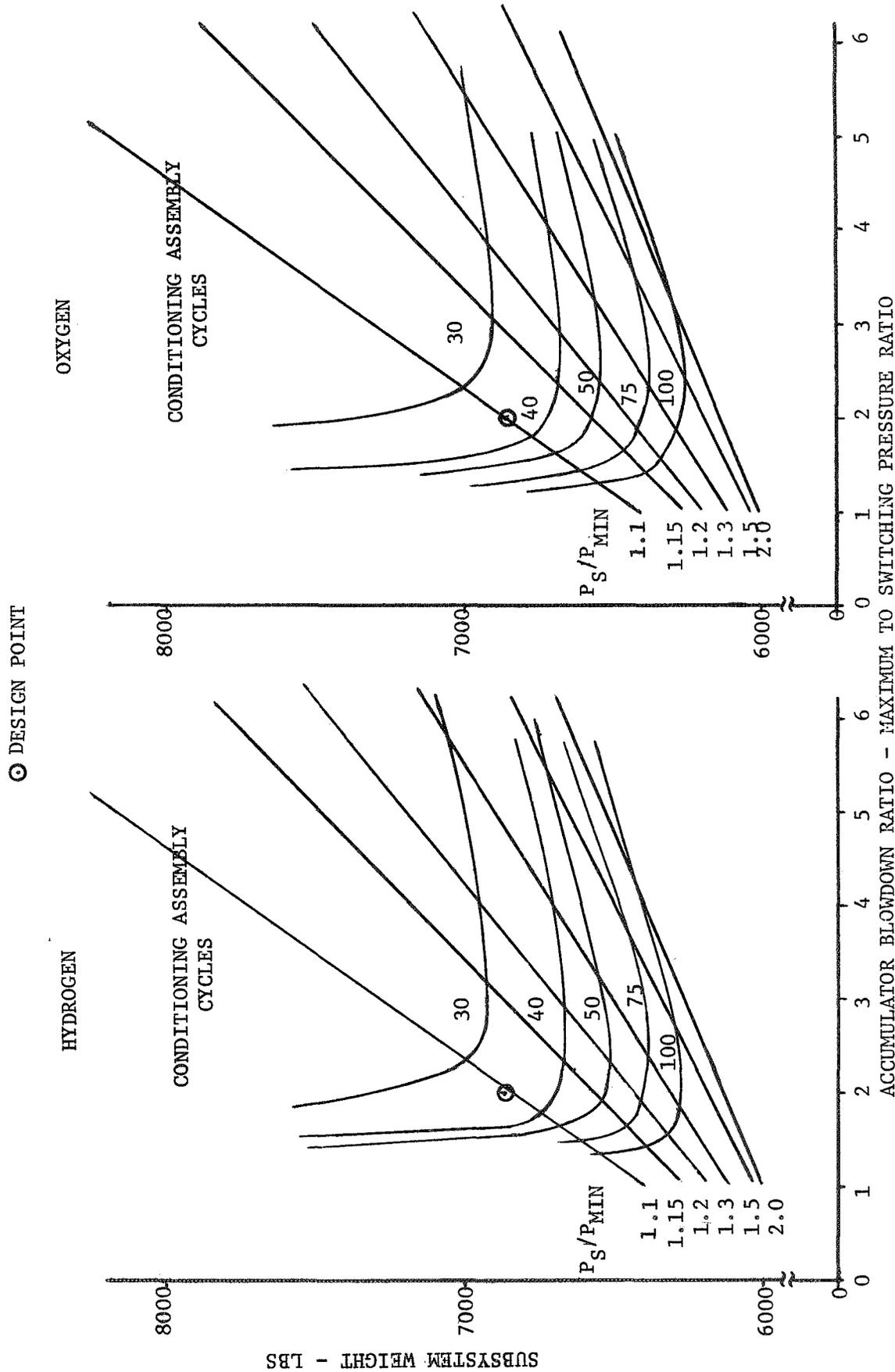
For analysis convenience, an alternate conditioner response model was used. This model initiates steady state conditioned flow at a ΔT after P_{switch} which results in the same P_{min} as the transient model. This ΔT , shown in Figure 8B, is defined as the conditioner response time. It is equal to the time between P_{switch} and P_{min} for the design accumulator discharge rate. The conditioner response time was .5 sec for the turbopump APS. Turbopump and supercritical concepts exhibit basically the same conditioner response. The compressor concept, however, shows appreciably longer response times resulting from the high inertia of the turbomachinery. Design response times and startup sequence for the APS concepts are illustrated in Figure B-9.

B-3.8 Accumulator Pressure Ratios - Figure B-3 illustrates the sensitivity of APS weight to accumulator pressure ratios. Two pressure ratios are shown; these are the maximum to switching pressure ratio of the accumulator or blowdown ratio, and the switching to minimum pressure ratio associated with the conditioner response time discussed in the preceding paragraph. Design values shown were selected based on accumulator sizing to provide a limitation in the number of conditioner operating cycles during the mission and on a given conditioner response time. Figure B-10 illustrates the number of conditioner cycles for a 735,000 lb-sec total impulse, the Orbiter A attitude maneuvering and control requirement (Appendix G). Subsystem weight is minimized at a blowdown ratio of approximately 2 for any preselected number of conditioning assembly cycles. At this prescribed blowdown ratio, the number of conditioning cycles will be indicated by the switching pressure ratio. For this study, 50 conditioner operating cycles was selected as an allowable number for each mission. With a fixed number of major +X maneuvers or OMS settling burns in each mission (15), the design number of pulsing cycles was 35. This defined the switching pressure ratio as 1.1 for the turbopump APS for a conditioning assembly response time of 0.5 sec. The selection of 50 operating life cycles (5,000 cycles in 100 missions) for the turbopump system was, of necessity, based largely on engineering judgment, because no turbopump assembly has demonstrated capability of extended cycle life in a cryogenic environment.



CONDITIONING ASSEMBLY STARTUP SEQUENCE

FIGURE B-9



TURBOPUMP ACCUMULATOR SIZING CRITERIA
Orbiter A (≤ 10 fps)
Conditioning Assembly Response Time = 0.5 Seconds

FIGURE B-10

However, inspection of Figure B-10 data shows that life capability below this level will severely increase overall subsystem weight; thus, 50 cycles was a very desirable technological goal. Since commercial turbomachinery life has been developed to the point that a cycle life of 5,000 cycles can be achieved (i.e., jet aircraft turbines) the point of 50 cycles for 100 missions selected is a reasonable design goal for turbopumps, but is also, clearly, a new technology development.

B-4. EFFECT OF TOTAL IMPULSE REQUIREMENT

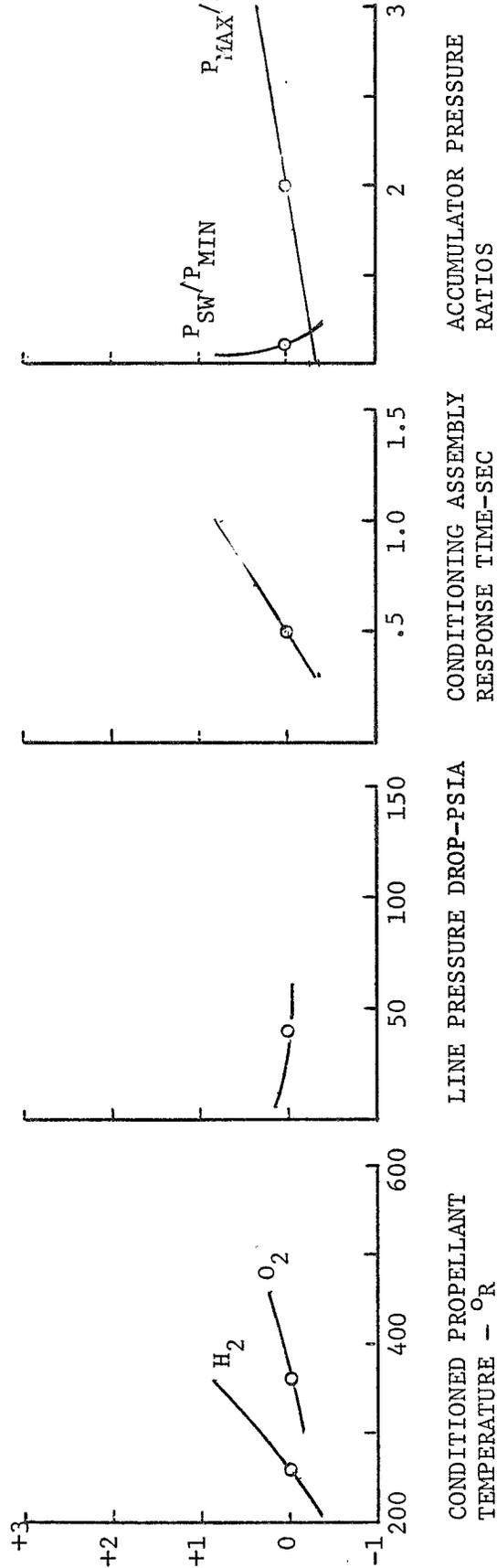
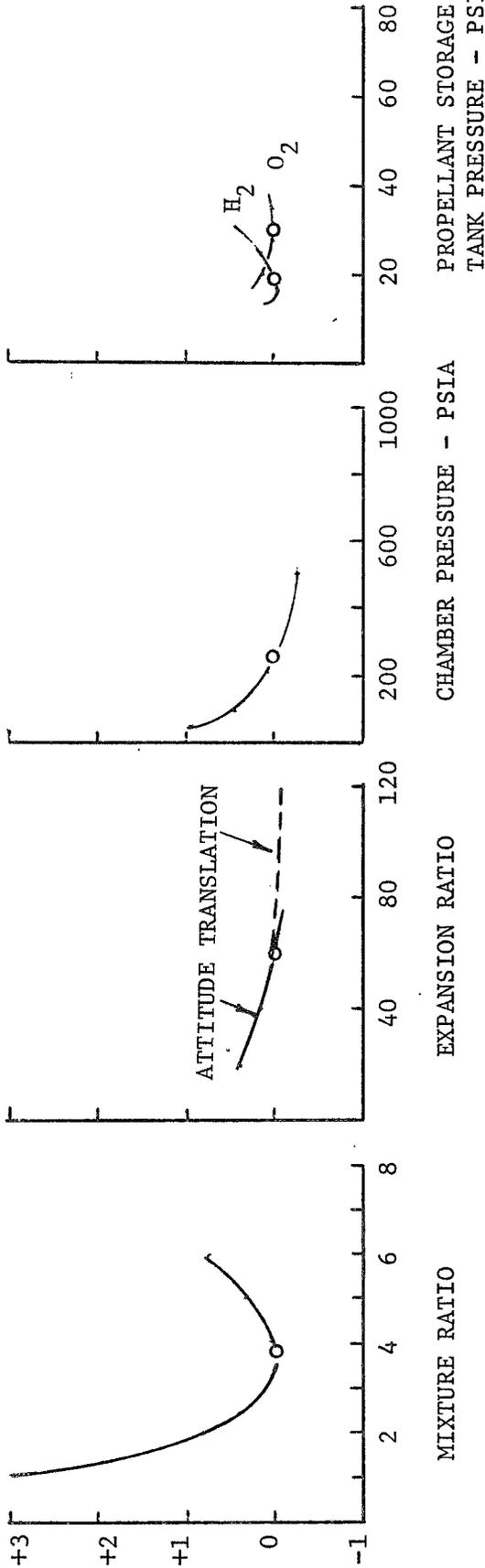
Figures B-11 and B-12 present sensitivity data for the turbopump subsystem at other impulse levels. Design values shown are very similar to those developed for the all-maneuver class; however, comparison of Figures B-11 and B-12 with Figure B-3 shows that, for the reduced impulse cases, subsystem weight sensitivity is much less pronounced. At the lower impulse level, the effect of propellant mass fraction drives the design mixture ratio to somewhat higher values. Also, at these impulse levels, translation impulse was a much smaller fraction of the total and there was little or no benefit derived from increased expansion ratio for the +X thrusters. All other APS design features are the same as previously defined.

Figures B-13, B-14 and B-15 present turbopump design sensitivity for Orbiter B. The data shown are similar in all respects to those for Orbiter A and the design points selected are the same, with the exception of operating chamber pressure. Reference to Figure B-5 shows that for Orbiter B, a design chamber pressure of 500 lbf/in² provides an acceptable thruster core mixture ratio, and hence, for this subsystem, the design chamber pressure was nearly optimum.

IMPULSE CLASS \leq 50 FPS

SUBSYSTEM
TURBOPUMP

VEHICLE
ORBITER A



SUBSYSTEM WEIGHT (1000 LB)
REFERENCED TO ZERO AT DESIGN POINT

ACCUMULATOR PRESSURE
RATIOS

CONDITIONING ASSEMBLY
RESPONSE TIME-SEC

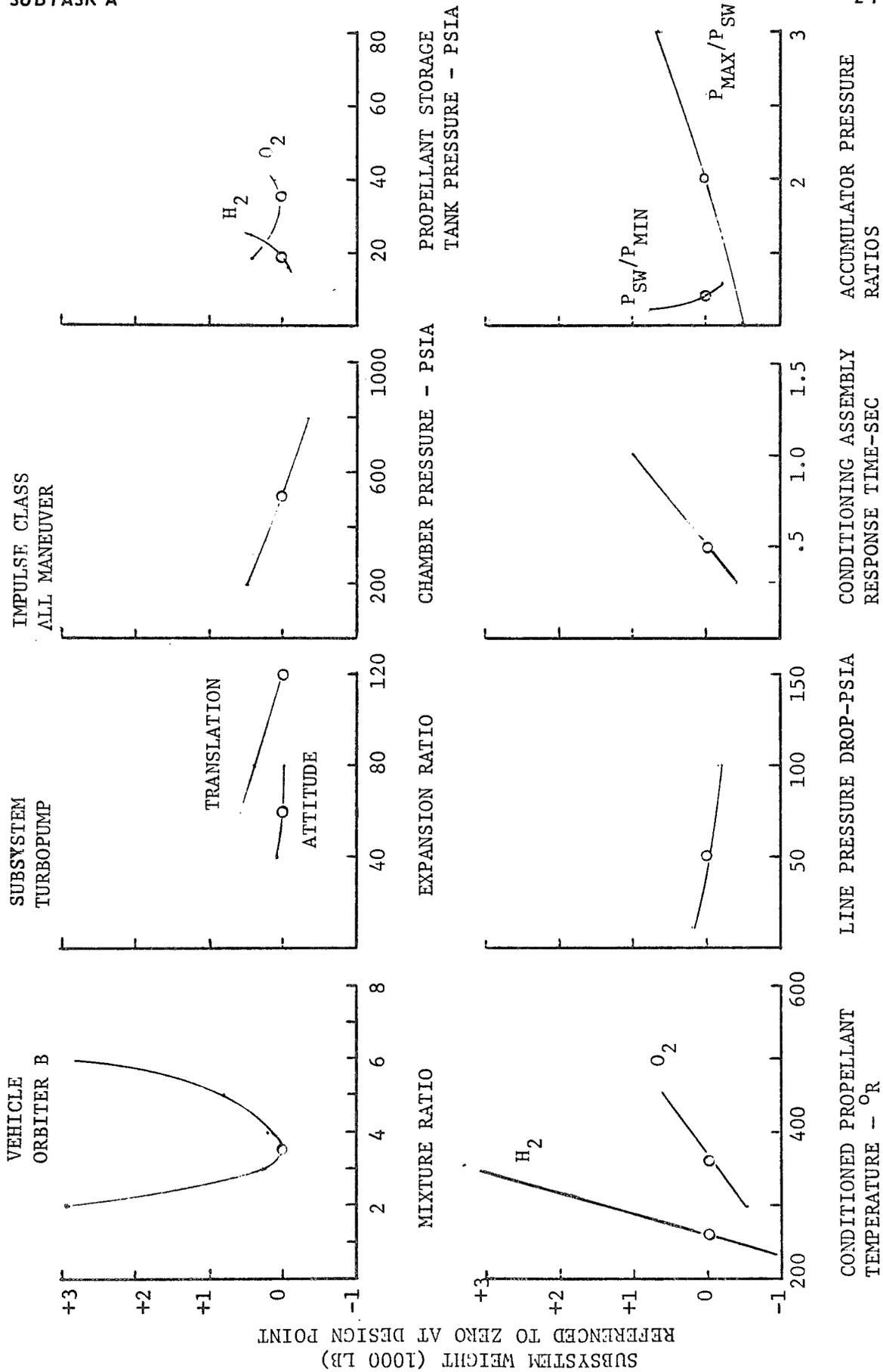
LINE PRESSURE DROP-PSIA

CONDITIONED PROPELLANT
TEMPERATURE - °R

°DESIGN POINT FOR TRADE STUDIES

WEIGHT SENSITIVITY DESIGN VARIABLES

OA/TP/50 FPS

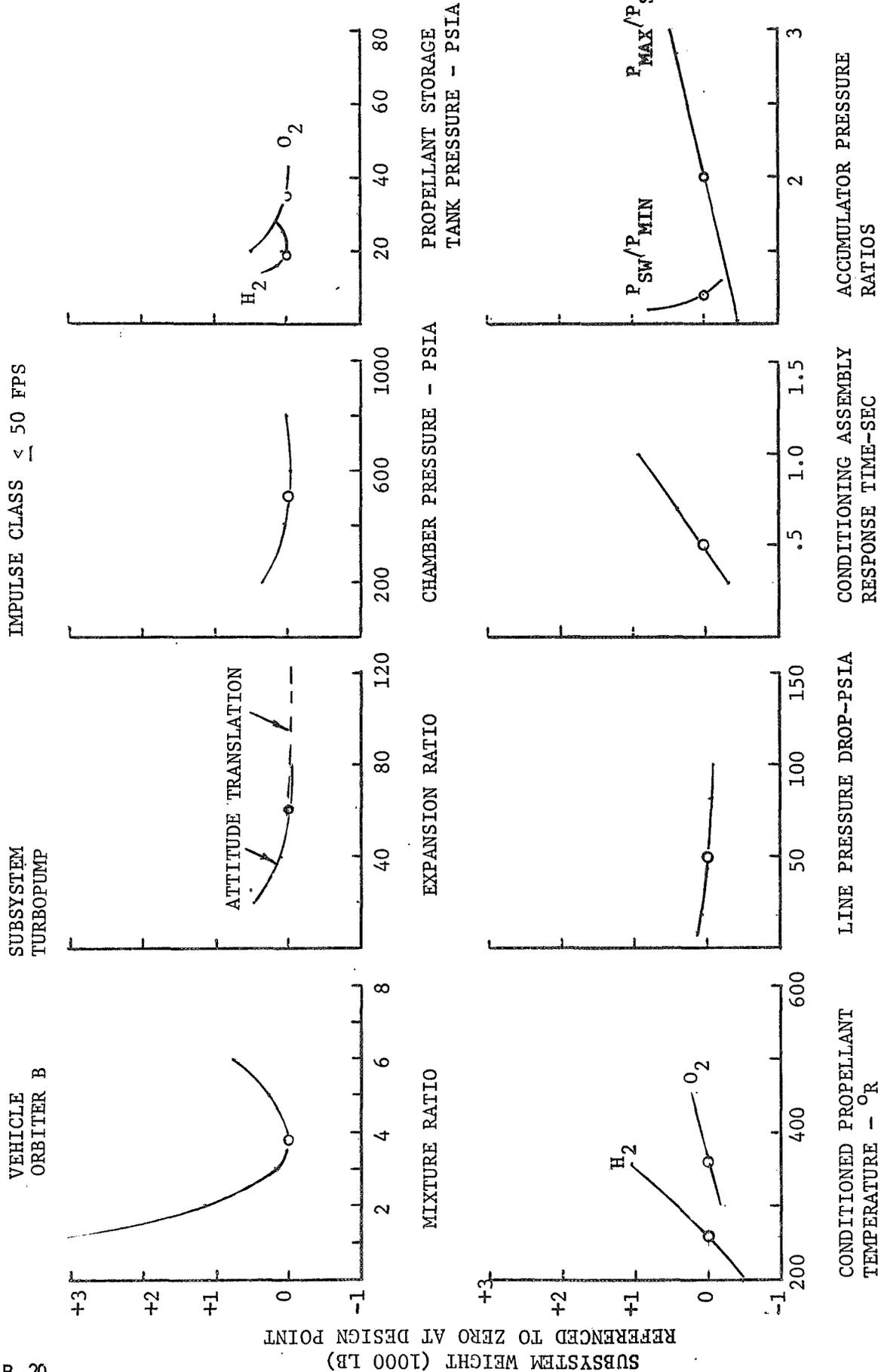


°DESIGN POINT FOR TRADE STUDIES

WEIGHT SENSITIVITY TO DESIGN VARIABLES

OB/TP/ALL

FIGURE B-13



WEIGHT SENSITIVITY TO DESIGN VARIABLES
OB/TP/50 FPS

FIGURE B-14

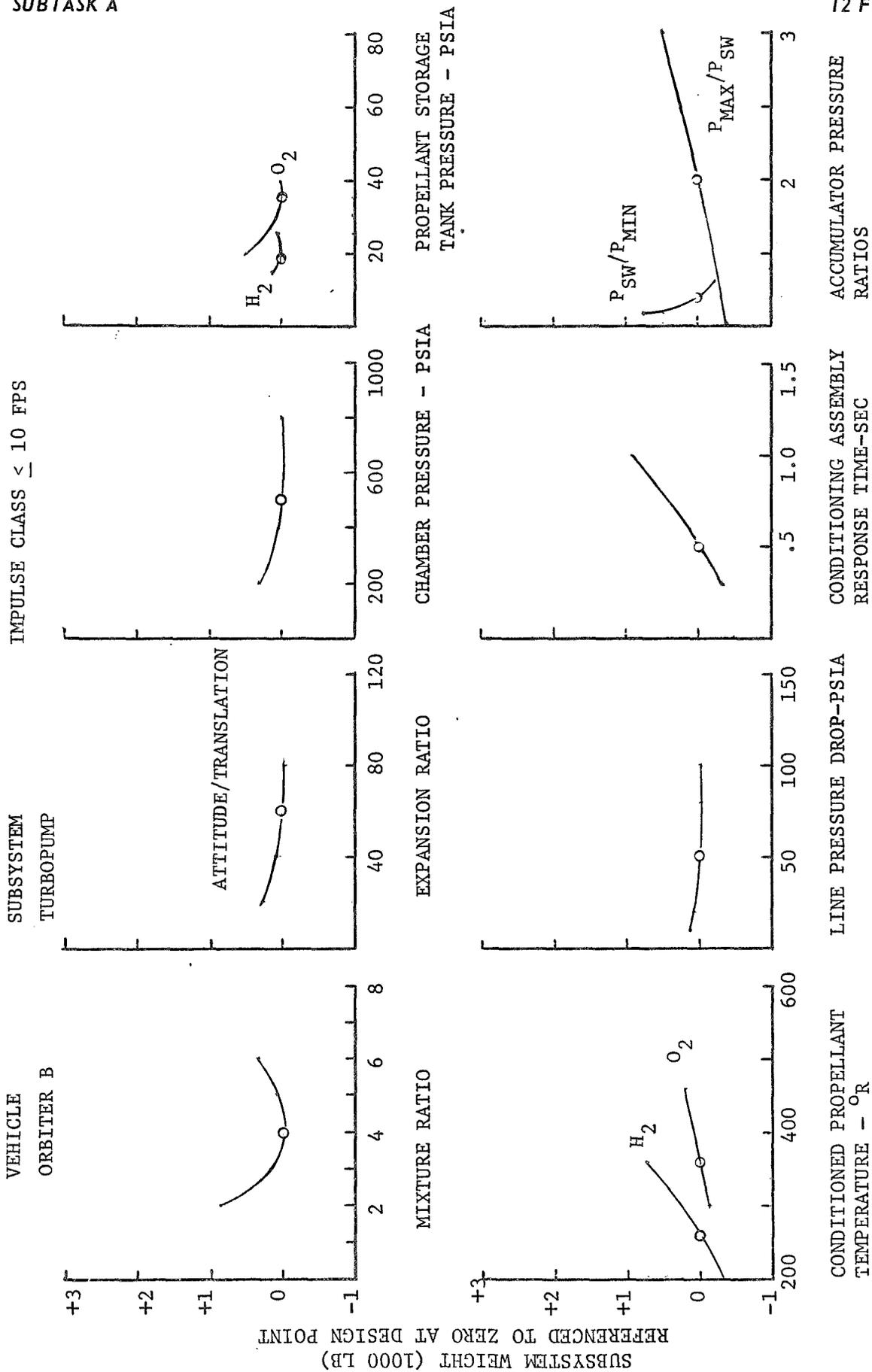
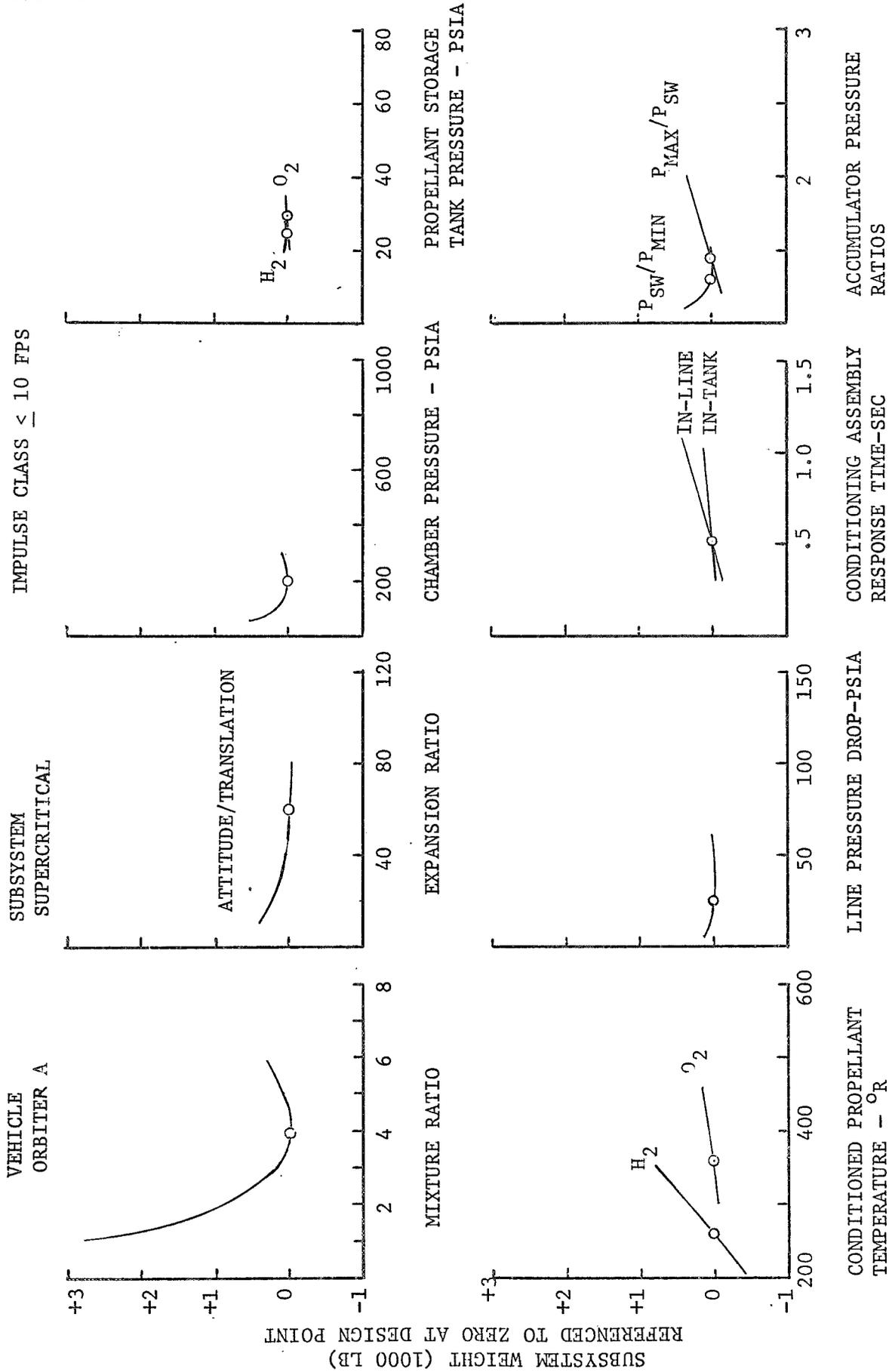


FIGURE B-15
OB/TP/10 FPS
WEIGHT SENSITIVITY TO DESIGN VARIABLES

B-5. SUPERCRITICAL SUBSYSTEMS

Figure B-16 presents weight sensitivity data for a supercritical subsystem. Design features for this subsystem are, in general, similar to those observed in the turbopump. At the low impulse level, the optimum mixture ratio is approximately 4.0 and there is no advantage to high expansion ratio on the translation thrusters. In contrast to the turbopump subsystem, however, the supercritical APS optimizes at a chamber pressure of 200 lbf/in²a for Orbiter A. This was below the constraint imposed by film cooling. Propellant storage tank pressures for the liquid tanks, which contain the majority of the APS propellant, are similar to those of the turbopump. Propellant conditioning temperatures are the same and were arrived at by the criteria defined in Section B-3.5. For this subsystem type, a greater sensitivity to pressure drop is exhibited, and the most desirable line pressure drops are somewhat lower than those observed in the turbopump subsystem. As defined in Section B-3.7, response time for this supercritical conditioning assembly was taken to be 0.5 sec. Accumulator pressure ratios selected for the supercritical subsystem are somewhat different than those of the turbopump. Figure B-17 presents data on accumulator pressure ratios similar to those previously provided for the turbopump. As shown, a higher number of conditioner cycles is considered acceptable because no turbomachinery is required in this subsystem.

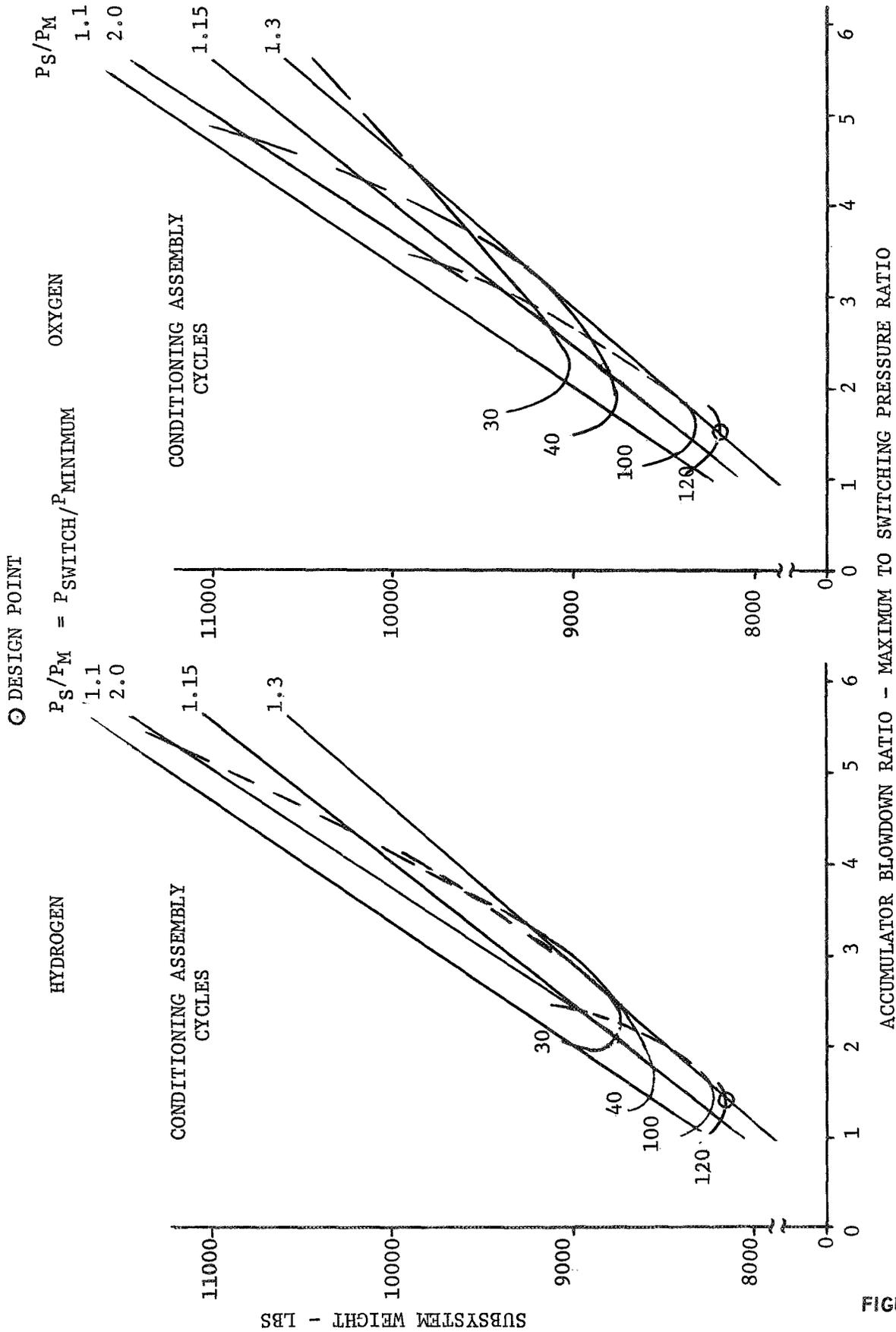
Figure B-18 presents weight sensitivity data on the supercritical concept for Orbiter B. Comparison of these data with those of Figure B-16 indicates no change in APS design points for Orbiter B.



°DESIGN POINT FOR TRADE STUDIES

WEIGHT SENSITIVITY TO DESIGN VARIABLES
OA/SC/10 FPS

FIGURE B-16

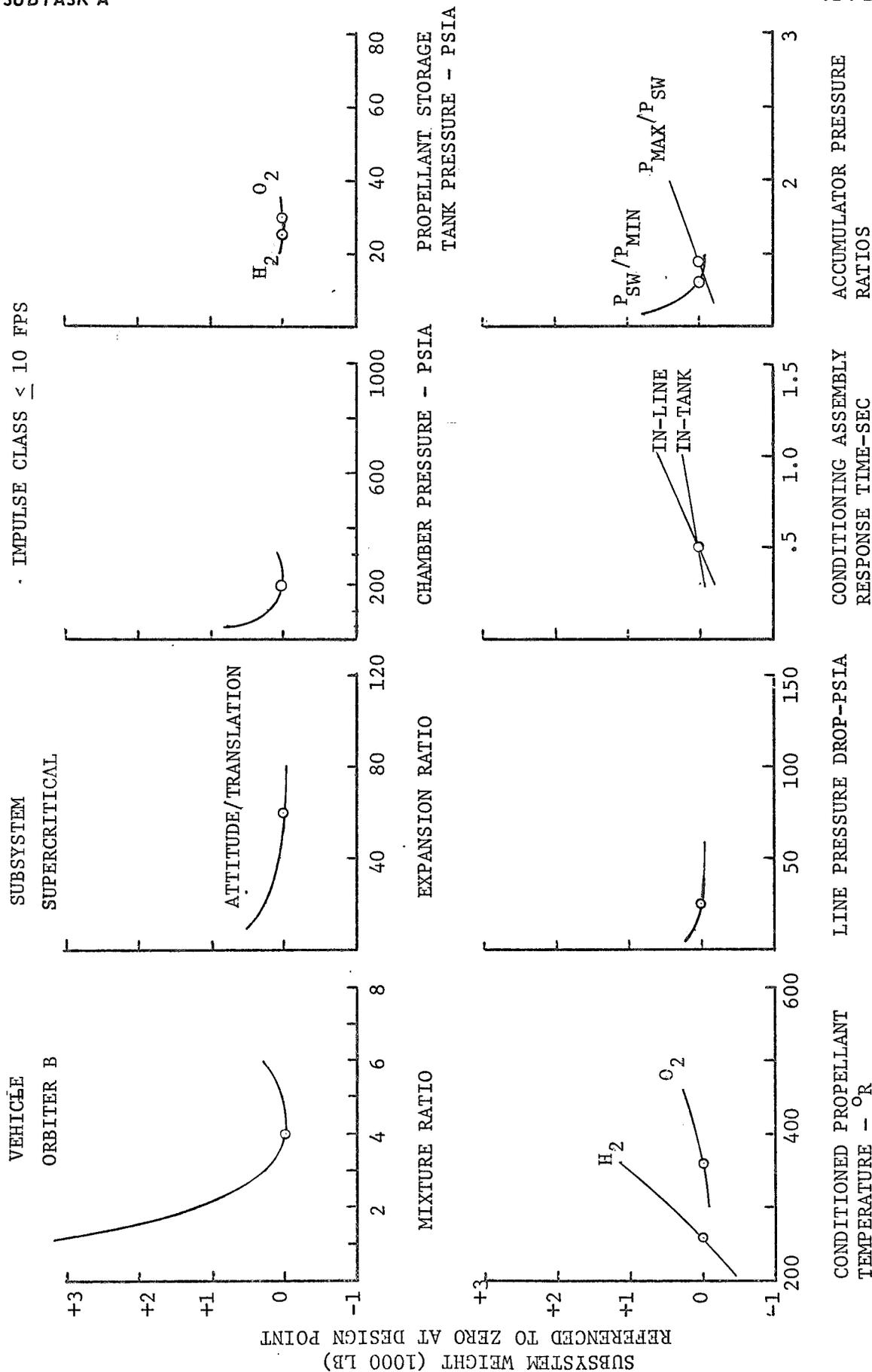


SUPERCRITICAL ACCUMULATOR SIZING CRITERIA

Orbiter A ≤ 10 fps

Conditioning Assembly Response Time = 0.5 Seconds

FIGURE B-17



°DESIGN POINT FOR TRADE STUDIES

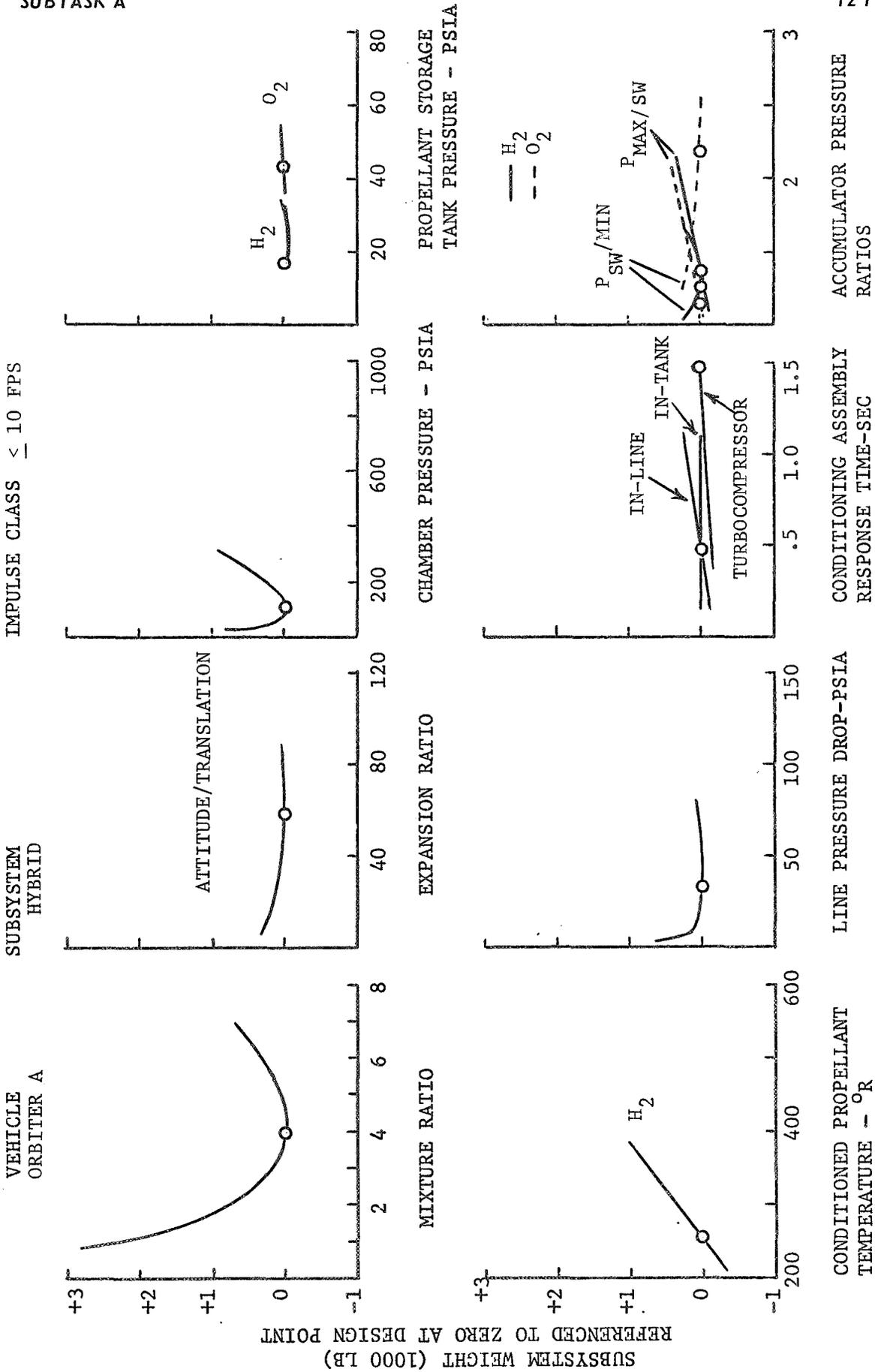
WEIGHT SENSITIVITY TO DESIGN VARIABLES

OB/SC/10 FPS

B-6. HYBRID SUBSYSTEM SENSITIVITY

Weight sensitivities to design variables for the hybrid subsystems are presented in Figures B-19 and B-20. Again, results are very similar to those provided by the turbopump APS. At the low impulse level, mixture ratio optimizes at a value of 4 to 1. Chamber pressure, however, optimizes at approximately 100 lbf/in²a. This relatively low value results from a compromise between the increased storage tank pressure on the hydrogen side and the increased bypass flow for operation of the oxygen compressor as chamber pressure increases, and the increased weight associated with larger thrusters and supply lines at low chamber pressure. Hydrogen storage tank pressures are similar to those of the supercritical APS. For oxygen, a pressure of 40 lbf/in²a was selected to provide transfer of propellant from storage tank to main engine propellant tank. Propellant conditioner temperature sensitivity is shown only for hydrogen, as the oxygen compressor discharges at a sufficiently high temperature after compression to operate the thrusters, and no additional conditioning is required.

There are three conditioning assembly response times. For the supercritical side of the subsystem, response time of both the downstream heat exchanger assembly and the tank pressurization heat exchanger assembly must be considered. For both assemblies a value of 0.5 sec response has been selected, based on results previously presented in Section B-3.7. For the turbocompressor side, a single response time of 1.5 sec has been utilized. Accumulator pressure ratios are shown in Figures B-19 and B-20 for both hydrogen and oxygen sides of the subsystem. As with the supercritical concept, APS maximum to switching pressure ratios were based on limitation of the number of operating cycles (as described in Section B-3.8) for the turbocompressor side of the subsystem, accumulator design pressure ratios were based on providing a minimum subsystem weight.



WEIGHT SENSITIVITY TO DESIGN VARIABLES

OA/HY/10 FPS

FIGURE B-19

B-7 BOOSTER APS SUBSYSTEMS

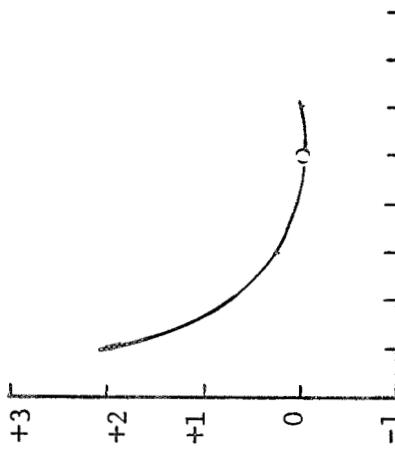
The weight sensitivity of a booster turbopump APS is shown in Figure B-21. For the booster APS a somewhat higher mixture ratio was more advantageous. A design mixture ratio of 5 to 1 is shown in Figure B-21. In the boosters there is less propellant required, hence the subsystem weight is less sensitive to slight reductions in thruster performance and higher mass fractions prove beneficial. Increased chamber pressure results because boosters require higher thrust levels than orbiters and have somewhat greater weight increases with reduced chamber pressure. This, combined with a reduced sensitivity to performance, drives the boosters to somewhat higher chamber pressures. All other sensitivities for the booster turbopump are similar to those of the orbiters.

A comparison of Figures B-21 and B-22 show that the supercritical subsystem design for the boosters is very similar to that of the turbopump with the exception that the boosters operate at a much lower chamber pressure than was previously observed on the orbiters.

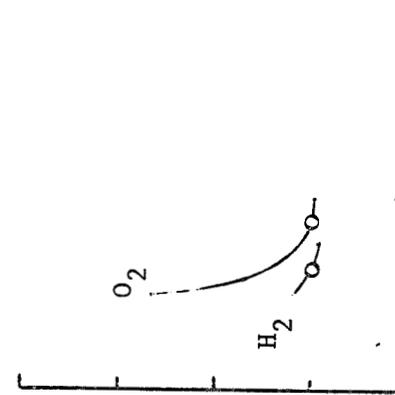
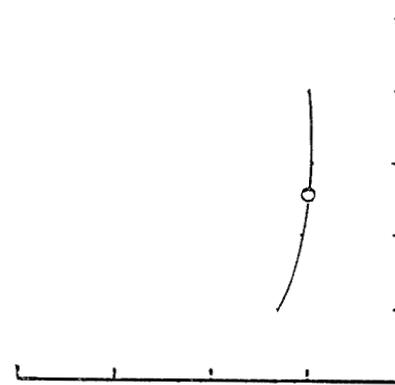
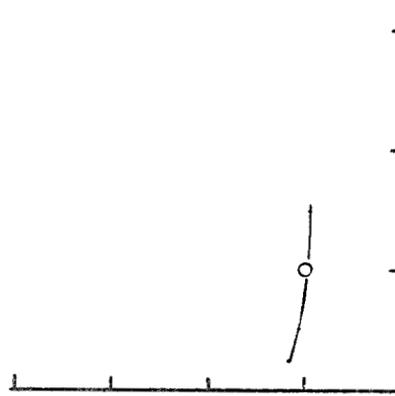
Figure B-23 presents the weight sensitivity of the turbocompressor subsystem. Here (for the booster) there are several significant differences between turbocompressor and turbopump. The compressor subsystem operates at a much higher mixture ratio, reflecting the sensitivity to turbocompressor size on the hydrogen side of the subsystem. Weight sensitivity to expansion ratio is quite different for this subsystem. No propellant performance loss is reflected since all propellants are obtained free from main booster tank residuals. Thus, very small expansion ratios are no penalty to this subsystem. As exhibited for the orbiter hybrid subsystem, the turbocompressor prefers to operate at relatively low chamber pressures. The power required for compression is free, but compressor weights increase with increased turbine pressure ratios. No propellant storage is required on the boosters; hence, there is no sensitivity to this particular design variable. Similarly, there is no conditioning temperature sensitivity for the same reason as observed on the orbiter hybrid, i.e., no conditioning other than the compression is required. Conditioning assembly response, line pressure drops, and accumulator pressure ratios are as previously described for the hybrid subsystems.

Of interest for the compressor is the operating compressor pressure ratio. This effects the size and weight of the turbocompressors. Figure B-24 shows

VEHICLE
BOOSTER A



SUBSYSTEM
TURBOPUMP



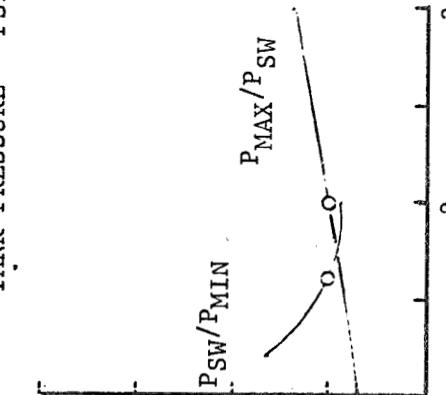
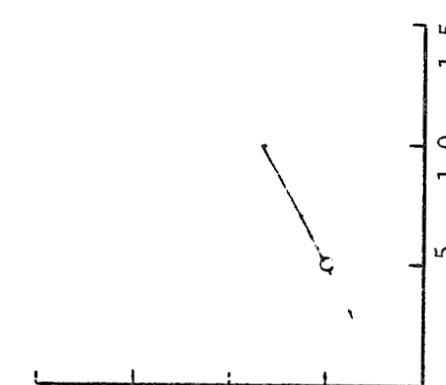
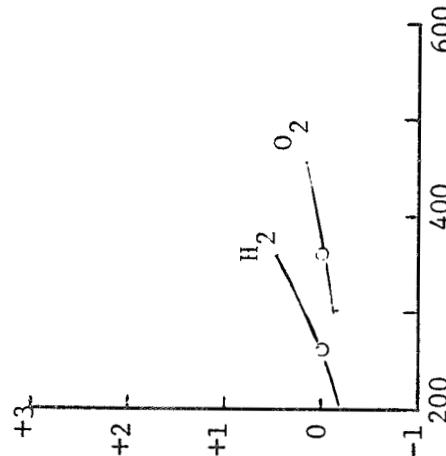
SUBSYSTEM WEIGHT (1000 LB)
REFERENCED TO ZERO AT DESIGN POINT

MIXTURE RATIO

EXPANSION RATIO

CHAMBER PRESSURE - PSIA

PROPELLANT STORAGE
TANK PRESSURE - PSIA



CONDITIONED PROPELLANT
TEMPERATURE - °R

LINE PRESSURE DROP-PSIA

CONDITIONING ASSEMBLY
RESPONSE TIME-SEC

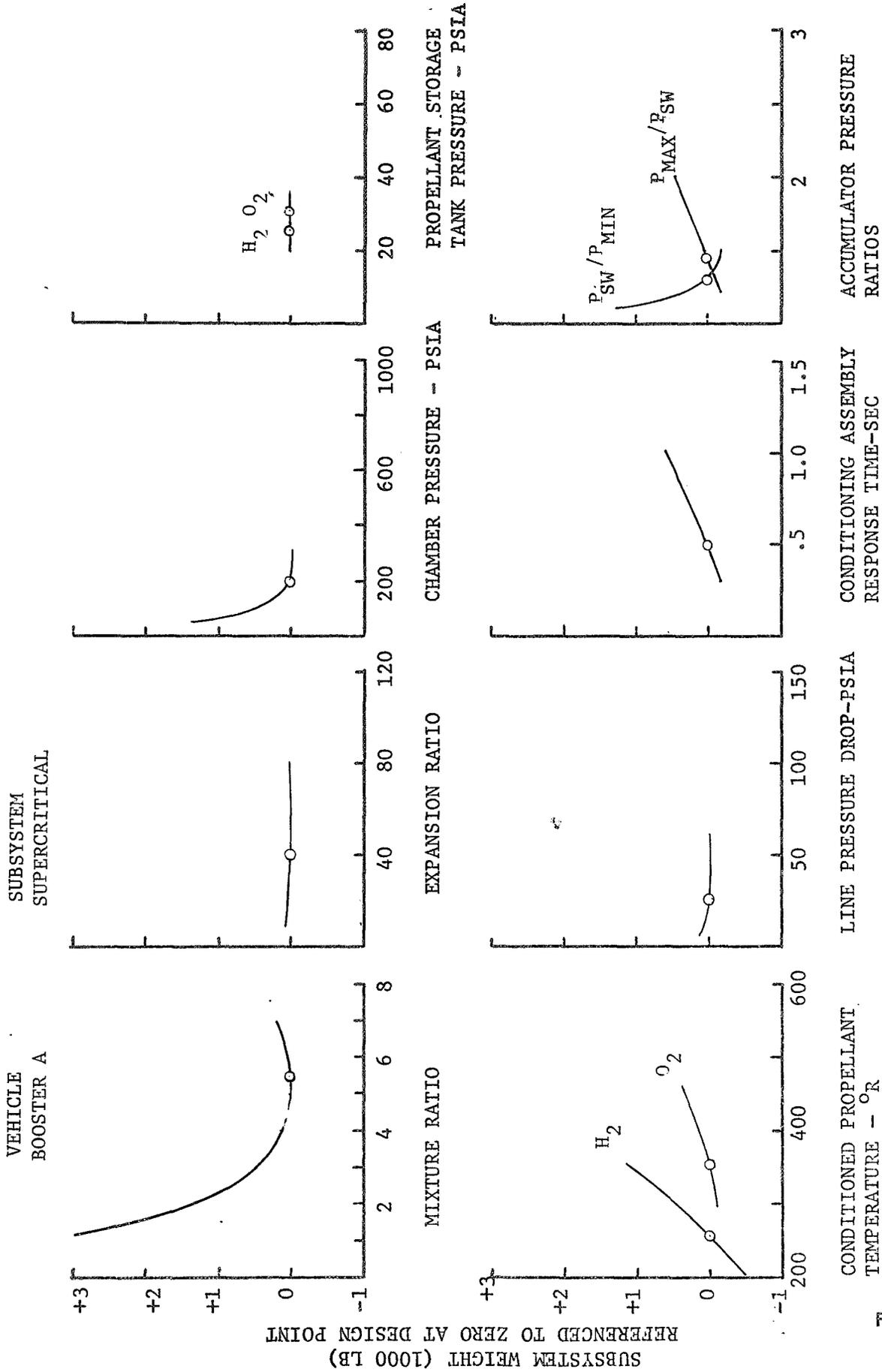
ACCUMULATOR PRESSURE
RATIOS

°DESIGN POINT FOR TRADE STUDIES

WEIGHT SENSITIVITY TO DESIGN VARIABLES

BA/TP

FIGURE B-21



WEIGHT SENSITIVITY TO DESIGN VARIABLES

BA/SC

FIGURE B-22

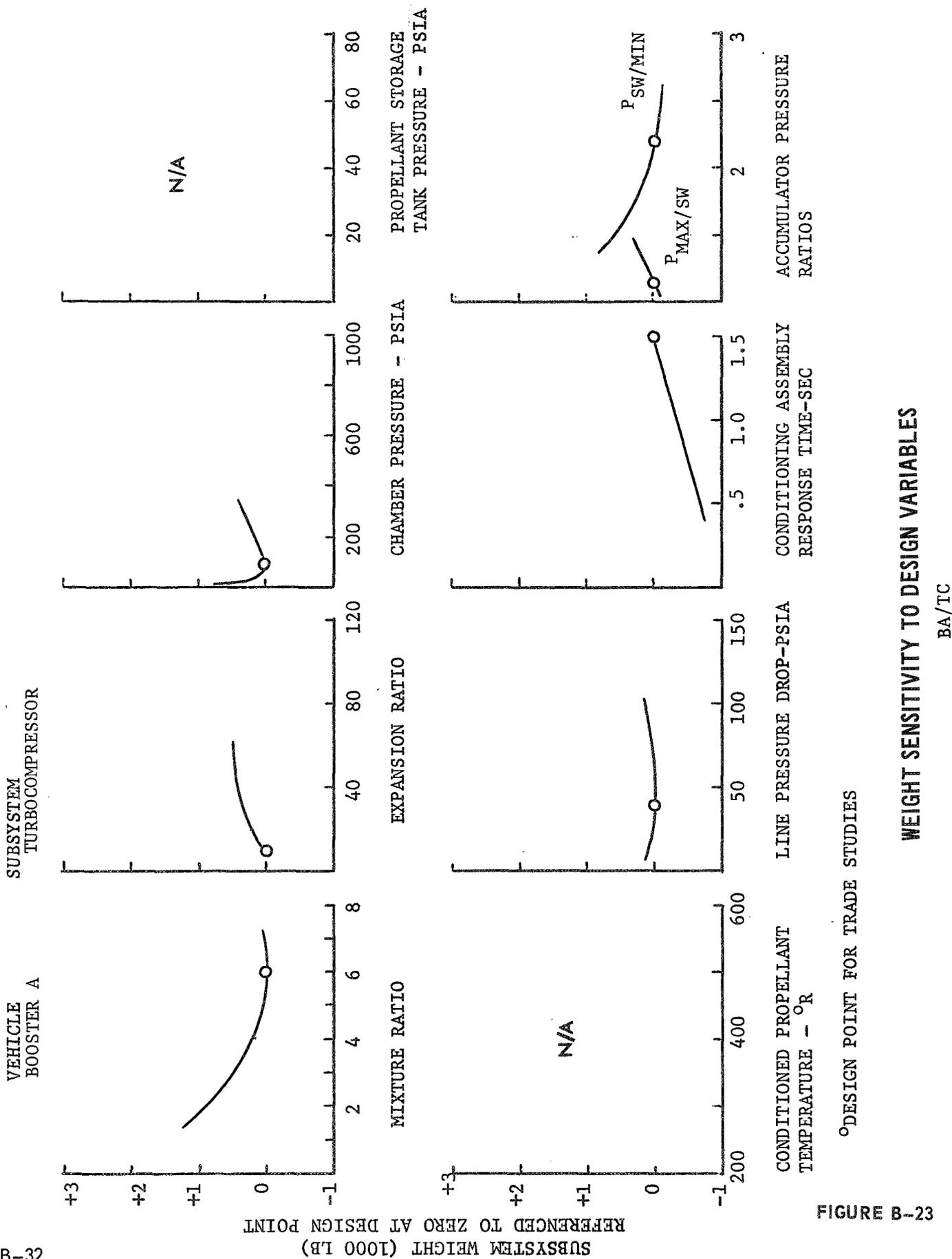
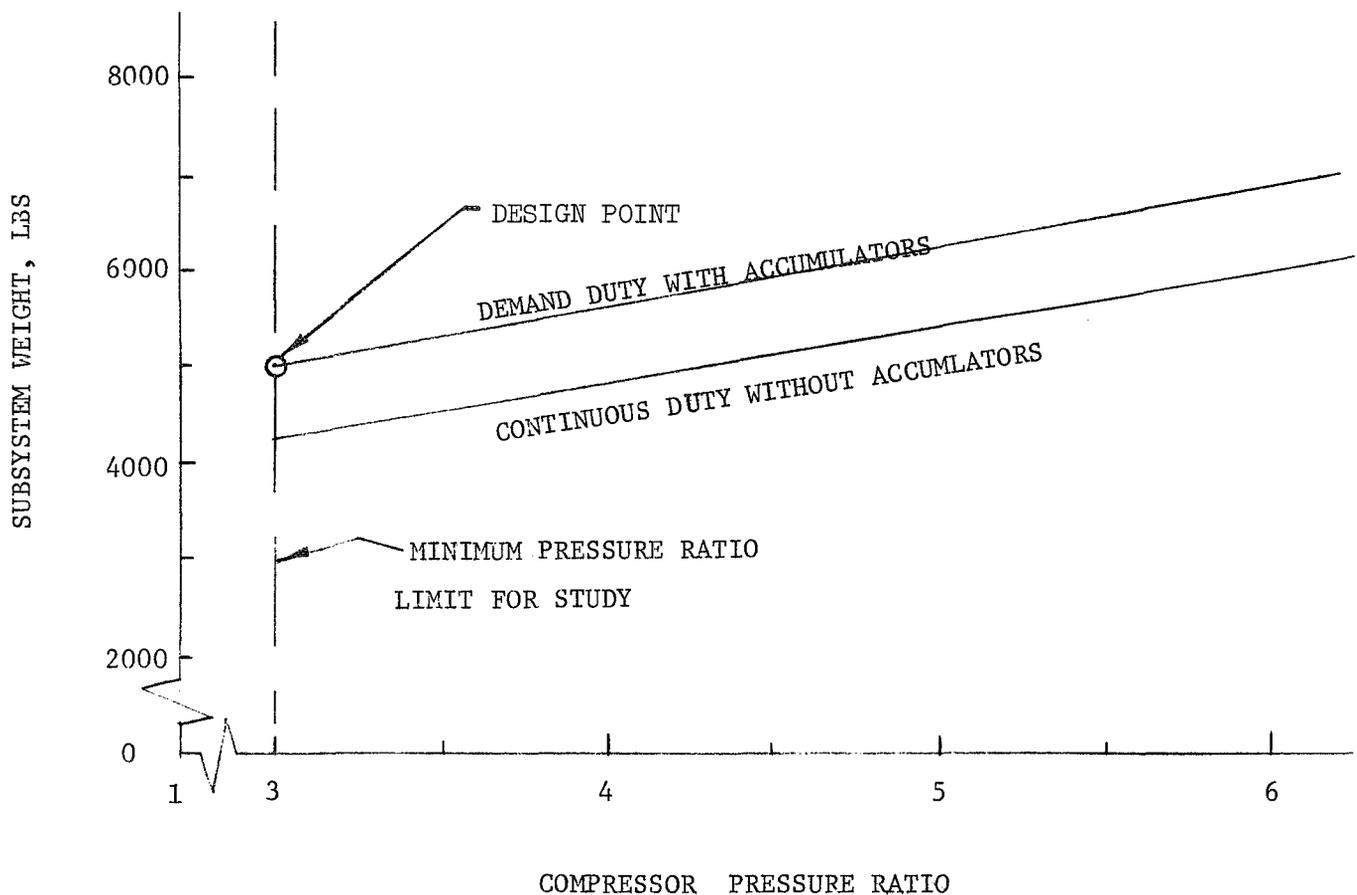


FIGURE B-23



WEIGHT SENSITIVITY TO COMPRESSOR PRESSURE RATIO
Booster A - Turbocompressor

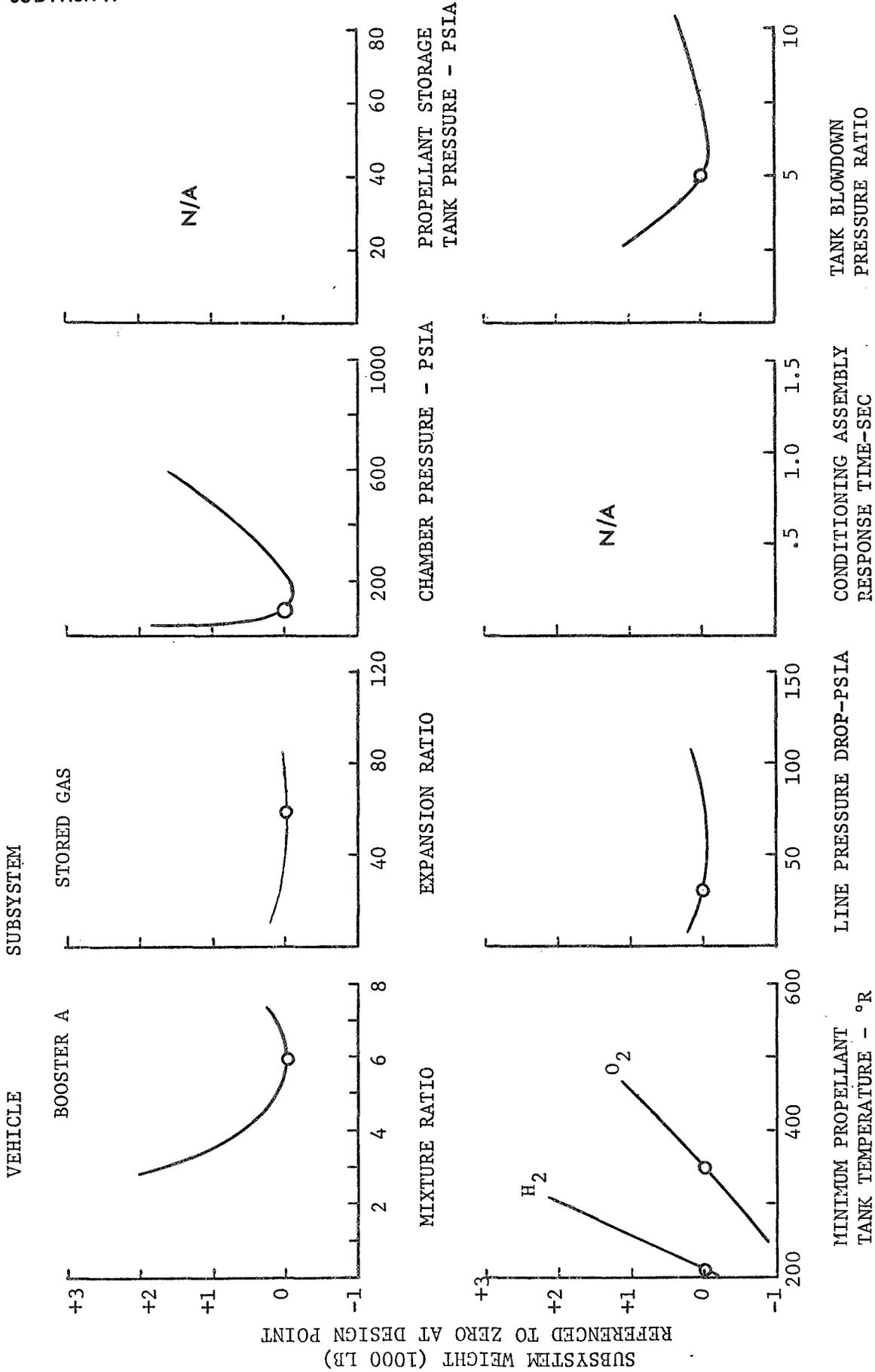
FIGURE B-24

subsystem weight as a function of compressor pressure ratio. Two operational modes are shown. These are:

- (1) conventional demand duty cycle with accumulators, and
- (2) continuous use of compressors for the short booster mission to eliminate accumulators from the subsystem.

As shown in Figure B-24, subsystem weight continuously decreases with reducing compressor pressure ratio. The design point of 3:1 was selected based on the contract definition of a high pressure subsystem as one which operated at or above main engine tank ullage pressures. The pressure of 3:1 provides a chamber pressure equal to main engine tank ullage pressure.

Booster APS weight sensitivity to design variables for the stored gas subsystem are shown in Figure B-25. The results here are similar to those in the turbopump, with the following exceptions. Chamber pressure in the stored gas subsystem optimizes at relatively low values. This results from the desire to



°DESIGN POINT FOR TRADE STUDIES

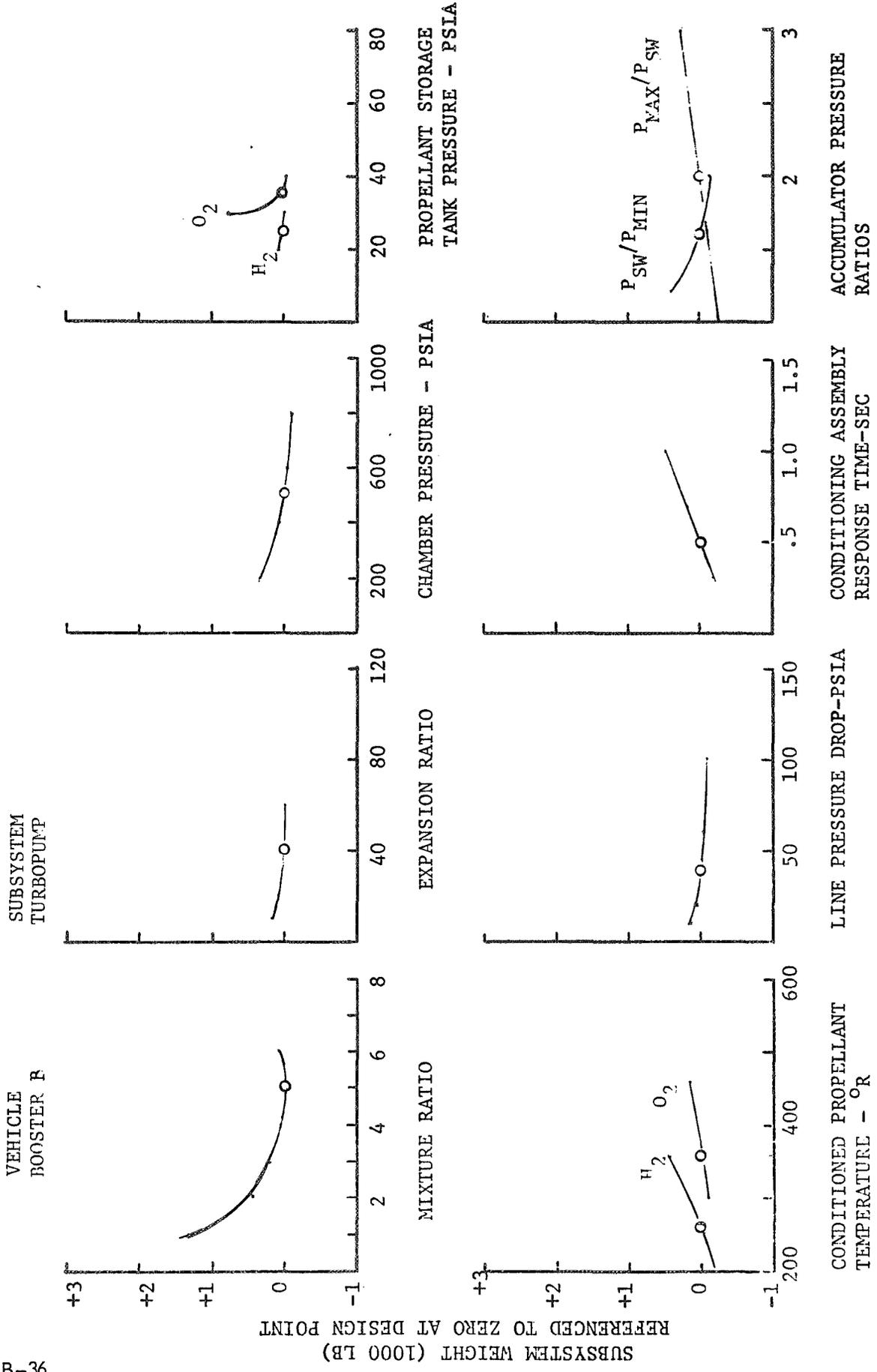
WEIGHT SENSITIVITY TO DESIGN VARIABLES

BA/SG

FIGURE B-25

leave as little residual gas in the high pressure gas storage tanks as possible. Storage tank pressure is reflected as accumulator blowdown or tank blowdown pressure ratio. Propellant temperature shown for the stored gas subsystem is not a true conditioning temperature, but rather the minimum storage temperature of the propellants. The initial gas storage temperature was designed based on this minimum tank temperature after blowdown. Tank blowdown pressure ratio is shown to be 5:1, which results in approximately 1000 lbf/in²a initial storage pressure for the gas. Figures B-26, B-27, B-28, and B-29 provide weight sensitivity data for Booster B. Comparison of these figures with the previous data for Booster A shows no significant differences between the two booster design points.

subsystem weight as a function of compressor pressure ratio. Two operational modes are shown. These are: (1) conventional demand duty cycle with accumulators, and (2) continuous use of compressors for the short booster mission to eliminate accumulators from the subsystem. As shown in Figure B-24, subsystem weight continuously decreases with reducing compressor pressure ratio. The design point of 3:1 was selected based on the contract definition of a high pressure subsystem as one which operated at or above main engine tank ullage pressures. The pressure of 3:1 provides a chamber pressure equal to main engine tank ullage pressure.



WEIGHT SENSITIVITY TO DESIGN VARIABLES

BB/TP

FIGURE B-26

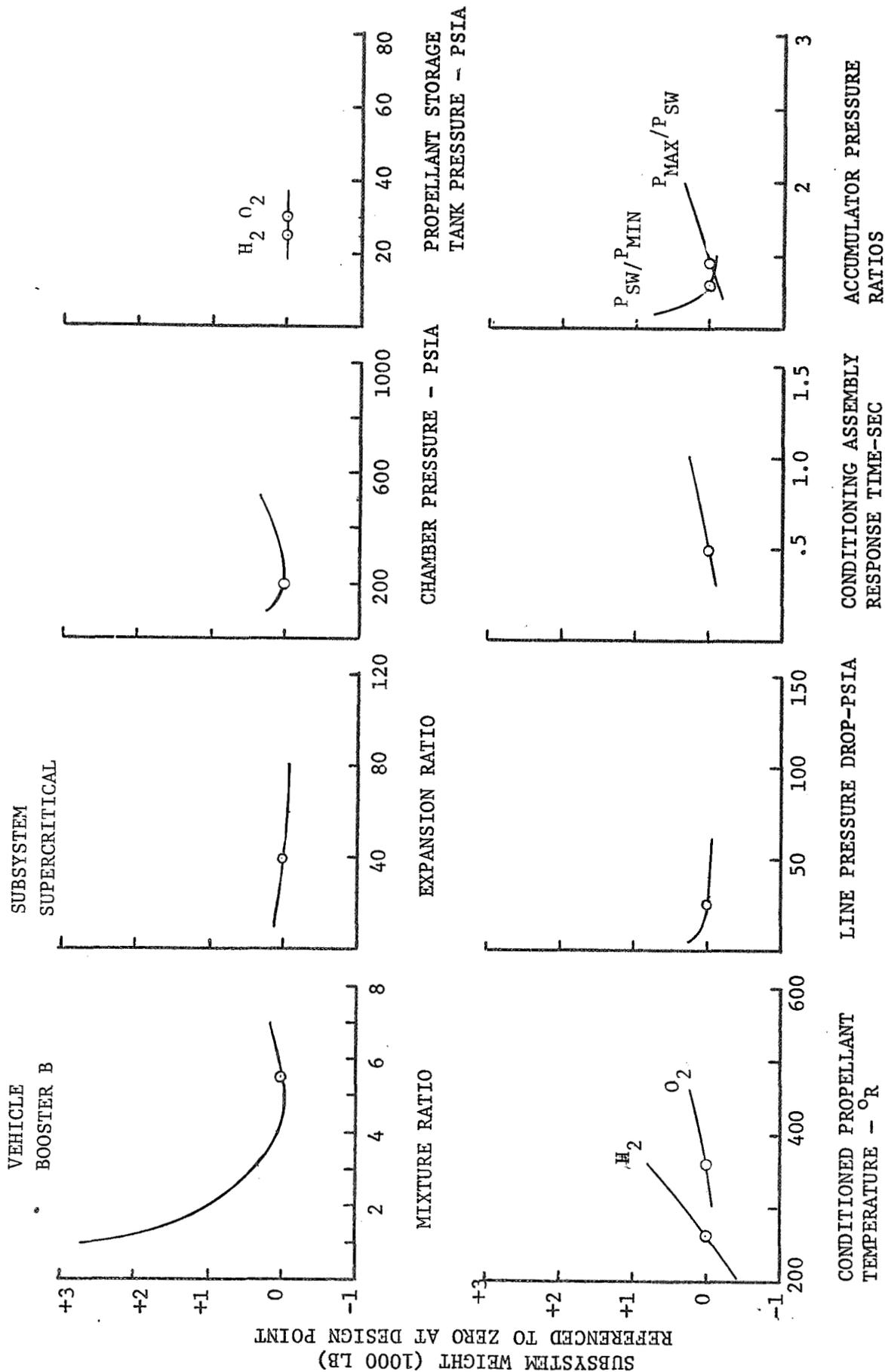
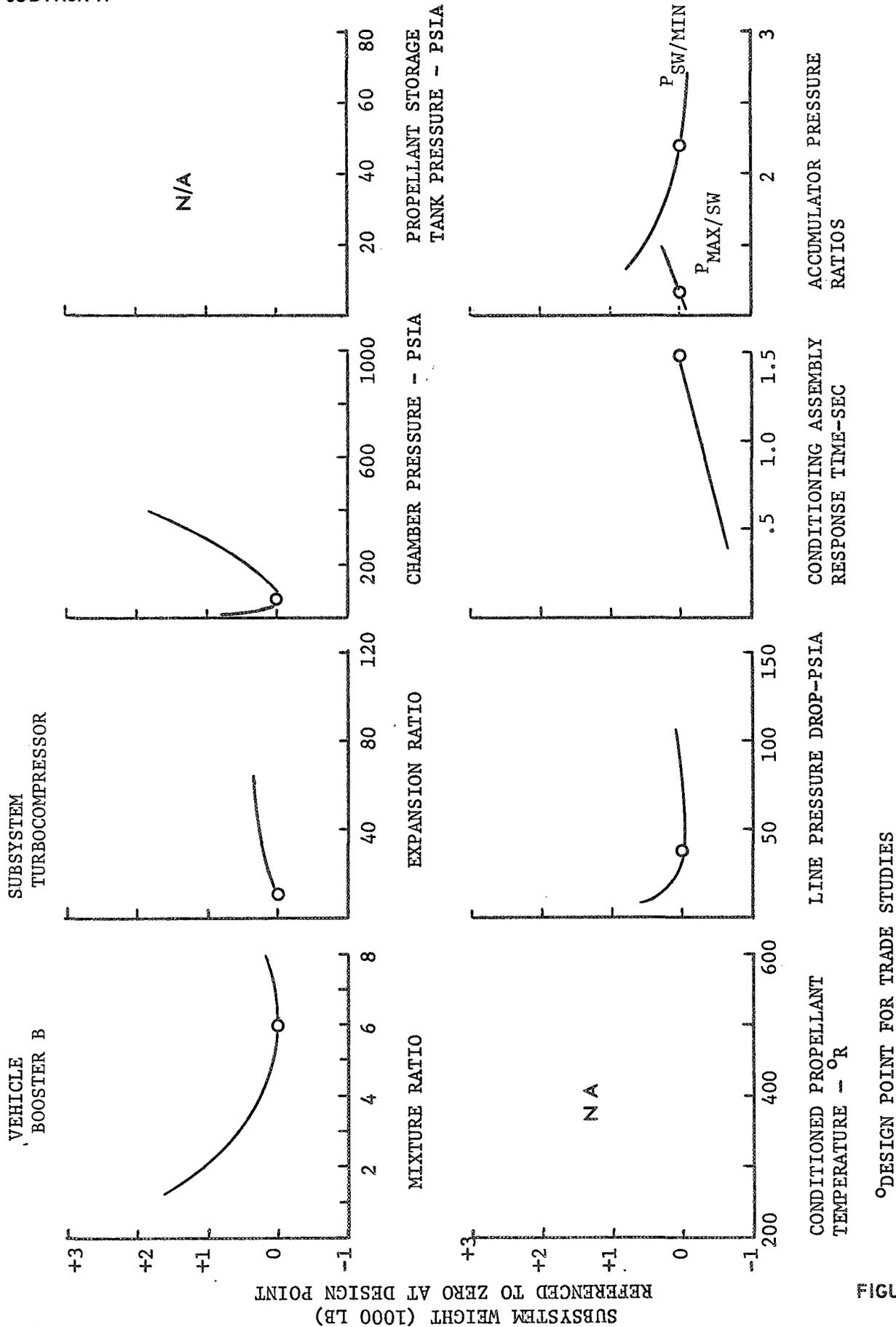


FIGURE B-27

WEIGHT SENSITIVITY TO DESIGN VARIABLES

BB/SC



WEIGHT SENSITIVITY TO DESIGN VARIABLES

BB/TC

FIGURE B-28

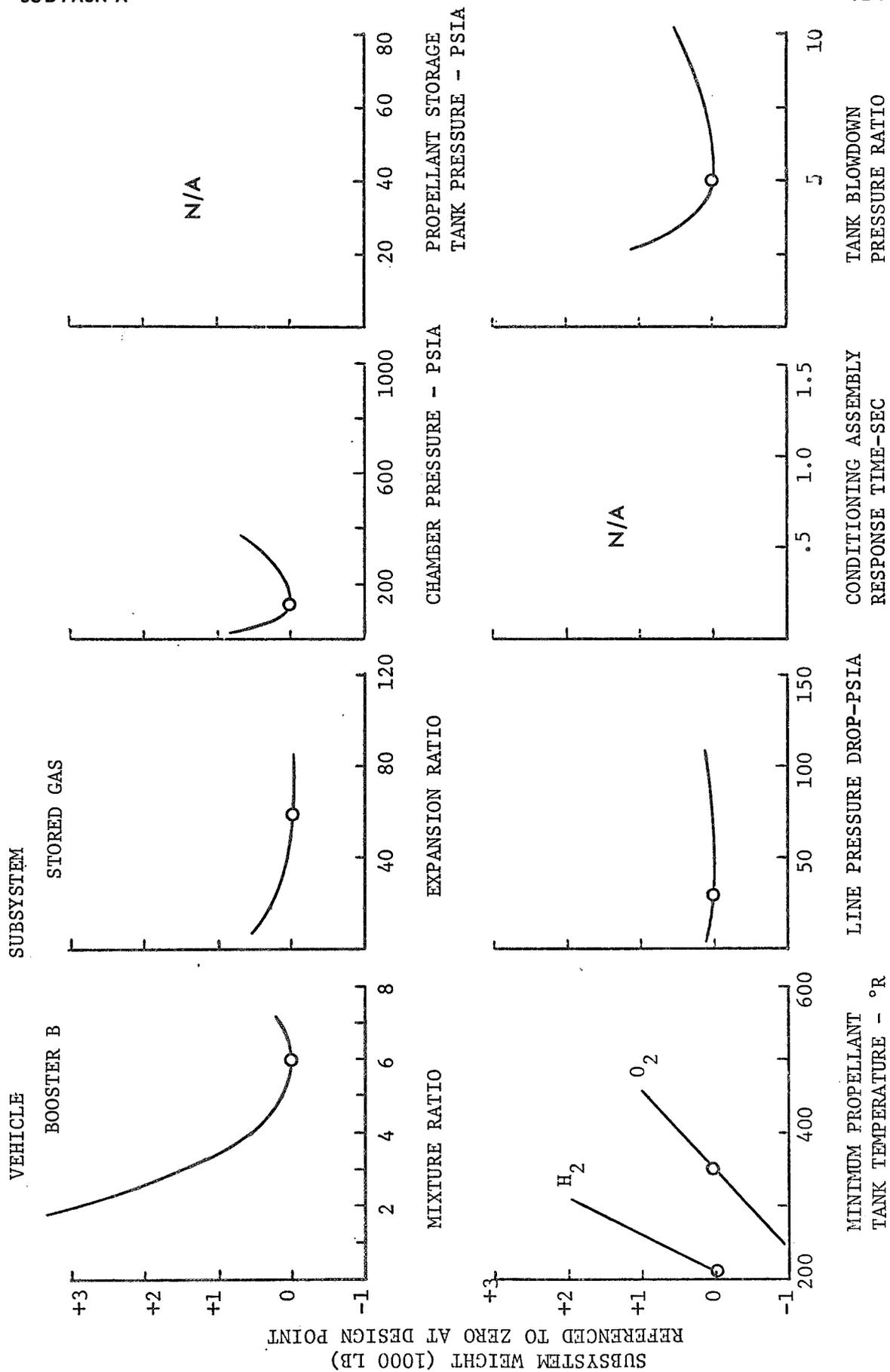


FIGURE B-29

DESIGN POINT FOR TRADE STUDIES

WEIGHT SENSITIVITY TO DESIGN VARIABLES

BB/SG

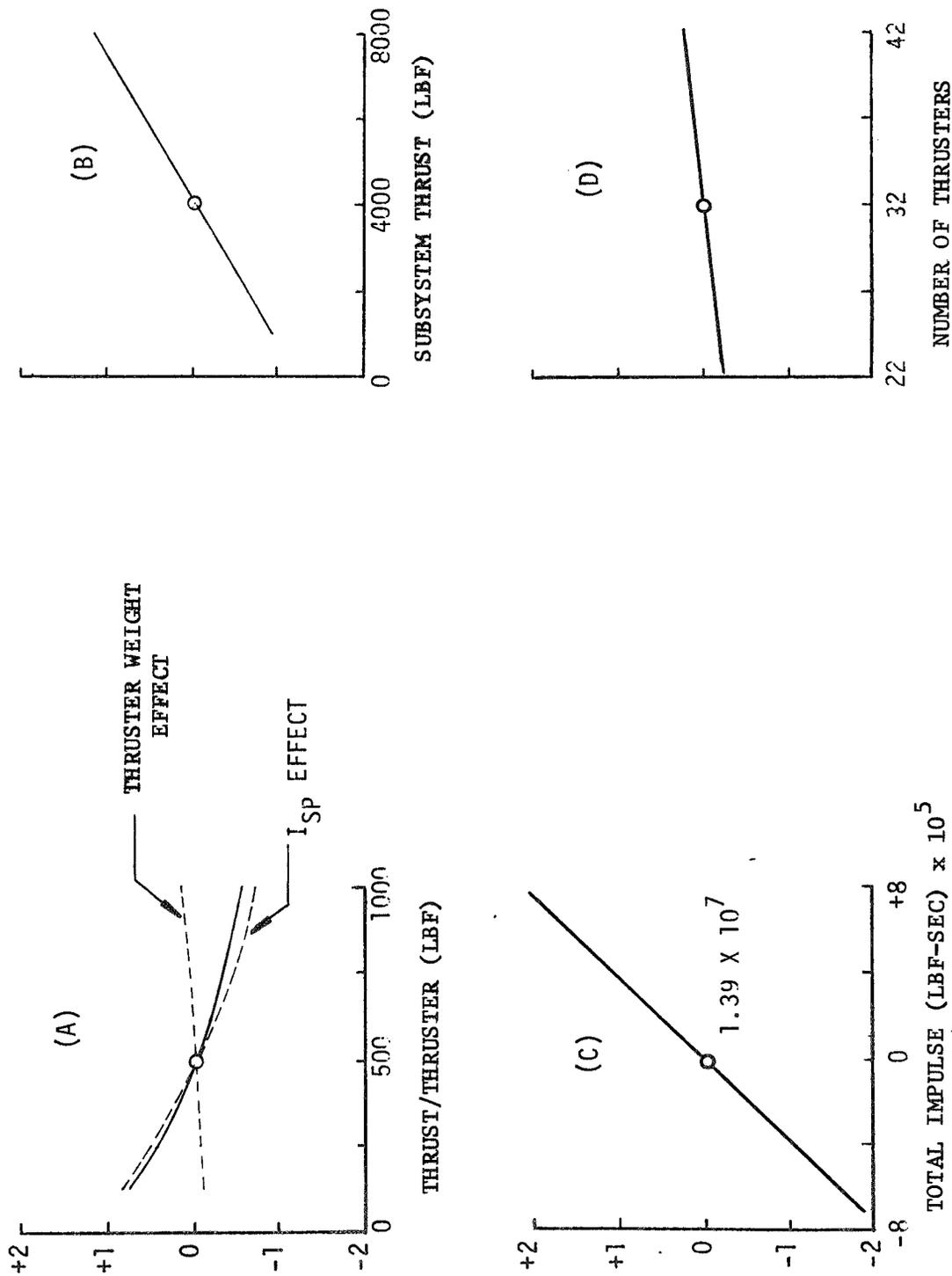
B-8. APS WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

Figures B-30 through B-47 present APS weight sensitivity for the 18 basic APS concepts as a function of APS thrust level per thruster, total subsystem thrust, APS total impulse, and number of APS thrusters. For purposes of these analyses, all sensitivities are partial derivatives of weight with respect to the parameter of interest. All other design variables were held constant. For example, when assessing the change in APS weight as a function of a change in thrust/thruster, size of conditioners and number of thrusters were held constant, as were all other design parameters such as mixture ratio, chamber pressure, and expansion ratio. Thus, only the change in thruster size is reflected. Similarly, when total impulse was changed, mixture ratio, expansion ratio, etc. were not reoptimized, but were held at their original design values.

As with weight sensitivity to design variables, there was significant similarity among results for the various subsystems. For this reason, the following discussion will treat a single example subsystem in some depth and, for the remainder, will concern itself only with areas of difference.

Figure B-30 shows weight sensitivity for the turbopump APS design for Orbiter A performing all control and maneuvering functions. Trends shown are generally as expected. The exception is the sensitivity of subsystem weight to thrust per thruster. As thrust is increased, subsystem weight decreases. This results from the fact that, at the fixed design chamber pressure, as thruster thrust is increased, the fraction of film cooling required can be decreased. As a result, thruster specific impulse is improved. This is shown in Figure B-30A, which illustrates three separate sensitivities to thrust per thruster. The first is the increase in inert hardware weight associated with increasing thruster size (thrust) at a constant chamber pressure. The second dashed line shows the effect of improved thruster specific impulse with reduced film cooling. Significant reductions in weight resulted from improvements in thruster performance. The solid curve for Figure B-30A combines these two sensitivities to show overall APS weight change with changing thrust per thruster. The net effect was a decrease in weight with increased thrust. Figure B-30B shows the sensitivity of APS weight to subsystem thrust. For this sensitivity, number of thrusters and thrust level was held constant; the only change being the maximum number of thrusters that could operate simultaneously (i.e., subsystem thrust). From the design point

VEHICLE ORBITER A SUBSYSTEM TURBOPUMP IMPULSE CLASS ALL MANEUVER



SUBSYSTEM WEIGHT (1000 LB) REFERENCED
TO ZERO AT DESIGN POINT

WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

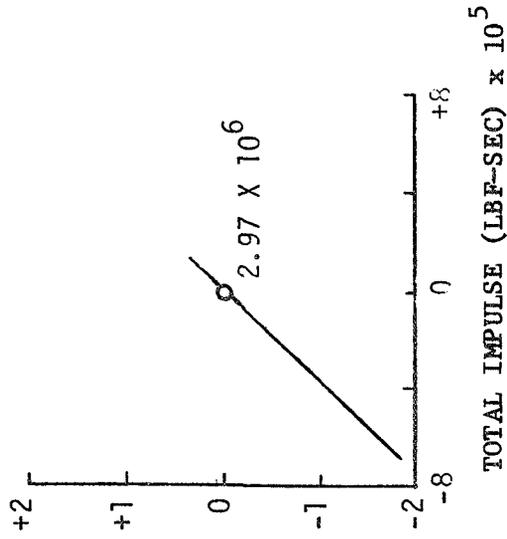
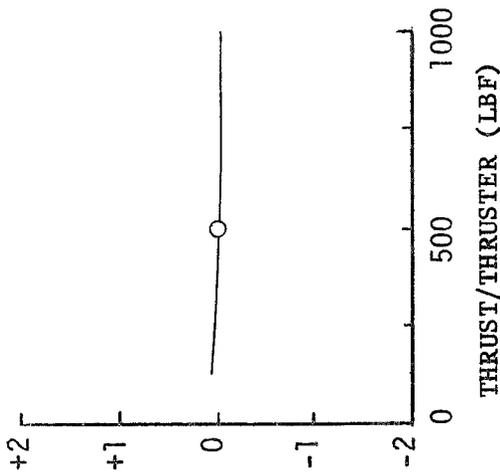
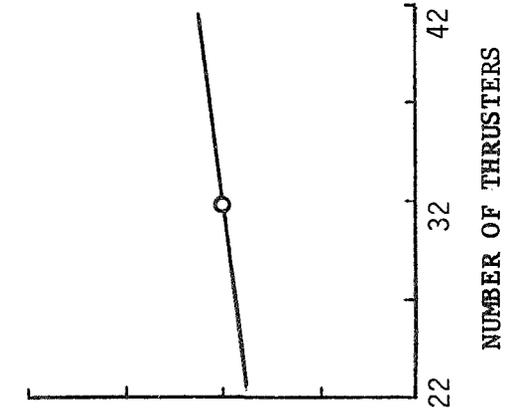
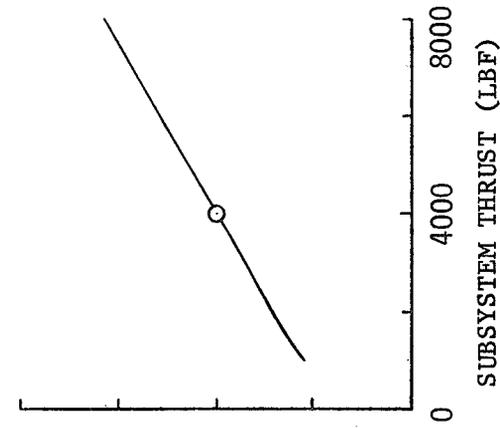
OA/TP/ALL

FIGURE B-30

IMPULSE CLASS \leq 50 FPS

SUBSYSTEM TURBOPUMP

VEHICLE ORBITER A

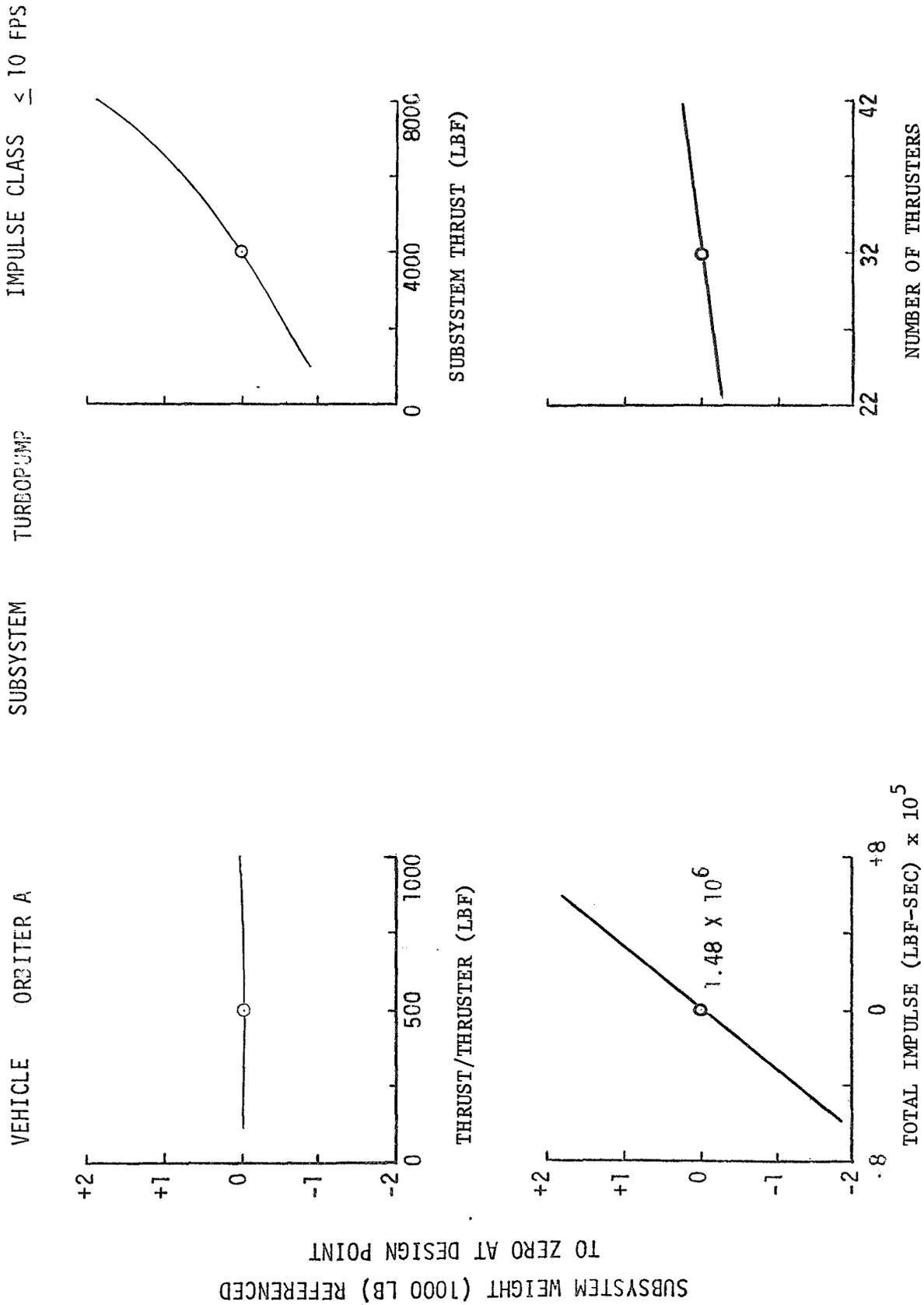


SUBSYSTEM WEIGHT (1000 LB) REFERENCED
TO ZERO AT DESIGN POINT

WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

OA/TP/50 FPS

FIGURE B-31



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

OA/TP/10 FPS

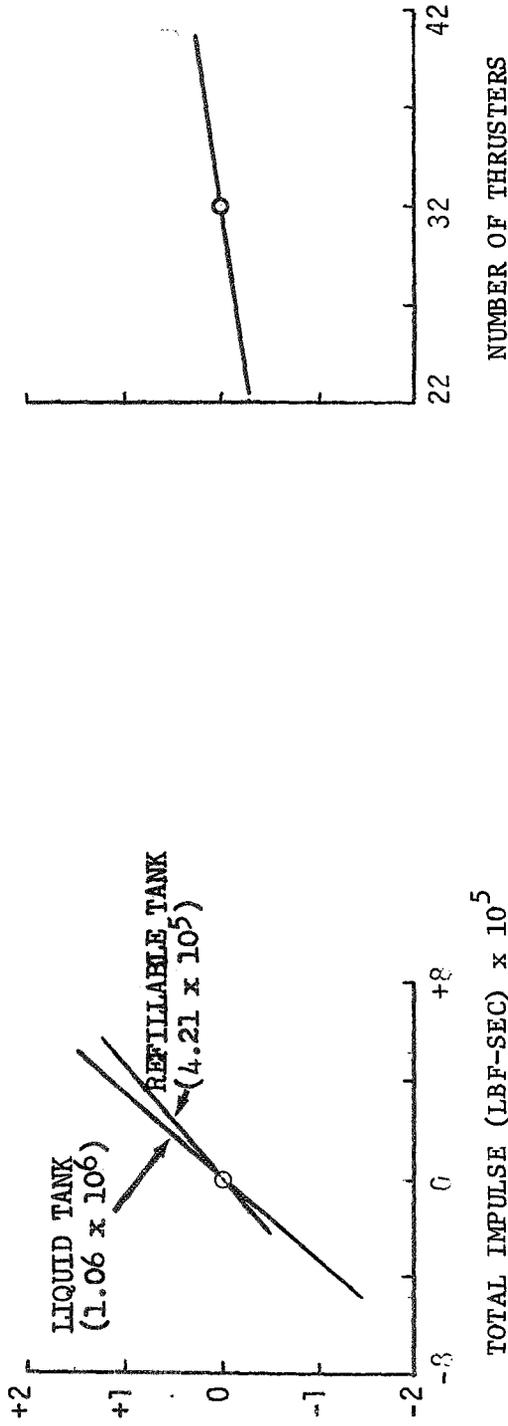
FIGURE B-32

VEHICLE ORBITER A SUBSYSTEM SUPERCRITICAL IMPULSE CLASS < 10 FPS



SUBSYSTEM THRUST (LBF)

THRUST/THRUSTER (LBF)



NUMBER OF THRUSTERS

TOTAL IMPULSE (LBF-SEC) x 10⁵

SUBSYSTEM WEIGHT (1000 LB) REFERENCED
TO ZERO AT DESIGN POINT

WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

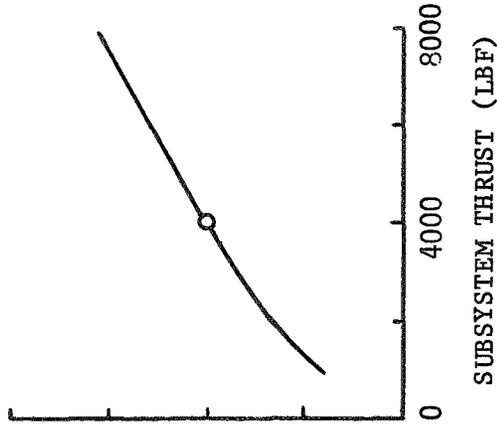
OA/SC/10 FPS

FIGURE B-33

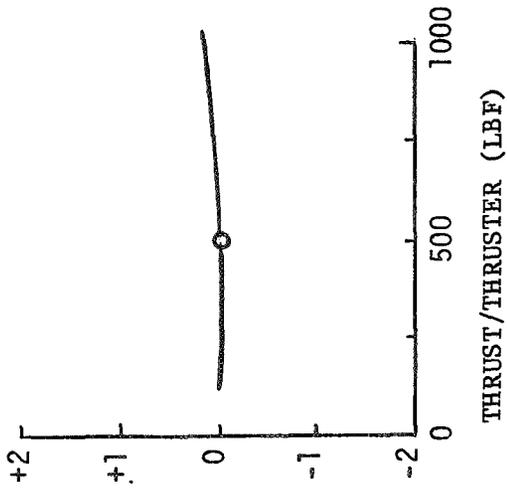
IMPULSE CLASS \leq 10 FPS

HYBRID

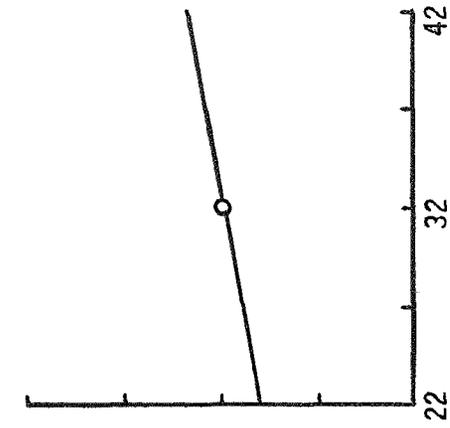
SUBSYSTEM



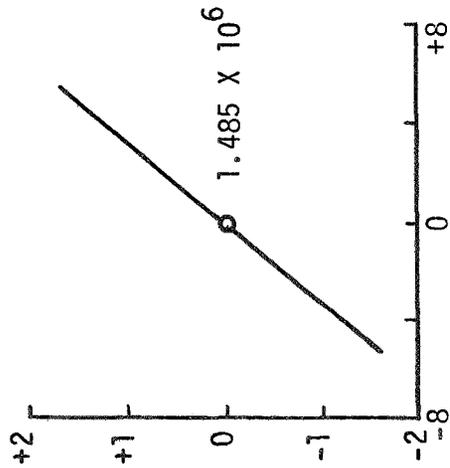
VEHICLE ORBITER A



SUBSYSTEM WEIGHT (1000 LB) REFERENCED
TO ZERO AT DESIGN POINT



NUMBER OF THRUSTERS



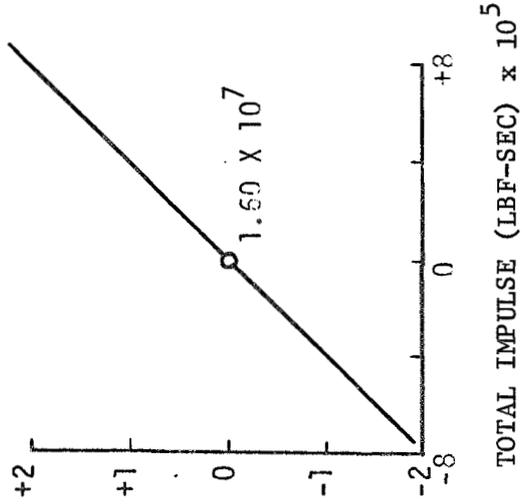
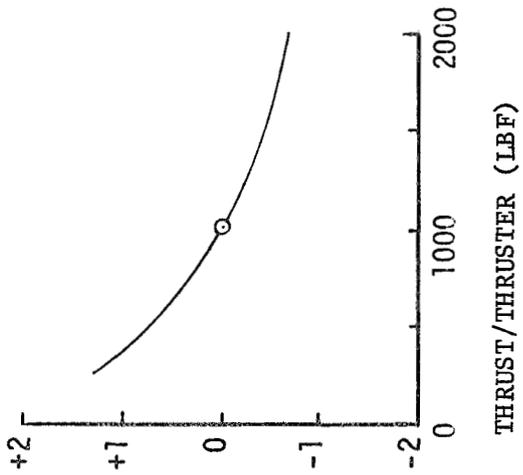
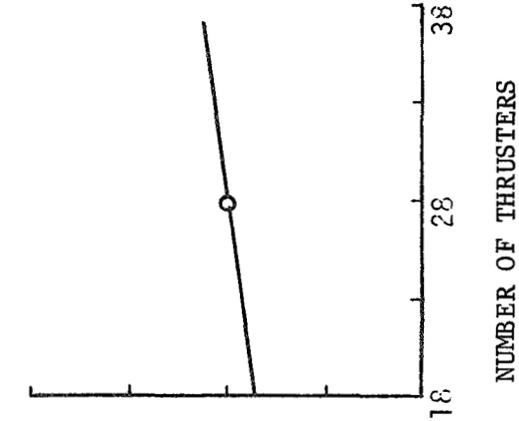
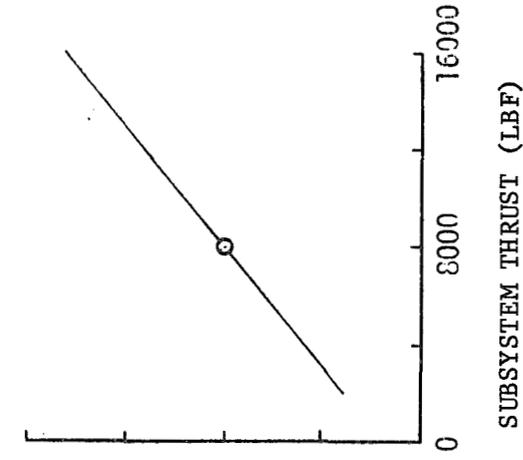
TOTAL IMPULSE (LBF-SEC) $\times 10^5$

WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

OA/HY/10 FPS

FIGURE B-34

VEHICLE ORBITER B SUBSYSTEM TURBOPUMP IMPULSE CLASS ALL MANEUVER



TO ZERO AT DESIGN POINT
SUBSYSTEM WEIGHT (1000 LB) REFERENCED

WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS
OB/TP/ALL

FIGURE B-35

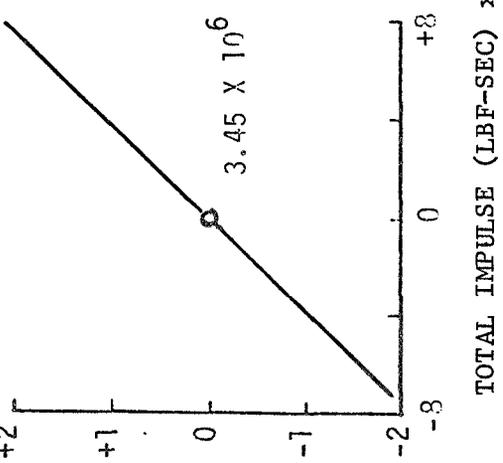
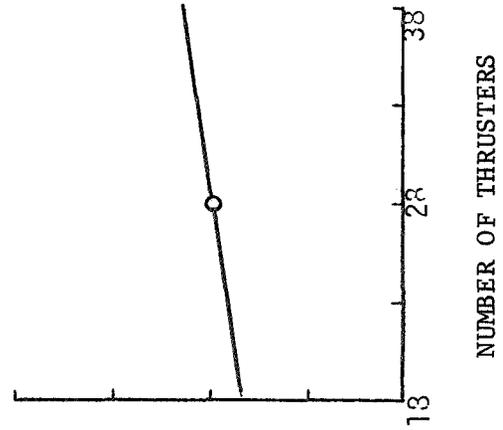
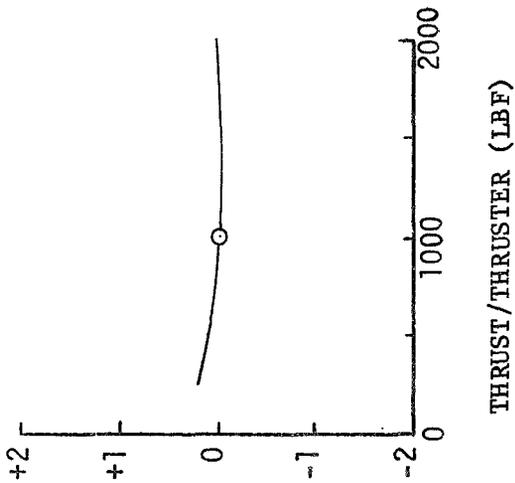
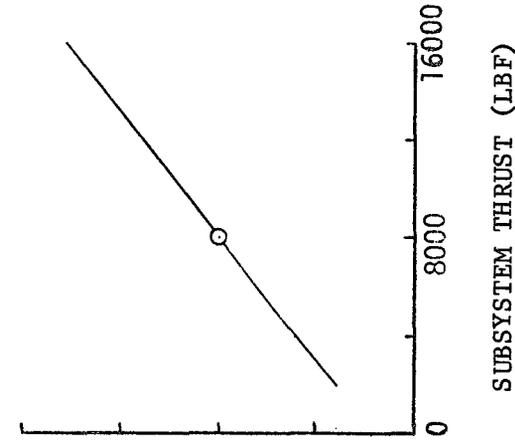
IMPULSE CLASS \leq 50 FPS

TURBOPUMP

SUBSYSTEM

ORBITER B

VEHICLE



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

OB/TP/50 FPS

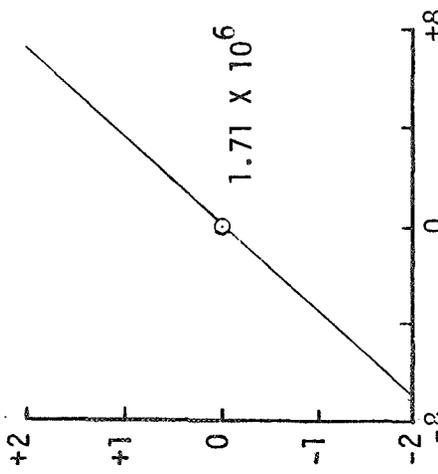
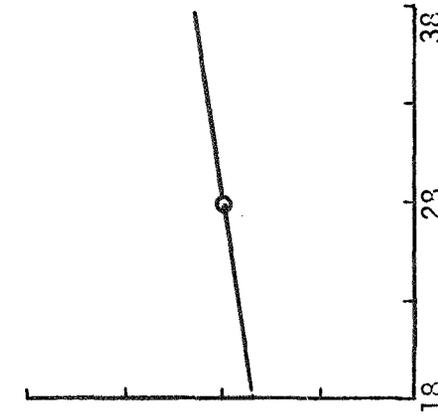
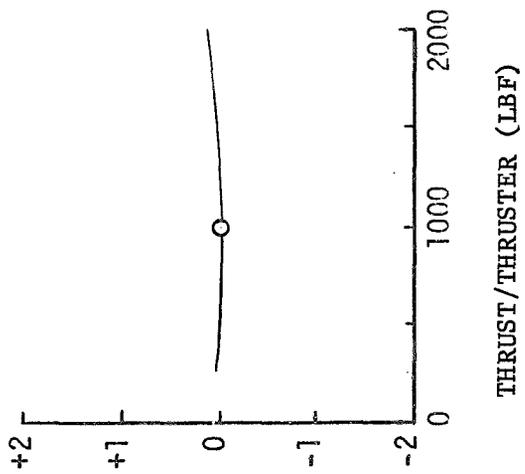
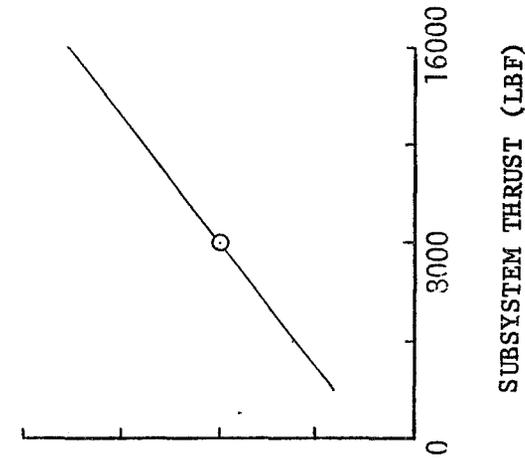
SUBSYSTEM WEIGHT (1000 LB) REFERENCED
TO ZERO AT DESIGN POINT

FIGURE B-36

IMPULSE CLASS \leq 10 FPS

SUBSYSTEM TURBOPUMP

VEHICLE ORBITER B



TOTAL IMPULSE (LBF-SEC) x 10⁵

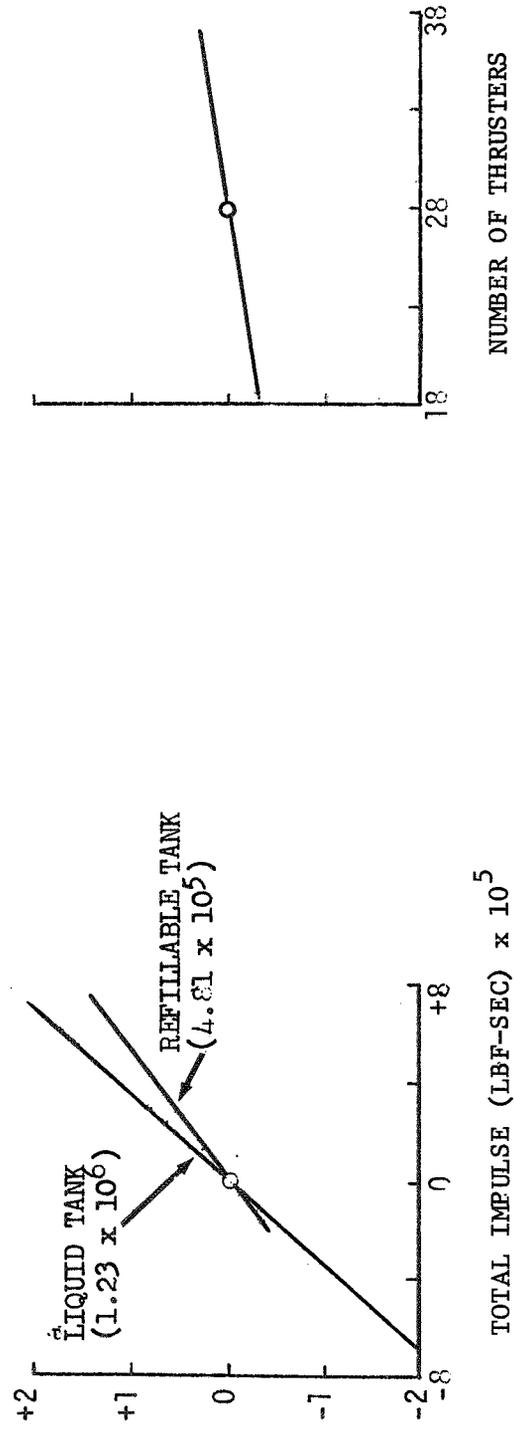
NUMBER OF THRUSTERS

WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS
OB/TP/10 FPS

SUBSYSTEM WEIGHT (1000 LB) REFERENCED
TO ZERO AT DESIGN POINT

FIGURE B-37

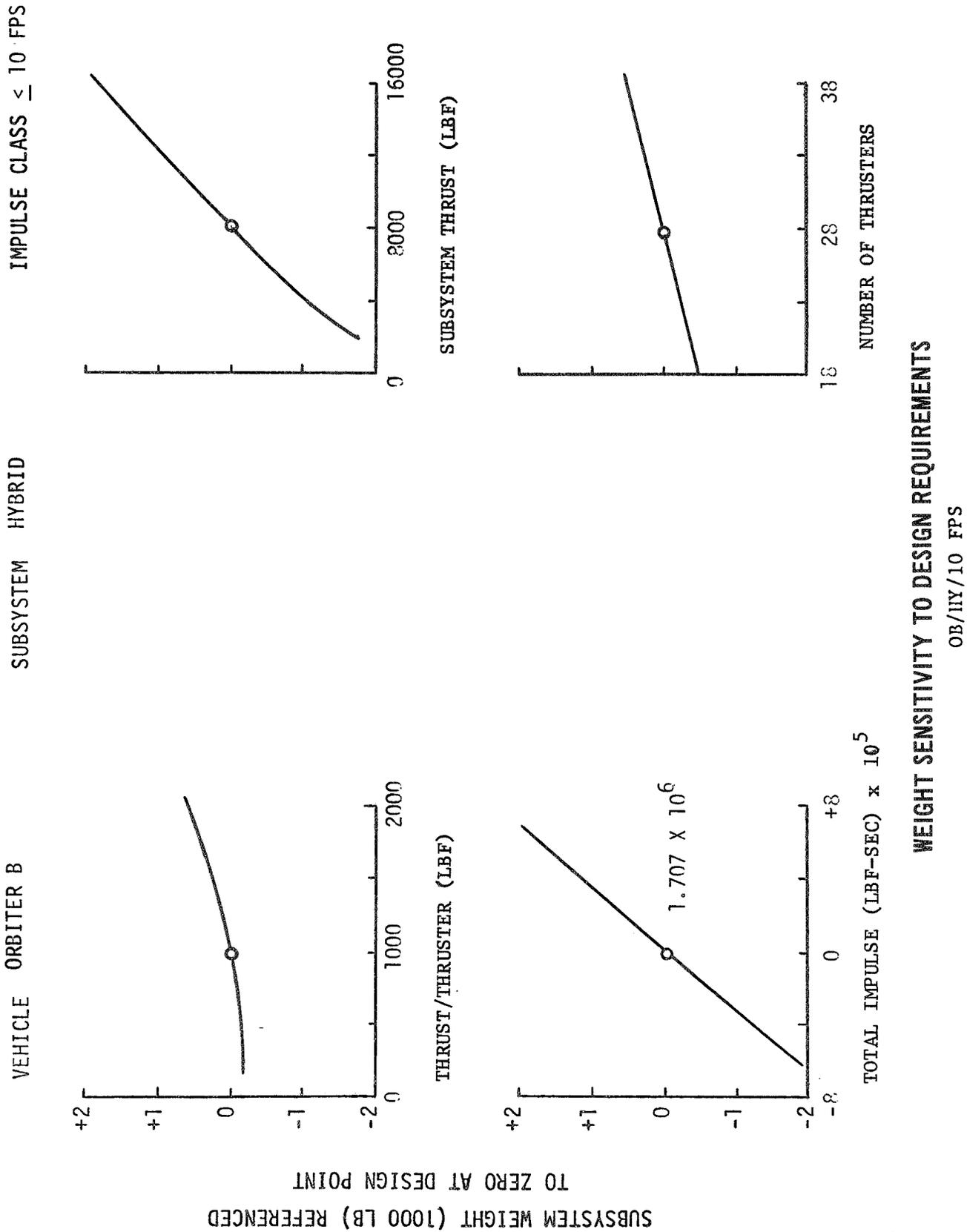
VEHICLE ORBITER B SUBSYSTEM IMPULSE CLASS \leq 10 FPS



SUBSYSTEM WEIGHT (1000 LB) REFERENCED
TO ZERO AT DESIGN POINT

WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS
OB/SC/10 FPS

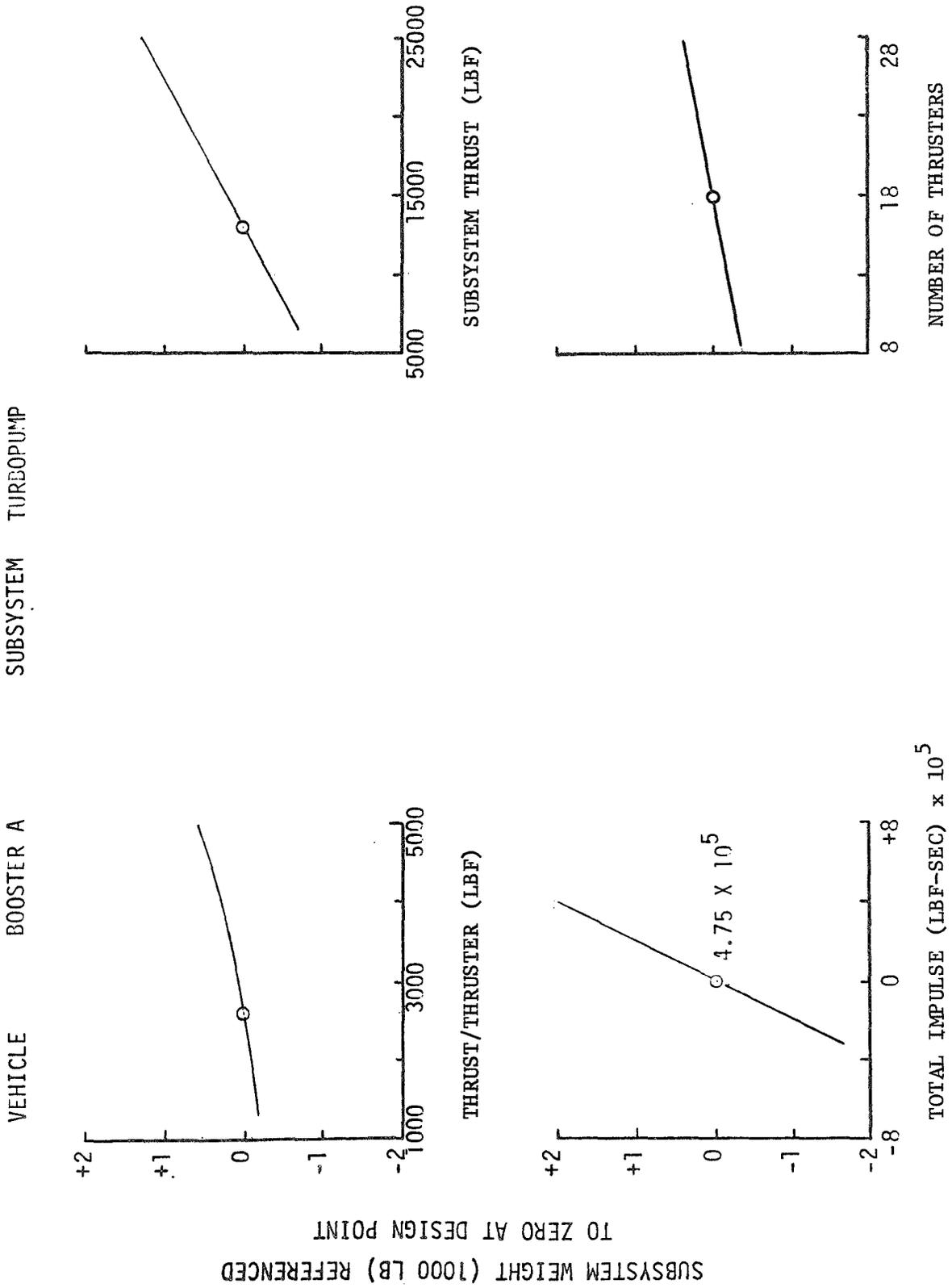
FIGURE B-38



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

OB/HY/10 FPS

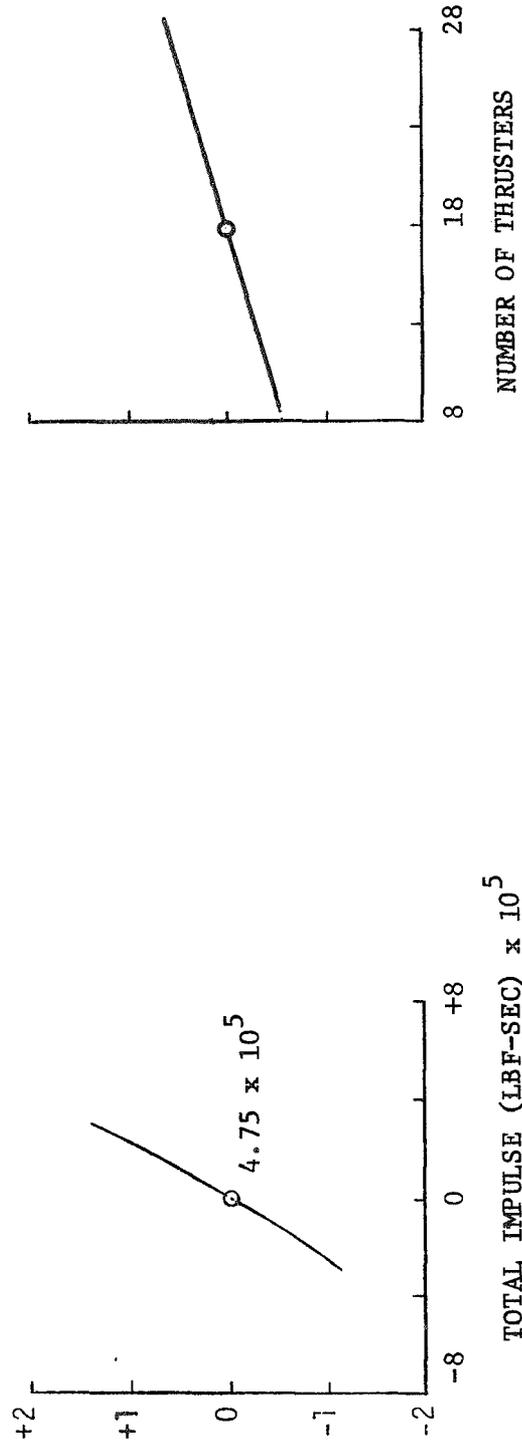
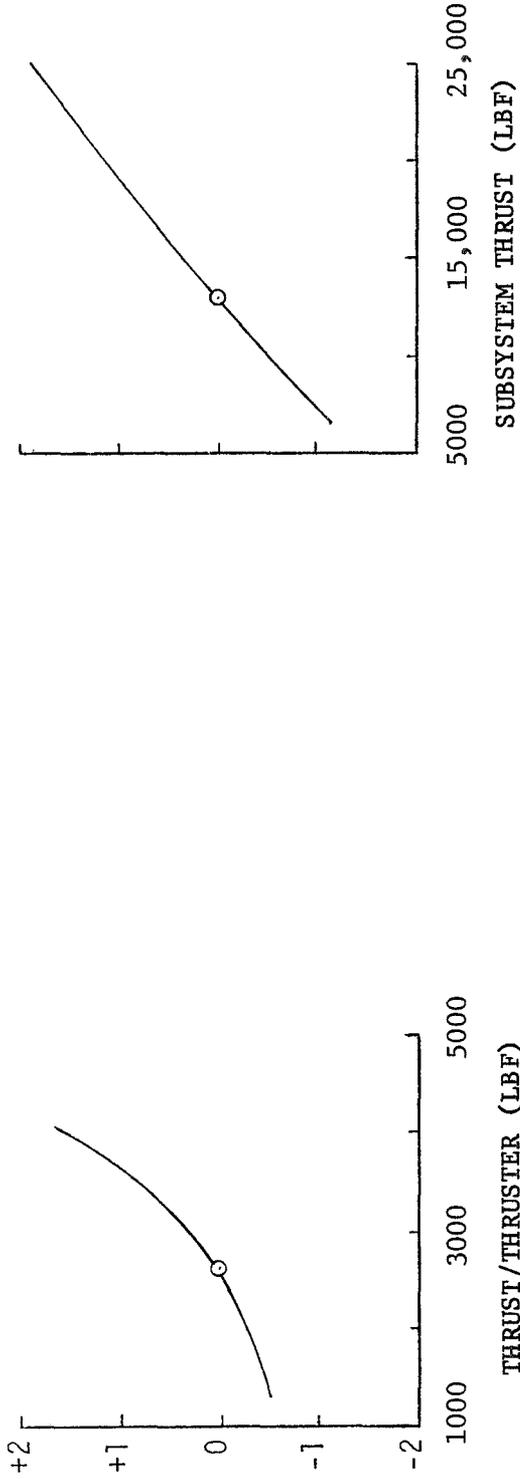
FIGURE B-39



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS
BA/TP

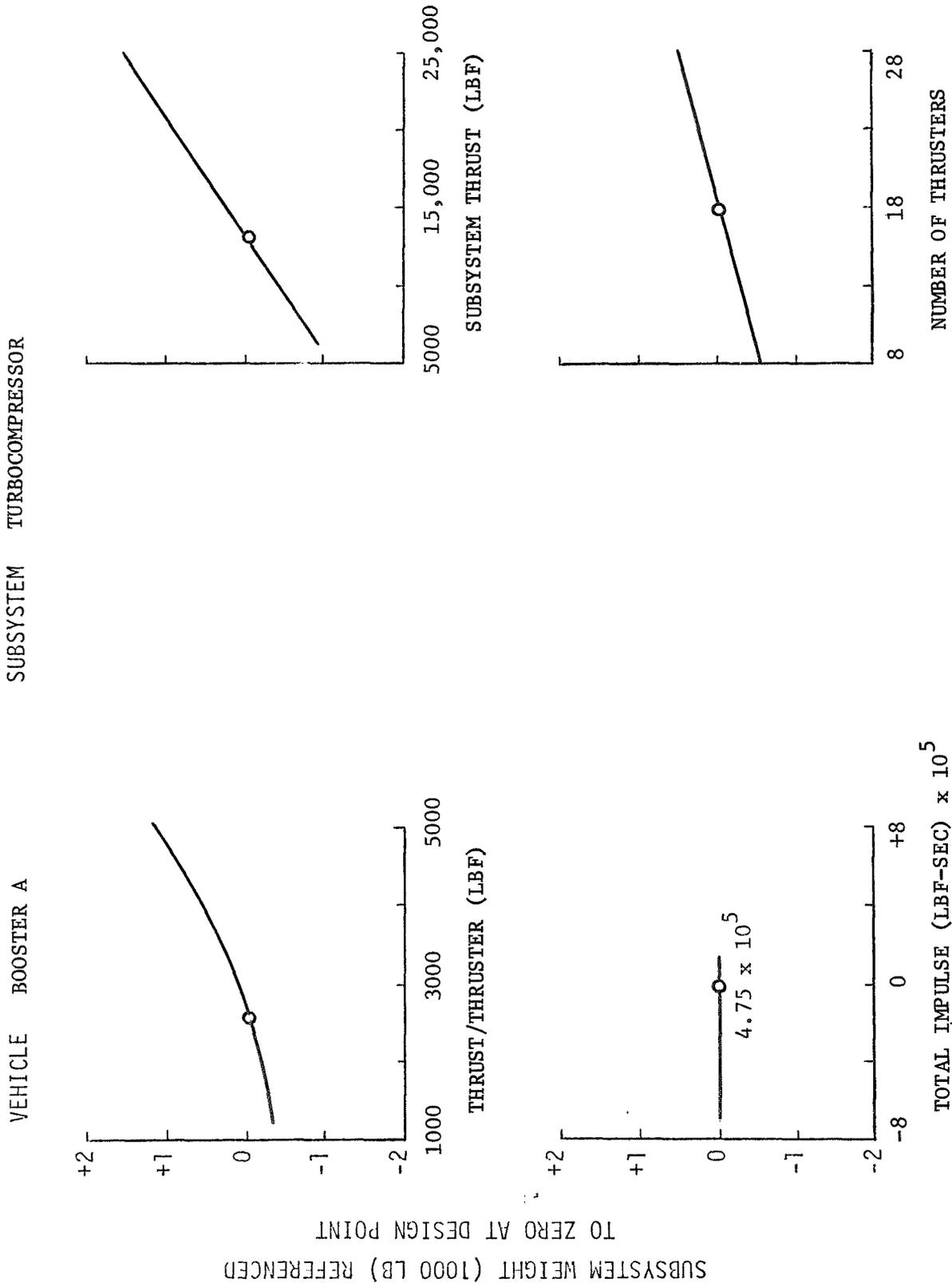
FIGURE B-40

VEHICLE BOOSTER A SUBSYSTEM SUPERCRITICAL



TOTAL IMPULSE (LBF-SEC) $\times 10^5$

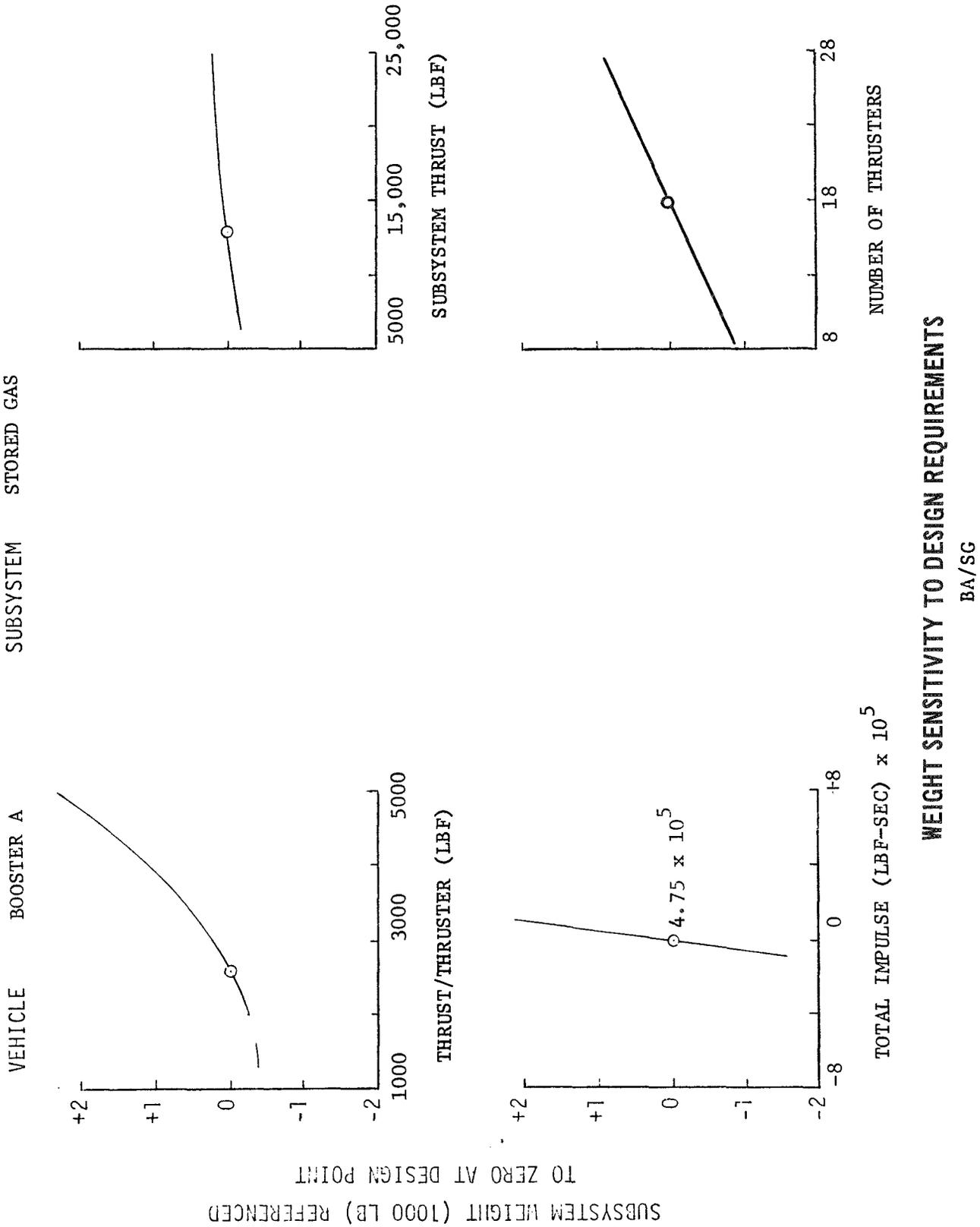
WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS
BA/SC



WEIGHT SENSITIVITY TO DESIGN VARIABLES

BA/TC

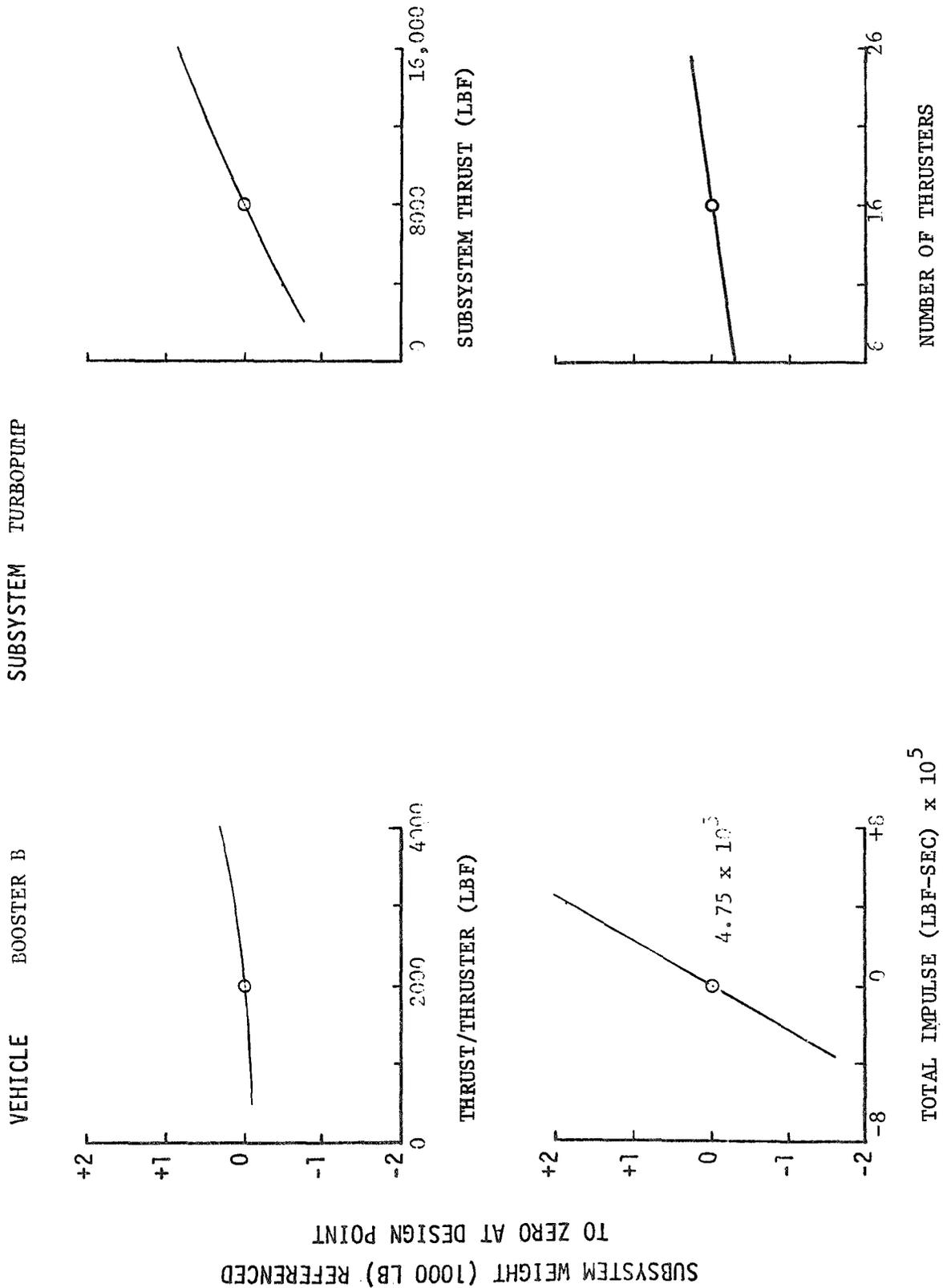
FIGURE B-42



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

BA/SG

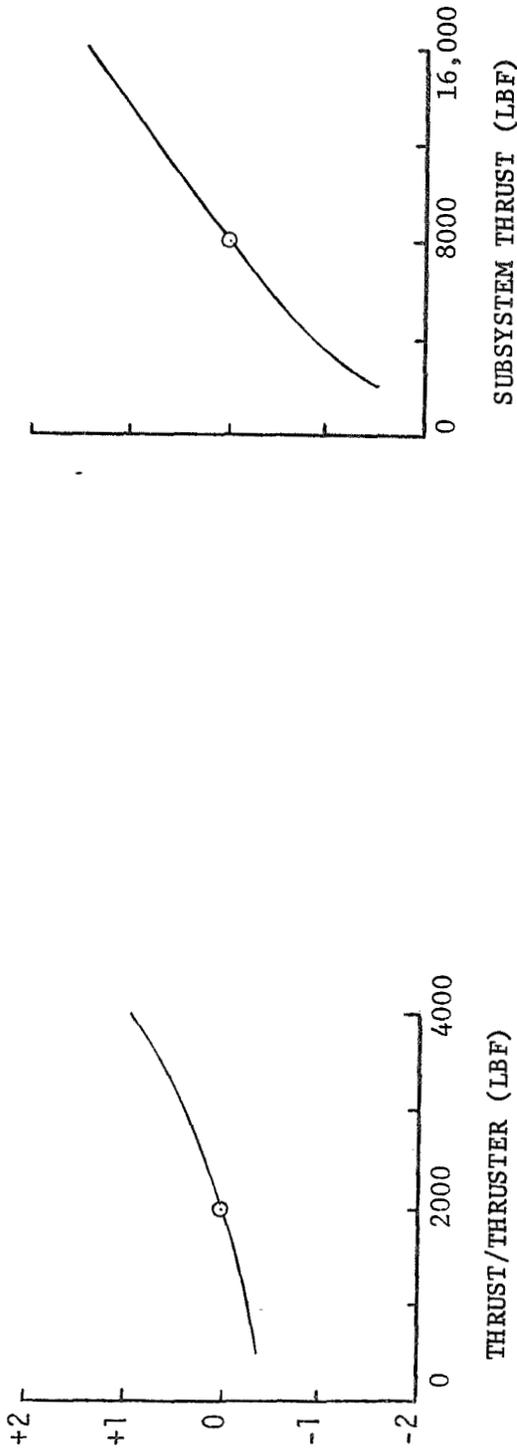
FIGURE B-43



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS
BB/TP

FIGURE B-44

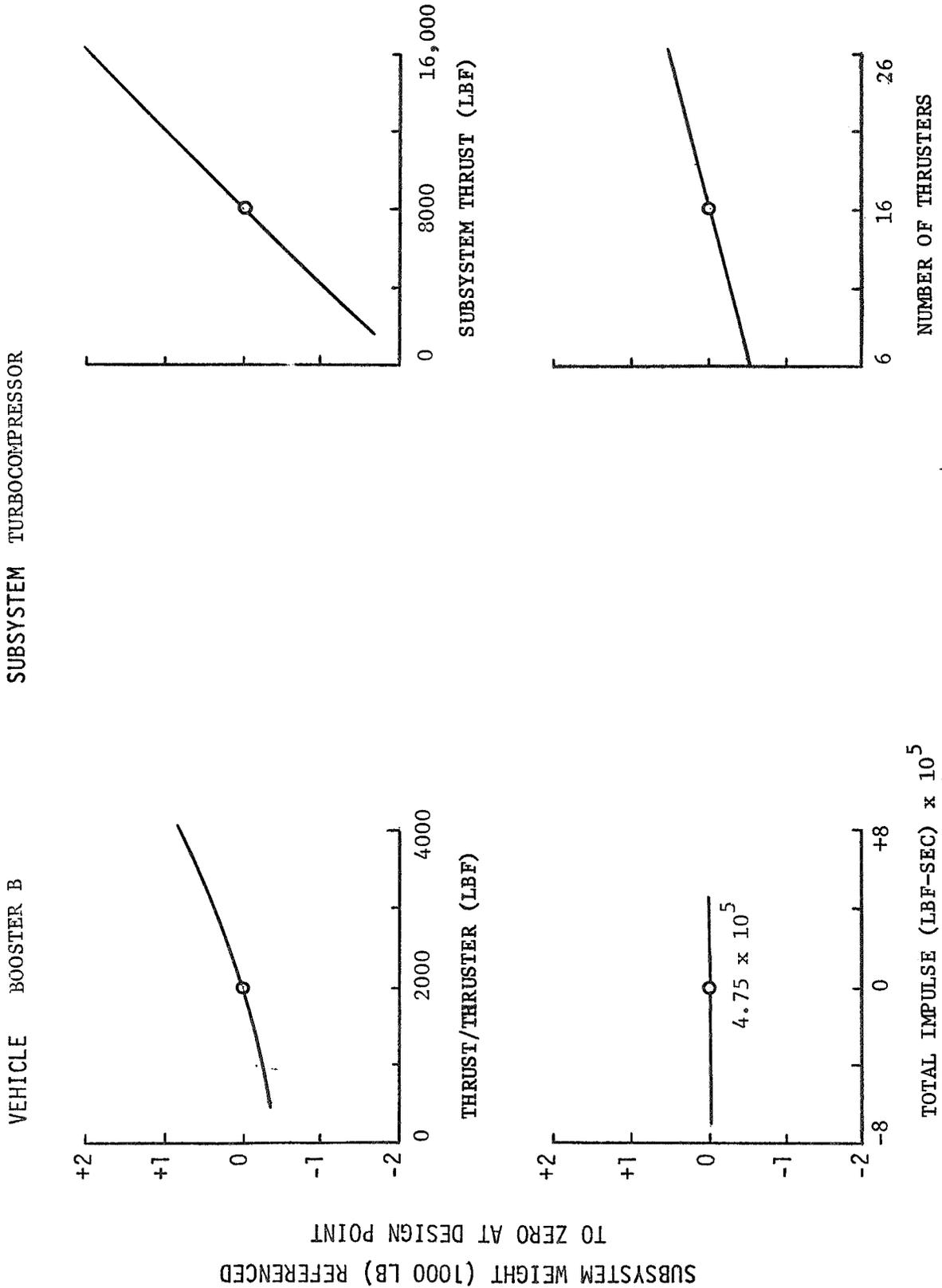
VEHICLE BOOSTER B SUBSYSTEM SUPERCRITICAL



SUBSYSTEM WEIGHT (1000 LB) REFERENCED
TO ZERO AT DESIGN POINT

WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS
BB/SC

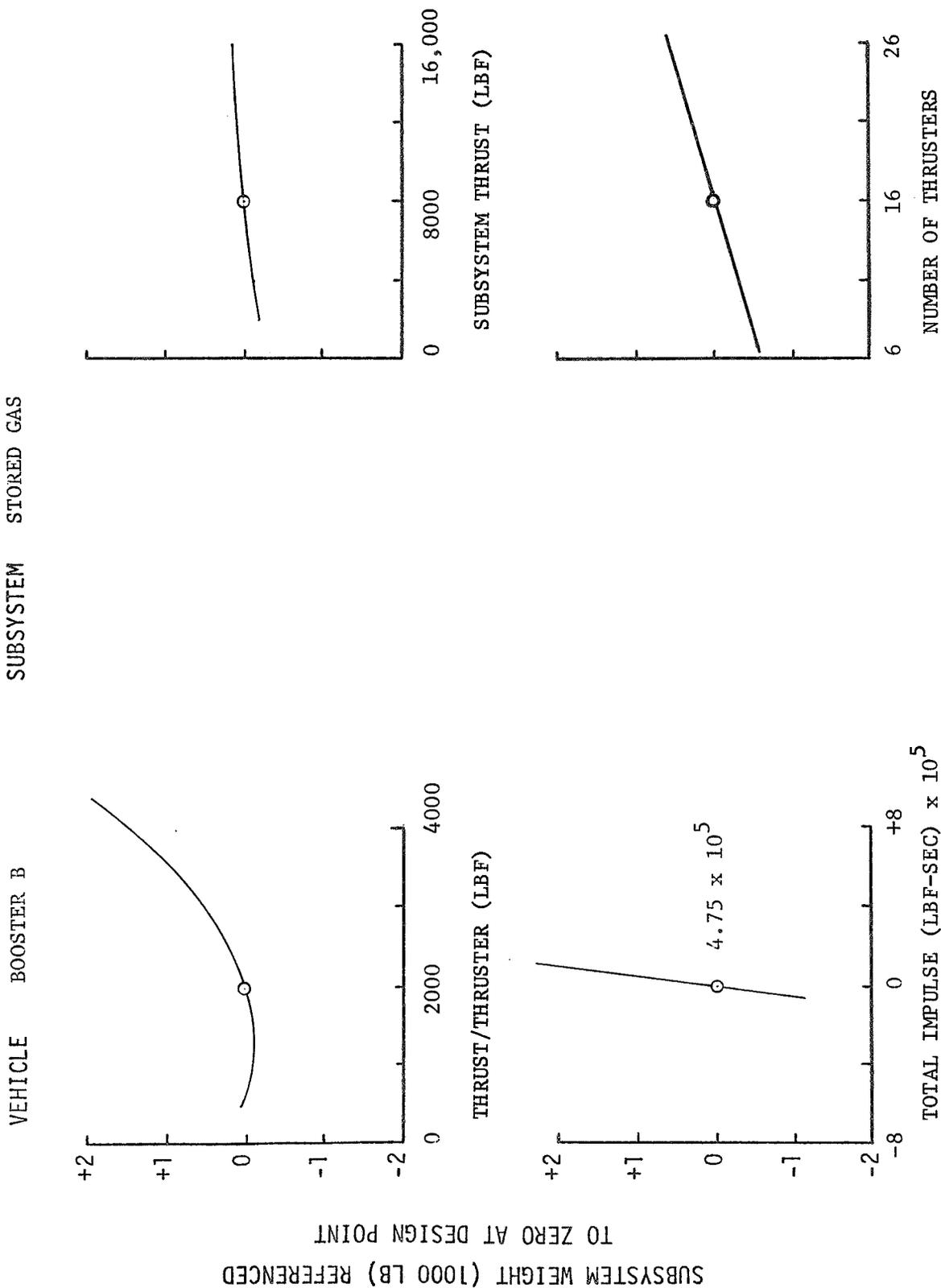
FIGURE B-45



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS
BB/TC

TO ZERO AT DESIGN POINT
SUBSYSTEM WEIGHT (1000 LB) REFERENCED

FIGURE B-46



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

BB/SG

FIGURE B-47

shown, as subsystem thrust was increased or the capability to fire more thrusters was provided, subsystem weight increased because all conditioner component sizes (turbopump, heat exchangers, and gas generators) and accumulator sizes were increased. Figure B-30C shows the sensitivity of APS weight to total impulse, and basically reflects subsystem specific impulse. Figure B-30D shows sensitivity of APS weight to number of APS thrusters. Figures B-31 and B-32 provide similar data for APS designs at ≤ 50 and ≤ 10 ft/sec respectively. All data are very similar with one exception: sensitivity to thrust per thruster is reduced as the importance of thruster performance was decreased. This came as a result of reducing APS total impulse.

Figure B-33 presents supercritical subsystem sensitivity to design requirements. Results are similar to those shown for the turbopump, with the exception of sensitivity to total impulse. Two sensitivities are shown. One is the sensitivity to total APS impulse described by the liquid tank sensitivity. In this case, the amount of propellant stored in the refillable tank would remain constant and the liquid storage tank would change. The second total impulse sensitivity is that associated with a quantity of propellant stored in the refillable tank. Here, from a base point of 4.21×10^5 lb-sec, the amount of impulse in the refillable tank was varied. This sensitivity reflects only an increase in tankage weight as total propellant weight remains constant.

Inspection of the remainder of orbiter sensitivity data (Figures B-34 to B-40) shows results very similar to those for initial cases. The only significant differences regarding sensitivity to design requirements are shown for the boosters in Figures B-40 through B-47. For the booster vehicle in Figure B-40, the higher thrust level effectively negates changes in film cooling resulting from an increase in thrust; thus, the slope of the weight versus thrust per thruster curve was always positive. For the turbocompressor subsystem on the boosters, no propellant is provided and all propellant is obtained free as booster tank pressurant. Thus, turbocompressor APS weight sensitivity to total impulse is zero for the boosters.

APPENDIX C

SUBSYSTEM SCHEMATICS AND INSTALLATION

C-1. INTRODUCTION

Definitions of valid design points and accurate assessment of overall subsystem weight required realistic subsystem schematics. Before subsystem schematics could be defined, propellant tankage implementation and component redundancy had to be established. To validly compare APS concepts, it was necessary to define the propellant integration approach best suited to each APS concept when used in conjunction with an OMS. Appendix H shows that the same propellant integration approach could not be used for all APS concepts, as no single approach could show each subsystem concept to best advantage. For this reason, a comparison of alternate means of integrating APS and OMS propellant was undertaken, using component models defined in Appendix E. Results of this comparison were used to establish preferred tankage approaches for each APS concept. Also of importance to the APS concept comparison was the number of components required for APS concepts operation. The importance of the component schematic was amplified for the Space Shuttle APS to demonstrate the required fail operational/fail safe criteria. Triple redundancy is, in effect, required of all functional components. Thus, the effect of component differences between subsystems was amplified. For example, the supercritical APS must provide three heat exchangers for propellant conditioning and the turbocompressor APS must provide three compressors. Thus, reliability considerations penalize the turbocompressor concept more than the other subsystem approaches.

The following paragraphs describe the APS/OMS propellant integration study and the rationale used to define component redundancy, and, finally, provide schematics for each candidate orbiter and booster APS subsystem.

C-2. PROPELLANT STORAGE

C-2.1 OMS/APS Propellant Integration - During Subtask A, three levels of APS +X maneuvering requirements were to be compared. These were:

- (1) APS designed to perform all post separation +X maneuvering
- (2) APS designed to provide +X maneuvering velocity levels of 50 ft/sec or less, and
- (3) APS designed to provide +X maneuvering velocity levels of 10 ft/sec or less.

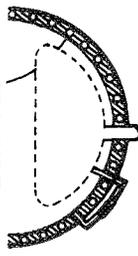
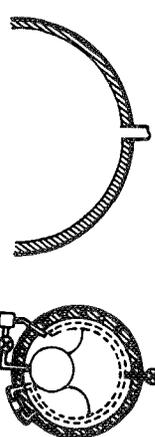
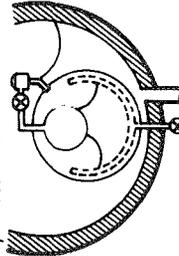
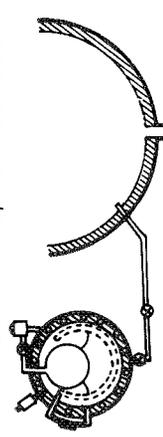
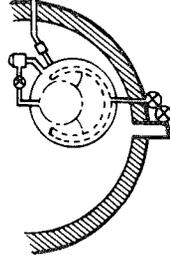
In these latter two cases, an orbit maneuvering subsystem (OMS) is required to accomplish major orbital maneuvers. For purposes of this study, a baseline OMS was assumed to establish the preferred propellant integration approaches. The OMS baseline used for these studies is shown in Figure C-1. To compare the combined APS/

SPECIFIC IMPULSE	458 SEC
THRUST LEVEL	6000 LB
MIXTURE RATIO	5:1
OMS ENGINES AND LINES	600 LB
PROPELLANT LOSSES PER ENGINE START	67 LB

BASELINE ORBITAL MANEUVERING SUBSYSTEM

FIGURE C-1

OMS with an all APS approach it was necessary to determine the preferred tankage concept for each APS +X maneuvering allocation. To allow comparison of the alternate subsystem types on a parallel basis, it was necessary to define the most attractive method of integration the APS and OMS propellant for each concept. For these comparisons a fully integrated tankage concept (APS and OMS propellant in a common tank) was used as a reference. The five options considered for liquid propellant storage are shown in Figure C-2 together with a listing of the technology, simplicity, and flexibility features applicable to each concept. The reference case required development of the largest propellant positioning screen, but it had the advantage of being the simplest of the approaches (in that a minimum number of components

CONCEPT	TECHNOLOGY	SIMPLICITY	FLEXIBILITY
<p>FULLY INTEGRATED</p> 	<ul style="list-style-type: none"> • LARGEST PROPELLANT POSITIONING SCREEN • REUSABLE HPI 	<ul style="list-style-type: none"> • MINIMUM COMPONENTS • ALL PASSIVE ASSEMBLY 	<ul style="list-style-type: none"> • FLEXIBLE OMS/APS IMPULSE ALLOCATION
<p>SEPARATE, NON-REFILLABLE</p> 	<ul style="list-style-type: none"> • LARGE PROPELLANT POSITIONING SCREEN • REUSABLE HPI 	<ul style="list-style-type: none"> • MINIMUM INTERFACE COMPLEXITY • ALL PASSIVE ASSEMBLY 	<ul style="list-style-type: none"> • FIXED OMS/APS IMPULSE ALLOCATION
<p>COMBINED, NON-REFILLABLE</p> 	<ul style="list-style-type: none"> • LARGE PROPELLANT POSITIONING SCREEN • REUSABLE HPI 	<ul style="list-style-type: none"> • LOW INTERFACE COMPLEXITY • ALL PASSIVE ASSEMBLY • INTERNAL TANK SUPPORTS • DIFFICULT MAINTENANCE 	<ul style="list-style-type: none"> • FIXED OMS/APS IMPULSE ALLOCATION
<p>SEPARATE, REFILLABLE</p> 	<ul style="list-style-type: none"> • SMALLER PROPELLANT POSITIONING SCREEN • REUSABLE HPI 	<ul style="list-style-type: none"> • COMPLEX OPERATIONAL INTERFACE • ACTIVE REFILL SUBASSEMBLY 	<ul style="list-style-type: none"> • FIXED APS IMPULSE ALLOCATION BETWEEN OMS BURNS
<p>COMBINED, REFILLABLE</p> 	<ul style="list-style-type: none"> • SMALLER PROPELLANT POSITIONING SCREEN • REUSABLE HPI 	<ul style="list-style-type: none"> • COMPLEX OPERATIONAL INTERFACES • ACTIVE REFILL SUBASSEMBLY • INTERNAL TANK SUPPORTS • DIFFICULT MAINTENANCE 	<ul style="list-style-type: none"> • FIXED APS IMPULSE ALLOCATION BETWEEN OMS BURNS

LIQUID STORAGE CONCEPTS

FIGURE C-2

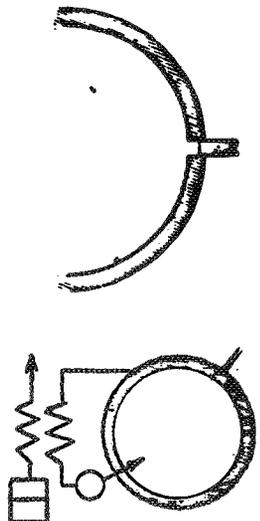
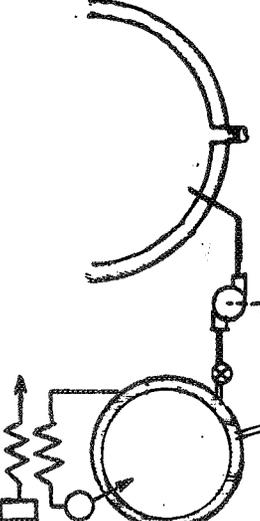
were required and it was an all passive assembly). The reference case allowed the most flexibility in OMS/APS impulse allocation. The other four candidates shown were compared with this reference. The basic variations are (1) refillable or nonrefillable tankage, and (2) separate or combined tankage.

The separate nonrefillable concept stores APS and OMS propellants in independent tanks. Only the APS tank requires a positive positioning screen. This approach has a minimum of interface complexity, but is inflexible in allocation of OMS/APS impulse. The third approach shown is a combined nonrefillable concept. It has the same features as the separate nonrefillable approach, with the exception of the APS tank which is mounted within the OMS tank and, therefore, does not require thermal protection.

The final two approaches shown in Figure C-2 are refillable concepts. In these concepts the refillable tank is sized to provide propulsion requirements between major OMS operations. During each major OMS burn, the APS tank would be refilled. Propellant transfer is accomplished with flow produced by a difference in tank pressures. This concept has the advantage of reducing the size of the APS tank, and, hence, the propellant positioning screen, but suffers in that the approach is more complex because of the active refill subassembly.

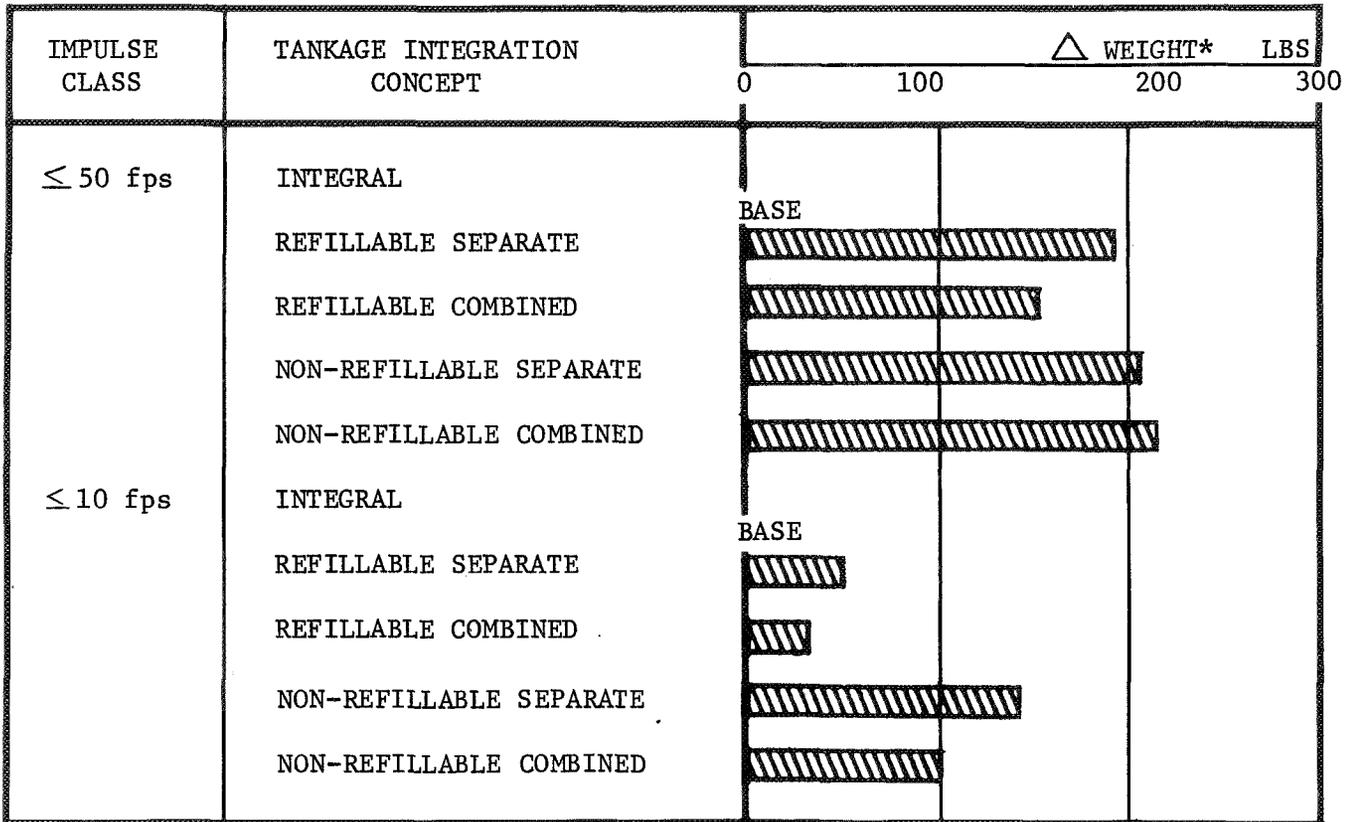
Also considered in the APS comparisons were supercritical and hybrid APS concepts. In the supercritical approach, both hydrogen and oxygen are stored at relatively high pressure. This made a fully integrated tankage concept impractical because of the high weight penalty for a large, high pressure tank. Due to the high temperature of the APS tankage, supercritical storage could not be considered for a combined tank approach (i.e., the APS tankage could not be stored inside of a liquid OMS propellant because the APS tank pressure would collapse). These constraints reduced the number of supercritical propellant integration alternates to the two shown in Figure C-3. Both approaches used separate tankage, but refillable concepts were considered. The primary difference between the two approaches was that the refillable was somewhat more complex because of the pump required in the active refill subassembly.

A weight comparison for the five tankage concepts of Figure C-2 is shown by the bar charts of Figures C-4 and C-5 for ~~Orbiters~~ A and B turbopump APS at the reduced velocity allocations. The integral tankage approach is the lightest weight for all cases. A weight comparison for the supercritical tanks of Figure C-3 is shown in Figures C-6 and C-7 relative to turbopump APS data previously shown. For both orbiters a refillable supercritical tank is much lighter than the nonrefillable concept.

CONCEPT	TECHNOLOGY	SIMPLICITY	FLEXIBILITY
<p><u>SEPARATE, NON-REFILLABLE</u></p> 	<ul style="list-style-type: none"> • REUSABLE HPI • THROTTLEABLE HEAT EXCHANGER 	<ul style="list-style-type: none"> • MINIMUM INTERFACE COMPLEXITY • ACTIVE PRESSURE CONTROL 	<ul style="list-style-type: none"> • FIXED OMS/APS IMPULSE ALLOCATION
<p><u>SEPARATE, REFILLABLE</u></p> 	<ul style="list-style-type: none"> • REUSABLE HPI • THROTTLEABLE HEAT EXCHANGER 	<ul style="list-style-type: none"> • COMPLEX OPERATIONAL INTERFACE • ACTIVE PRESSURE CONTROL SYSTEM • ACTIVE REFILL 	<ul style="list-style-type: none"> • FIXED APS IMPULSE ALLOCATION BETWEEN OMS BURNS

SUPERCritical STORAGE CONCEPTS

FIGURE C-3



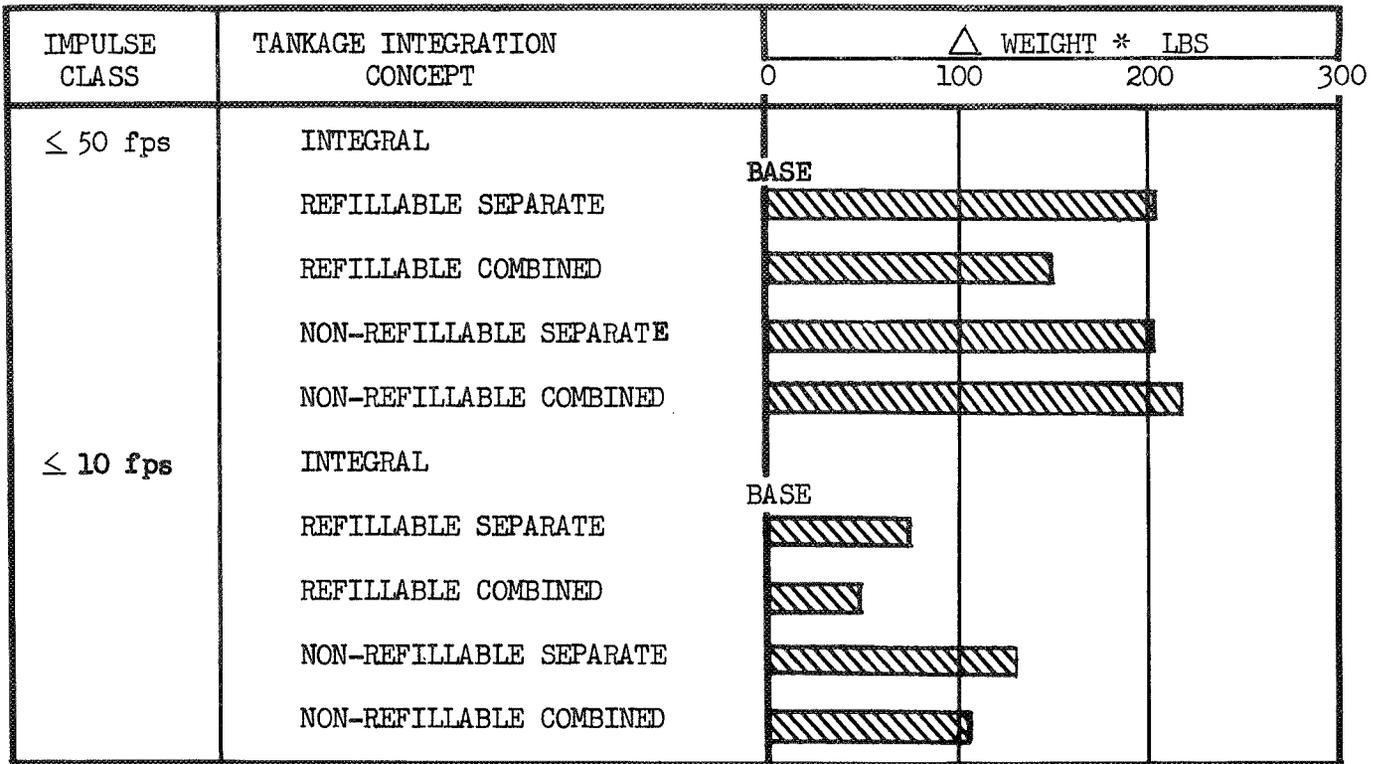
*INCLUDES PROPELLANT TANKAGE AND PRESSURANT ASSEMBLY

TANKAGE INTEGRATION CONCEPT WEIGHTS

ORBITER A-TURBOPUMP

FIGURE C-4

The hybrid APS concept combines the features of the supercritical APS for hydrogen and a turbocompressor concept for oxygen. In this subsystem, hydrogen tank characteristics were identical to those previously described for the supercritical; thus, a refillable separate tankage arrangement was best suited. For the oxygen, refill tank storage pressures in this concept are somewhat above those for the turbopump in order to provide sufficient pressure for propellant transfer and injection into main engine propellant tanks; therefore, weight results for oxygen are somewhat different. Figures C-6 and C-7 also provide the weight of the hybrid oxygen tankage systems for both Orbiters A and B. Unlike the turbopump, the integral approach is not the most attractive from a weight standpoint. A combined refillable oxygen tank provides the lightest weight approach.

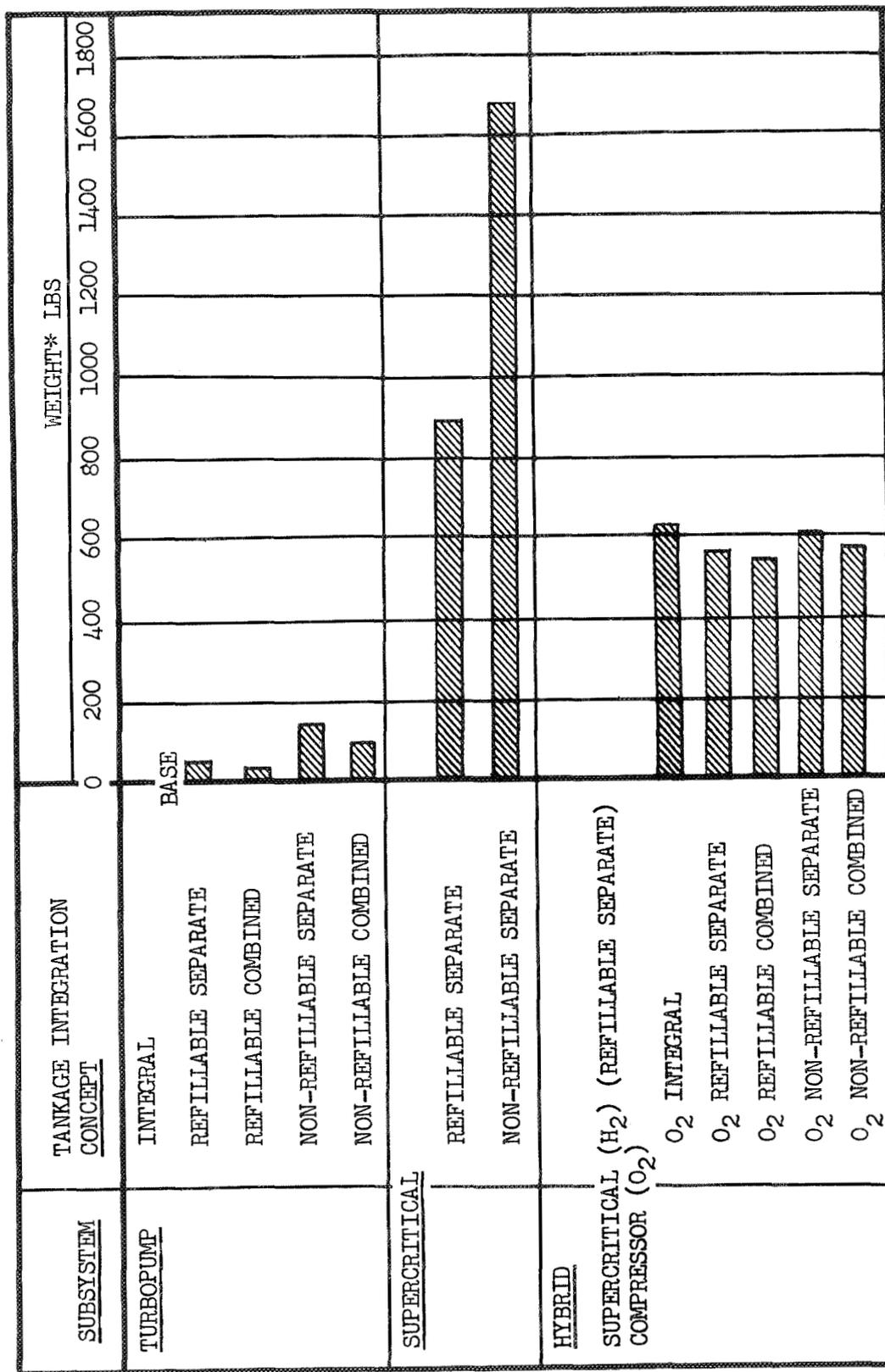


* INCLUDES PROPELLANT TANKAGE AND PRESSURANT ASSEMBLY

TANKAGE INTEGRATION CONCEPT WEIGHTS
ORBITER B - TURBOPUMP

FIGURE C-5

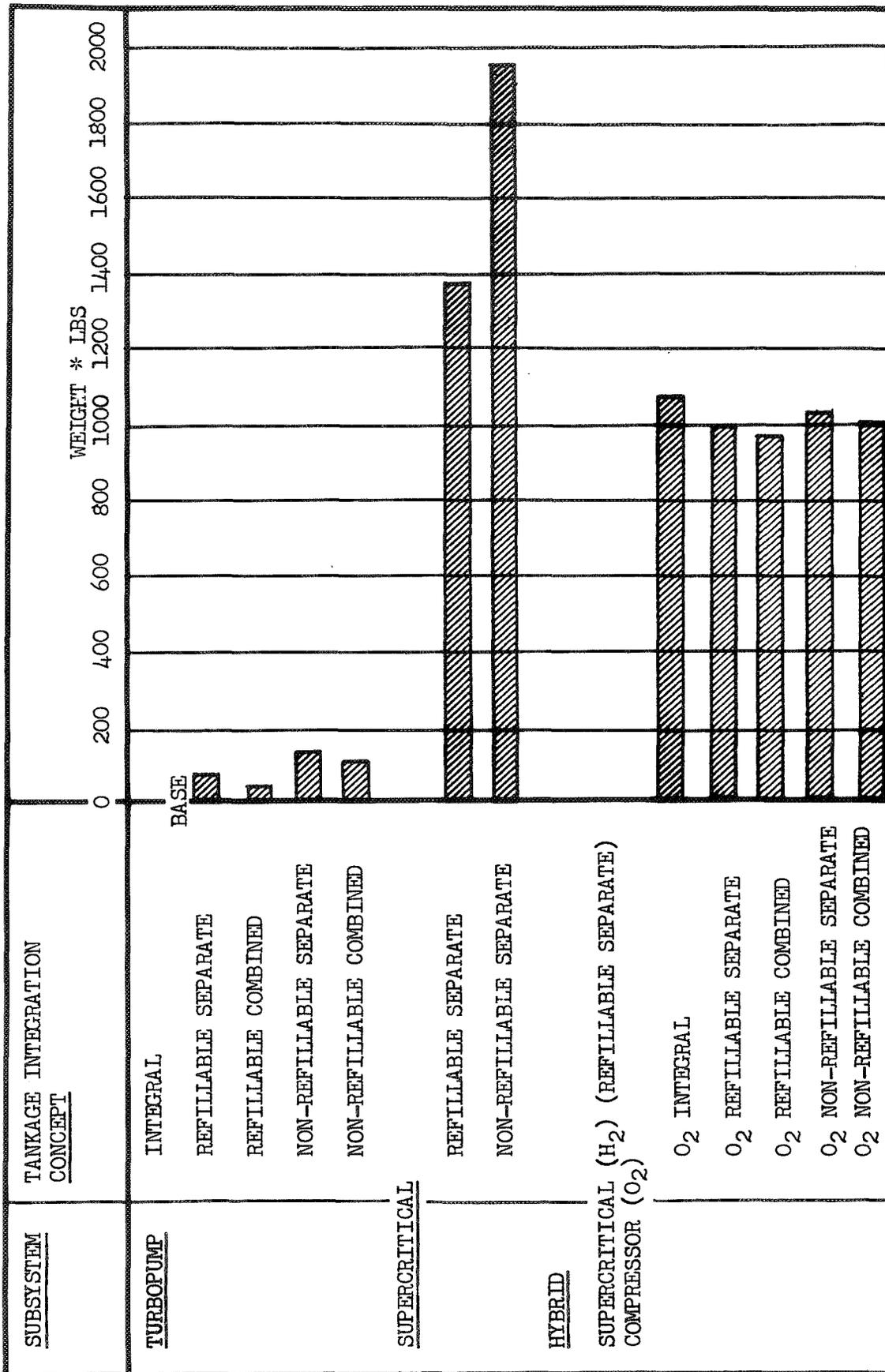
C-2.2 Comparison of Storage Options - For the three different APS alternates, the various means of propellant storage were compared on the basis of technology, simplicity, weight, and flexibility. Figure C-8 provides a summary of the point rating assigned to each integration approach for the various concepts. The point ratings shown in Figure C-8 are based on weights previously provided and on various considerations shown in Figures C-2 and C-3 for the other selection criteria. Figure C-8 shows a total point scoring for the various approaches. For a turbopump APS, a fully integrated tankage subsystem is most attractive. For the supercritical APS, weight is a determining feature, and weight advantages more than offset the complexity of a refill system, making a separate refillable tank the most attractive. This supercritical tankage approach would also be that used in the hybrid, along with a fully integrated oxygen tank. As observed in Figures C-6 and C-7, the fully integrated oxygen tank was somewhat heavier, but its simplicity and flexibility counterbalance the penalties in weight and technology.



* INCLUDES PROPELLANT TANKAGE, PRESSURANT ASSEMBLY AND THRUSTERS

TANKAGE INTEGRATION CONCEPT WEIGHTS
Orbiter A ≤ 10 fps

FIGURE C-6



* INCLUDES PROPELLANT TANKAGE, PRESSURANT ASSEMBLY AND THRUSTERS

TANKAGE INTEGRATION CONCEPT WEIGHTS
Orbiter B \leq 10 fps

FIGURE C-7
C-9

SUBSYSTEM/STORAGE CONCEPT	SELECTION CRITERIA					TOTAL *
	TECHNOLOGY (25%)	SIMPLICITY (20%)	WEIGHT/VOL (25%)	FLEXIBILITY (30%)		
<u>TURBOPUMP</u>						
FULLY INTEGRATED	12	20	25	30	87	
SEPARATE, NON-REFILLABLE	23	18	24	15	70	
COMBINED, NON-REFILLABLE	23	15	24	15	77	
SEPARATE, REFILLABLE	25	12	25	25	87	
COMBINED, REFILLABLE	25	9	25	25	84	
<u>SUPERCRITICAL</u>						
SEPARATE, NON-REFILLABLE	25	20	17	25	87	
SEPARATE, REFILLABLE	25	10	25	30	90	
<u>HYBRID (O₂ SIDE)</u>						
FULLY INTEGRATED	15	20	24	30	89	
SEPARATE, NON-REFILLABLE	23	18	24	15	80	
COMBINED, NON-REFILLABLE	23	15	25	15	78	
SEPARATE, REFILLABLE	25	12	25	25	87	
COMBINED, REFILLABLE	25	9	25	25	84	

* RELATIVE RATINGS APPLY ONLY WITHIN THE SPECIFIED SUBSYSTEM/STORAGE CONCEPTS

PROPELLANT STORAGE CONCEPT SELECTION

C-3. COMPONENT REDUNDANCY

Each of the candidate APS concepts was evaluated to develop realistic sub-system schematics for definition of APS design points and APS weight. To define the number of components required by each candidate APS, the redundancy rationale of Figure C-9 was applied. In general, this rationale resulted in provision of

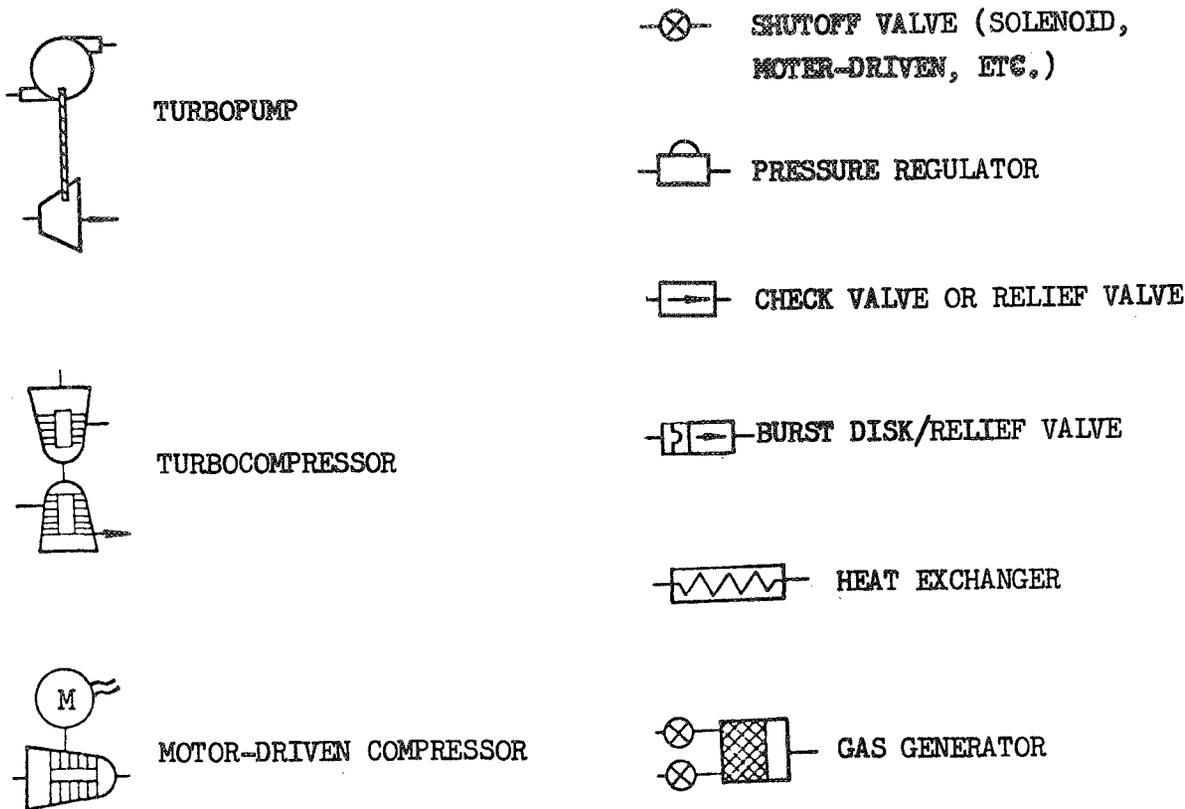
- (1) Subsystem will be fully operational after one component failure
- (2) Subsystem must retain capability of providing or supporting a safe deorbit after two component failures
- (3) Structure, lines, tanks, and fittings will not fail catastrophically, and leakage rates for the leakage mode will be low enough to allow a safe deorbit.
- (4) Thrust chambers will not fail in a catastrophic mode as long as propellants are supplied at acceptable pressures and mixture ratio.
- (5) A "normally closed" shutoff valve will not fail open prior to first flight operational cycle.
- (6) A "normally open" shutoff valve will not fail closed prior to first flight operational cycle.
- (7) Propellant accumulators will not normally require venting.
- (8) Heat exchangers are not considered structural (i.e., reliability \neq 1.0).
- (9) Configurations which use OMS will have two OMS engines. After two OMS engine failures, the APS will provide safe deorbit.

REDUNDANCY RATIONALE

FIGURE C-9

triple redundancy for each functional assembly. Except as modified by the rationale of Figure C-9, all components were considered in a go/no go operating mode.

Figure C-10 provides a legend for the subsystem schematics shown in Figures C-11 through C-22. Figure C-11 shows a schematic of the turbopump subsystem configured for the orbiter all-maneuver requirement case. Integral propellant tanks were used, and triple redundancy was provided for pressure regulation and conditioner assemblies. Figure C-12 shows the turbopump subsystem schematic for the other velocity allocations. The only difference between the schematic of Figure C-12 and that for the all-

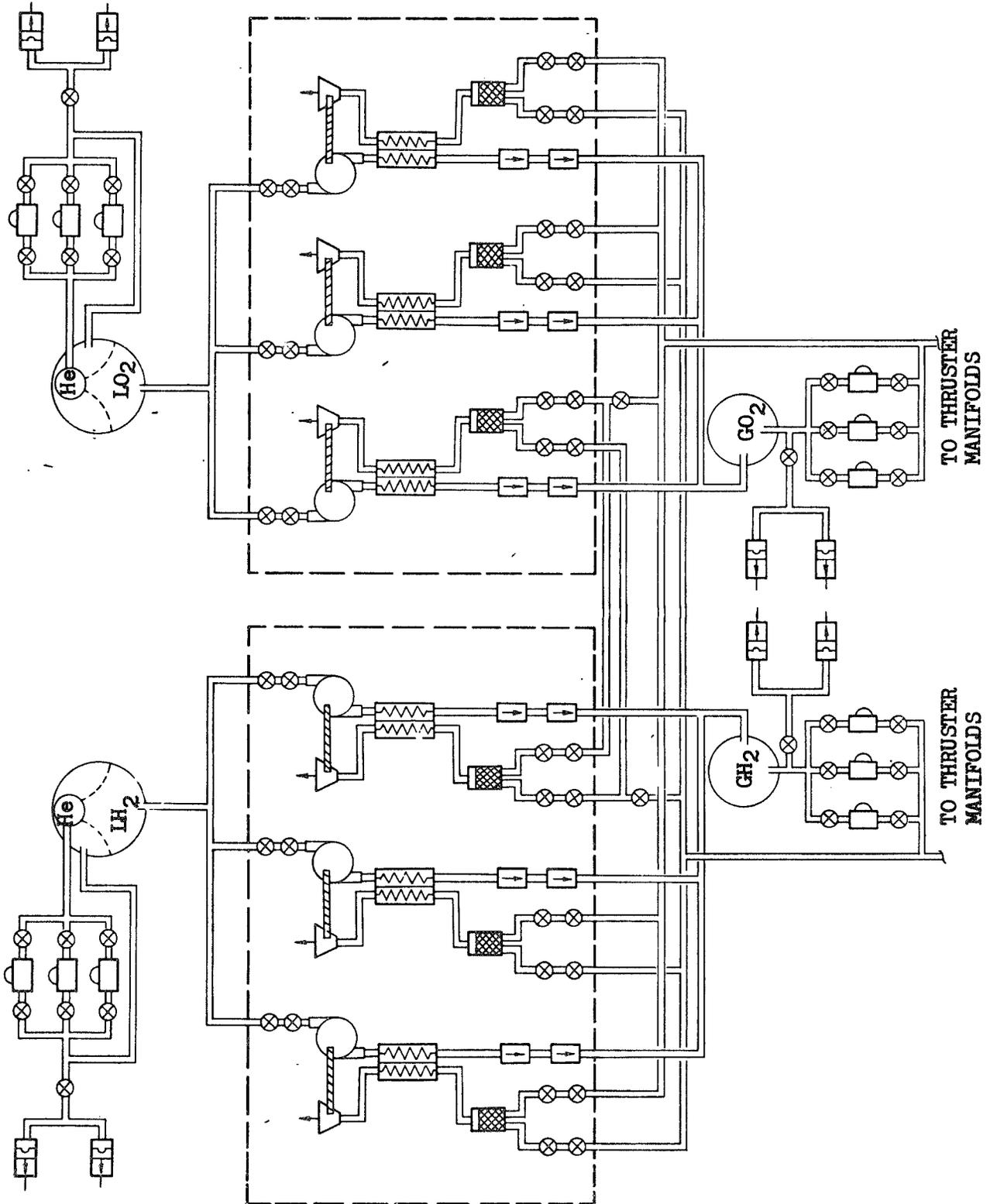


SCHEMATIC LEGEND

FIGURE C-10

maneuver case was the provision for propellant supply to the orbit maneuvering subsystem. Figure C-13 provides a schematic of the supercritical subsystem. Separate refillable APS tanks were used. Triple redundancy was provided for both the downstream and in-tank heaters. The propellant transfer assembly pumps were also triply redundant to satisfy the shuttle failure criteria. Figure C-14 presents a schematic of the hybrid subsystem. An active conditioning loop for oxygen resupply to main engine tank was provided. Figures C-15 and C-16 show the propellant distribution lines and isolation valves to the thruster assemblies in Orbiters A and B respectively. The juncture in the supply line to the accumulators matches the similar juncture shown in the subsystem schematics of Figures C-11 through C-14. Thus, propellant distribution schematics apply to any of the candidate APS schematics previously shown.

Booster subsystem schematics are shown in Figures C-17 through C-22. Figure C-17 shows a booster turbopump subsystem. Comparison of this with the orbiter for all maneuvers shows that the schematics are identical. The same applies to the supercritical subsystem of Figure C-18, with the exception that in the boosters, no propellant resupply system is required. Figure C-19 shows a turbocompressor



TO THRUSTER
MANIFOLDS

TO THRUSTER
MANIFOLDS

TURBOPUMP SUBSYSTEM SCHEMATIC
Orbiters A & B - All Maneuvers

FIGURE C-11

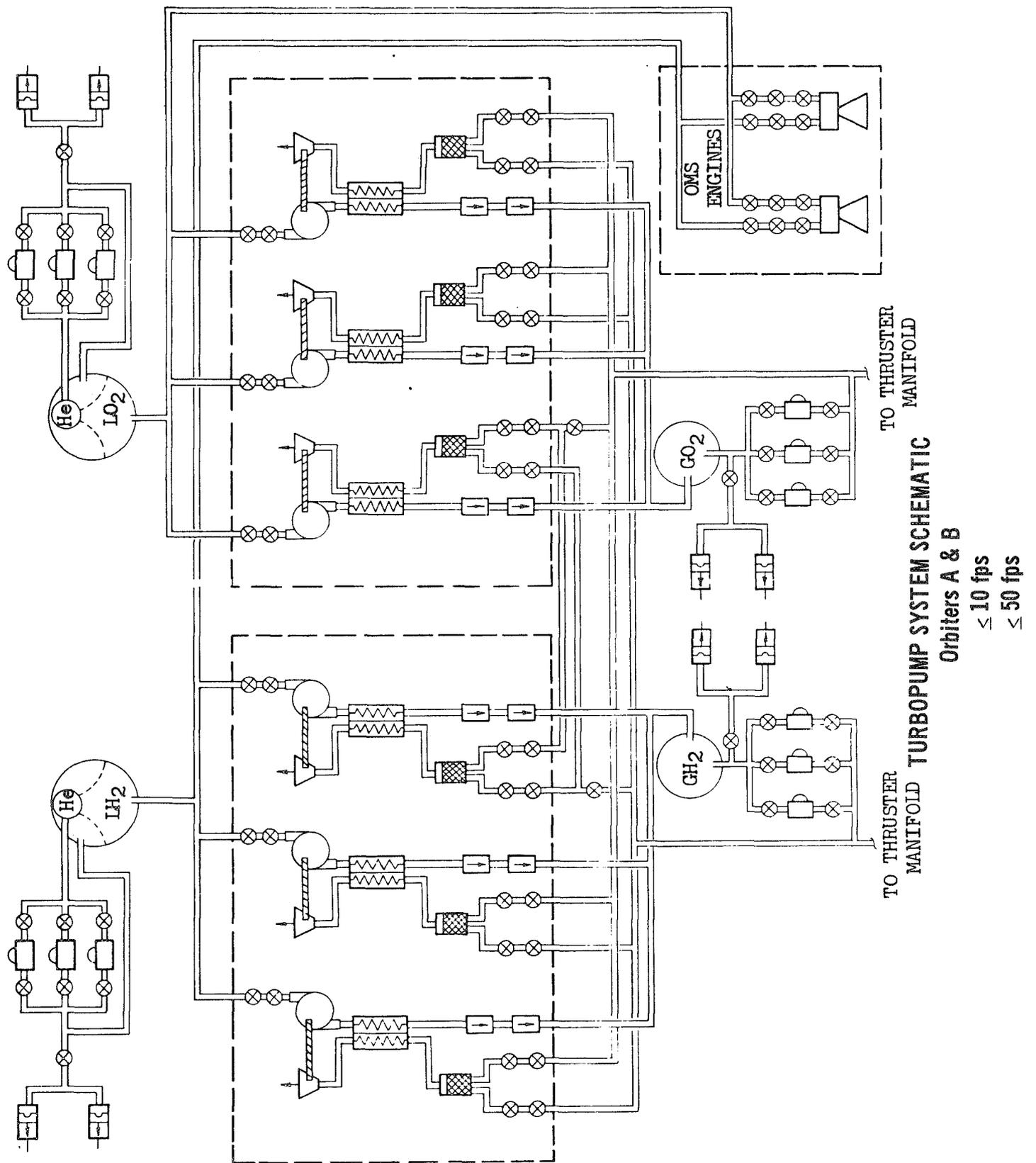
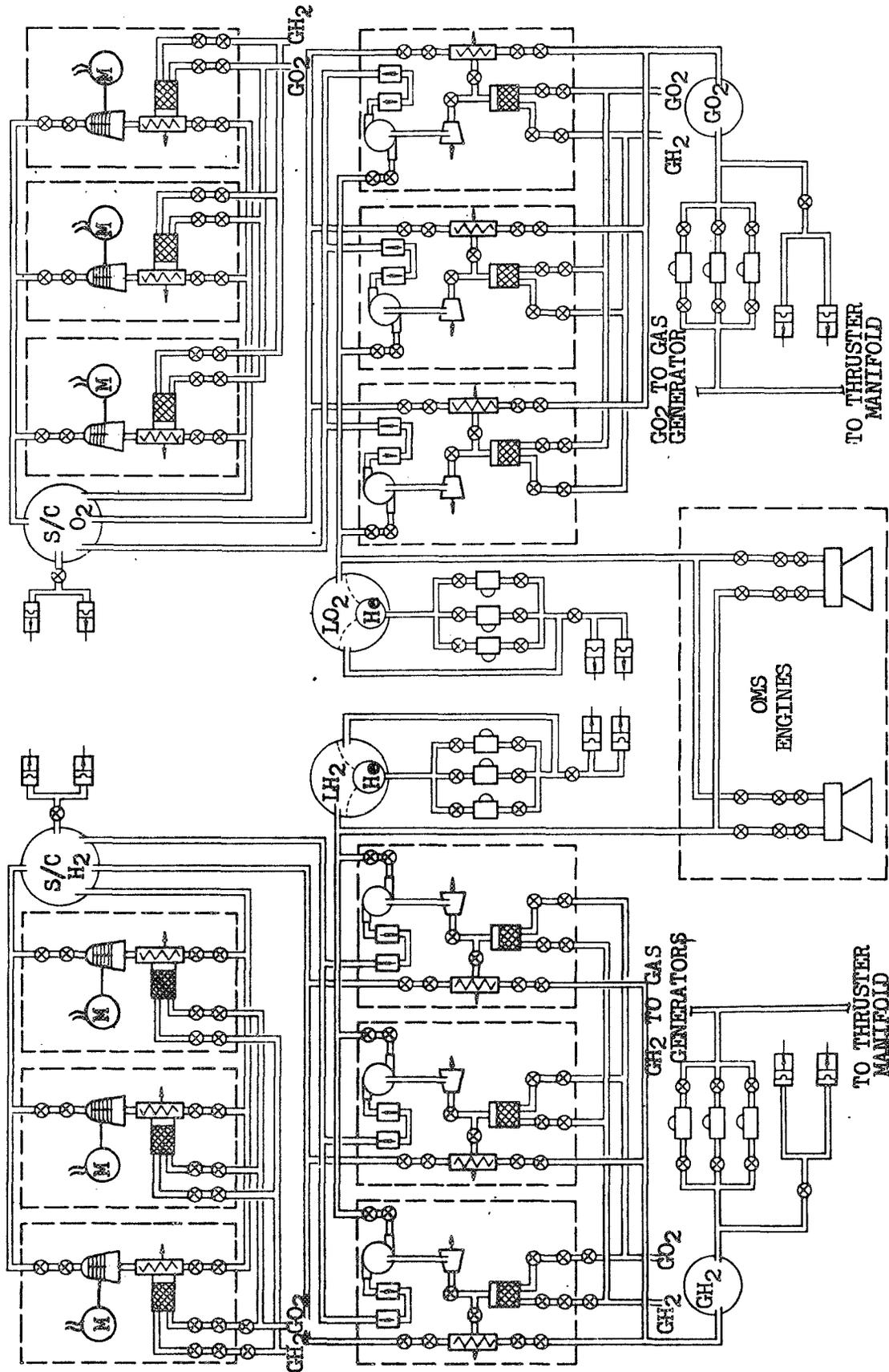
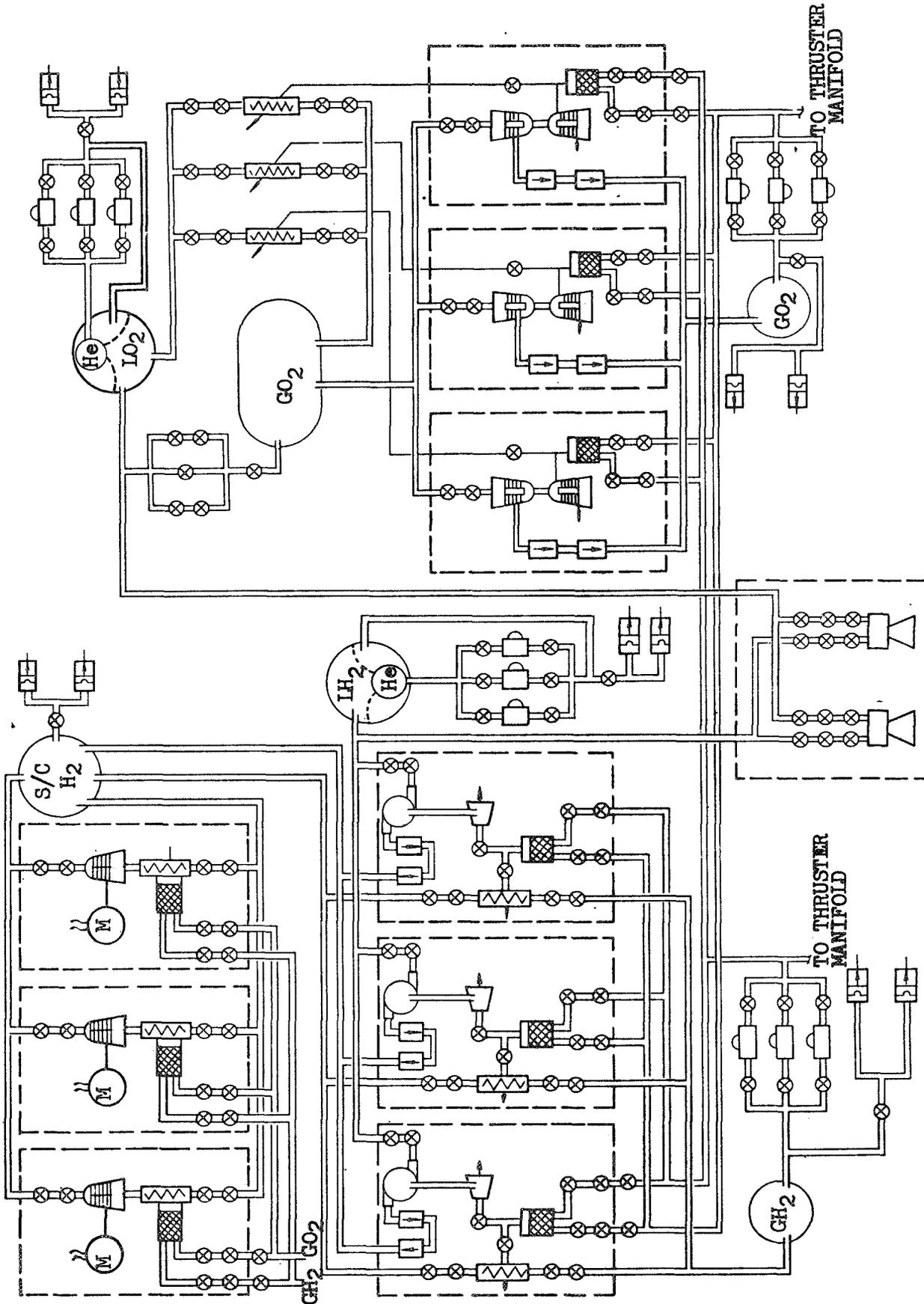


FIGURE C-12

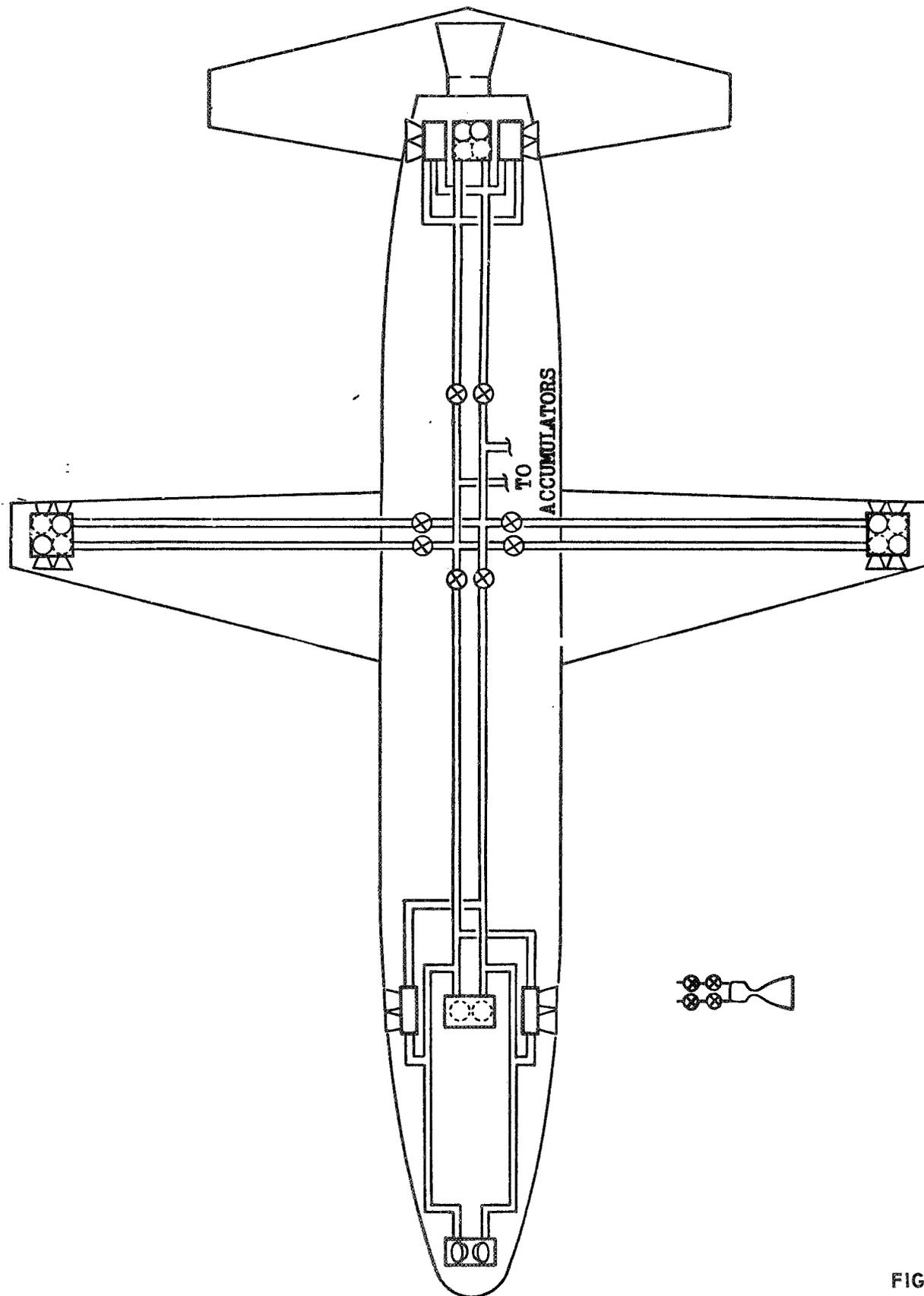


SUPERCritical SUBSYSTEM SCHEMATIC
Orbiters A & B
≤ 10 fps

FIGURE C-13

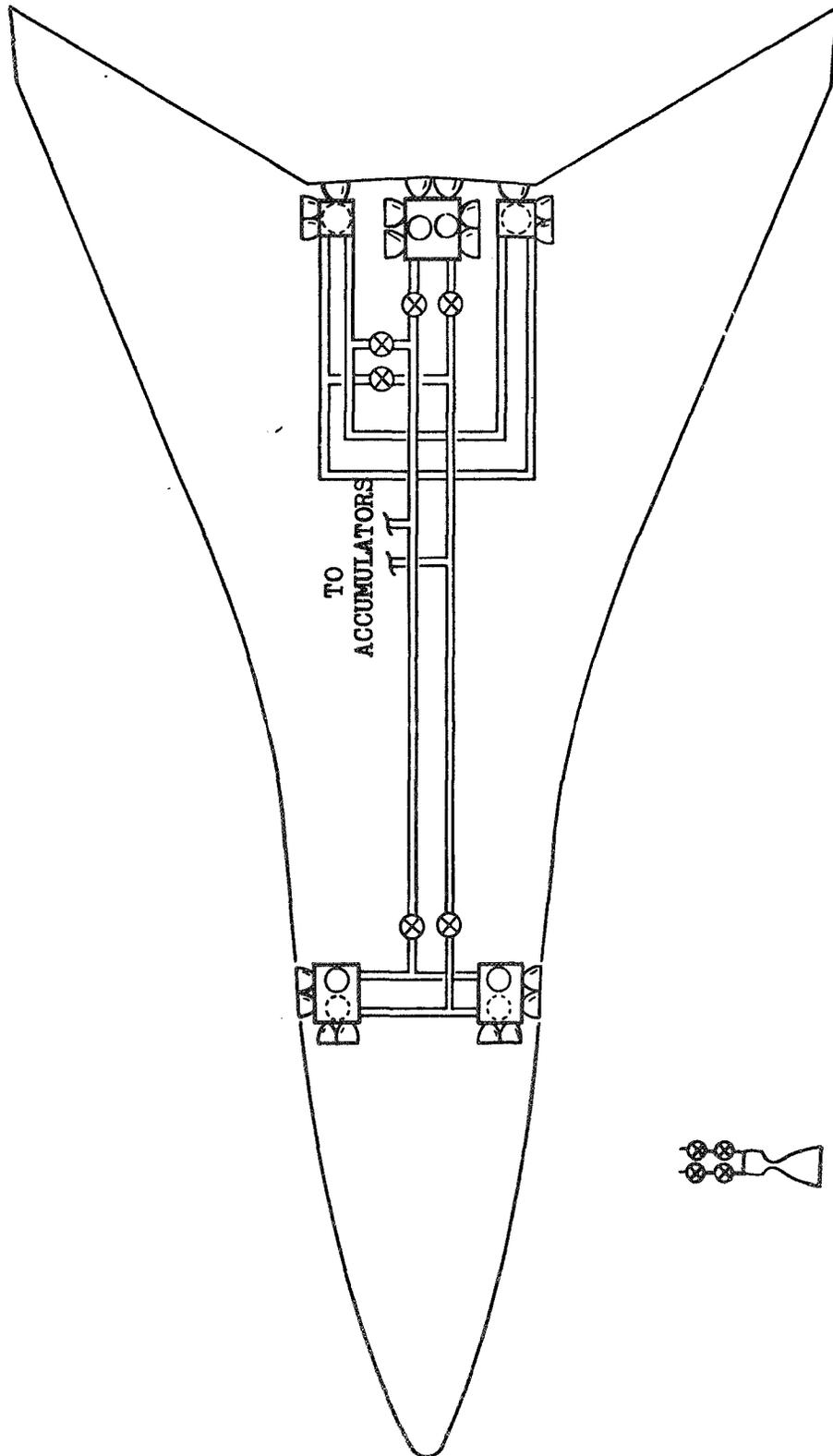


OMS ENGINES
HYBRID SYSTEM SCHEMATIC
Orbiters A & B
≤ 10 fps



PROPELLANT DISTRIBUTION TO THRUSTERS
Orbiter A

FIGURE C-15



PROPELLANT DISTRIBUTION TO THRUSTERS
Orbiter B

FIGURE C-16

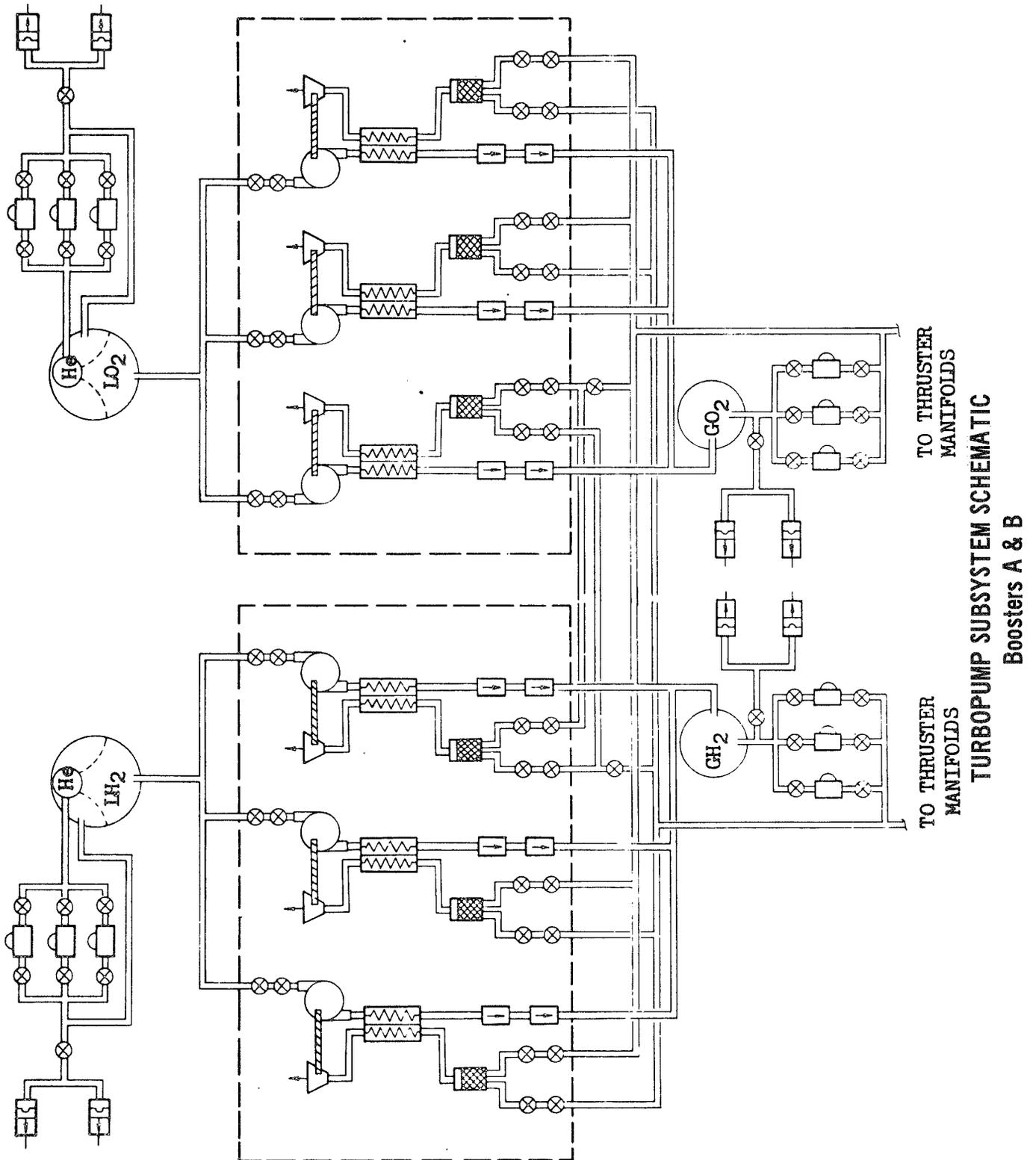
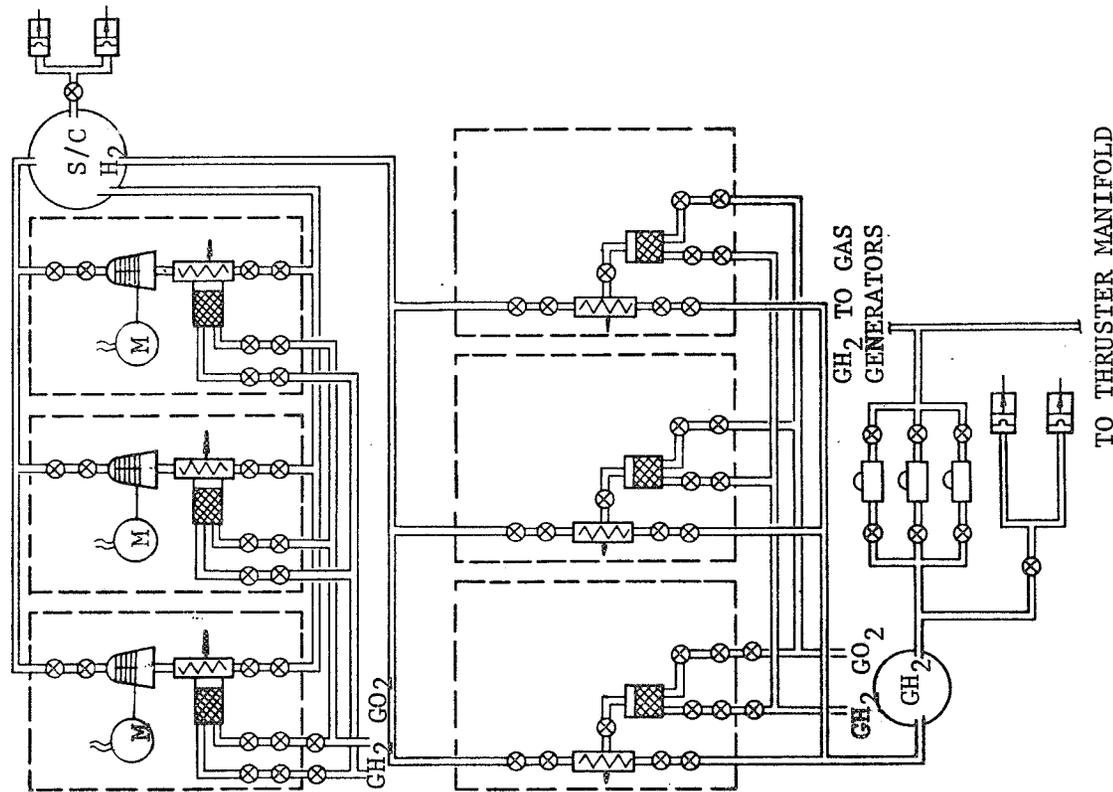
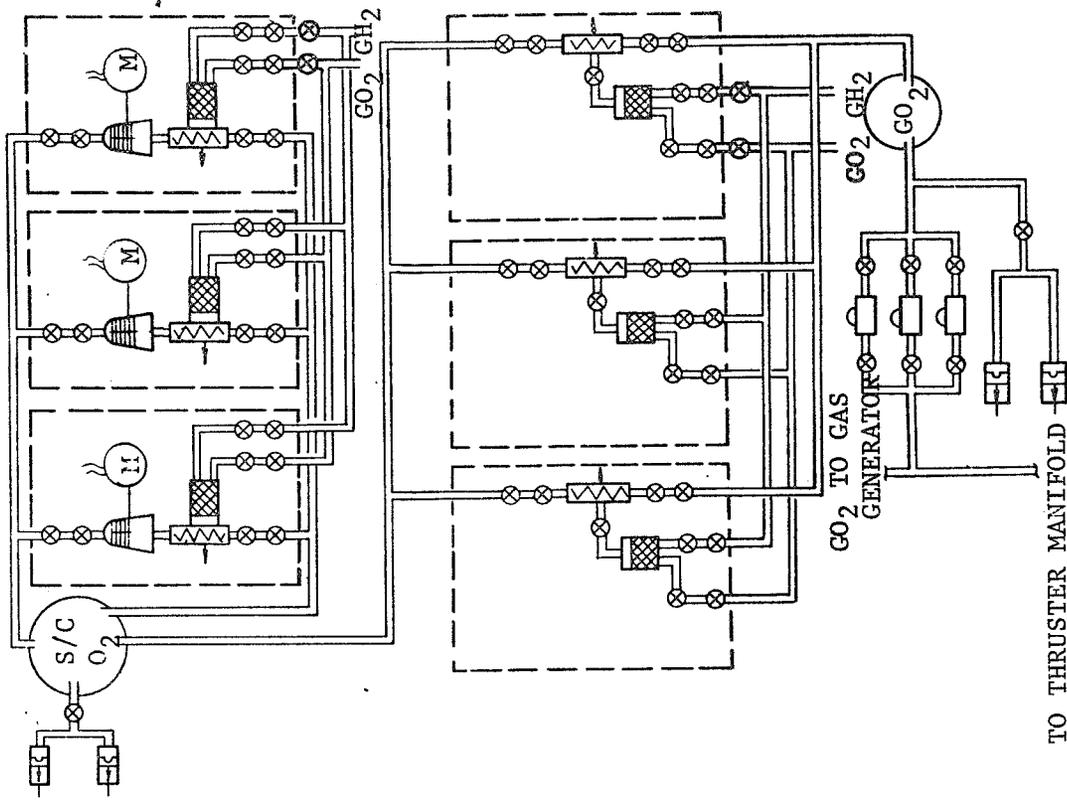
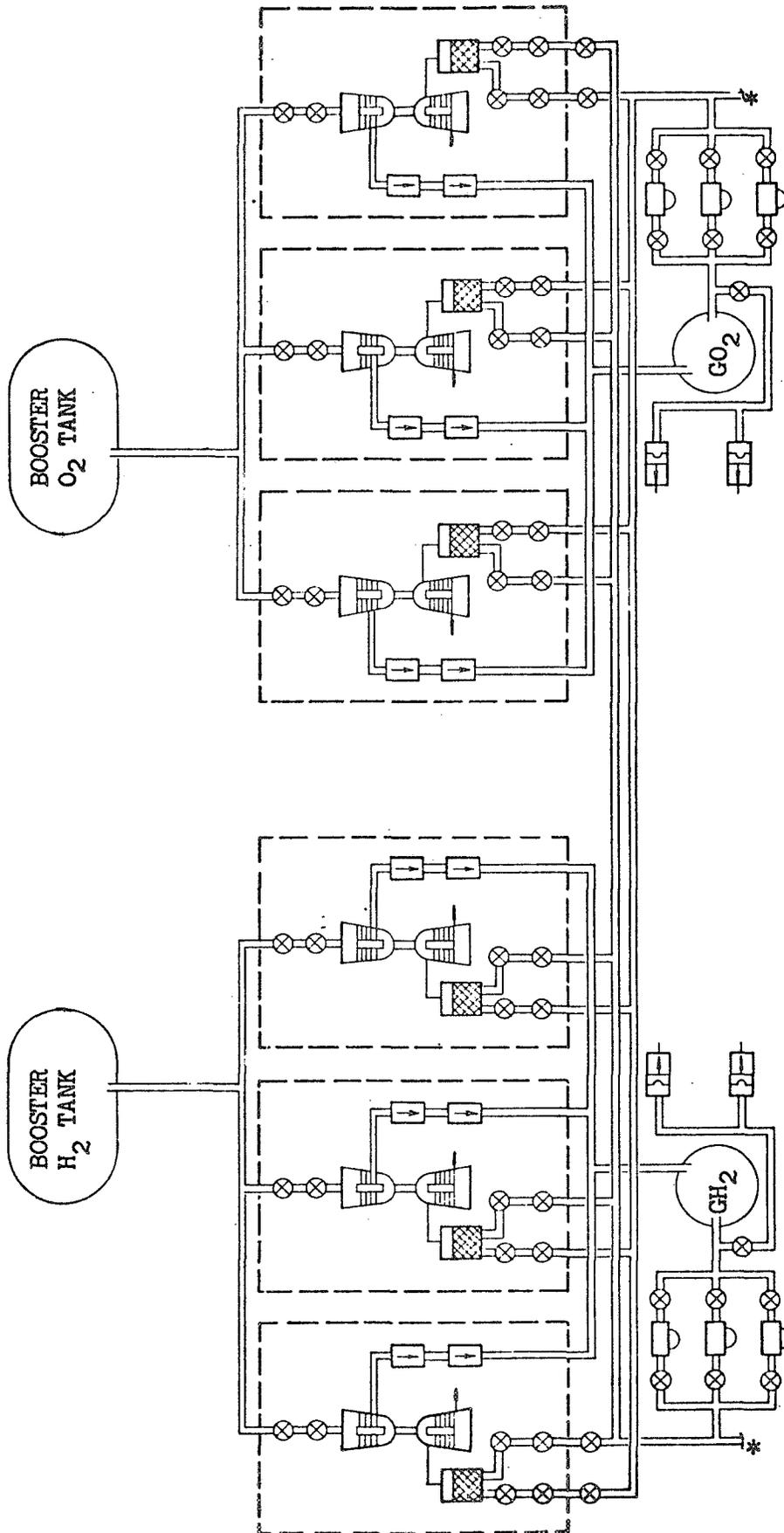


FIGURE C-17



SUPERCRITICAL SUBSYSTEM SCHEMATIC
Booster A & B

FIGURE C-18

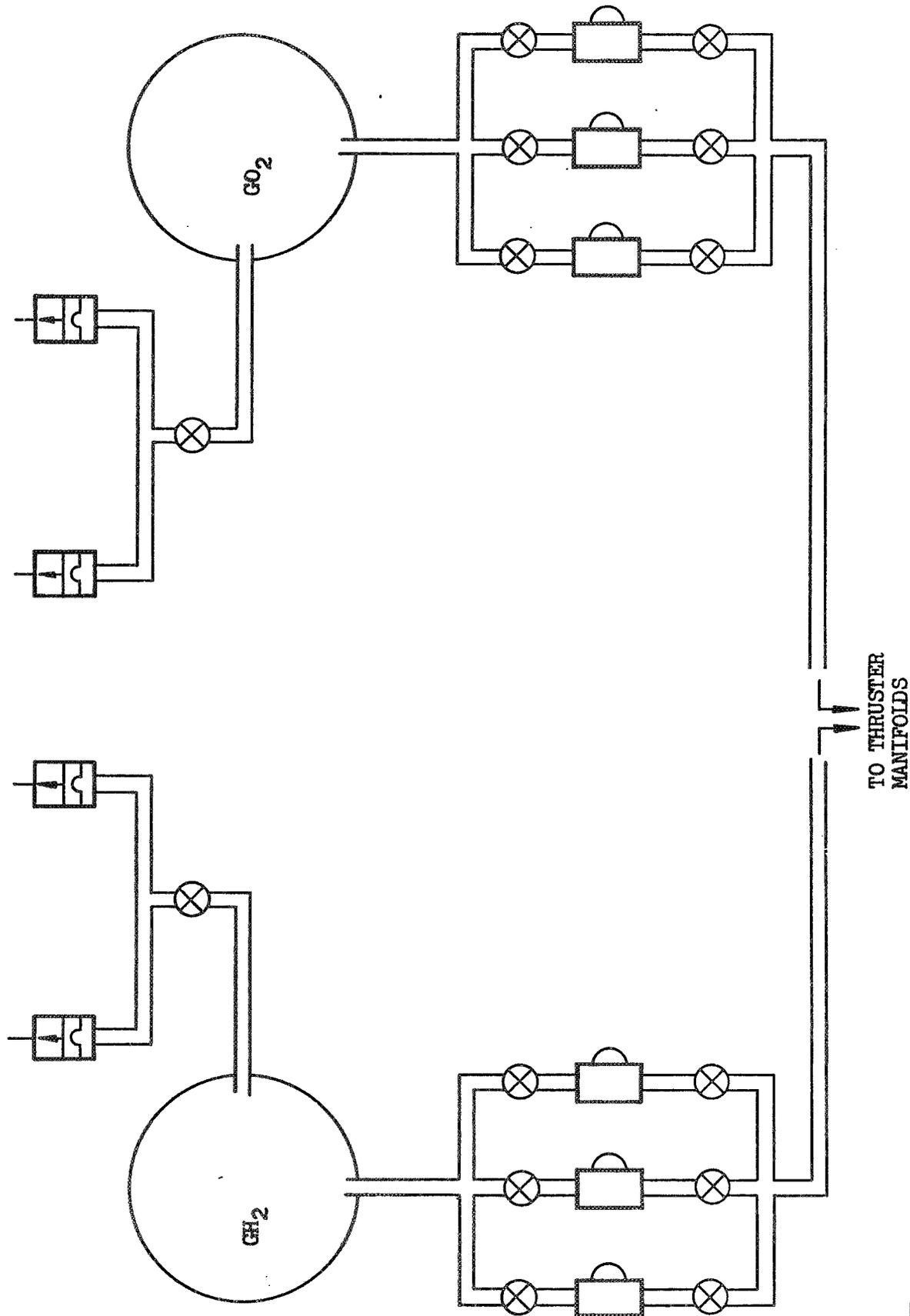


* TO THRUSTER MANIFOLDS

TURBOCOMPRESSOR SUBSYSTEM SCHEMATIC
Boosters A & B

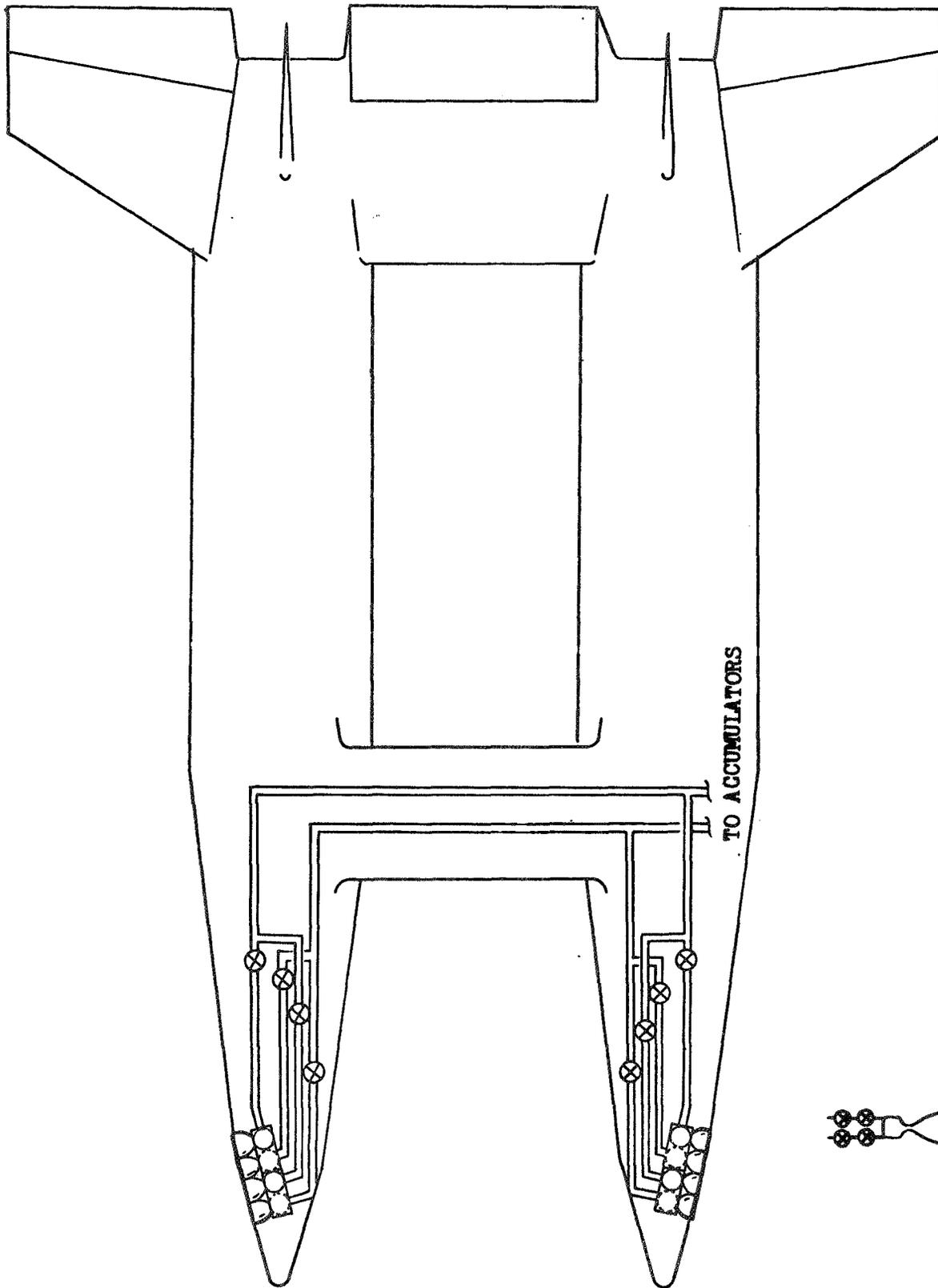
FIGURE C-19

concept for the booster. Comparison of this with the oxygen side of the hybrid subsystem shows that the turbocompressor APS on the booster was, relatively, much simpler. This results primarily from no separate APS storage system being required because all APS requirements could be satisfied by residual propellant vapor in the boosters. The simplest booster subsystem is that shown in Figure C-20 for the stored gas APS concept. Propellant distribution for the booster APS concepts and associated isolation valves for thruster malfunction are shown in Figures C-21 and C-22 for Boosters A and B, respectively. As for the orbiters, data in these schematics apply to all booster APS schematics previously shown.



GASEOUS SUBSYSTEM SCHEMATIC
Boosters A & B

FIGURE C-20



BOOSTER B PROPELLANT DISTRIBUTION
TO THRUSTERS

FIGURE C-22

**APPENDIX D
CONDITIONER CONCEPT COMPARISON**

D-1 INTRODUCTION

This appendix provides a description of the conditioner concepts considered, the various methods of implementation, the resulting effects on overall subsystem performance, and, finally, the selection of concepts to be used in APS trade studies. The objective of this effort was to provide an understanding of the impact of conditioner design on the relative merit of different conditioning approaches and/or of different APS concepts. Since conditioner design and performance was a driving factor in the weight of the overall APS, it was necessary to consider conditioner design in more depth to provide the most realistic values of absolute APS weight. The alternate conditioner concepts were compared on the basis of their weight, simplicity, and technology required for assembly development.

D-2. CONDITIONER CONCEPTS

The purpose of the conditioner assembly in the APS is to convert propellants from their storage state to the gas phase conditions required for thruster operation. Basic conditioning requirements are very similar between different APS concepts (i.e., turbopump, supercritical, hybrid), and a change in conditioner concept similarly impacts APS concepts. Thus, the driving consideration selection is not the type of APS to be used, but rather the total impulse that must be provided by the APS.

Figure D-1 illustrates a matrix of APS conditioner concepts covering the entire spectrum of the trade study; however, based on the fact that conditioner selection is primarily dependent on impulse level and not the type of APS or the vehicle, conditioner alternates were evaluated for one APS concept for one vehicle. The turbopump APS for Orbiter A was selected as the study configuration.

Figure D-2 provides schematics of the five basic conditioner candidates considered in this study. Each concept shown in Figure D-2 differ in overall performance level and/or in technology. As conditioner operating temperature is lowered, technology becomes a less important consideration, but more flow is required for propellant conditioning. Hence, the conditioner assembly design directly effects the effective specific impulse of the subsystem.

D-2.1 Concept A - Concept A of Figure D-2 is the simplest, most straightforward conditioner approach. A single gas generator and heat exchanger are used, with the gas generator operating at 2000°R. All gas generator products are passed through the heat exchanger for propellant thermal conditioning, then through the turbine to power the turbopump. Turbine exhaust products are then vented, either nonpropulsively or, if a + X maneuver is in process, propulsively. The performance of unburned turbine exhaust gas is shown in Figure D-3 as a function of the heat exchanger outlet pressure. In these data, gases are expanded in the vent nozzle to incipient separation (condensation). At lower pressure, more enthalpy change is possible, hence the specific impulse is somewhat improved. For example, with an 800°R vent temperature, approximately 190 lbf-sec/lbm can be obtained from the vent with an outlet pressure of 50 lbf/in²a. If 10 percent bypass

VEHICLE	SUBSYSTEM					
	SUPERCRITICAL		TURBOPUMP		HYBRID	
	IMPULSE CLASS	CONDITIONING ASSEMBLY	IMPULSE CLASS	CONDITIONING ASSEMBLY	IMPULSE CLASS	CONDITIONING ASSEMBLY
ORBITER A			ALL MAN.	A, B, C, D, E		
	≤10 FPS	A, B, C, D, E	≤50 FPS	A, B, C, D, E	≤10 FPS	A, B, C, D, E
			≤10 FPS	A, B, C, D, E		
ORBITER B			ALL MAN.	A, B, C, D, E		
	≤10 FPS	A, B, C, D, E	≤50 FPS	A, B, C, D, E	≤10 FPS	A, B, C, D, E
			≤10 FPS	A, B, C, D, E		

CONDITIONING ASSEMBLY

A. 1HX, 1GG, TGG = 2000°R, WITH AND W/O VENT

B. 1HX, 1GG, TGG = 2000°R, WITH TAPOFF

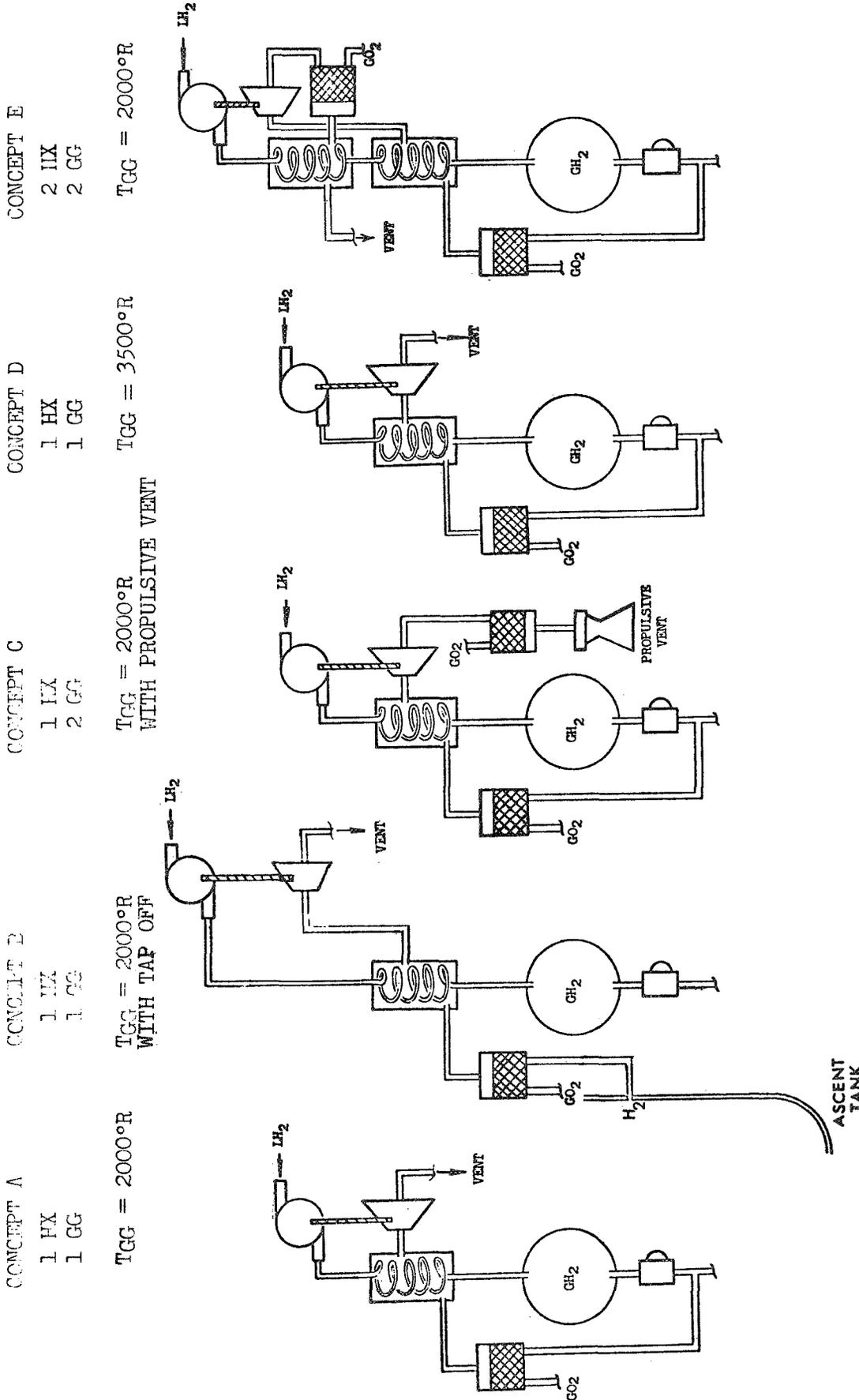
C. 1HX, 2GG, TGG = 2000°R, WITH PROPULSIVE VENT

D. 1HX, 1GG, TGG = 3500°R, WITH AND W/O VENT

E. 2HX, 2GG, TGG = 2000°R, WITH AND W/O VENT

FIGURE D-1
D-3

ORBITER CONDITIONER COMPARISON



CANDIDATE CONDITIONING ASSEMBLY CONCEPTS

FIGURE D-2

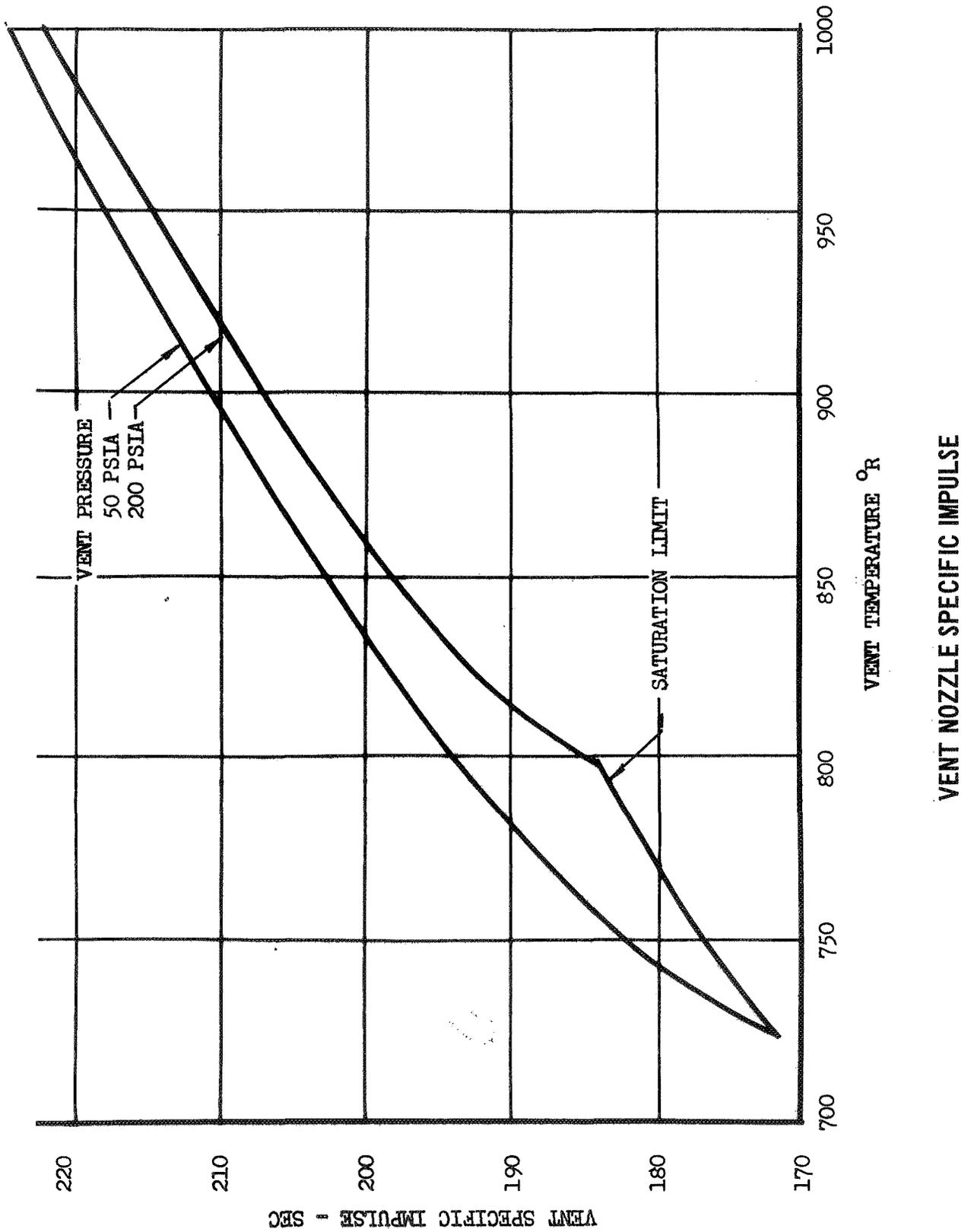


FIGURE D-3

flow is used to drive the turbines and provide energy to the heat exchangers, the vent would provide an increase of 19 lbf-sec/lbm in overall APS performance.

Concept A is the lowest performance conditioner concept considered; however, it offered a minimum of technical risks and was used as a technology reference for comparison of other conditioner concepts.

D-2.2 Concept B - Concept B of Figure D-2 is an adaptation of the Concept A conditioner and operates in the same manner. The difference is that the gas generator propellant is extracted from the main engine ascent tanks and operates at lower pressure. Thus, so long as vapor is available from the main engine tank, conditioner flow for this assembly is free to the APS. When main ascent tanks have been depleted and tank pressure level is below that needed for assembly operations, vapor is extracted from the APS to supply the gas generators. In this mode, then, subsystem performance is the same as that of concept A. Figure D-4 identifies differences in Concept B component technology. The gas generator operates at low pressure, but there was no identifiable technology difference for low pressure combustion. The low pressure on the hot side of the heat exchanger presented no particular problem; however, in the turbopump area, it was felt that a gear box probably would be required to optimize turbine and pump speed, and that operation with low pressure gas would result in much larger turbine flow areas and heavier turbopumps.

D-2.3 Concept C - Concept C of Figure D-2 is again an adaptation of the baseline reference (Concept A). This concept is identical to Concept A, except it is modified to recover the remaining energy in the fuel rich turbine exhaust by combustion. When the subsystem is performing a + X translation maneuver, this turbine exhaust gas would be reburned with supplemental oxygen, and directed along the + X axis of the vehicle to provide useful impulse. Overall performance would be higher than that of Concept A, as its overall operating mixture ratio would be nearer that of the thrusters and less hydrogen would be wasted. The technology associated with Concept C is summarized in Figure D-4. With respect to turbine and heat exchanger, there is no difference between this concept and that of reference baseline; however, the recombustion device in the propulsive vent has certain technology features that must be accounted for in selection. Specifically, this unit must be designed to accept a mixed gas as fuel, and must provide gaseous mixing and combustion. The unit would, of necessity, operate at very low pressure, and it was anticipated that performance would be difficult to predict and that

CONCEPTS	A	B	C	D	E
	1 HX 1 GGA T _{GG} = 2000°R	1 HX 1 GGA T _{GG} = 2000°R WITH TAPOFF	1 HX 2 GGA T _{GG} = 2000°R WITH PROPULSIVE VENT	1 HX 1 GGA T _{GG} = 3500°R	2 HX 2 GGA T _{GG} = 2000°R
GAS GENERATOR	BASELINE REFERENCE	1. LOW PRESSURE COMBUSTION - EQUAL TECH- NOLOGY	1. STAGED COMBUS- TION OF PROPULSIVE VENT - IGNITION - DIFFICULT - PERFORMANCE - PREDICTABIL- ITY - GOX THROTTLE AND CONTROLS	1. COOLED GGA CHAMBER 2. INTEGRATED GGA AND HX	1. STAGED COM- BUSTION OF SECOND GGA - IGNITION - DIFFICULT - TEMPERATURE CONTROL - GOX THROTTLE AND CONTROLS
HEAT EXCHANGER	BASELINE REFERENCE	1. LOW PRESSURE HOT GAS SIDE- EQUAL TECHNOLOGY	BASELINE REFERENCE	1. COOLED HX SHELL 2. PROPELLANT SEQUENCING 3. INTEGRATED GGA AND HX	1. HOT GAS TEMP. PREDICTABILITY IN SECOND HX 2. ASSY. START SEQUENCING 3. COLD SIDE TEMP CONTROL
TURBINE	BASELINE REFERENCE	1. LOW PRESSURE TURBINE - GEARBOX TO OPTIMIZE N _T AND N _p - TURBINE FLOW AREA HIGH	BASELINE REFERENCE	1. TURBINE INLET TEMP CONTROL	BASELINE REFERENCE

CONDITIONING ASSEMBLY RELATIVE TECHNOLOGY CRITIQUE

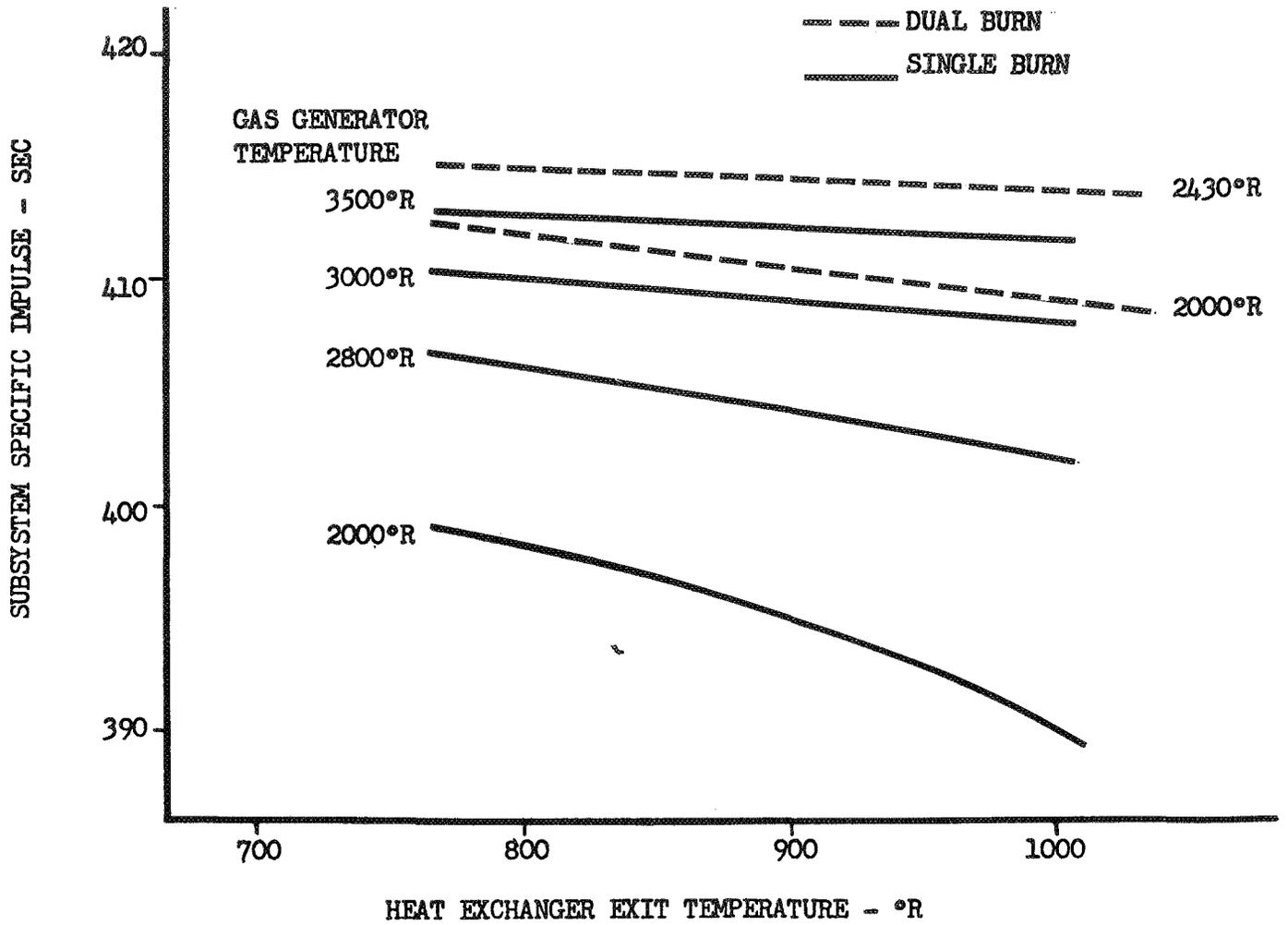
FIGURE D-4

throttling control of oxygen flow would be required to preclude unit burnout.

D-2.4 Concept D - This concept is implemented precisely as Concept A, except that the gas generator operates at much higher temperature, hence, the overall assembly operates at a higher mixture ratio and has a greater heat release than the Concept A baseline. Figure D-4, however, shows that the technology required for this concept is appreciably more difficult than that for the baseline. Both gas generator chamber and heat exchanger must have complete structural cooling. In addition, heat exchanger starting would require propellant sequencing or staging of mixture ratio to allow start-up at a lower mixture ratio. Potentially, this assembly may also require control of turbine inlet temperature if the heat exchanger exhaust was above desirable limits.

The performance improvement offered by this concept is illustrated in Figure D-5. Shown is the subsystem specific impulse for various gas generator temperatures. For purposes of this phase of the study, a temperature of 3,500°R was selected, since it provided both nearly maximum performance for this approach, and the same overall assembly mixture ratio as achieved with Concept E operating at 2,000°R.

D-2.5 Concept E - The final concept considered is the dual burn concept with two heat exchangers and two gas generators operating at 2000°R. This approach is similar to that envisioned for Concept C, except that in the second gas generator, exhaust products are used in a heat exchanger rather than propulsively in a vent nozzle. The first stage of this assembly is precisely the same as that of Concept A; however, in this approach, turbine exhaust is extracted and burned in a second gas generator assembly, where supplemental oxygen is added to raise the temperature back to 2,000°R for preheating of the propellants. The vent can be used either propulsively or nonpropulsively. Overall performance of using this approach is quite high, Figure D-5 illustrates subsystem specific impulse as a function of the gas generator combustion temperature and heat exchanger exit temperature. As shown in Figure D-5 for the same operating temperatures of 2,000°R, this dual burn approach affords approximately a 15 lbf-sec/lbm improvement in subsystem specific impulse over the single burn approach.



SUBSYSTEM SPECIFIC IMPULSE \leq 10 FT/SEC

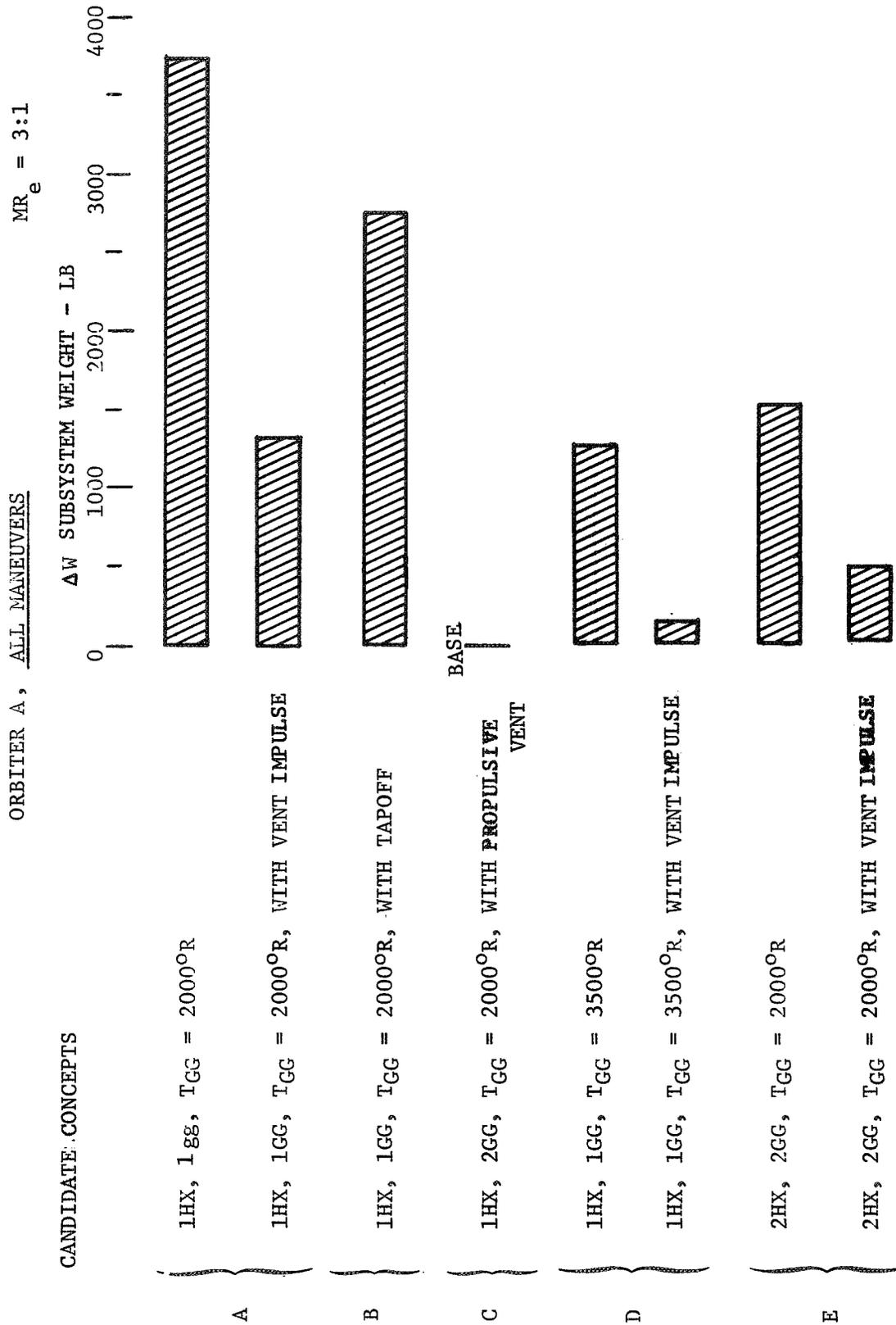
FIGURE D-5

D-3. COMPARISON OF APS WEIGHTS

A comparison of changes in overall APS weight resulting from use of different conditioner candidates of Figure D-2 is shown in Figures D-6, D-7 and D-8, in terms of incremental subsystem weights from an arbitrary base point. Figure D-6 shows weight changes for the all-maneuver impulse class. As shown, the simplest concept (Concept A without vent impulse) is the heaviest. Use of this conditioning approach would result in approximately a 3700 lb APS weight penalty. This weight penalty can be reduced to 1400 lbs by providing vent impulse for +X maneuvers. All the lower weight subsystems utilized the vent impulse. Concept C, with an active propulsive vent is the lightest. Nearly identical in performance is Concept D, which uses the high temperature gas generator with vent impulse. The staged combustion approach, using the second gas generator to provide energy to a heat exchanger instead of a propulsive vent, was also competitive on a weight basis.

Figure D-7 provides similar data except at the ≤ 50 ft/sec velocity allocation. Here the proportion of impulse expended in the +X axis was greatly reduced; hence, weight penalties for reduced conditioner performance were not appreciable. For this maneuver class, the simple heat exchanger/gas generator approach (Concept A) results in only a 570 lb weight penalty. Utilizing vent impulse with this subsystem reduced the weight penalty to 300 lbs. For this case, the lightest weight approach is a high temperature gas generator/heat exchanger. Figure D-8 provides a conditioner comparison for the lowest impulse level, in which the tap-off gas generator assembly is the lightest weight but the simplest approach resulted in only a 270 lb weight penalty. There was virtually no advantage to an assembly with impulsive vent capability.

The amount of free propellant which was provided by use of main engine residuals (tap-off) is defined in Appendix F.

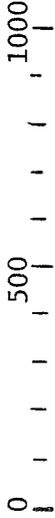


CANDIDATE CONDITIONING ASSEMBLY CONCEPT COMPARISON

FIGURE D-6

ORBITER A, ≤ 50 FT/SEC. $MR_e = 4:1$

ΔW SUBSYSTEM WEIGHT - LB



CANDIDATE CONCEPTS

1HX, 1GG, T_{GG} = 2000°R

1HX, 1GG, T_{GG} = 2000°R, WITH VENT IMPULSE

1HX, 1GG, T_{GG} = 2000°R, WITH TAPOFF

1HX, 2GG, T_{GG} = 2000°R, WITH PROPULSIVE VENT

1HX, 1GG, T_{GG} = 3500°R

1HX, 1GG, T_{GG} = 3500°R, WITH VENT IMPULSE

2HX, 2GG, T_{GG} = 2000°R

2HX, 2GG, T_{GG} = 2000°R, WITH VENT IMPULSE

A

B

C

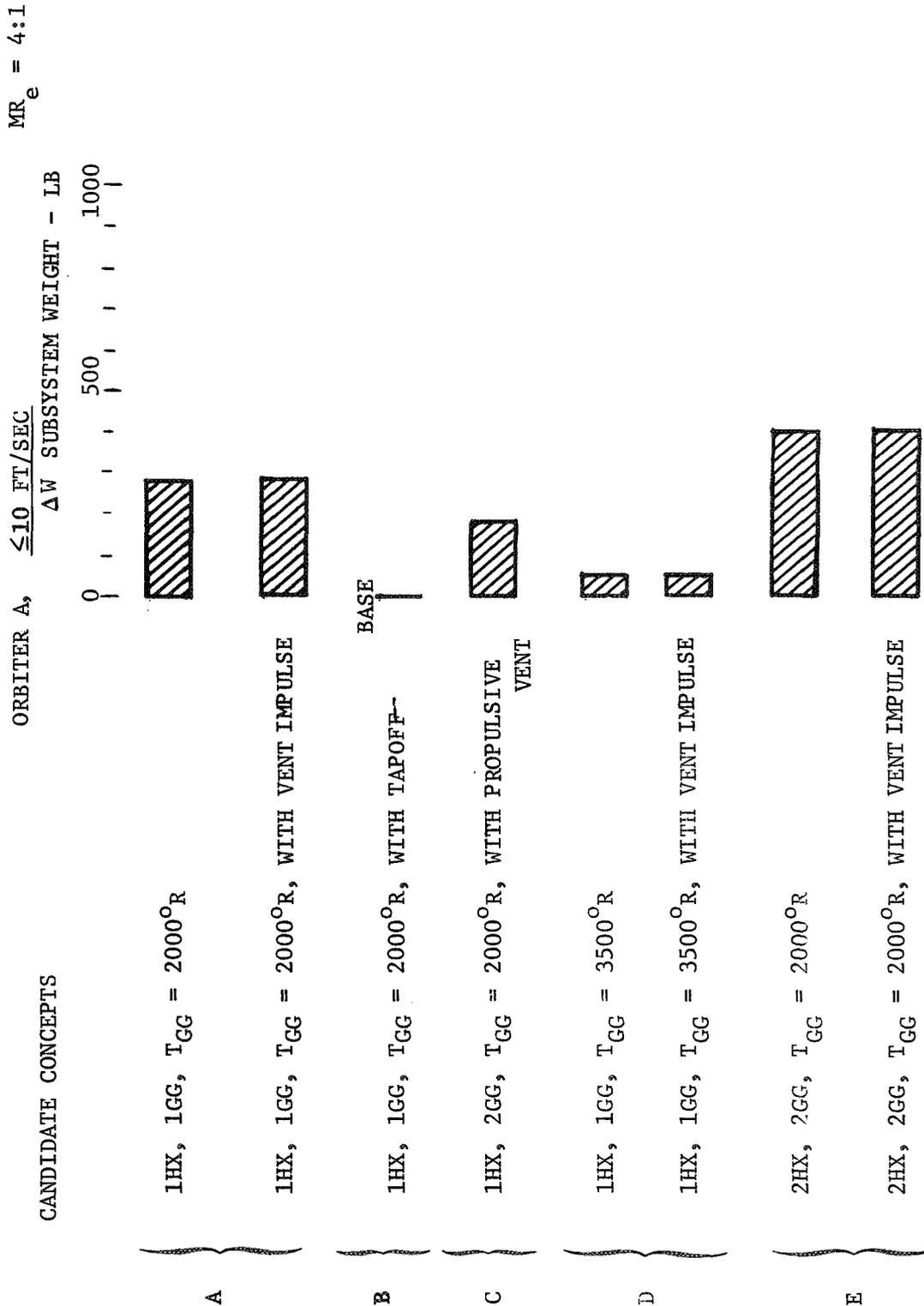
D

E

BASE

CANDIDATE CONDITIONING ASSEMBLY CONCEPT COMPARISON

FIGURE D-7



CANDIDATE CONDITIONING ASSEMBLY CONCEPT COMPARISON

FIGURE D-8

D-4. SELECTION OF CONDITIONER CONCEPT

The type of conditioner concept best suited to the different missions was selected on technology requirement, simplicity, weight, and volume. Since each conditioner must be designed to operate on demand, there is no difference in flexibility of concepts and, for this reason, flexibility was scored equally for all conditioner concepts. Figure D-9 presents a quantitative point rating of the different assembly concepts for each of the three mission profiles. From a technology standpoint, Concepts C and E (with an impulse vent) are considered the highest risk, and were scored the lowest in this assessment. From a simplicity standpoint, Concepts A and B are similar. Concept E was considered the most complex, as it required the most components and the most complex controls. Weight and volume were independently scored for each of the three maneuver classes, since certain concepts had distinctly attractive features when used for large impulse requirements. Weight ratings were based on data presented in Figures D-6, D-7, and D-8, allocating specific ratings in terms of points per pound of weight. As shown for the all maneuver case, the highest point total is provided by Concept D, the 3500°R gas generator concept utilizing vent impulse. For the ≤ 50 ft/sec case, the same concept is applicable but the advantage of the vent impulse does not warrant the additional complexity. For the low maneuver case, the simplest, most straightforward concept provides the highest rating. While it suffers somewhat in weight, this deficiency is more than made up by technological and simplicity advantages. Based on these results, selections for concept comparison shown in Figure D-10 were made. Concept D was selected for the all maneuver and ≤ 50 ft/sec cases for both orbiters. In the all maneuver class, the impulsive vent capability (with its improved weight) was selected. For the ≤ 10 ft/sec case, the simple 2000°R gas generator heat exchanger assembly was selected. In addition, since selection was clearly dependent on total impulse level (and at low total impulse the 2000°R gas generator concept was clearly the most suitable), this approach was used for comparison of booster APS concepts, since the required booster impulse was even lower.

Subsequent to Subtask A, the selected APS conditioner assembly concept shown

GAS GENERATOR CONCEPT	TECHNOLOGY (25)	SIMPLICITY (20)	WEIGHT/VOLUME (25)		FLEXIBILITY (30)	TOTAL	
			ALL	≤50 ≤10		ALL	≤50 ≤10
A { 1HX, 1GG, T _{GG} = 2000°R W/O Vent 1HX, 1GG, T _{GG} = 2000°R With Vent	25	20	X	19	30	X	94
			12	22		78	88
B 1HX, 1GG, T _{GG} = 2000°R With Tapoff	21	13	X	25	30	X	89
C 1HX, 2GG, T _{GG} = 2000°R With Propulsive Vent	12	14	25	23	30	81	79
D { 1HX, 1GG, T _{GG} = 3500°R W/O Vent 1HX, 1GG, T _{GG} = 3500°R With Vent	20	20	12	24	30	82	94
			24	25		86	87
E { 2HX, 2GG, T _{GG} = 2000°R W/O Vent 2HX, 2GG, T _{GG} = 2000°R With Vent	16	14	10	20	30	70	81
			20	21		72	73

X UNACCEPTABLE ($\Delta W > 2500$ LB)
 SELECTED

ORBITER A TURBOPUMP
CONDITIONING ASSEMBLY CONCEPT SELECTION

FIGURE D-9

VEHICLE	SUBSYSTEM					
	SUPERCRITICAL		TURBOPUMP		HYBRID	
	IMPULSE CLASS	CONDITIONING ASSEMBLY	IMPULSE CLASS	CONDITIONING ASSEMBLY	IMPULSE CLASS	CONDITIONING ASSEMBLY
ORBITER A			ALL MAN.	A, B, C, D, E		
	≤ 10 FPS	(A, B, C, D, E)	≤ 50 FPS	A, B, C, D, E	≤ 10 FPS	(A, B, C, D, E)
	≤ 10 FPS	(A, B, C, D, E)	≤ 10 FPS	(A, B, C, D, E)	≤ 10 FPS	(A, B, C, D, E)
ORBITER B			ALL MAN.	A, B, C, D, E		
	≤ 10 FPS	(A, B, C, D, E)	≤ 50 FPS	A, B, C, D, E	≤ 10 FPS	(A, B, C, D, E)
	≤ 10 FPS	(A, B, C, D, E)	≤ 10 FPS	(A, B, C, D, E)	≤ 10 FPS	(A, B, C, D, E)

CONDITIONING ASSEMBLY

- A. 1HX, 1CG, TGG = 2000°R, WITH AND W/O VENT
- B. 1HX, 1GG, TGG = 2000°R, WITH TAPOFF
- C. 1HX, 2GG, TGG = 2000°R, WITH PROPULSIVE VENT
- D. 1HX, 1GG, TGG = 3500°R, WITH AND W/O VENT
- E. 2HX, 2GG, TGG = 2000°R, WITH AND W/O VENT

ORBITER CONDITIONER CONCEPT SELECTION

FIGURE D-10

for the all-maneuver case, (i.e., the turbopump using a 3,500°R gas generator), was changed. During the initial phases of Subtask B preliminary design, matching of turbopump to flow rates provided by this high temperature gas generator was determined not feasible; therefore, a more detailed comparison of conditioners for the all-maneuver class was undertaken in Subtask B. The result was selection of a conditioner which provided similar performance levels, but redistributed the oxygen addition within the assembly to maintain 2000°R turbine temperature, yet provided the same overall energy release. This later study is documented in detail in the Subtask B Report (Reference (a)).

References:

- (a). Gaines, R. D., Goldford, A. I., Kaemming, T. A., High Pressure Auxiliary Propulsion Subsystem Definition Study Subtask B Report: McDonnell Douglas Report No. MDC E0298, dated 12 February 1971.

APPENDIX E

COMPONENT AND SUBASSEMBLY MODELS

E-1 INTRODUCTION

Component and subassembly weight and performance models were required to perform valid trade studies and to allow accurate subsystem weight and performance comparisons. Models were developed for the APS thrust chamber, gas generator, heat exchangers, turbopumps and turbocompressors, propellant tankage, pressurization sub-assemblies, flow controls, accumulators, and supply lines. For each component, parametric data were developed relating weight and performance. These data were then described in equation form for use in the computer sizing program. In addition, component operating characteristics such as response time and operation limits were defined as required. The following sections describe in detail the component and assembly models used and the rationale for their development.

E-2. THRUSTER

E-2.1 Thruster Design - APS concepts use gaseous oxygen-hydrogen thrusters to provide for space shuttle vehicle control. For the APS studies, it was necessary to provide a rather detailed evaluation of thruster performance and design in order to determine APS weight.

The baseline design selected for the APS thruster was based primarily upon a previous development and test demonstration program conducted by the Aerojet Liquid Rocket Company for a 1500 lb thrust unit operating at 300 lbf/in² chamber pressure. The baseline APS thruster is composed of an injector, film cooled thrust chamber, electrical spark igniter assembly, and integrated bipropellant poppet valve assembly. Each of these component concepts has been satisfactorily demonstrated. Figures E-1 and E-2 show this thruster and nominal design conditions.

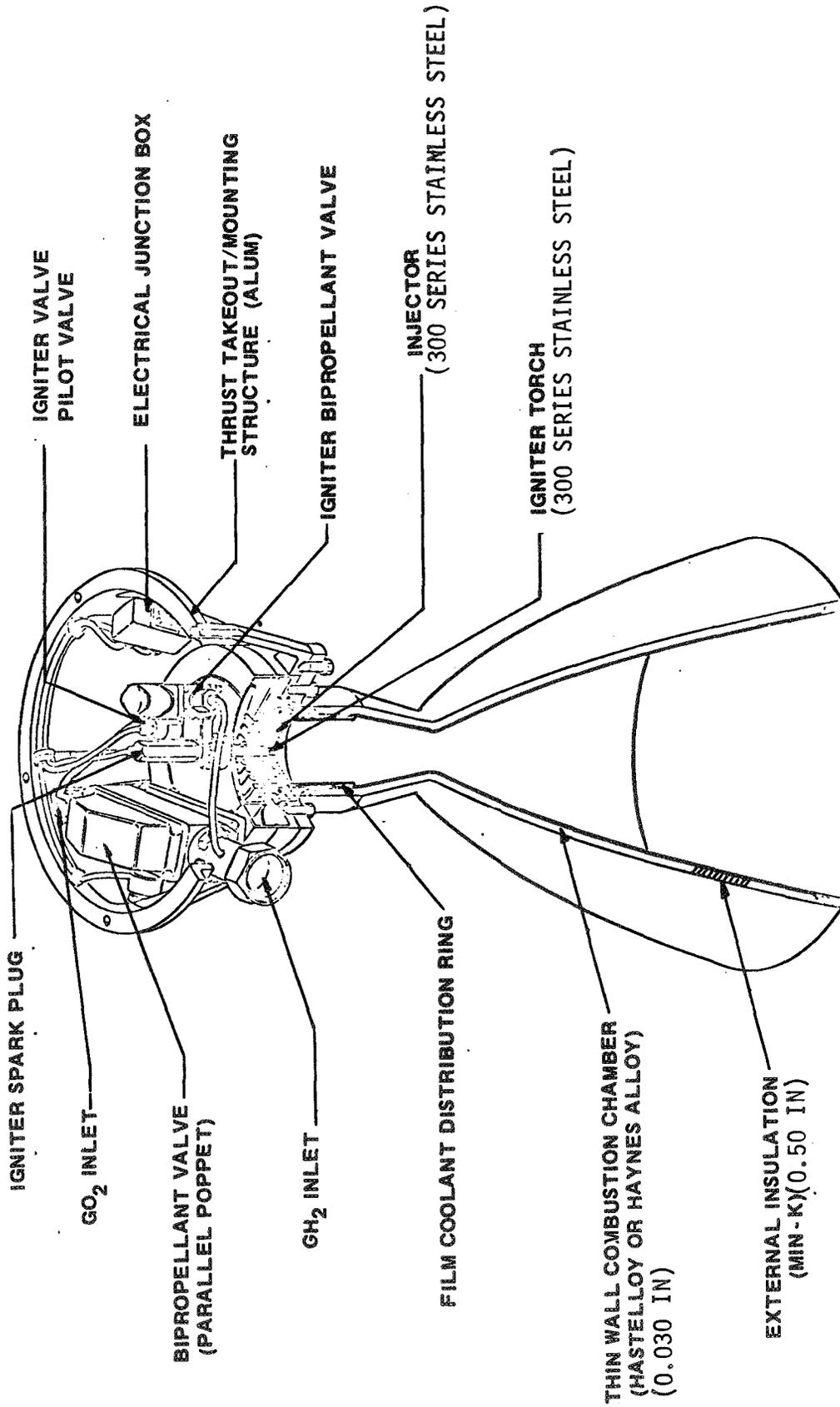
The baseline injector assembly was based on prototype demonstration testing. This testing demonstrated 98 percent energy release efficiency from the injector in conjunction with very short characteristic length combustion chambers which reduce the combustion chamber cooling requirement. The injector was fabricated of 300 series stainless steel.

Because of the availability of demonstrated data, a film cooled concept was chosen. The combustion chamber is a monolithic steel shell fabricated of a Haynes alloy using external insulation to minimize radiation heating to the vehicle. It is estimated that 27 percent of the hydrogen will be required to maintain the chamber surface at the required temperature for high cycle life.

The electrical spark igniter selected was demonstrated in a test program. This igniter utilized separate control valves to provide positive propellant control to the torch sequenced chamber. This concept provides very fast response and demonstrated life capability.

Preprototype injectors, coupled with a fast response electrical spark ignition and quick actuating, workhorse bipropellant valves have demonstrated transient response capabilities of 50 ms to 90 percent of rated thrust for a 3000 lb thrust engine. Pulse mode testing has demonstrated the feasibility of producing a repeatable minimum impulse bit of less than 100 lb-sec with the 3K lb thrust injector.

A minimum propellant pressure drop for the thruster was established at 20 percent of chamber pressure for system pressure schedule determination. This limit is



HIGH PRESSURE APS THRUSTER DUCTED FILM COOLED

FIGURE E-1

THRUSTER LEVEL - LBF	1500
CHAMBER PRESSURE - PSIA	300
EXPANSION RATIO - Ac/At	40
MIXTURE RATIO	4
SPECIFIC IMPULSE - LB SEC	436
INLET PRESSURE - PSIA	375
PROPELLANT INLET TEMP - °R (H ₂ & O ₂)	540
PERCENT FUEL FILM COOLANT	27
WEIGHT - LB	33
LENGTH MAX - IN	28
DIAMETER MAX - IN	13

NOMINAL THRUSTER DESIGN CONDITIONS

FIGURE E-2

based upon decoupling the combustion dynamics from the gaseous propellant feed pressure oscillations. These oscillations can be eliminated by selective feed system design or by increasing injector pressure drop. The value of 20 percent of Pc provides sufficient margin for injector and valving.

E-2.2 Performance Analysis - Thruster performance on the high pressure engines was calculated over the range of conditions shown in the following table.

<u>Parameter</u>	<u>Units</u>	<u>Nominal</u>	<u>Range</u>
Chamber Pressure	lbf/in ² _a	300	20 - 800
Thrust	lb	1500	500 - 5000
Mixture Ratio	O/F	4	1 - 10
Area Ratio	Ae/At	40	10 - 120
Oxygen Inlet Temperature	°R	540	300 - 800
Hydrogen Inlet Temperature	°R	540	100 - 800

In order to completely assess the impact of each of the variables on thruster performance, a rigorous performance analysis was conducted around the design point. Standard assessments of the magnitude of these losses were accomplished by using the ICRPG Performance Standardization Working Group Performance Loss Evaluation

Technique. With this technique, each of the specific impulse losses which make up the aggregate total of performance inefficiency was calculated over the variable ranges indicated in the table. Figure E-3 presents a summary of typical

	ISP-SEC	%
ONE DIMENSIONAL EQUILIBRIUM $\epsilon = 40$ $P_c = 300 \text{ LBF/IN}^2 \text{ A}$ $F = 1500 \text{ LB F}$ $MR = 4.0$	474.4	100
KINETIC LOSS	5.1	1.1
DIVERGENCE LOSS	4.2	.9
BOONDARY LAYER LOSS	5.7	1.2
ENERGY RELEASE LOSS	9.0	1.9
FILM COOLING LOSS	14.2	3.0
PREDICTED	436	92%

ESTIMATED SPECIFIC IMPULSE LOSSES

FIGURE E-3

losses. These losses, subtracted from theoretical, result in performance delivery for any operating point. The following paragraphs discuss performance losses.

E-2.3 Reaction Kinetics - Variations from shifting equilibrium performance are partially a result of reaction kinetics. The ability of the thruster to achieve balanced performance is directly dependent on its operating pressure, temperature, expansion pressure ratio, and stay time within the thruster. As chamber pressure decreases, molecular mean free path increases, resulting in a lower rate of intermolecular activity. This lower rate results in a recombination lag during the expansion process. Increases in area ratio produce greater expansion pressure ratios, causing decreased molecular activity in the nozzle. This effect is less severe since chemical composition does not change significantly at higher area ratios. Conversely, increased thrust level produces a longer stay time within the chamber-nozzle confines and increases recombination.

The most significant variable in analyzing kinetics loss is the combustion temperature. As temperature increases and the mixture approaches stoichiometric, a large percentage of the combustion products are in a dissociated state. Dissociated products require a molecular recombination during the expansion process for complete thermal energy release; consequently, potential kinetic loss is greatest at highest combustion temperature, which usually occurs near stoichiometric.

E-2.4 Cooling Requirements - Thruster cooling requirements were extrapolated from design point calculations using suitable influence characteristics. Each calculated coolant flow is sufficient to ensure the integrity of a film-cooled chamber. Cooling requirement is adjusted for particular changes in thrust and chamber pressure. This, in turn, readjusts the coolant heat flux with respect to total flow and surface area change. Final coolant flow adjustment was made for inlet propellant temperature changes where a constant coolant bulk temperature was maintained, requiring increased coolant flows for higher inlet temperatures.

Specific impulse losses resulting from FFC were evaluated by mass weighting coolant and core stream tubes performance contribution and by transferring core enthalpy to the coolant (consistent with coolant bulk temperature at the throat.)

E-2.5 Boundary Layer Heat Transfer - This analysis calculates degradation of performance due to shear drag and heat loss at thrust chamber boundary. Loss decreases as operating thrust and chamber pressure increase. Mixture ratio had only a secondary effect on the magnitude of this loss and was, therefore, not included.

E-2.6 Nonaxial Exhaust Velocities - Two dimensional expansion of the combustion gases in the nozzle results in a nonaxial exit velocity profile. This profile produces a thrust decrement which decreases with area ratio.

E-2.7 Performance Results - Design and operating variables included in performance analysis were thrust, chamber pressure, area ratio, mixture ratio, and oxygen and hydrogen propellant inlet temperatures. All these design conditions affect thruster specific impulse performance.

Thruster performance as a function of thrust level shows increasing vacuum specific impulse with increasing thrust. Three factors cause this trend, reductions in kinetic, boundary layer, and film cooling losses. The last results from a decrease in film cooling requirements due to a smaller mixture ratio maldistribution, allowing the injector core to operate closer to the engine mixture ratio.

Performance increases with area ratio are attributable to increase in exit velocity, resulting from corresponding larger pressure ratio (area ratio). Increases

in boundary layer and kinetic losses tend to restrict the performance increase to small value when area ratio increases over 120.

The strongest influence on performance is the design point mixture ratio. Performance increases on the fuel-rich side of the design point reflect reductions in kinetic and film cooling mixture ratio maldistribution losses. Operating on the oxidizer rich side shows the opposite affect, with corresponding decreases in performance.

Only slight variations in performance are noted with design point chamber pressure for engines operating at the same area ratio, mixture ratio, and thrust. Only very slight increases in theoretical performance are noted with large chamber pressure increases. This condition is caused by two factors. Performance losses due to kinetics and boundary layer heat transfer are directly reduced (with increasing chamber pressure), while film cooling requirements and corresponding mixture ratio maldistribution loss increases. The two compensate for each other.

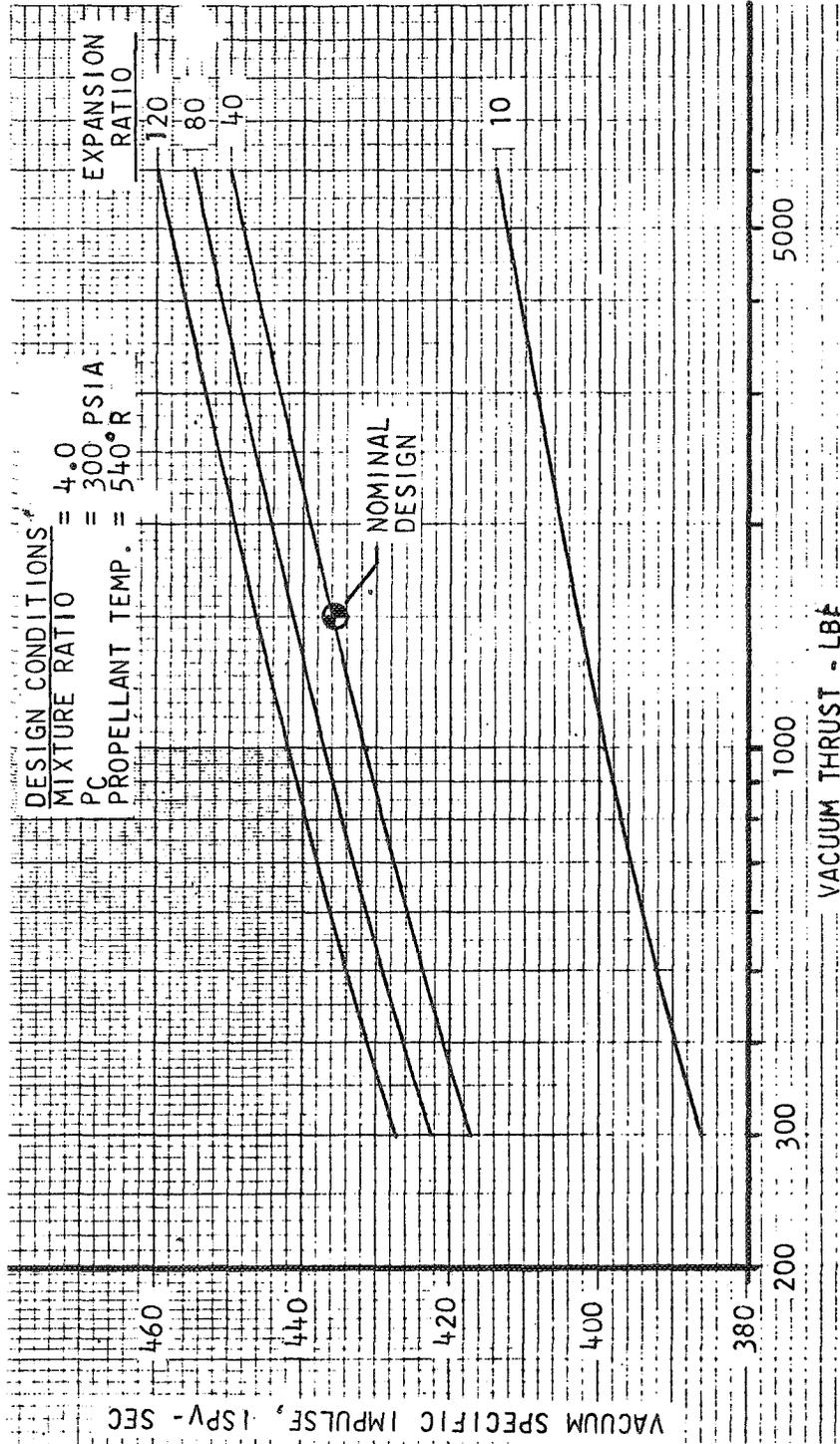
Increases in propellant inlet temperature increase the combustion product enthalpy level for expansion in the nozzle. The most influential effect is hydrogen temperature because of its high specific heat. This trend is only slightly affected by changes in other design variables.

Figure E-4 presents TCA specific impulse performance for varying thrust levels and nozzle expansion ratios at a fixed mixture ratio and propellant inlet temperature. The effect of mixture ratio, and hydrogen inlet temperature, is presented in Figures E-5 and E-6, respectively.

The influence of the design conditions upon required percentage of fuel film coolant is presented in Figures E-7, E-8, and E-9. These illustrations show the percentage of film coolant required to establish desired chamber wall conditions as a function of design thrust, mixture ratio, chamber pressures, and hydrogen propellant inlet temperature.

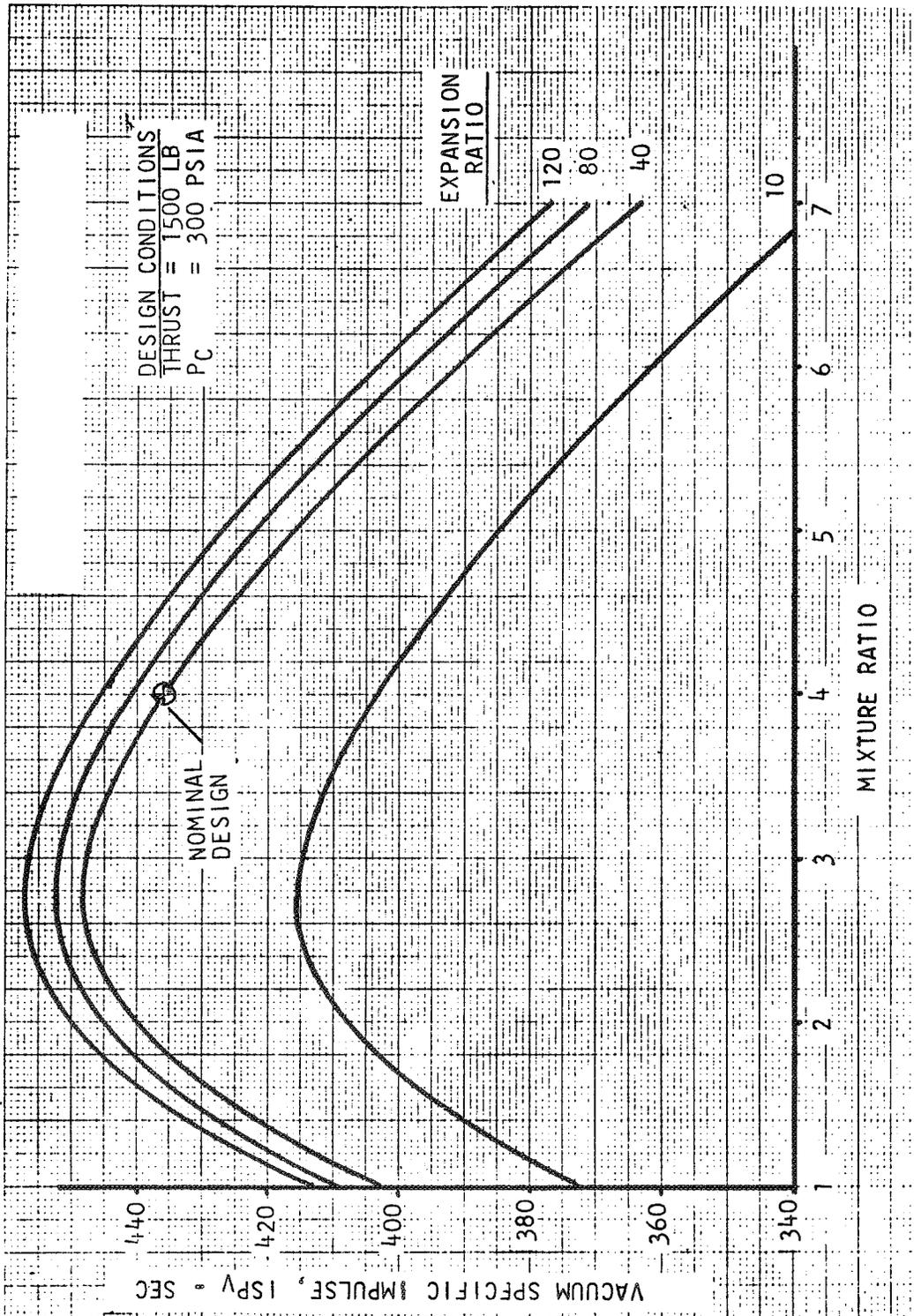
E-2.8 Design Physical Characteristic Data - The sensitivity of engine weight, length, and diameter to different design point conditions was determined in Subtask A. The physical characteristics were identified through calculation of physical geometry for nominal and for representative extreme design point engines, and through subsequent calculation of material weights.

An optimum nozzle configuration was used for the engine, and weights calculated used selected material density and chamber wall thickness for the combination of pressure, thrust, and area ratio being evaluated. External insulation weight was added to chamber metal weight.



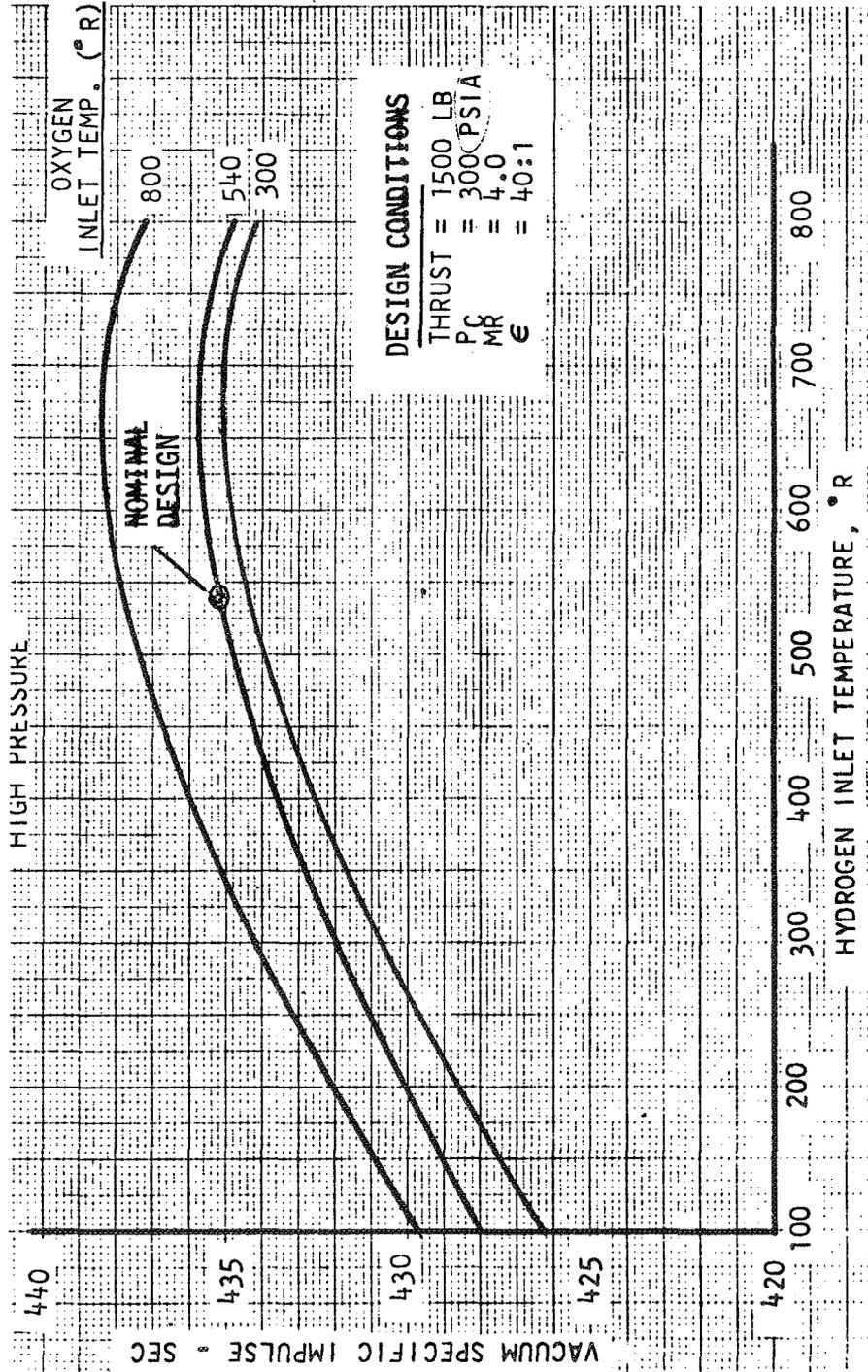
DESIGN THRUST INFLUENCE ON VACUUM SPECIFIC IMPULSE

FIGURE E-4



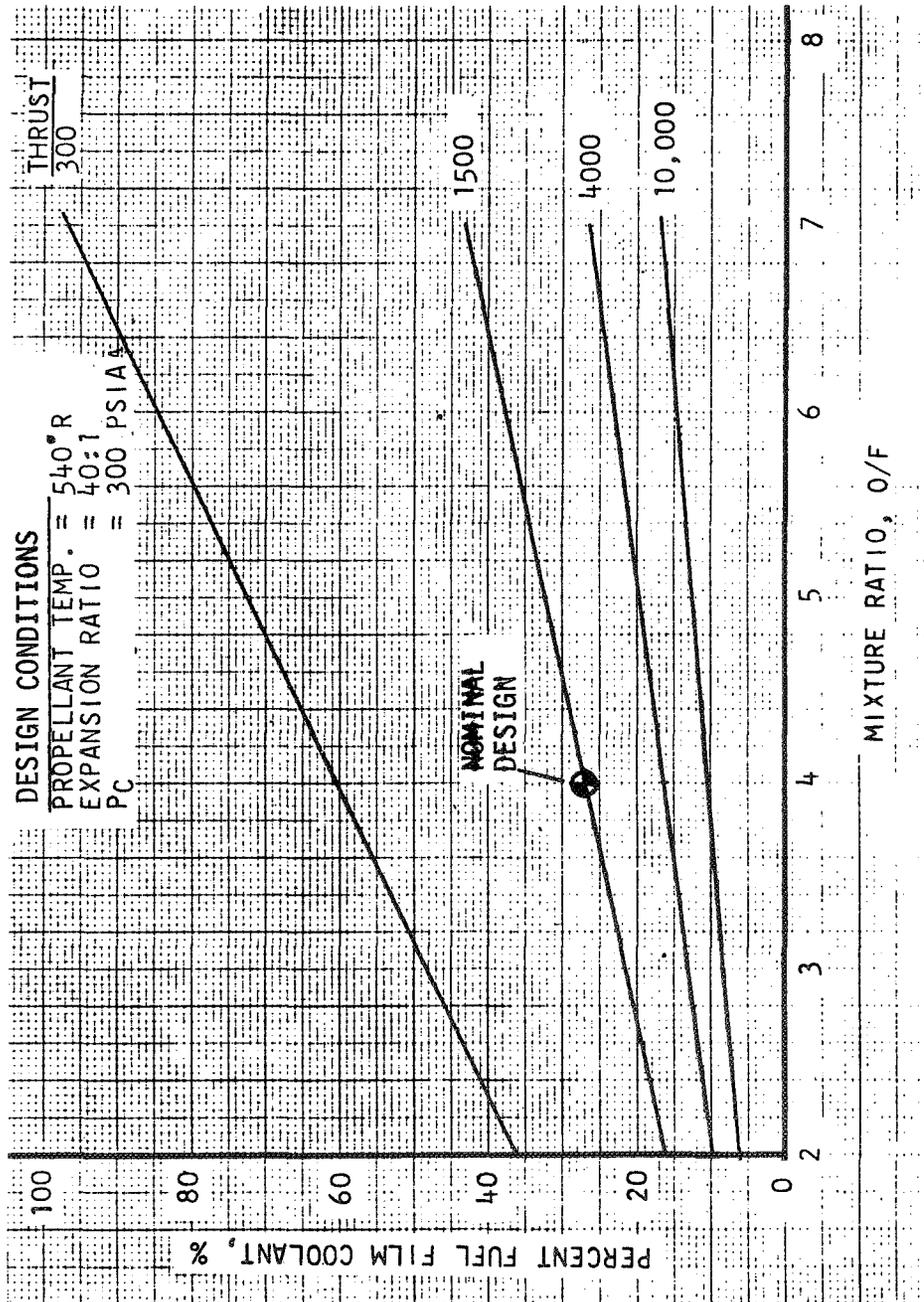
DESIGN MIXTURE RATIO INFLUENCE ON SPECIFIC IMPULSE

FIGURE E-5



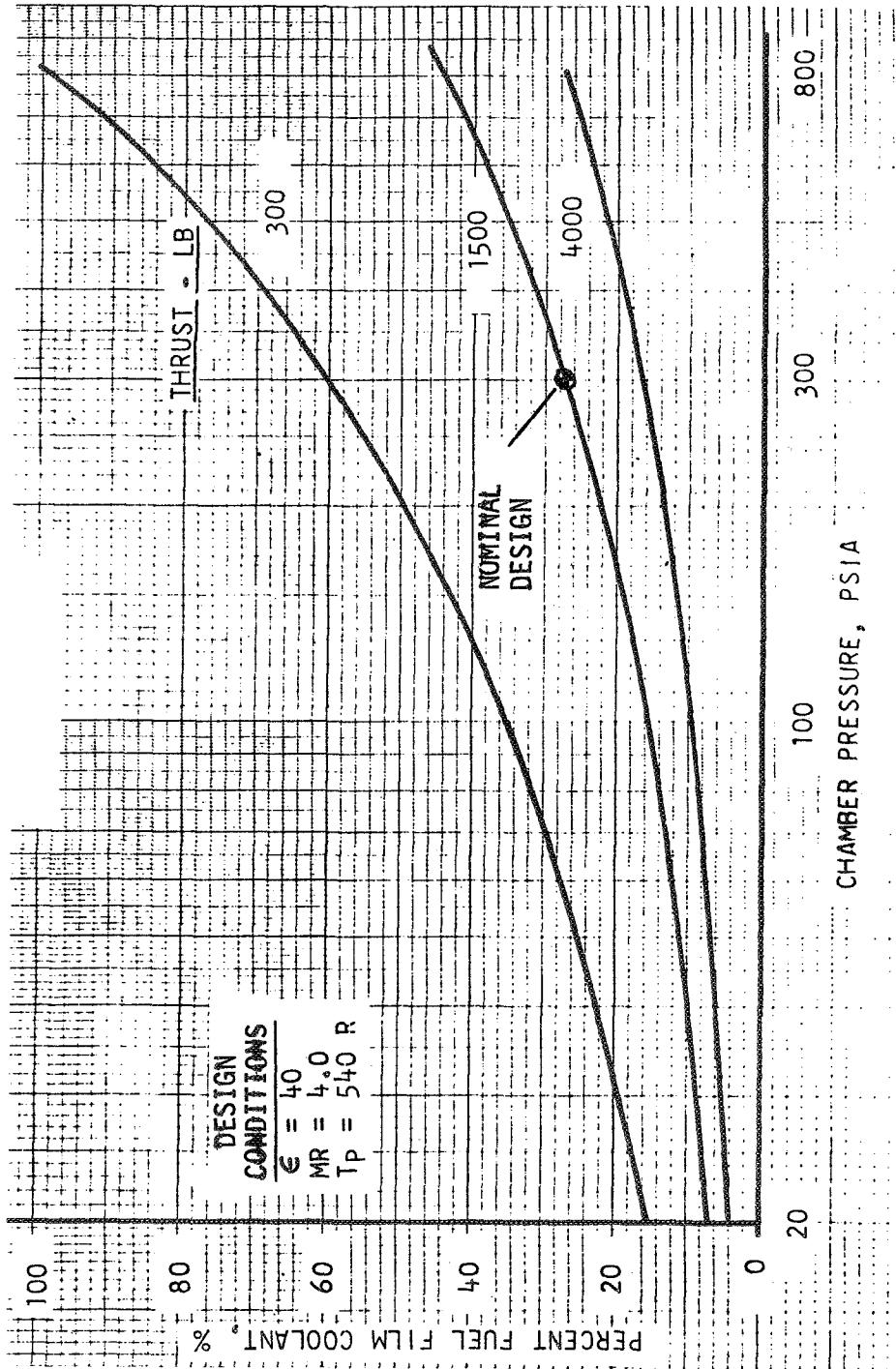
DESIGN HYDROGEN INLET TEMPERATURE
INFLUENCE ON PERFORMANCE
High Pressure

FIGURE E-6



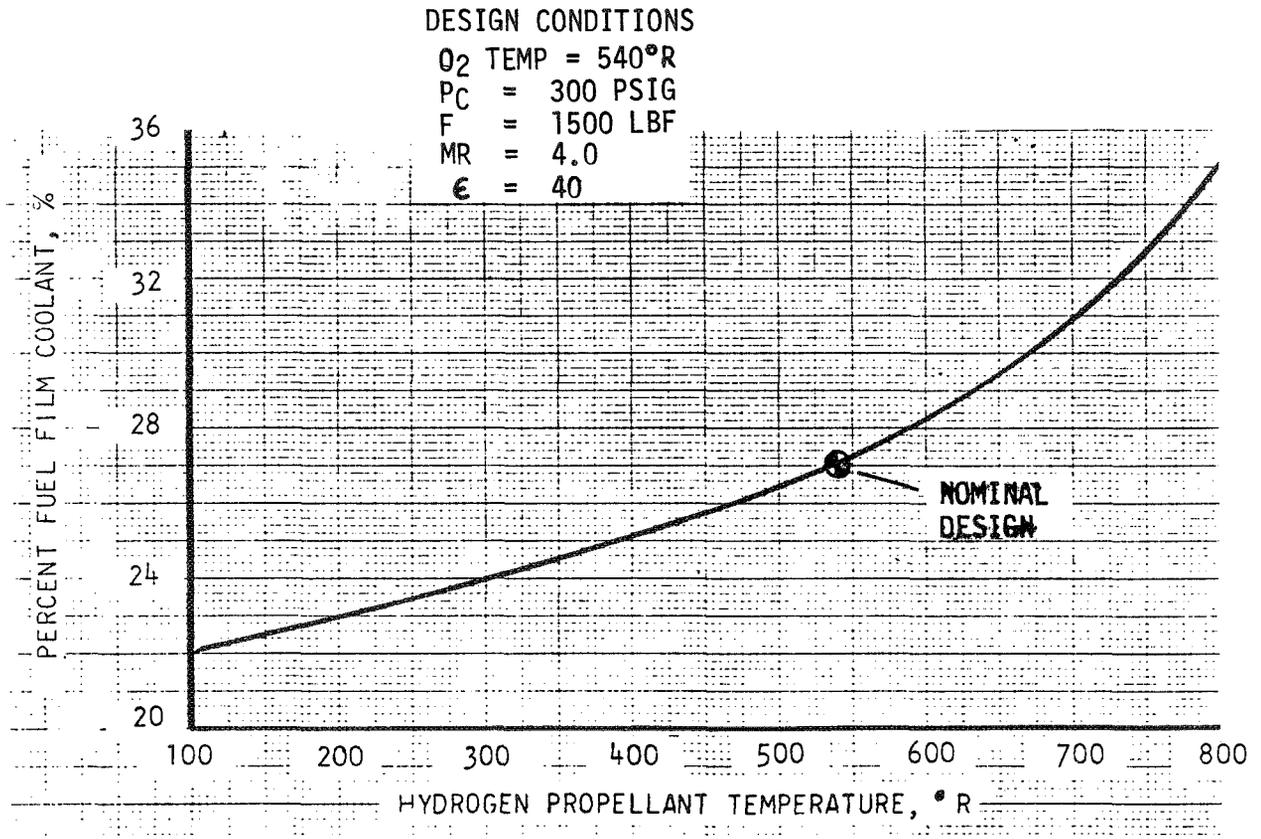
FUEL FILM COOLANT VARIATION WITH DESIGN MIXTURE RATIO

FIGURE E-7



CHAMBER PRESSURE INFLUENCE ON FUEL FILM COOLANT
High Pressure

FIGURE E-8



DESIGN HYDROGEN INLET TEMPERATURE INFLUENCE
ON REQUIRED FUEL FILM COOLANT

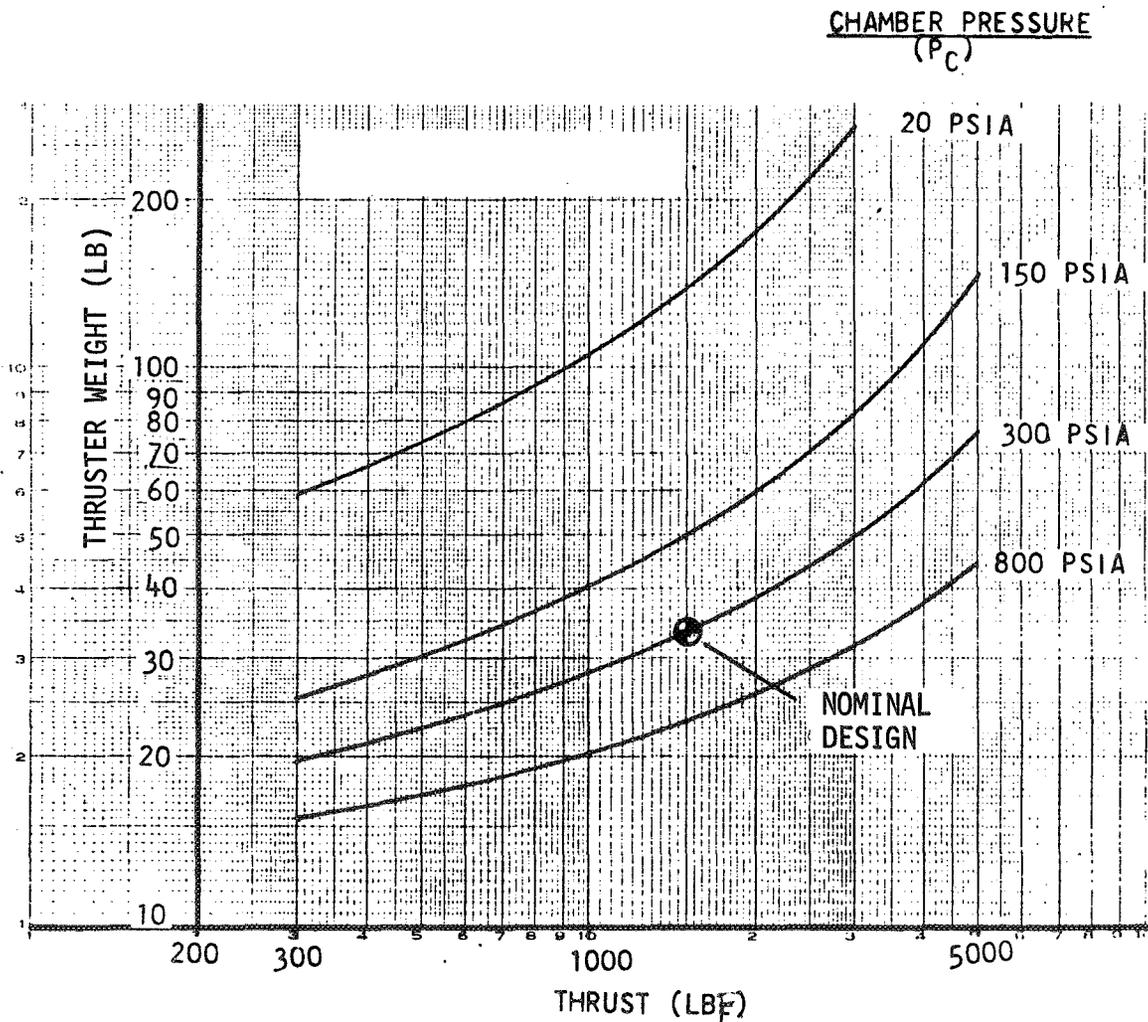
FIGURE E-9

Injector physical size was calculated based upon the design point flow rate, thrust, and chamber pressure. The weight was then calculated using the same density as the demonstrated APS engine injectors.

Bipropellant valve physical size and weight were derived from parametric curves of engine controls which consider design flow rate and pressure level. A pneumatic actuation system was considered for the engine bipropellant valve.

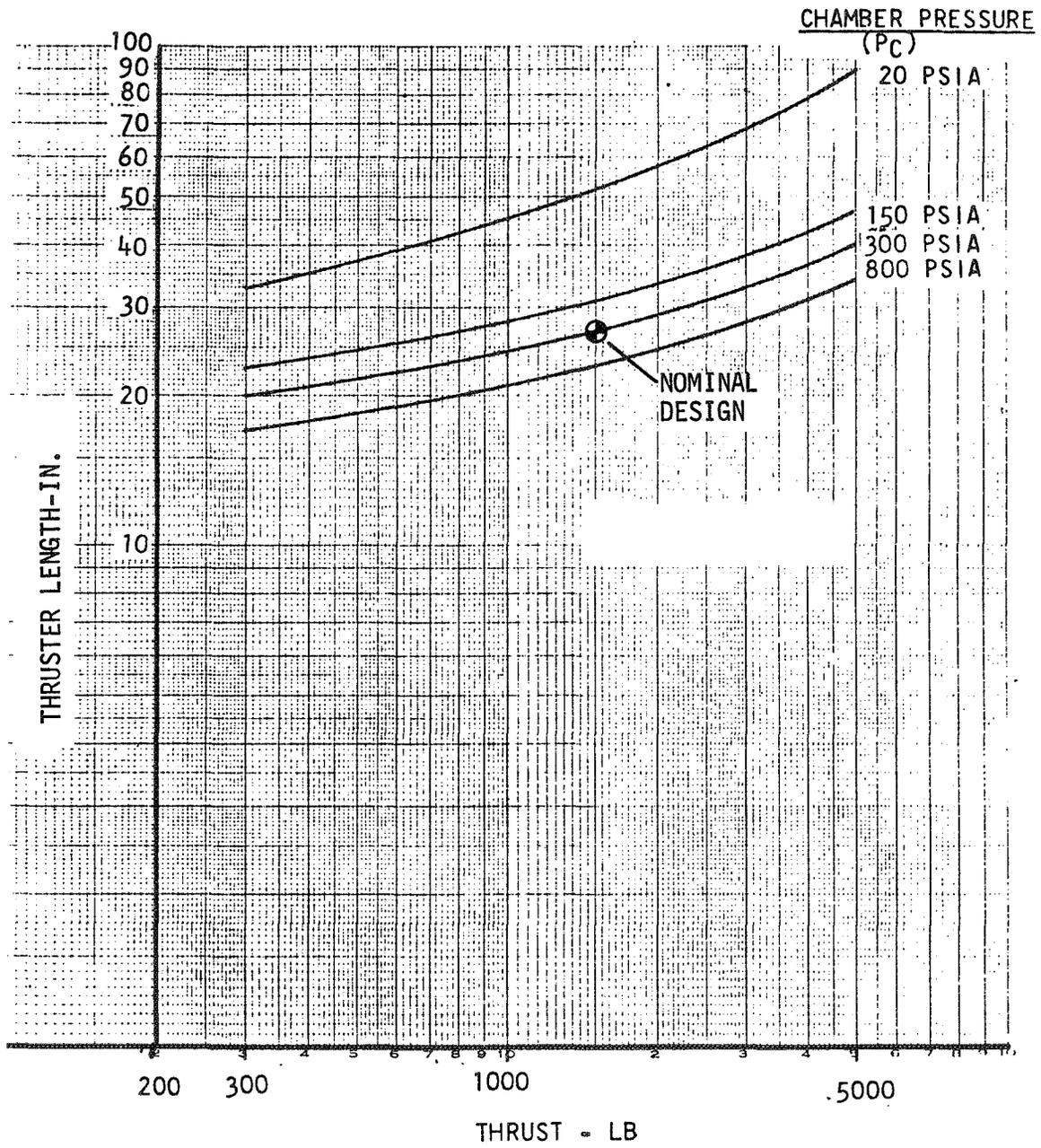
Igniter assembly weight was derived from extrapolation of the prototype, electrical igniter torch assembly. These weights were extrapolated as a function of engine thrust. Electrical sequencer, cable, and plug are included in the weights.

Engine weights and lengths are presented as a function of thrust and chamber pressure in Figures E-10 and E-11. Exit diameter is presented as a function of chamber pressure, thrust, and area ratio in Figure E-12.



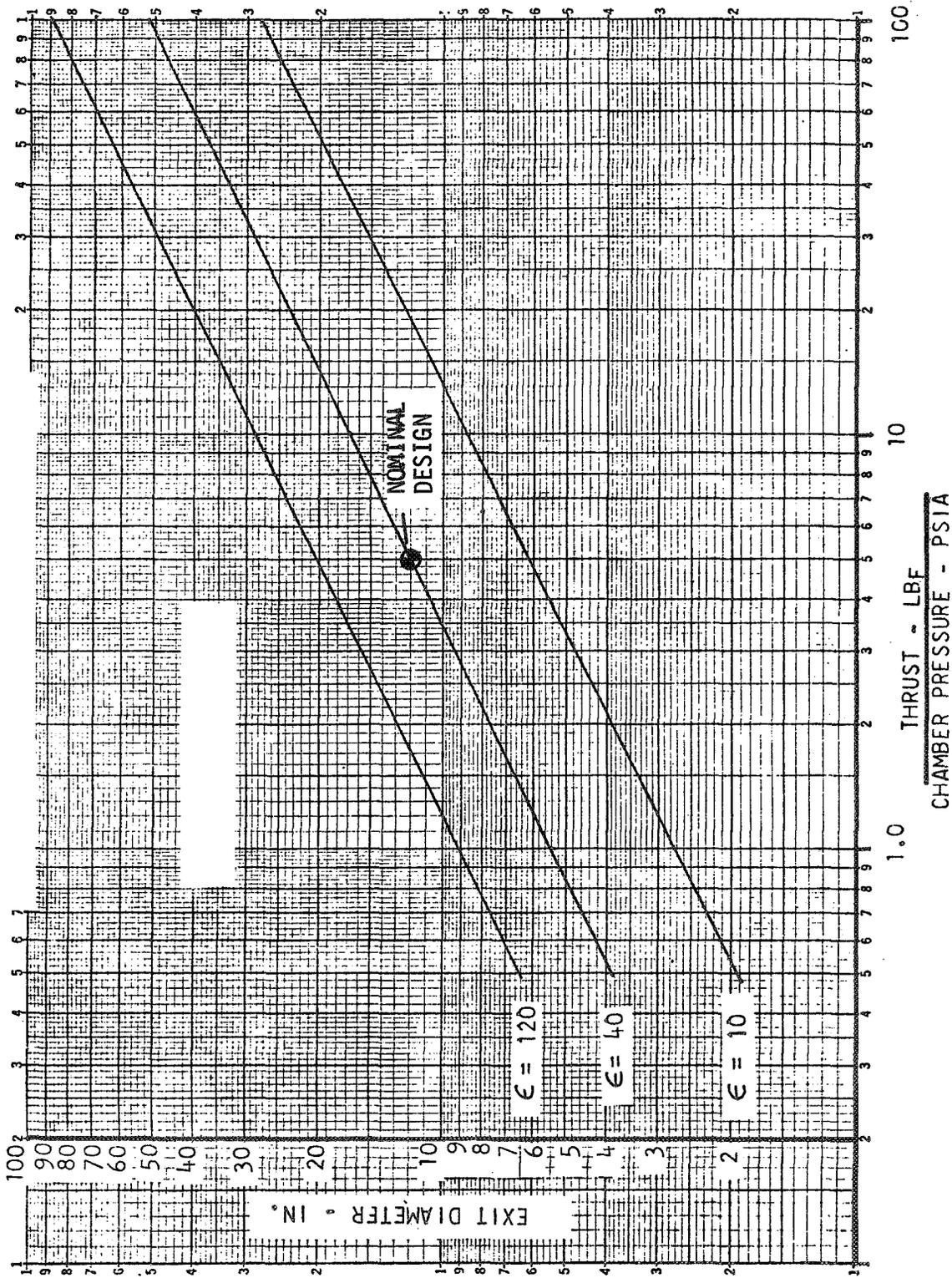
THRUSTER WEIGHT AS A FUNCTION OF THRUST
Area Ratio = 40

FIGURE E-10



OVERALL THRUSTER LENGTH AS A FUNCTION OF THRUST
Area Ratio = 40

FIGURE E-11



EXIT OUTSIDE DIAMETER AS A FUNCTION OF THRUST
TO CHAMBER PRESSURE RATIO

FIGURE E-12

E-3. GAS GENERATOR

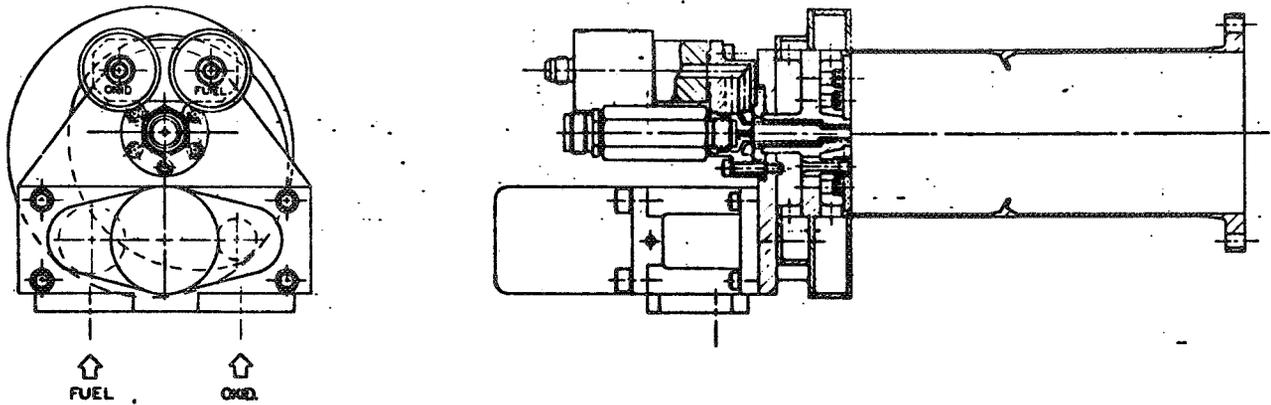
The APS concepts require the use of gas generators to supply the energy for turbomachinery operation, propellant conditioning, and supercritical tank pressurization.

The gas generator assembly consists of a cylindrical combustion chamber, bipropellant injector, electrical spark ignition, and bipropellant poppet control valves (as shown in Figure E-13). The valves will be actuated either electrically or electro-pneumatically, depending on power requirements. The chamber uses a gas turbulence ring, located approximately on half to three-quarters of the chamber length from the injector face, to promote uniform mixing of combustion gases and assure an even distribution of gas temperature. In materials and configuration, injector design is similar to that of the APS thrusters.

Gas generator weight and size was based upon a L/D of approximately 2.5 for chamber design, and chamber diameter was sized to obtain a combustion gas Mach number of 0.2. Chamber material was A286. Injector height was approximately 0.3 times the diameter and its weight was based on an idealized design assuming three circular stacked plates with side closure, injector elements, and allowance for igniter and valve mounting pads. Valve weight was calculated from previously established weight versus line size curves. Line sizes were established based on 0.3 Mach number for both hydrogen and oxygen. An injector pressure drop of approximately 20 percent of chamber pressure was used.

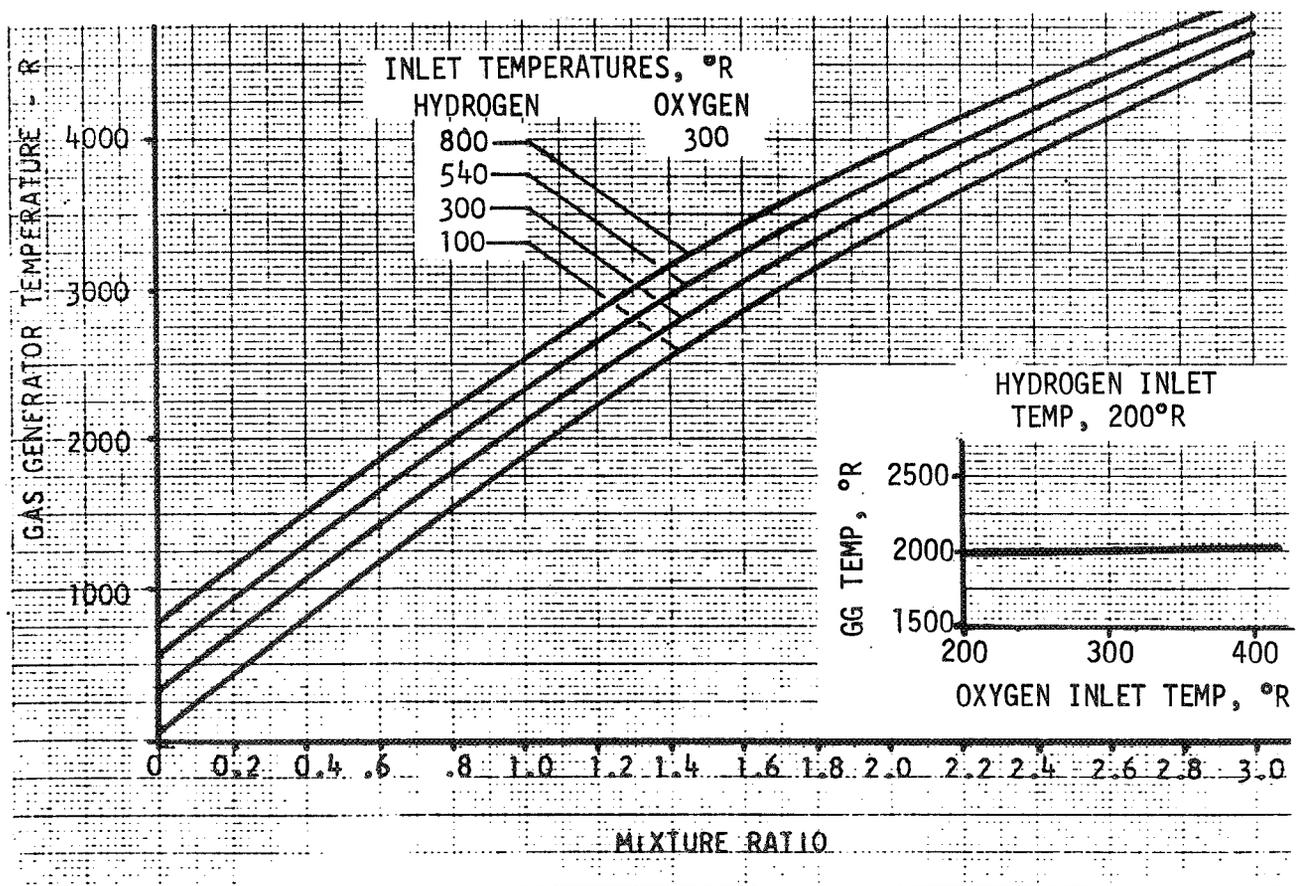
Gas generator performance was based upon one dimensional shifting equilibrium performance for variations in chamber pressure and inlet propellant conditions. Combustion temperature performance is presented in Figure E-14 for a range of mixture ratios and hydrogen inlet temperatures. Gas generator ignition response will occur in 20-40 ms. Permitting valve response times of 5-15 ms will give an overall gas generator response of less than 50 ms to 90 percent of $P_{c_{GG}}$.

Gas generator weight is dependent on chamber pressure because of diameter increase required at lower pressures to maintain Mach number constant. Figure E-15 presents gas generator weight for various flow rates and chamber pressures.



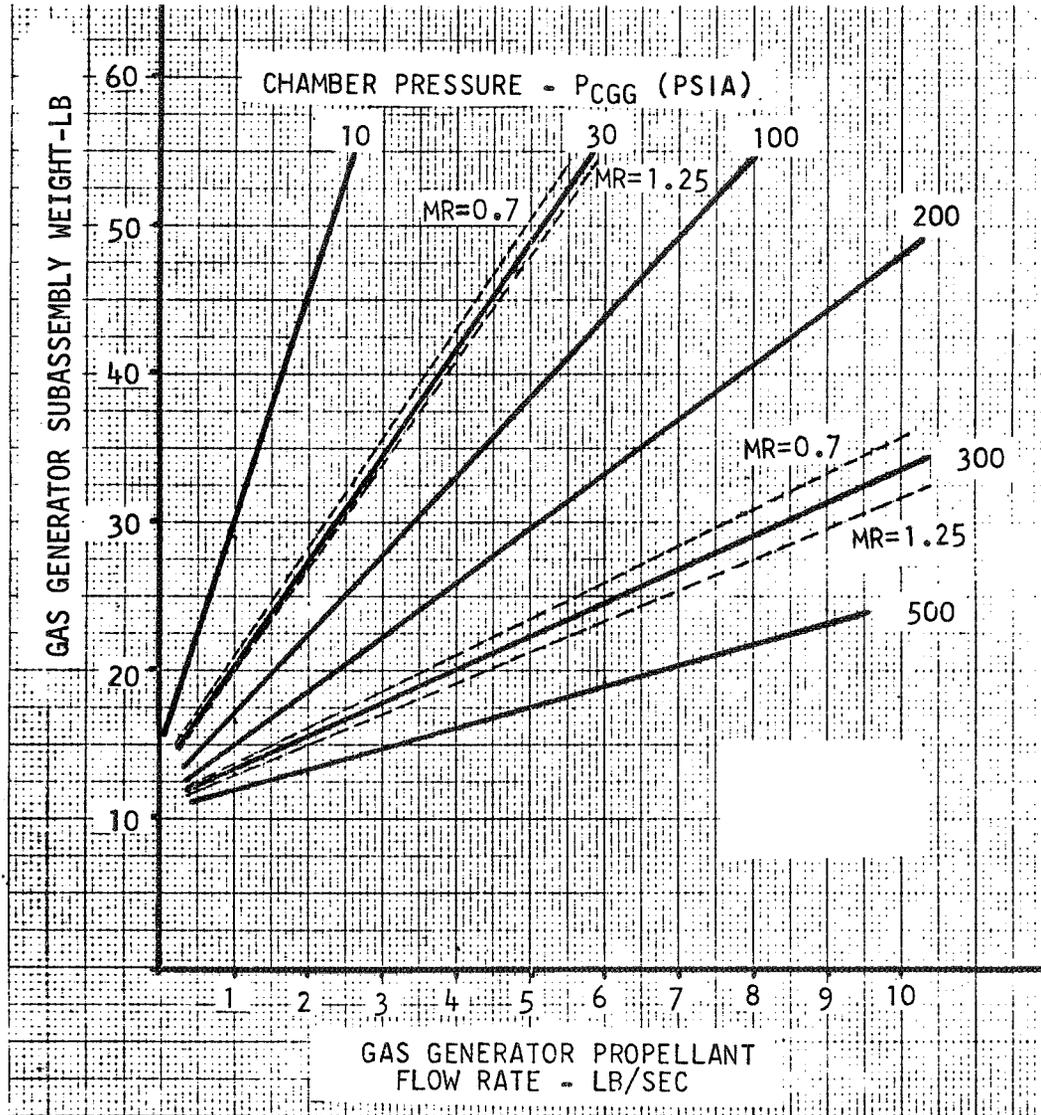
GAS GENERATOR

FIGURE E-13



GAS GENERATOR PERFORMANCE T_{GG} AS A FUNCTION OF MR_{GG}

FIGURE E-14



GAS GENERATOR SUBASSEMBLY WEIGHT
VS. GAS GENERATOR PROPELLANT FLOW RATE

FIGURE E-15

E-4. HEAT EXCHANGER

E-4.1 Selection - APS concepts require cryogenic liquid or supercritically stored propellants to be heated and vaporized by the propellant conditioning sub-assembly. The subassembly uses a heat exchanger to perform this function.

The basic heat exchanger design concept selected for both hydrogen and oxygen conditioning is a concentric, helical tube and shell design (Figure E-16). A two phase oxidizer (N_2O_4) heat exchanger configuration similar to the selected concept has been used successfully in the autogenous pressurization assembly for the first stage Titan II, and in both the first and second stage Gemini and Titan III propulsion subsystems.

The baseline configuration uses hot combustion gases from a hydrogen/oxygen gas generator to heat the propellants. A center manifolding arrangement, located in the cold-side tube bundle (between the inlet and outlet manifolds), permits collection and redistribution of vaporized propellant from small to larger tubes. Such a feature is desirable due to the large density reduction which occurs, particularly with oxygen, when propellant is heated and vaporized at lower operating pressures. The center manifold also provides a convenient bypass flow distribution port, which can be used for precise temperature control balancing of the propellant (cold) side.

The coiled tubes of the APS heat exchanger are supported by longitudinal plate baffles, attached to each manifold and holding the center diffuser in position. Propellant is distributed to, and collected from, the tubes by multiple radial manifolds. Each group of manifolds (inlet, middle, and outlet) is symmetrically mounted spoke-like in a plane normal to the hot gas flow.

The multimanifold configuration with single tube rows permits each row to be exposed to identical hot gas environments and makes each tube more accessible for brazing during fabrication, a distinct improvement over stacked rows in each manifold. Because of the multimanifold concept, each tube row need not end at a special manifold position, permitting the use of minimum coil lengths.

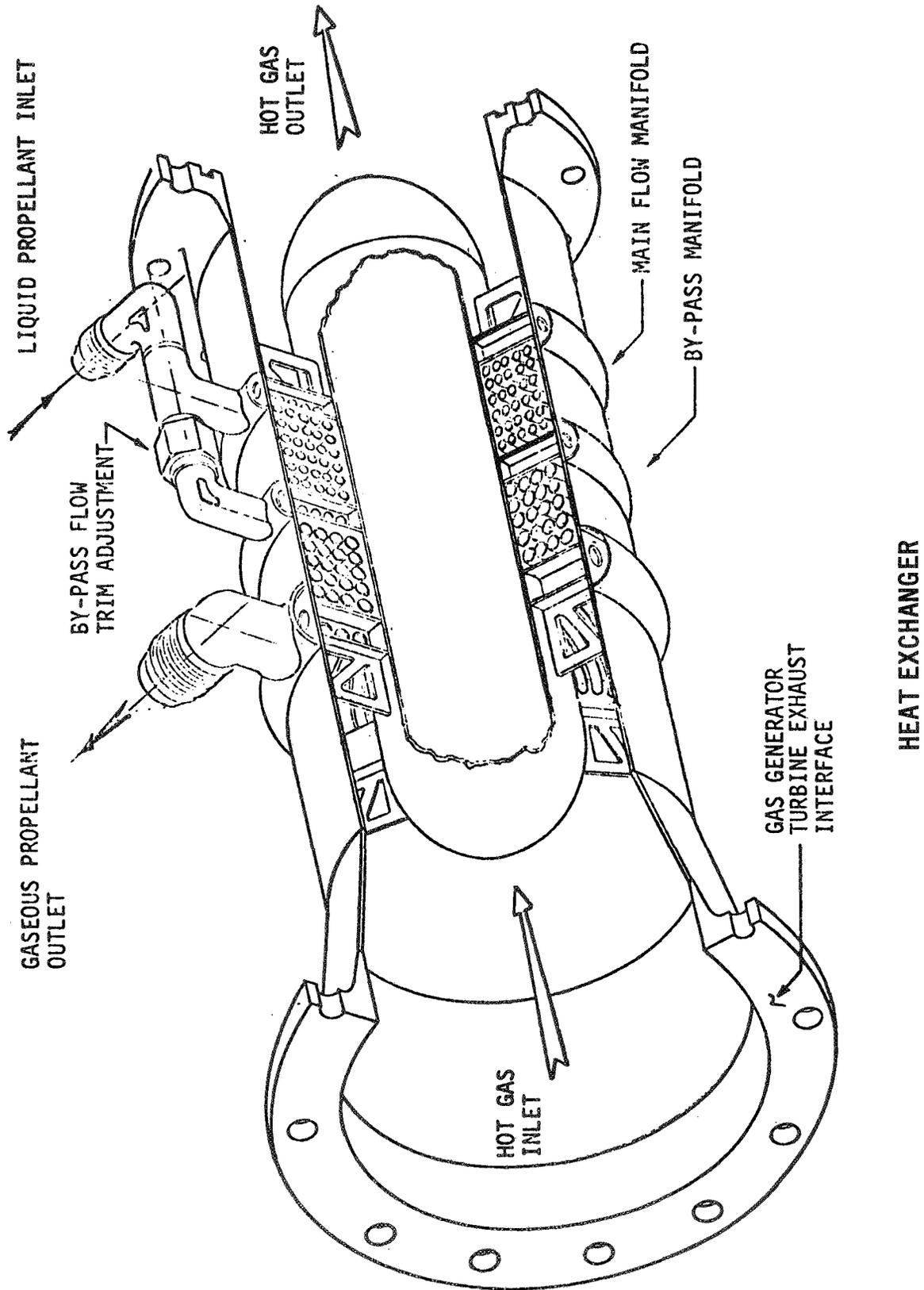


FIGURE E-16

From the standpoint of cycle life and weight, the baseline design concept required a counter-flow unit, because this type results in lower weight and lower differential tube wall temperatures than the parallel flow type. The thermal cycle life capability of heat exchangers can be significantly reduced by excessively high operating differential temperatures across the tube wall. Thin tube walls provide minimum weight, better heat transfer, and longer thermal cycle life capability. Tubes of AS347 were selected because of its strength, desirable fabrication characteristics, and reasonable heat transfer capability. It is commercially available, has reasonably good cycle life characteristics, and is compatible with the APS propellants and combustion gases.

Control of propellant flow rate through the heat exchanger must occur at the inlet side in order to achieve stable flow and pressures. This has been effected in the Titan systems by use of a cavitating venturi at the superheater inlet.

E.4-2 Design Analysis - Parametric curves of weight, length, and diameter were generated for heat exchangers operating within the ranges depicted in the following table.

OPERATING LIMITS FOR HIGH PRESSURE HEAT EXCHANGERS

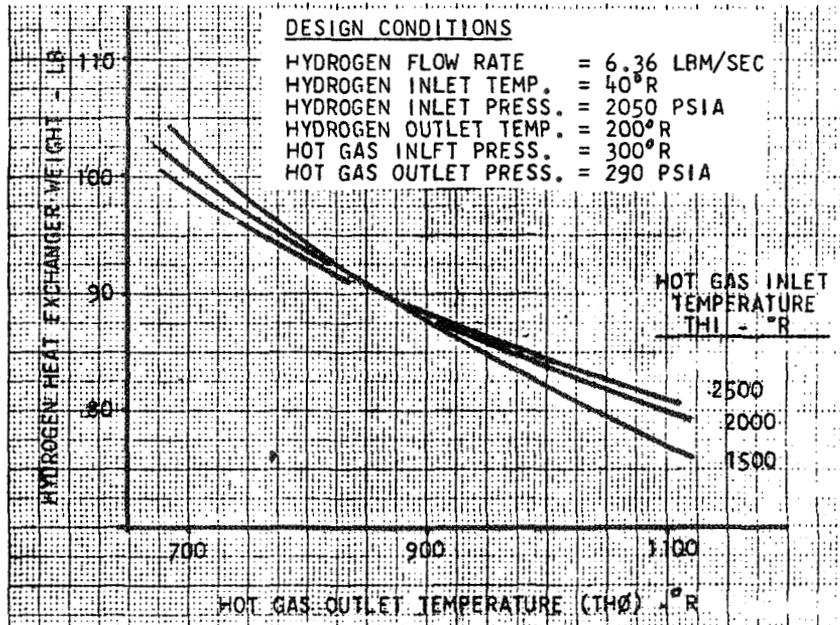
	<u>Hydrogen</u>			<u>Oxygen</u>		
	Min	Max	Nominal Design Point	Min	Max	Nominal Design Point
P_{inc} lbf/in ² A	500	4000	2050	500	4000	2050
T_{inc} (°R)	40	40	40	160	160	160
T_{out}^c (°R)	200	500	200	300	600	300
W_c (lb/sec)	0.5	20	6.36	1	40	22
$P_{in\ hot}$ lbf/in ² A	20	800	300	20	800	300
$T_{in\ hot}$ (°R)	1600	2500	2000	1600	2500	2000
$T_{out\ hot}$ (°R)	700	1000	900	700	1000	900

Details were established for actual heat exchanger design configurations for each set of nominal and design criteria to be analyzed. Detailed design choices included tube size, number of tubes, number of manifolds, wall thickness, shell thickness, core diameter, and tube spacing. Generally, the smallest tube sizes were selected

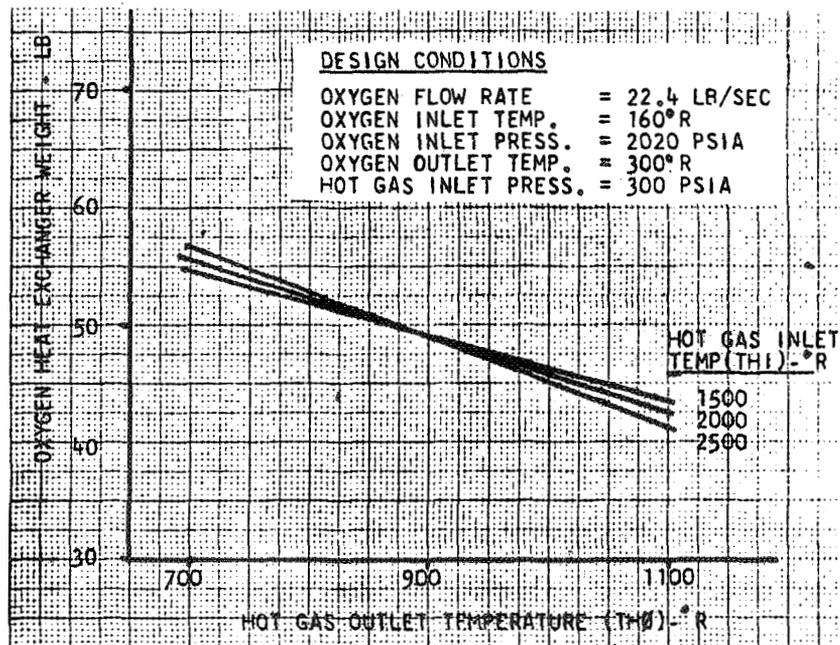
that were consistent with limiting criteria for flow velocity and number of tubes. Liquid inlet velocity was maintained at approximately 30 ft per second or less, and outlet velocity was maintained at approximately Mach 0.2 or less. The number of tubes was held below 100 as a practical limit. The number of manifolds selected was strictly arbitrary, based upon engineering judgment for reasonable packaging. Tube spacing was consistently maintained at 0.150 in, and coil pitch was selected on the basis of that spacing, the number of manifolds (tube rows), plus an allowance for the manifolds. Using the previously reviewed data, a thermal analysis determined tube bundle length. A digital computer program was written to calculate geometry, fluid flows, and component weights. Equations for various film coefficients, two phase flow conditions, etc., were selected on the basis of engineering judgment for applicability and validity of correlations within specific operating regimes. In developing the mathematical model, it was assumed that no ice or liquid water forms on the hot side tube walls. Time precluded a thorough examination of this problem at the time.

E-4.3 Physical Characteristics - Once the heat exchanger tube length had been determined, it was possible to define overall heat exchanger envelope and calculate weight. Detailed weight calculations were broken down to include tube bundle, manifolds, baffles and core, and shell (including allowances for connection flanges, fittings, etc., based upon size and pressures). Heat exchanger size and weight data were generated as functions of propellant flow rate, inlet pressure, outlet temperature, and hot side outlet temperature. This analysis showed that changes in design conditions for propellant pressure drop, hot side inlet temperature, and hot side pressure do not cause significant variations for heat exchanger size and weight. Propellant pressure drop shows little influence because density change with pressure is small at the pressures considered. Heat transfer in both heat exchangers is controlled by the hot side. The design minimum tube spacing used allows an area flow sufficient for almost all hot side conditions. Thus, the geometry used for different hot side temperature and pressure levels remained the same. A change in pressure causes change in density in one direction, but an opposite change in velocity, resulting in constant film coefficient. Raising inlet temperature increases driving temperature, but lowers flow rate, thus reducing film coefficient. The net result is a constant heat transfer rate. Lowering outlet temperature not only lowers driving temperature, but also lowers flow rate. Therefore, outlet temperature strongly influences heat exchanger size and weight.

Figures E-17 and E-18 present LO₂ and LH₂ heat exchanger weight estimates, and Figures E-19 and E-20 show length and diameter.



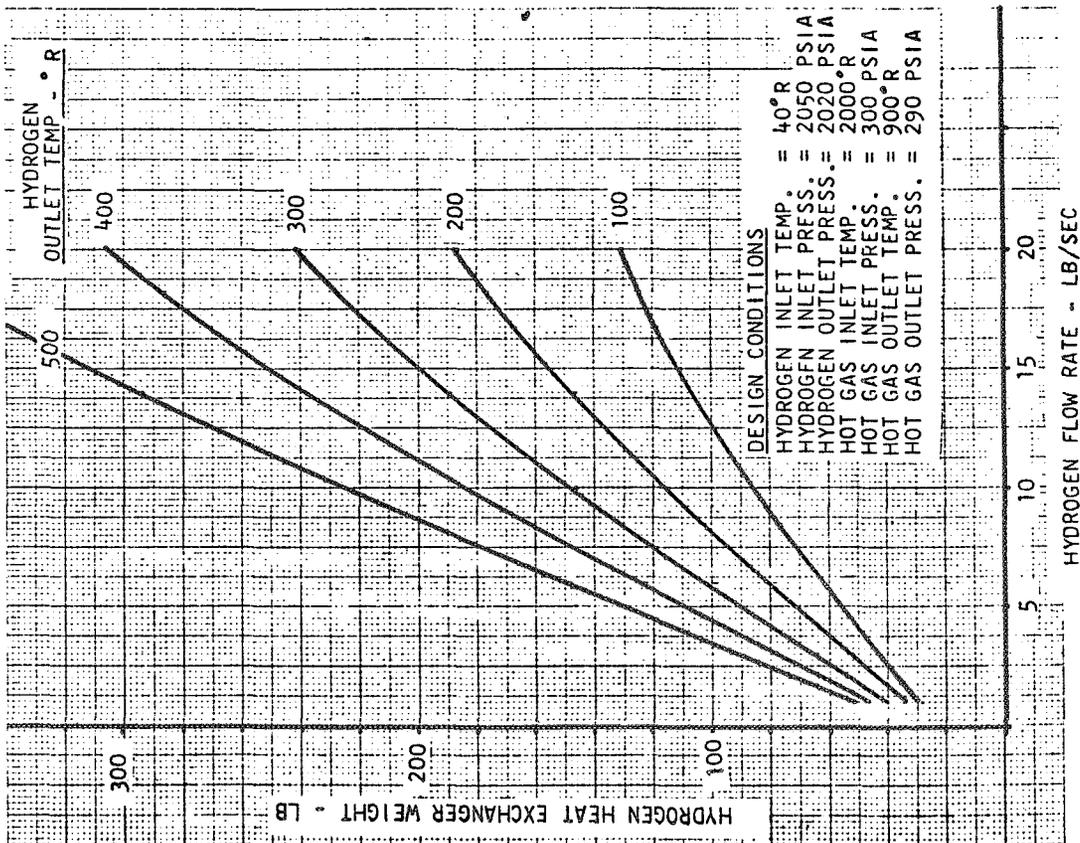
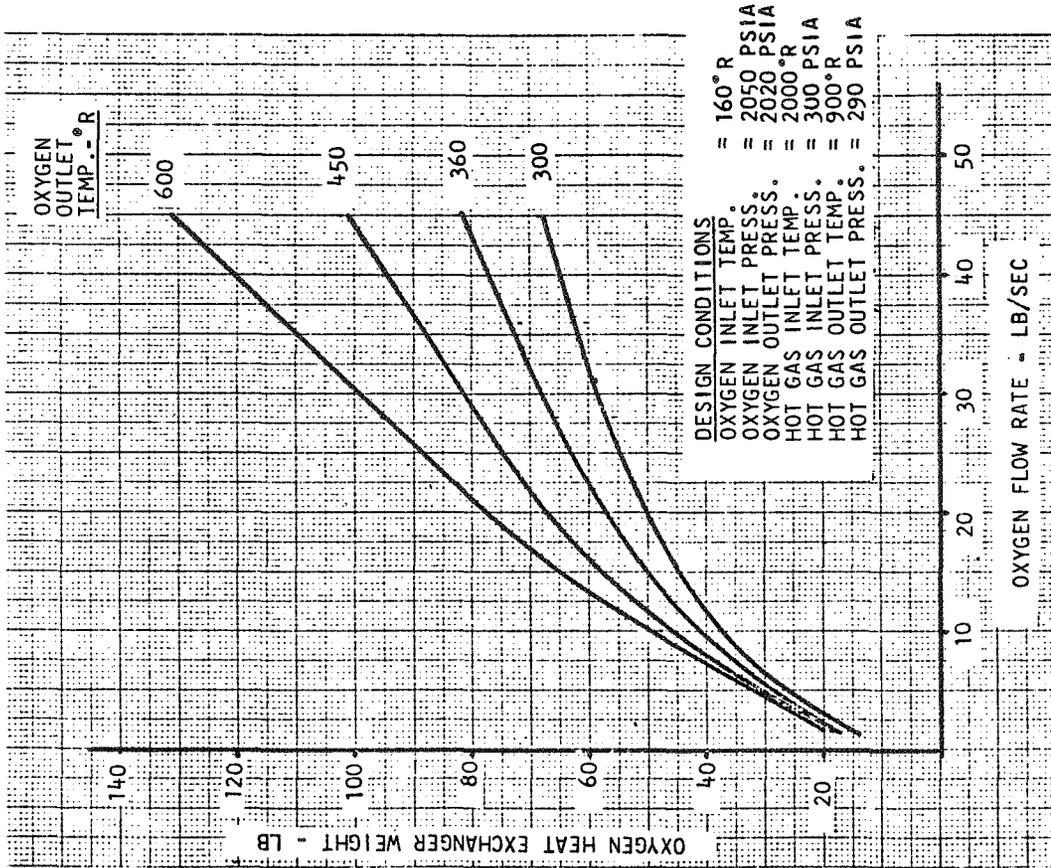
HYDROGEN



OXYGEN

**HEAT EXCHANGER WEIGHT
AS A FUNCTION OF HOT GAS OUTLET TEMPERATURE**

FIGURE E-17

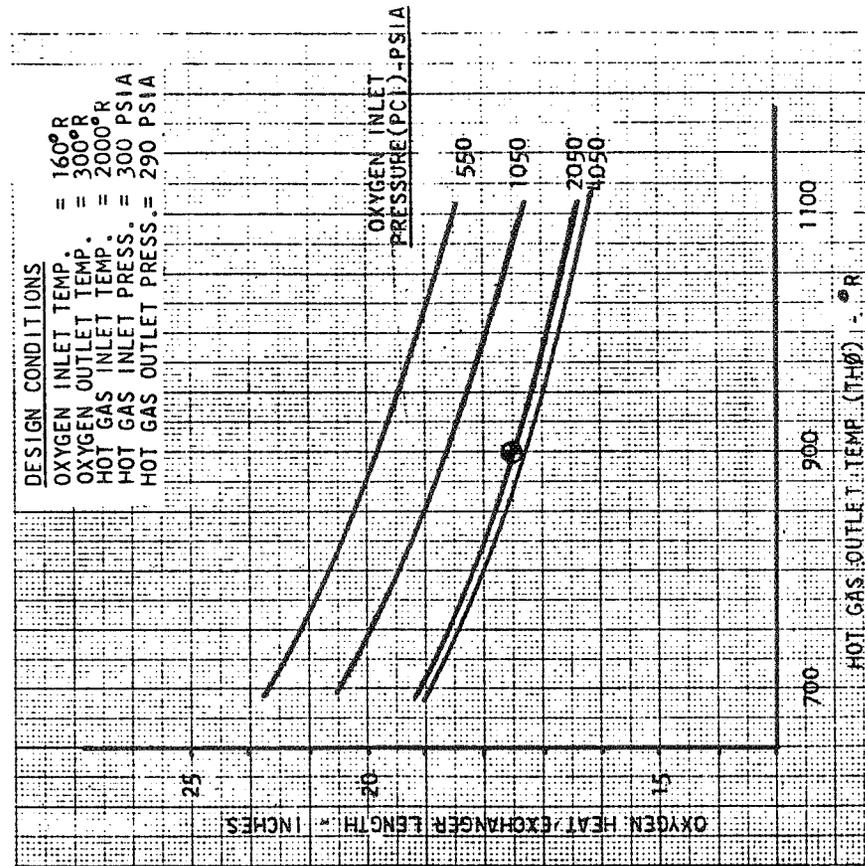


OXYGEN

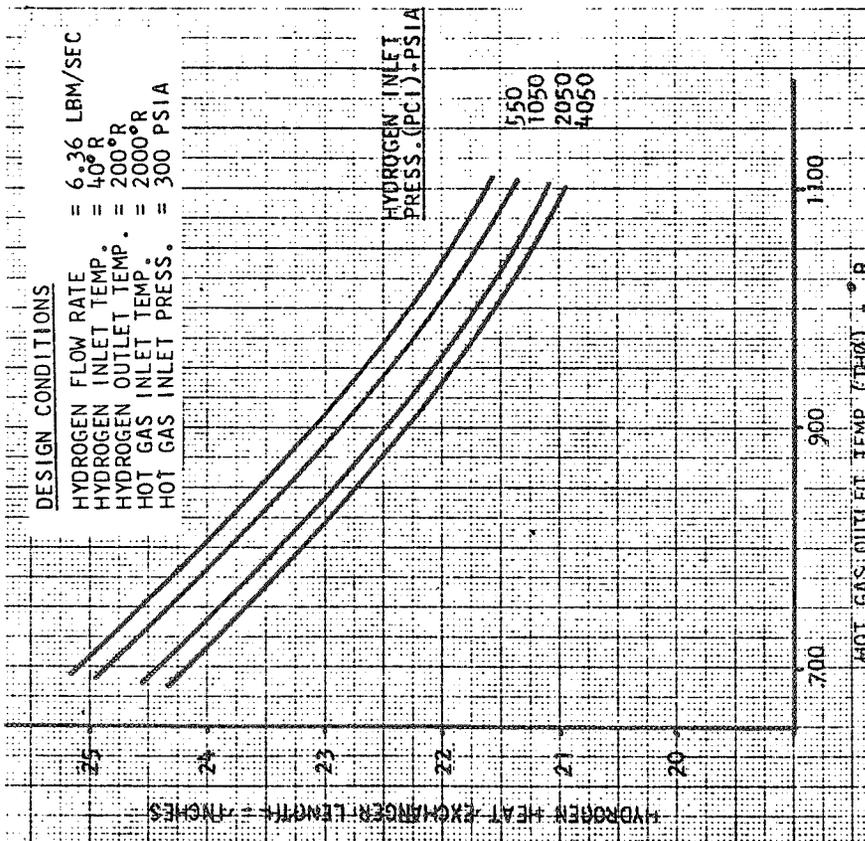
HEAT EXCHANGER WEIGHT

HYDROGEN

FIGURE E-18



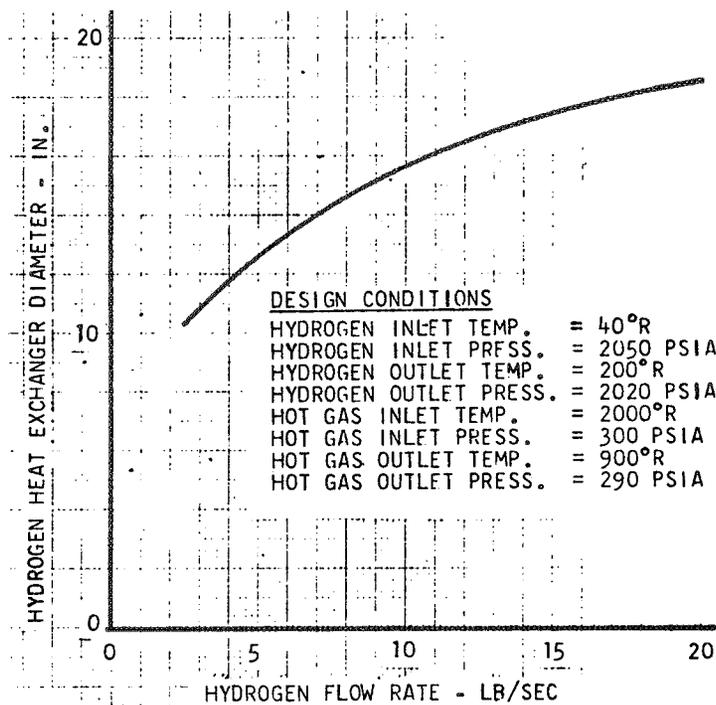
OXYGEN



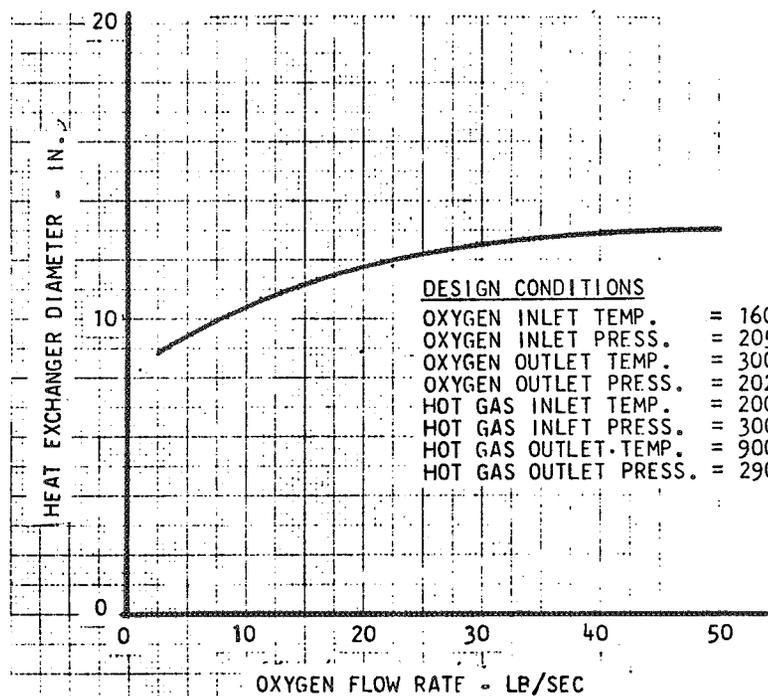
HYDROGEN

HEAT EXCHANGER LENGTH
AS A FUNCTION OF HOT GAS OUTLET TEMPERATURE

FIGURE E-19



HYDROGEN



OXYGEN

HEAT EXCHANGER DIAMETER

FIGURE E-20

E-5. TURBOPUMP

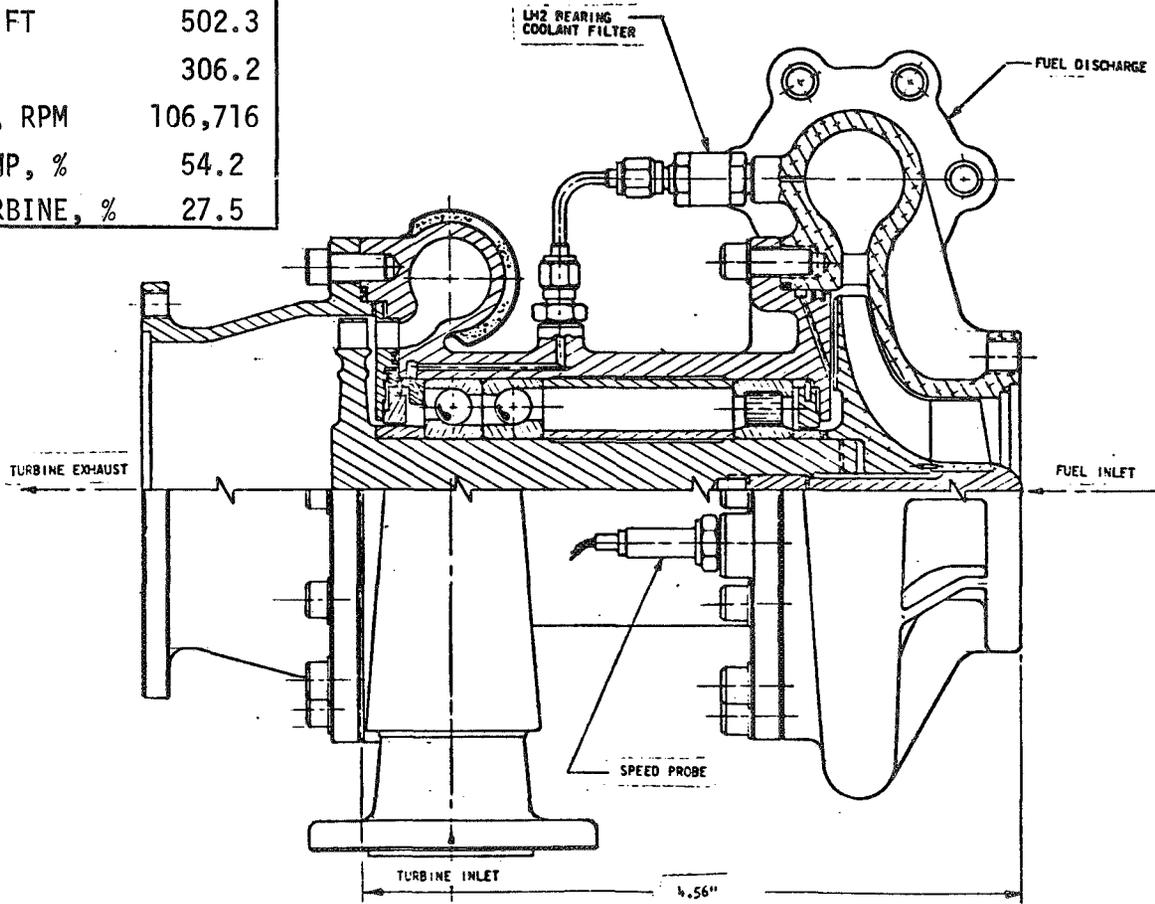
Liquid hydrogen and oxygen centrifugal turbopump assemblies are required to move propellants from low pressure cryogenic storage tanks into high pressure sub-assemblies. Turbopump assemblies are used either to pump propellant through the conditioning subassembly into accumulators or to resupply supercritical propellant storage tanks. Pumps are driven by a direct coupled axial flow turbine, which is driven in turn, by hot gas from a gas generator. Typical LH₂ and LO₂ turbopumps are shown in Figures E-21 and E-22.

This study emphasized achieving minimum component weight. Preliminary studies suggest that pump and turbine efficiency values have little influence on APS propellant feed system performance. Deemphasis of pump and turbine efficiency permitted selection of design concepts well within the state-of-the-art, and conservatively rated with respect to stress of hot rotating components.

Typical 750 lbf/in² turbopumps utilize single stage pumps and turbines. Propellant lubricated bearings support the rotating components. The LO₂ turbopump utilizes LO₂ to lubricate pump end bearing and gaseous hydrogen (from the propellant feed system accumulator) to cool turbine and bearing. GH₂ flows through the bearing into the turbine housing downstream of the turbine nozzle. An interpropellant seal uses hydrostatic shaft seals to limit GH₂ and LO₂ flows to GH₂ and GO₂ vents. An additional vent is provided between GH₂ and GO₂ vents. The low pressure of this central vent eliminates the possibility of combustion in the seal cavity. An example of a typical 2000 lbf/in² hydrogen turbopump with two stage pump and turbine is shown in Figure E-23.

Parametric analysis of the LH₂ and LO₂ turbopumps was performed with Aerojet Liquid Rocket Company's "Turbopumps Propellant Feed System Parameter Analysis Program" to define effects of net positive suction pressure (NPSP), weight flow, and pressure rise on turbopump weight, performance, response time, and envelope. Assumptions and limiting criteria used in this analysis are given in Figure E-24 and represent state-of-the-art design levels. Multistage pumps and turbines were evaluated for pump pressures over 1500 lbf/in² to achieve reduction in pump weight, start times, and turbine flow requirements. Pump speeds were based on a relatively conservative suction specific speed value of 20,000. The effect of thermodynamic suppression head (TSH) on pump cavitation performance is not included in the analysis. Use of TSH permits a reduction in inlet pressure to the LH₂ pump. Since

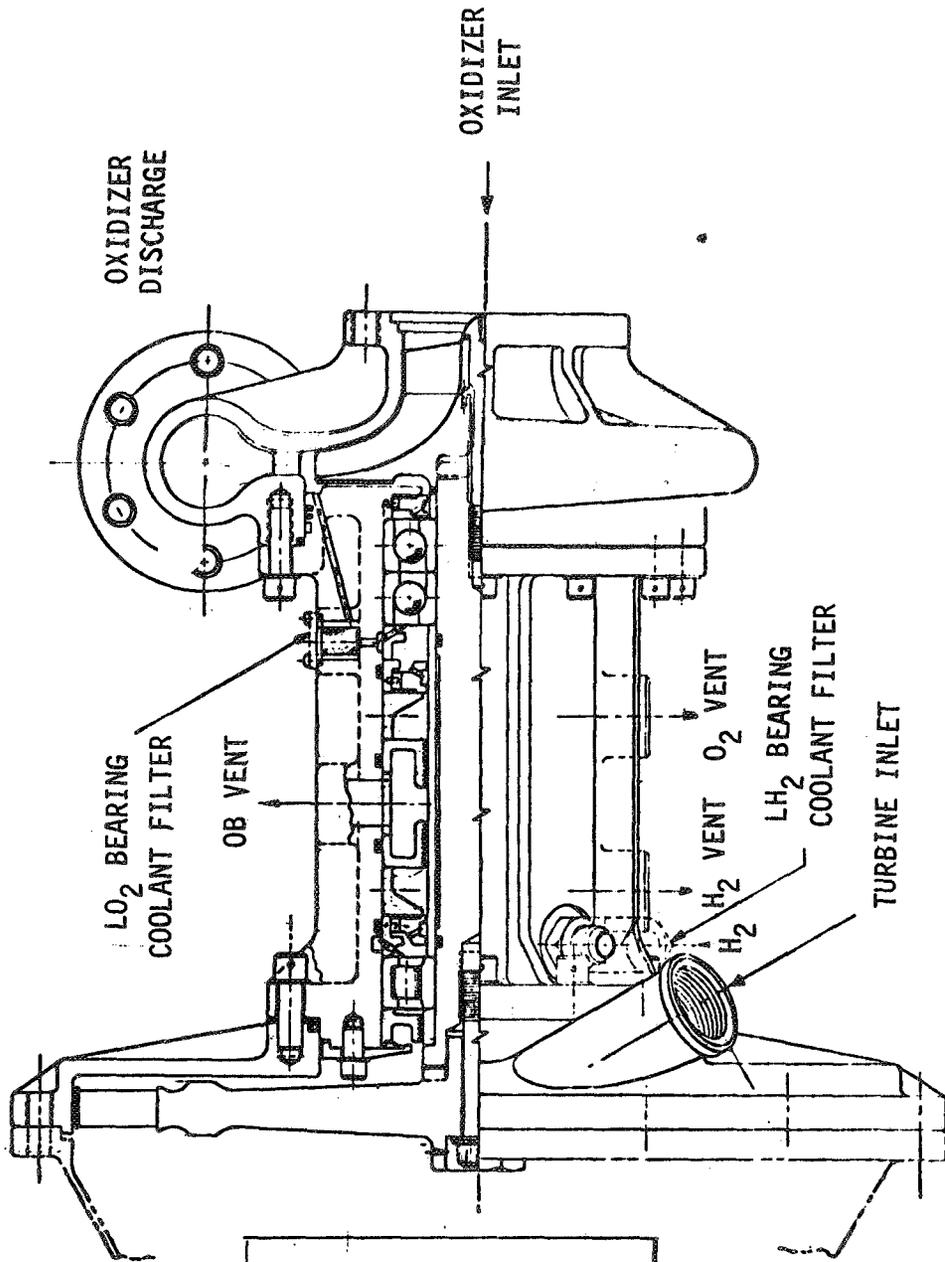
PARAMETERS	
W_F , LB/SEC	3.78
ΔP PSI	750
NPSH, FT	502.3
SHP	306.2
SPEED, RPM	106,716
η PUMP, %	54.2
η TURBINE, %	27.5



TYPICAL SINGLE STAGE LH₂ TURBOPUMP ASSEMBLY

FIGURE E-21

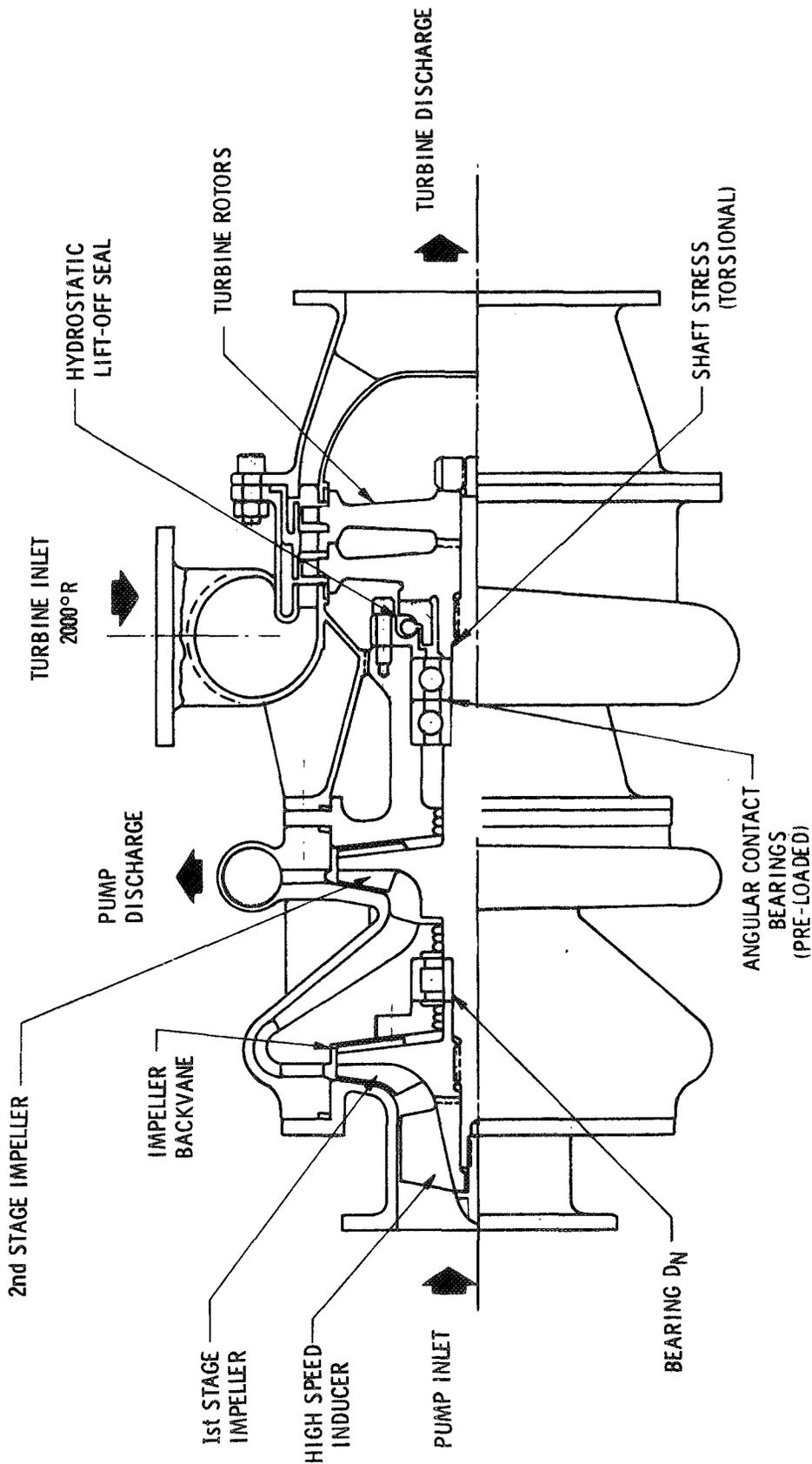
the pump may be required to operate over a wide flow range, however, the TSH effect was utilized as a design safety factor. The turbine mean blade speeds were selected at 1000 ft/sec on the LH₂ TPA to achieve low turbine stress and at 650 ft/sec on the LO₂ TPA to achieve start response times of the same order as those of the LH₂ TPA. A turbine inlet temperature of 2000°R was selected and represents the best estimate of maximum gas temperature that can be used with an uncooled turbine. Turbopump analysis consisted of computing pump and turbine efficiencies and effecting a power balance between pump and turbine. Size, weight, polar moment of inertia,



PARAMETERS	
W_0 , LB/SEC	15.36
ΔP , PSI	750
NPSH, FT	30.6
SHP	75.7
SPEED, RPM	26,331
η PUMP, %	54.2
η TURBINE, %	18.5

TYPICAL SINGLE STAGE OXIDIZER TURBOPUMP

FIGURE E-22



TYPICAL 2 STAGE HYDROGEN TURBOPUMP

FIGURE E-23

	<u>LO₂ TPA</u>	<u>LH₂ TPA</u>
PUMP ΔP UP TO 1500 PSI	ONE STAGE PUMP AND TURBINE	ONE STAGE PUMP AND TURBINE
PUMP ΔP 1501 TO 2500 PSI	TWO STAGE PUMP AND TURBINE	TWO STAGE PUMP AND TURBINE
PUMP ΔP 2501 TO 3500 PSI	THREE STAGE PUMP AND TURBINE	THREE STAGE PUMP AND TURBINE
PUMP OPERATING SUCTION SPECIFIC SPEED	20000	20000
TURBINE MEAN BLADE SPEED	650 FT/SEC	1000 FT/SEC
TURBINE INLET TEMPERATURE	2000°R	2000°R
TURBINE INLET PRESSURE	290 PSI	290 PSI
TURBINE PRESSURE RATIO	4:1	4:1
TURBINE INLET PRESSURE DURING START	300 PSI	300 PSI
TURBINE GAS PROPERTIES	COMPUTED FROM GG MODEL	COMPUTED FROM GG MODEL
BEARING DN	10 ⁶ MM X RPM	10 ⁶ MM X RPM
DENSITY PUMP IMPELLER & HSG	0.10 LB/IN ³	0.10 LB/IN ³
DENSITY TURBINE ROTOR & HSG	0.286 LB/IN ³	0.286 LB/IN ³
PROPELLANT FLOW RANGE	4 TO 60 LB/SEC	0.5 TO 10 LB/SEC
PRESSURE RISE RANGE	500 TO 3500 PSI	500 TO 3500 PSI
NET POSITIVE SUCTION PRESSURE RANGE	5 TO 20 PSI	2 TO 8 PSI
PROPELLANT TEMPERATURE	162°R	36°R

TURBOPUMP LIMITING CRITERIA AND ASSUMPTIONS

FIGURE E-24

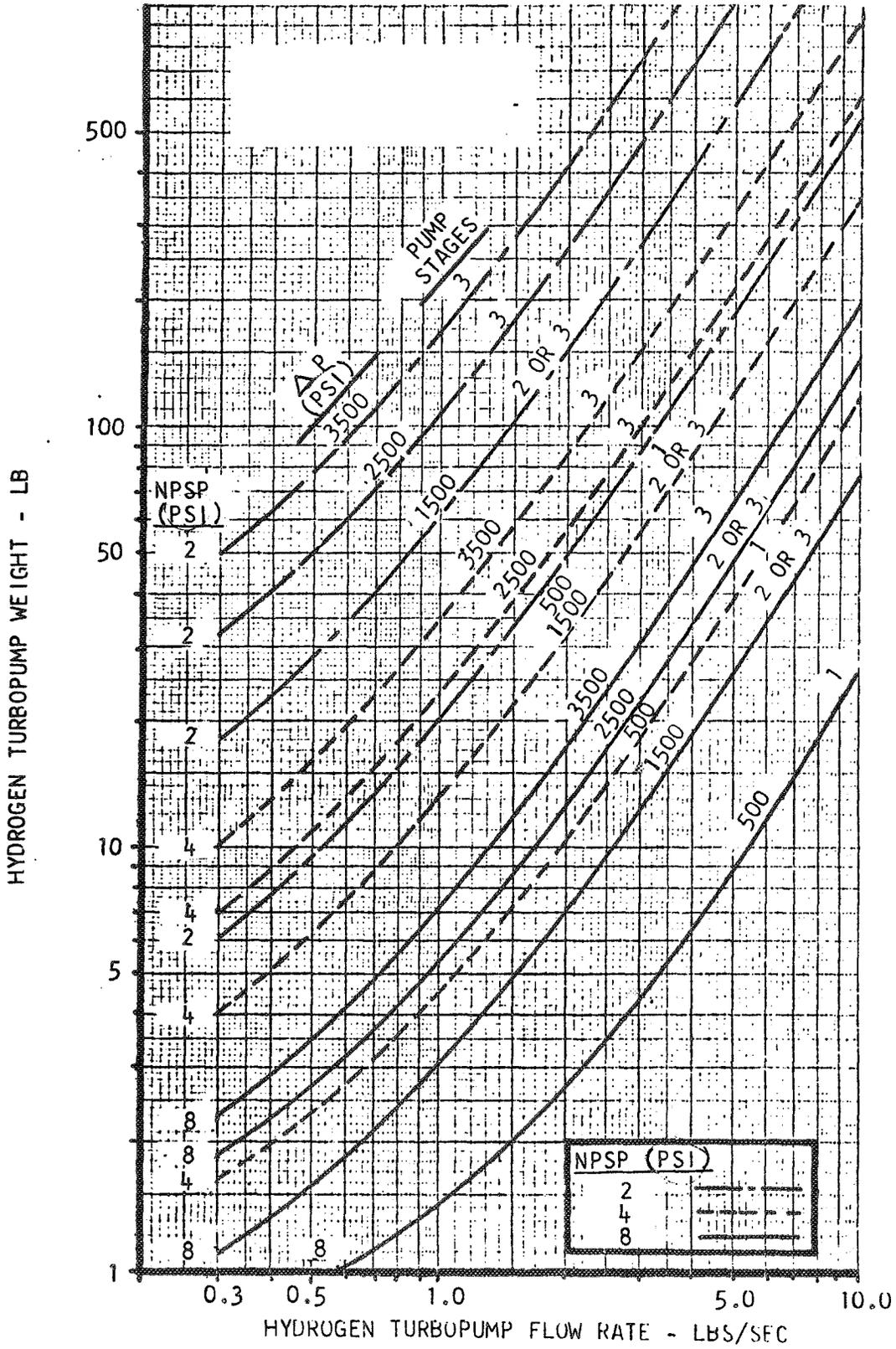
and start times are computed in turn. Computed start time values were based on turbine inlet pressure stepping to design inlet pressure at fire switch. The analysis results are summarized below.

Turbopump Weight and Envelope - Turbopump weight is shown in Figures E-25 and E-26 for the LH₂ and LO₂ turbopumps, respectively. Equations used to model weight are given in Figures E-27 and E-28. As shown, independent variables are pump weight flow, pressure rise, and NPSP. A hydrogen NERVA turbopump weighs 335 lb and pumps 75 lb/sec to 1000 lbf/in² at NPSP of 4. As shown in Figure E-25, actual NERVA weight value is greater than that projected. This weight difference is due to the difference in turbine stage number. The NERVA TPA utilizes a two-stage turbine, whereas the study configuration is based on a single stage turbine for the 1000 lbf/in² pressure range.

Component Efficiencies - Examples of pump efficiencies (as a function of pressure rise, flow and NPSP) are presented in Figure E-29. Increasing pump NPSP yields significant increase in pump efficiency through higher design shaft speeds and increased specific speeds. In addition, efficiency is decreased with increased pressure rise.

Turbine efficiencies, shown in Figure E-30, increase with increasing pump pressure rise. This increased efficiency is achieved by turbine staging for turbopumps with higher pressure rise operation. The turbine pressure ratio is maintained at 4:1 for all cases. The effect of operating the turbine at pressure ratios above or below 4.0:1, has a minimal impact on turbopump weight. Turbine efficiency, however, does increase with reduced pressure ratios.

Start Response Times - Turbopump start response times are shown in Figure E-31. Start times are seen to be dependent on flows and pump NPSP values. These are relatively insensitive to pump pressure rise except in the case of the LO₂ pump under low NPSP conditions.



HYDROGEN TURBOPUMP WEIGHT

FIGURE E-25

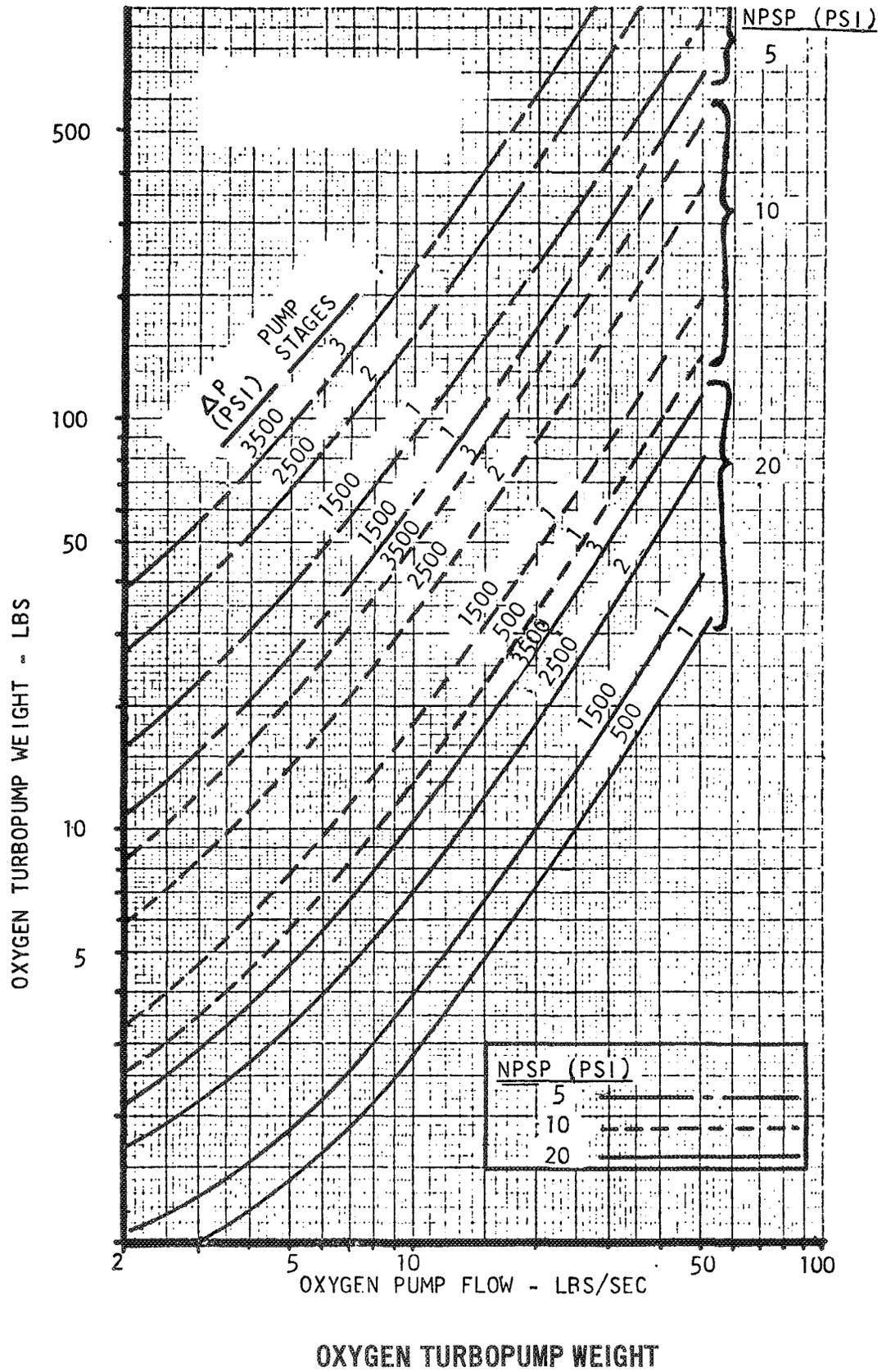


FIGURE E-26

EQUATION

$$W_T - TPA = \left[.85578253 + 17.557147 (W_F) + 5.623065 (W_F)^2 - .12876270 (W_F)^3 \right] \left(\frac{4}{NPSP_F} \right)^{2.18} \left(\frac{\Delta P_F}{2500} \right)^{1.108}$$

VALID RANGE: $W_F = 0.5$ TO 10 LBS/SEC
 $NPSP_F = 2$ TO 8 PSI
 $\Delta P_F = 1000$ TO 4000 PSI

SAMPLE CASE: $W_F = 1.0$, $NPSP_F = 4$, $P_F = 2500$
 WEIGHT = 23.907 LBS.

LIQUID HYDROGEN TURBOPUMP WEIGHT EQUATION

FIGURE E-27

EQUATION

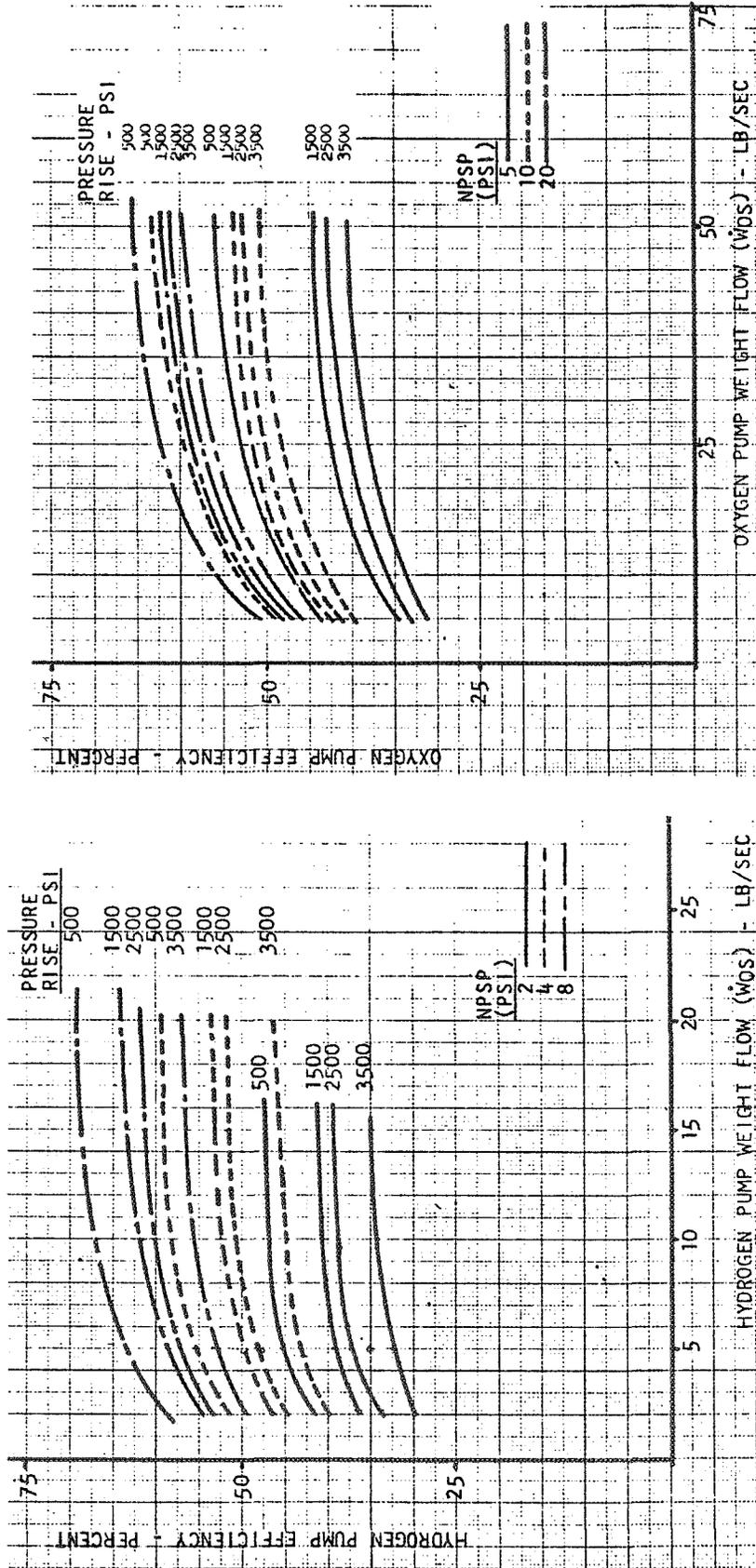
$$W_T - TPA = \left[1.1766937 + 2.0551820 (W_0) + .1261244 (W_0)^2 - .00054883008 (W_0)^3 \right] \left(\frac{10}{NPSP_0} \right)^{2.18} \left(\frac{\Delta P_0}{2500} \right)^{1.108}$$

VALID RANGE: $W_0 = 4$ TO 60 LBS/SEC
 $NPSP_0 = 5$ TO 20 PSI
 $\Delta P_0 = 1000$ TO 4000 PSI

SAMPLE: $W_0 = 10$, $NPSP = 10$, $P = 2500$
 WEIGHT = 33.792 LBS.

LIQUID OXYGEN TURBOPUMP

FIGURE E-28



OXYGEN

HYDROGEN

PUMP EFFICIENCY

FIGURE E-29

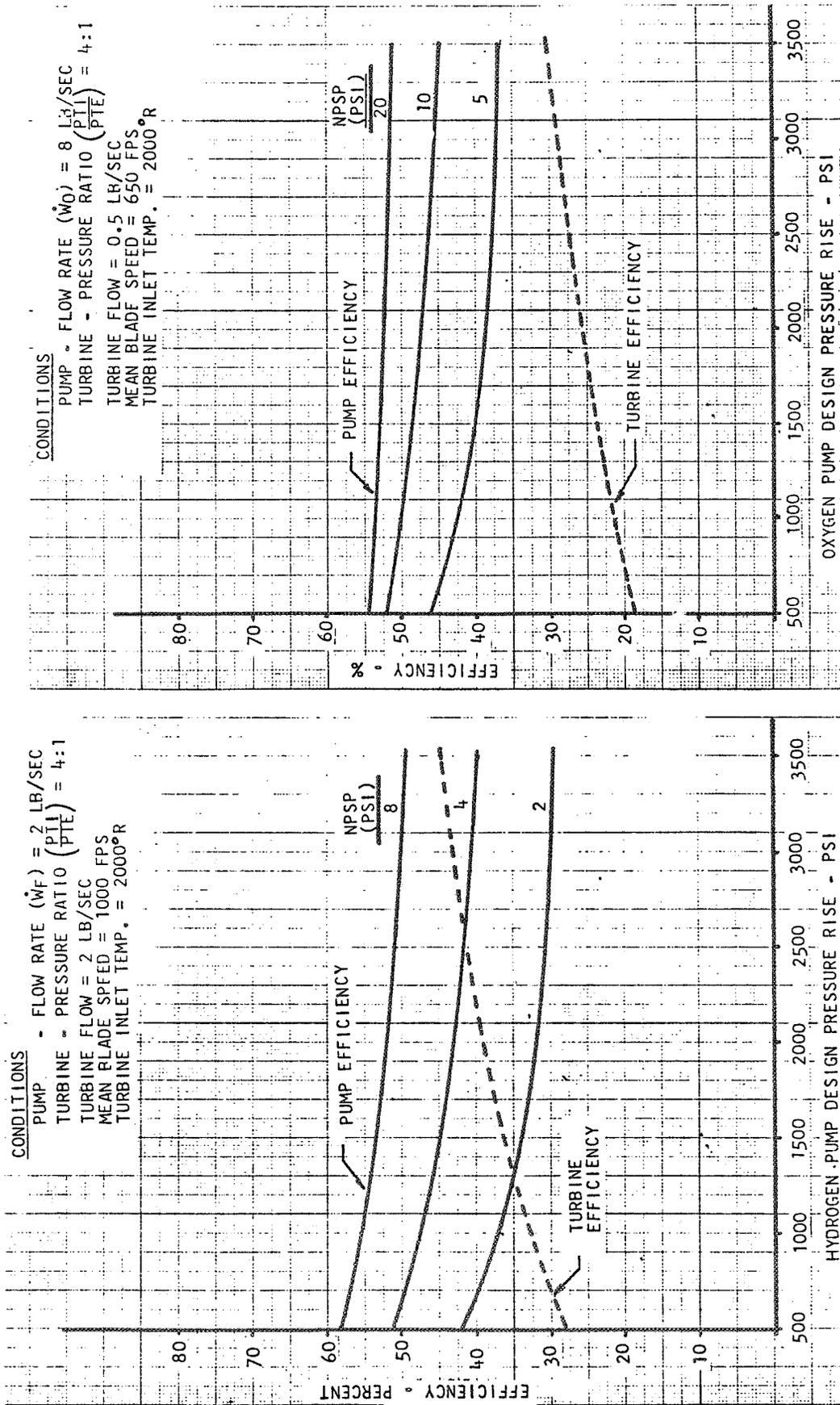
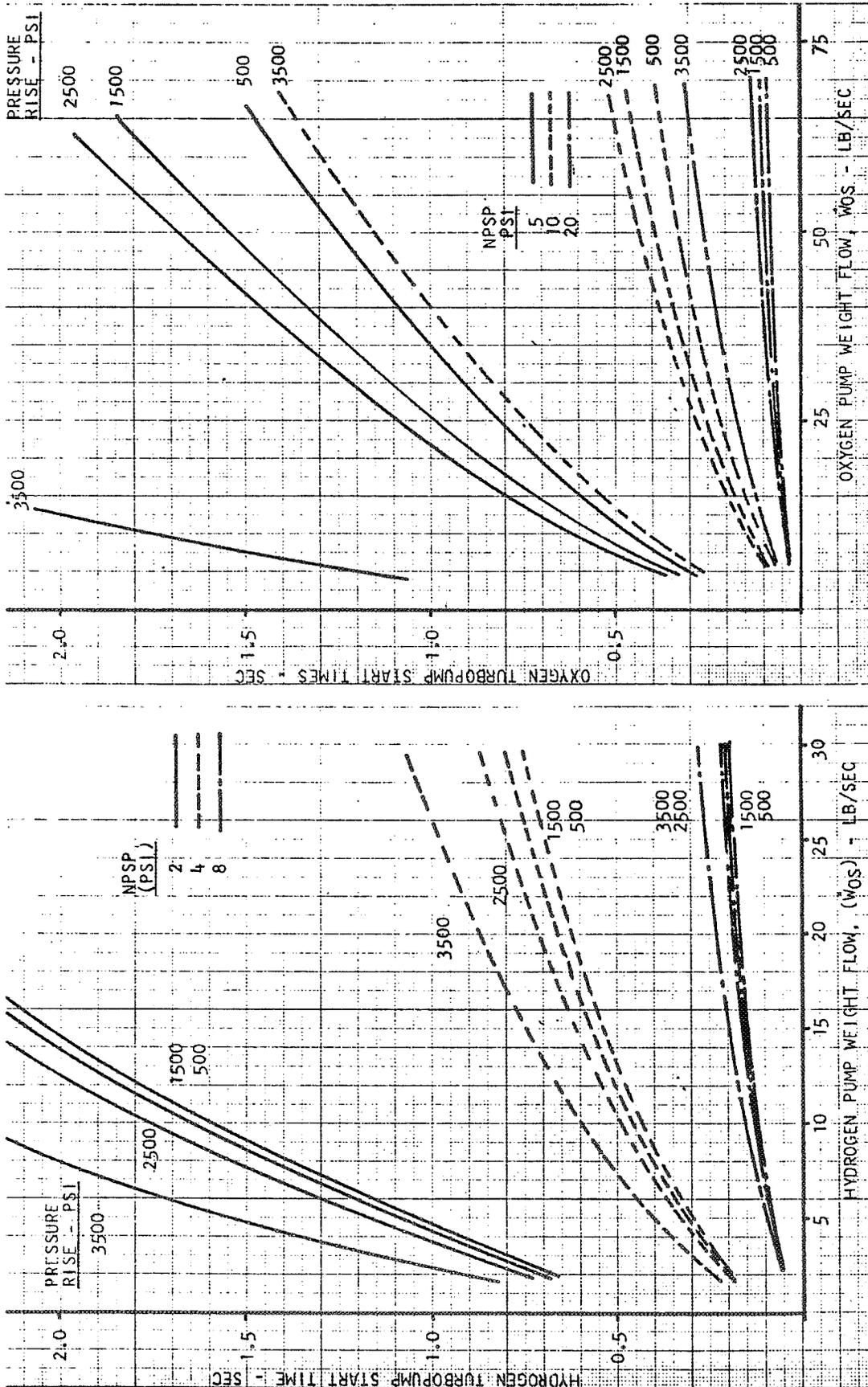


FIGURE E-30



OXYGEN

TURBOPUMP Start Times

HYDROGEN

FIGURE E-31

E-6. TURBOCOMPRESSOR

Hydrogen and oxygen turbocompressors are required to receive vaporized propellant from vehicle main boost tank, and by means of a staged centrifugal compressor, supply the propellant at the pressure required for operation. The compressor is driven by a direct coupled multistage axial flow turbine which is driven with hot gas produced by a gas generator. Centrifugal compressors were utilized to achieve a broad operating range. Since energy management is of primary concern when compressing a vapor, emphasis was placed on selecting turbocompressor components which operate at specific speeds resulting in highest achievable efficiency. For GH_2 this study showed that a minimum weight turbocompressor resulted when the design delivered the specific usable flow at maximum efficiency.

Parametric analyses of hydrogen and oxygen vapor turbocompressors were performed with Aerojet Liquid Rocket Company's "Turbocompressor Propellant Feed System Parametric Analysis Program" computer program. It defined the effects of inlet temperature and pressure, weight flow, and pressure ratio on turbocompressor weight, performance, response time, and envelope.

Assumptions and limiting criteria used in this analysis are presented in Figure E-32. Compressor shaft speeds were computed for an inlet blade tip speed of 550 ft/sec maximum, and an inlet relative Mach number of 0.9. Impeller geometry and sizing were based on optimum specific diameters for selected specific speed. The number of compressor stages is based on an equal work split between stages. A turbine mean blade speed of 1000 ft/sec was selected for the GH_2 and GO_2 turbocompressors.

Compressor and turbine efficiency values were defined from specified design specific speed. These values were used throughout this analysis. Since minimizing turbine drive gas flow rate was of primary concern, the turbine program for the turbocompressor computed the maximum allowable pressure ratio that the turbine can achieve while maintaining a specified design hub/tip diameter ratio of the last stage rotor. Maximum delivered specific power was obtained from the turbine drive gas by expanding the gas to the maximum pressure ratio in an efficient turbine. Achievement of the high design efficiency values required a relatively low energy extraction per stage resulting in multiple staging and affecting weight significantly. Thus, the GO_2 turbocompressor will weigh significantly more than a typical turbocompressor from an aircraft jet engine. A jet engine has a high mass

	<u>GO₂ TPC</u>	<u>GH₂ TPC</u>
COMPRESSOR FLOW RANGE	4 TO 50 LB/SEC	0.5 TO 6 LB/SEC
COMPRESSOR INLET TEMP RANGE	360* TO 560°R	360°* TO 560°R
COMPRESSOR INLET PRESSURE	10 TO 50 PSIA	10 TO 50 PSIA
COMPRESSOR PRESSURE RATIO	1.5 TO 19.5	1.5 TO 4.5
COMPRESSOR SPECIFIC SPEED	100	150
COMPRESSOR INLET TIP BLADE SPEED	550 FT/SEC	550 FT/SEC
MAX RELATIVE INLET MACH NO	0.9	0.9
MAX INLET LINE MACH NO	0.6	0.6
TURBINE INLET TEMPERATURE	2000°R	2000°R
TURBINE INLET PRESSURE	0.5 COMPRESSOR EXIT PRESSURE	0.5 COMPRESSOR EXIT PRESSURE
TURBINE PRESSURE RATIO	AS COMPUTED FOR LAST STAGE ROTOR HUB RATIO = 0.7	AS COMPUTED FOR LAST STAGE ROTOR HUB RATIO = 0.7
TURBINE SPECIFIC SPEED	90	90
TURBINE START PRESSURE	SAME AS STEADY STATE	SAME AS STEADY STATE
TURBINE GAS PROPERTIES	COMPUTED FROM GG MODEL	COMPUTED FROM GG MODEL
BEARING DN	10 ⁶ MM X RPM	10 ⁶ MM X RPM
DENSITY COMPRESSOR IMPELLER & HSG	0.10 LB/IN ³	0.10 LB/IN ³
DENSITY TURBINE ROTOR & HSG	0.286 LB/IN ³	0.286 LB/IN ³

*TEMPERATURE RANGE INCLUDED IN WEIGHT PREDICTIONS ONLY

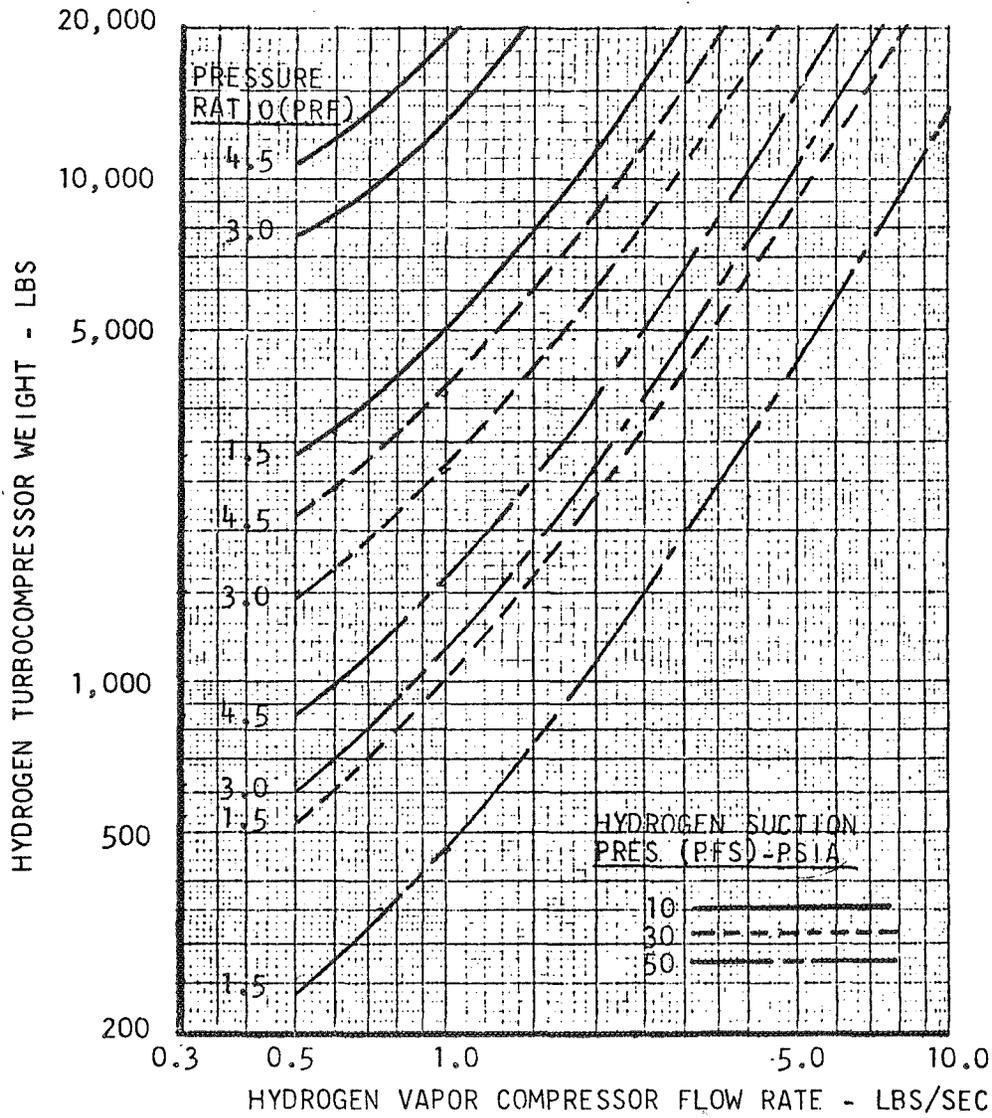
TURBOCOMPRESSOR LIMITING CRITERIA AND ASSUMPTIONS

flow, a low pressure ratio, and a two or three stage turbine, whereas the vapor turbocompressor turbine desires a low mass flow, a high pressure ratio, and up to 20 turbine stages.

E-6.1 Turbocompressor Weight and Envelope - Weights of hydrogen and oxygen turbocompressors are shown in Figures E-33 and E-34, as a function of weight flow, pressure ratio, and inlet pressure.

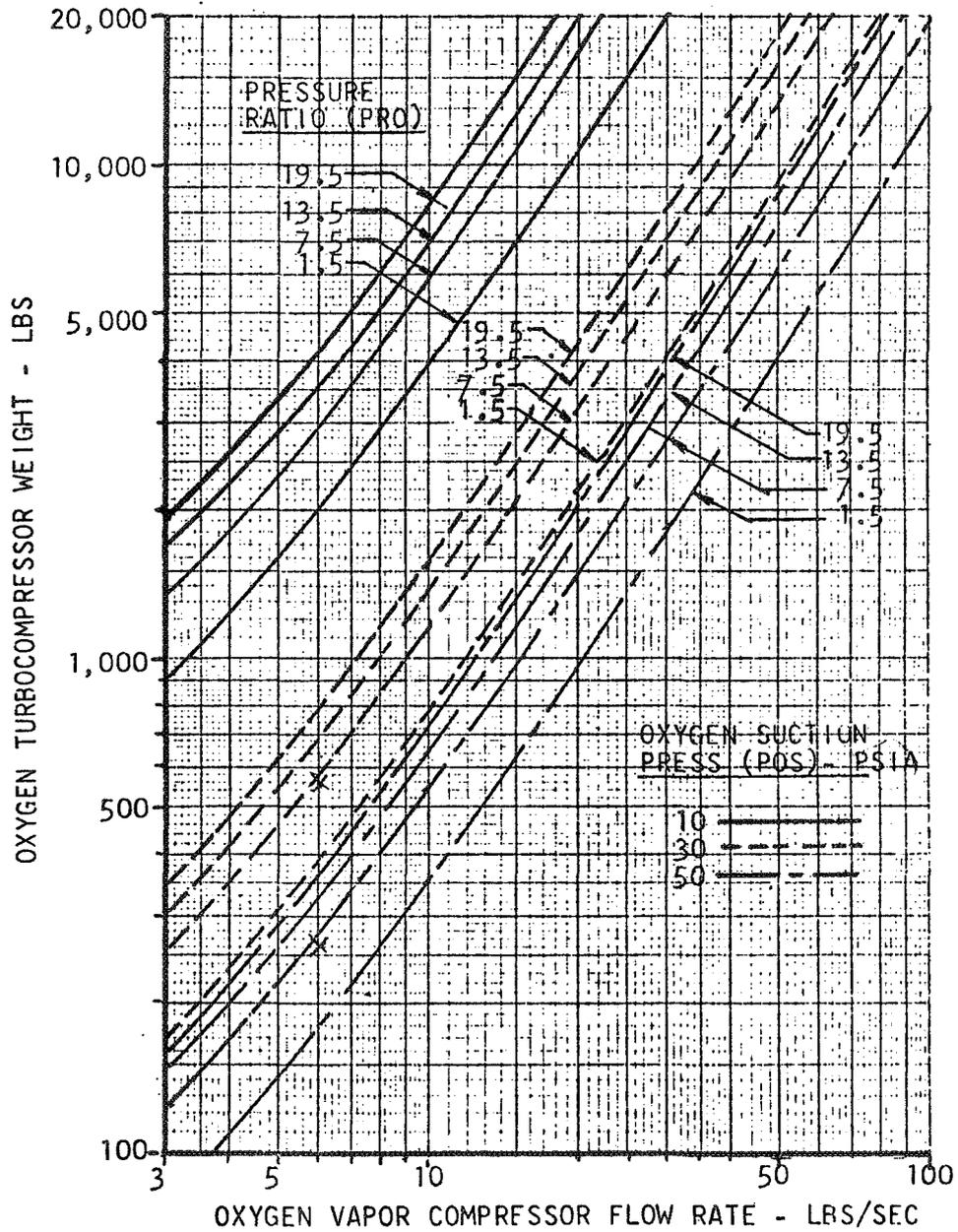
E-6.2 Compressor Efficiencies - Component efficiencies and design specific speed values are tabulated below.

	<u>GO₂</u>	<u>GH₂</u>
Compressor Specific Speed	100	150
Compressor Efficiency	84	85
Turbine Specific Speed	95	95
Turbine Efficiency	90	90



HYDROGEN TURBOCOMPRESSOR WEIGHT
Inlet Temperature = 560°R

FIGURE E-33



OXYGEN TURBOCOMPRESSOR WEIGHT
Inlet Temperature = 560°R

FIGURE E-34

E-7. PROPELLANT TANKAGE

APS concepts require tankage assemblies to store cryogenic or supercritical hydrogen and oxygen propellants until required for subsystem operation. Cryogenic propellant tankage stores the propellants at low pressure in a subcooled liquid state. Supercritical propellant tankage stores the propellants at significantly higher pressure levels in a supercritical state. The cryogenic tankage assembly consists basically of a pressure vessel, insulation and thermal conditioning subassembly, propellant positioning device, and associated vent valves and support hardware. The insulation and thermal conditioning subassembly is used to maintain propellants in a subcooled state by controlling heat leakage to these propellants. The propellant positioning device maintains propellant at the tank outlet for zero g conditions. The supercritical tankage assembly consists of a pressure vessel, insulation subassembly, and associated vent valves and support hardware. Since propellants are in a supercritical state, no propellant positioning device is required. Weight models were developed for these tankage assemblies, based upon tankage size, materials, and safety factors shown in the Space Shuttle Vehicle Design and Requirements Document.

E-7.1 Pressure Vessel and Associated Hardware - The propellant pressure vessel is a spherical tank of 2014-T6 aluminum with wall thickness determined by internal pressure. Wall thickness was determined by the largest of the following with a minimum thickness of 0.04 in. set by fabrication limits.

- o $T = 0.04$ in (Minimum wall)
- o $T = \frac{P}{2\sigma} \times \text{Tank radius}$ for $P = 2.0 \times \text{operating tank pressure}$ and $\sigma = 64$ KSI, the ultimate stress; or for $P = 1.5 \times \text{operating tank pressure}$ and $\sigma = 57$ KSI, the yield stress.

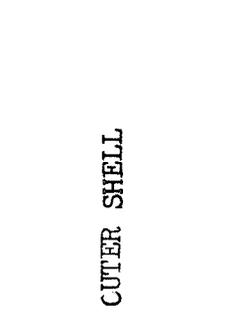
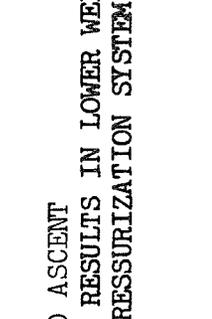
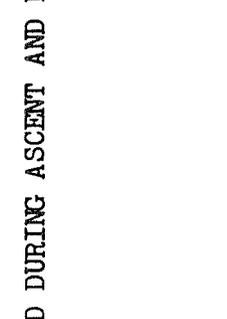
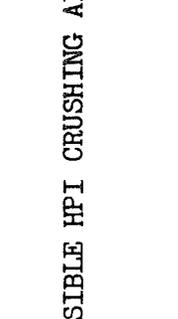
Shell weight is determined from the relation, $\text{weight} = 1.1 A_s \rho$, where A_s is the surface area of the tank and ρ is the wall density. The 1.1 factor, allows for nonoptimum weight increase, and is based upon previously designed tankage. Wall surface area is sized from tank volume. For storage of subcooled liquid propellants, tank volume includes volumes of propellant, pressurization system, which is stored in the tank, and 3 percent ullage. For supercritical tanks, volume includes only propellant volumes.

The propellant tankage weights include structural mount weights based upon 10 lb/ft dia for O_2 tanks and 0.1 lb/ft^3 vol for the H_2 tanks.

The subcooled liquid propellant tanks contain a propellant positioning sub-assembly which maintains liquid propellant at the tank outlet. This positioning subassembly is modeled as a double layer screen with a surface area equal to that of the propellant tank. A typical weight for a double layer positive expulsion screen is 0.25 lb/ft^2 .

E-7.2 Insulation and Thermal Conditioning of the Propellant Tanks - Both subcooled liquid and supercritical stored propellants require control of propellant ambient heating. Pressure increase due to supercritical propellant ambient heating is relieved by venting propellant. To limit the amount of propellant vented, propellant tanks are covered with high performance insulation. Subcooled liquid stored propellants must be prevented from being heated to saturation conditions in the tank. This would require the pump to operate with mixed phase flow. To prevent this, the liquid propellant is maintained in a subcooled state by use of thermal conditioning subassembly. A tube heat exchanger is brazed to a thin foil which surrounds the propellant tanks. Propellant, bled from the tank, flows through the tube heat exchanger, where it is vaporized by absorbing incoming heat flux. High performance insulation (HPI) is used to lower the heat flux. Insulation and propellant used by the thermal conditioner were optimized so that the combined weight of insulation and of propellant bled from the tank was minimal. The HPI consists of layers of radiation reflecting aluminized mylar, separated by layers of nonconductive netting operating in a vacuum. A protective outer jacket is required to protect the HPI against moisture, which reduces its reflectivity, and against crushing loads, which would cause the layers to touch, producing heat shorts. A pressurized fiberglass outer jacket concept was selected from the following four concepts (shown in Figure E-35):

- (1) outer aluminum jacket (dewar) which is evacuated and sealed. Although simple, this method requires a heavy outer shell to withstand the crushing pressure of the atmosphere during ascent and descent.
- (2) light fiberglass jacket, pressurized during ascent and descent, and vented to vacuum on orbit. This concept provides nearly the same protection as the dewar, but with weight savings.
- (3) flexible, vented bag which is purged during ascent and descent. This is the lightest concept, but provides only limited protection for the HPI.
- (4) evacuated and sealed flexible bag. This subjects the HPI to crushing pressures during ascent and descent, and presents a vacuum sealing technology problem.

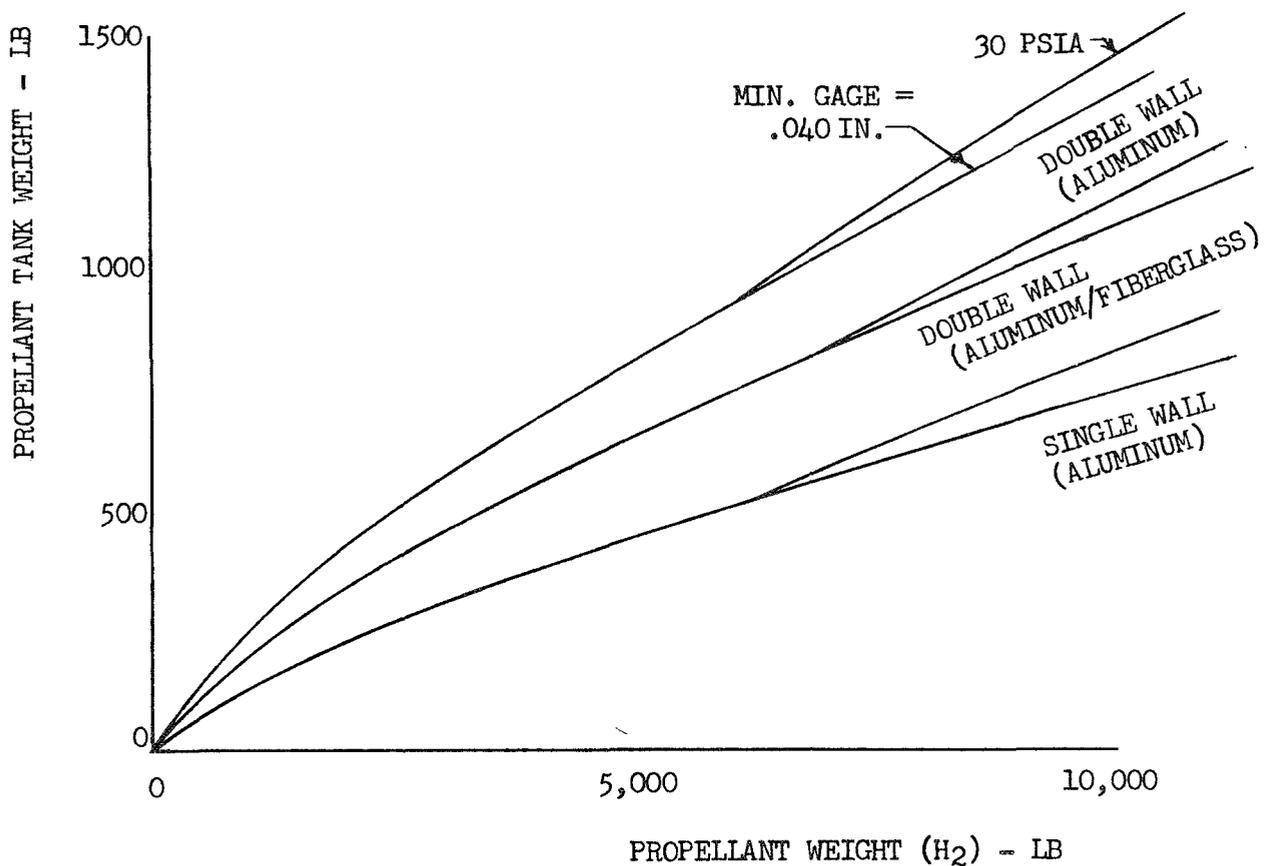
TANKAGE/HPI CONCEPTS	FEATURES
<p>VACUUM JACKET/HPI</p> 	<ul style="list-style-type: none"> ◦ REUSABLE HPI WITH ALUMINUM COVER ◦ VACUUM JACKETED PRESSURE VESSEL ◦ ALUMINUM INNER AND OUTER SHELL ◦ COLLAPSE PRESSURES RESULT IN HEAVY OUTER SHELL ◦ NO PURGE OF HPI REQUIRED
<p>PRESSURIZED JACKET/HPI</p> 	<ul style="list-style-type: none"> ◦ REUSABLE HPI WITH FIBERGLASS COVER ◦ HPI PRESSURIZED DURING DESCENT AND ASCENT ◦ PRESSURIZED FIBERGLASS OUTER SHELL RESULTS IN LOWER WEIGHT ◦ INCREASED COMPLEXITY DUE TO VENT/PRESSURIZATION SYSTEM
<p>PURGED JACKET/HPI</p> 	<ul style="list-style-type: none"> ◦ REUSABLE HPI WITH FLEXIBLE COVER ◦ HPI VENTED TO ATMOSPHERE AND PURGED DURING ASCENT AND DESCENT ◦ LOW STRUCTURAL WEIGHT
<p>SEALED JACKET/HPI</p> 	<ul style="list-style-type: none"> ◦ REUSABLE HPI WITH FLEXIBLE COVER ◦ HPI EVACUATED AND SEALED ◦ LOWEST WEIGHT CONCEPT ◦ HIGHEST TECHNOLOGY RISK DUE TO POSSIBLE HPI CRUSHING AND DEVELOPMENT OF SEALING METHOD

LIQUID PROPELLANT INSULATION CONCEPTS

SELECTED

Weight comparison of protective jacket concepts is shown for a liquid hydrogen storage tank in Figure E-36. Propellant tank weights include a hydrogen propellant tank pressurized at 30 lbf/in², outer protective jacket, and tank mounting assembly. The tank material 2014-T6 AL, is used for the aluminum jacket at a wall thickness of 0.04 in. This thickness is not sufficient to support the crushing atmospheric pressure, therefore, this concept would be heavier than shown. The fiber glass jacket is also 0.04 in thick. The flexible outer bag is assumed negligible in weight.

The fiberglass jacket concept was selected for the baseline design, because of protection for the HPI (ensuring reuse).



TANK WEIGHT -- INCLUDING SUPPORT STRUCTURE
Liquid Hydrogen Storage

FIGURE E-36

E-8. PRESSURIZATION SUBASSEMBLY

APS propellant storage concepts require that propellants be maintained at or above a minimum pressure. This pressure is provided by a storage tank pressurization subassembly. Many alternate pressurization subassembly concepts, such as cold helium, autogenous, mechanical, etc., are possible. The concept which results in optimum APS design depends on propellant storage conditions. Two storage conditions considered in Subtask A were subcooled liquid and supercritical fluid. The following paragraphs discuss the design of required pressurization subassemblies.

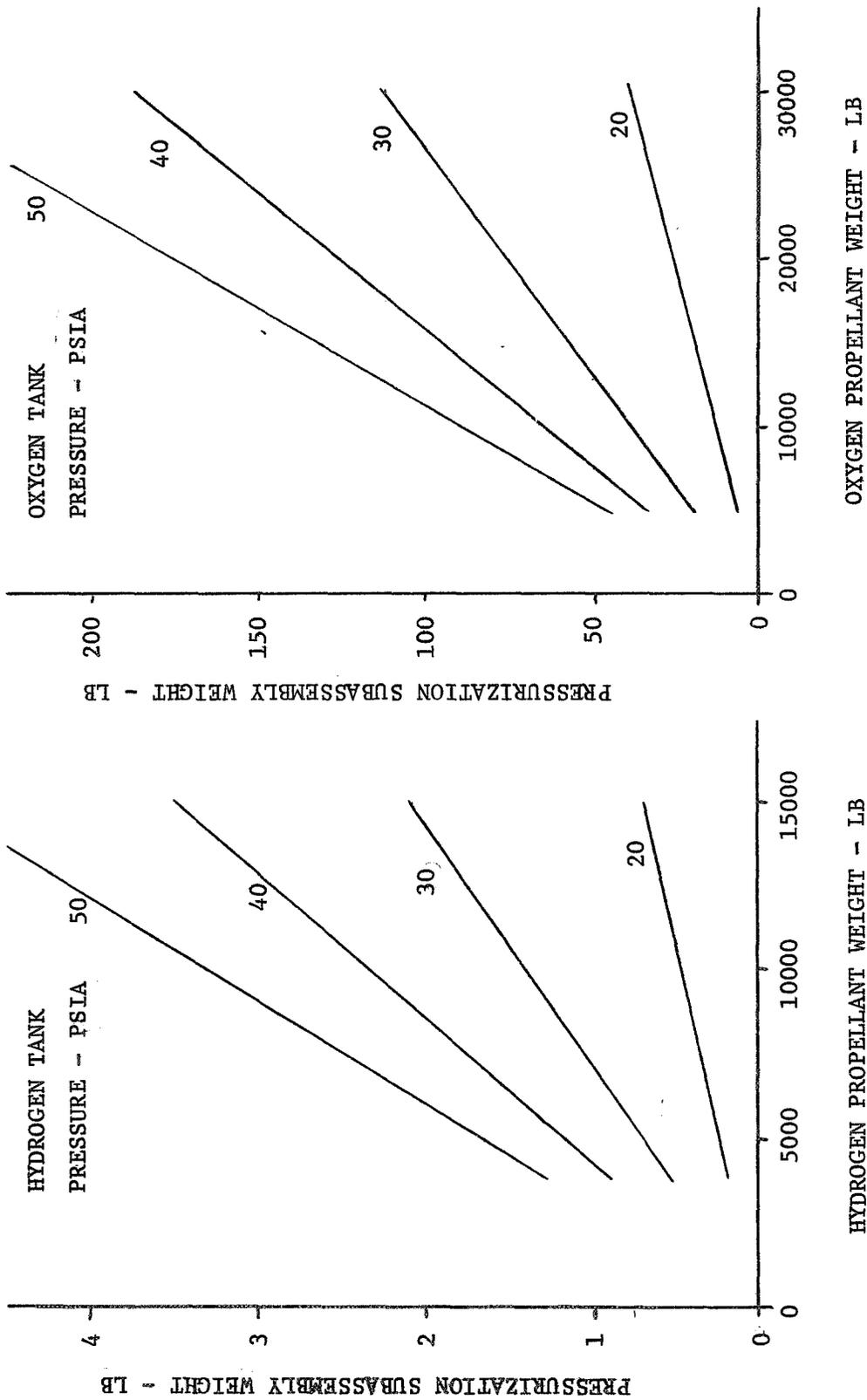
E-8.1 Subcooled Liquid Propellant Pressurization - APS propellant for the turbopump concept is stored as a subcooled liquid. One of the turbocompressor approaches also uses a subcooled liquid storage. Because propellant must be kept in the liquid state for proper turbopump operation, pressurization of propellant must be achieved by replacing the volume of expelled liquid with a solid, liquid, or vapor, rather than by changing propellant volume. Most practical, state-of-the-art pressurization concepts use either a piston, propellant vapor (autogenous), or inert gas as a pressurant. The inert gas approach was used in Subtask A with cold helium as pressurant. This approach was selected because previous studies of similar applications showed light weight, practicality, and achievability.

In using cold helium pressurization, it is assumed that the helium pressurant is stored within each propellant tank. Stored at cryogenic temperatures, pressurant subassemblies constitute minimum volume and weight relative to ambient storage. In the analysis of pressurant subassembly weight, it was assumed that:

- (1) pressurant is stored in an aluminum spherical tank
- (2) pressurant is initially stored at $3000 \text{ lbf/in}^2 \text{ a}$
- (3) pressurization process is isothermal
- (4) ullage volume of 3 percent is required
- (5) vapor pressure of propellants contributes a portion of pressurization

Figure E-37 presents pressurization subassembly weights for the O_2 and H_2 propellant tanks as a function of propellant weight and tank pressure.

E-8.2 Supercritical Propellant Pressurization - Two concepts studied in Subtask A stored APS propellant in the supercritical state. These concepts were the supercritical concept and one approach to the turbocompressor concept. In both propellants are maintained at a sufficiently high pressure level to remain supercritical and to provide the pressure head required to provide flow through the



PRESSURIZATION SUBASSEMBLY WEIGHT

FIGURE E-37

subsystem. As propellant leaves the tank, specific volume must be increased so that required pressure is maintained. To achieve this, supercritical propellants are heated by the gas generator and heat exchanger.

Five heat exchanger concepts were considered. These are shown in Figure E-38.

Concept 1 is an in-tank heat exchanger, using a circulation device to produce convective heat transfer on the cold side.

Concepts 2 and 3 are counter-flow tube-in-shell heat exchangers external to the tank. Cold side fluid is circulated through the shell by means of a pump. The difference between concepts 2 and 3 is that the pump is located at the heat exchanger outlet in concept 2, and at the inlet in concept 3. Thus, concept 2 pump operates on a higher, but more variable, density fluid.

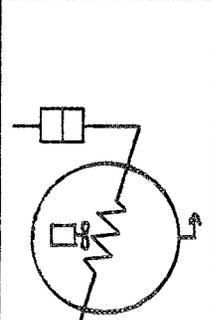
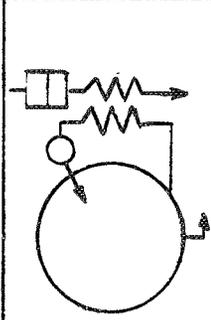
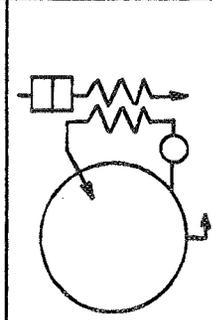
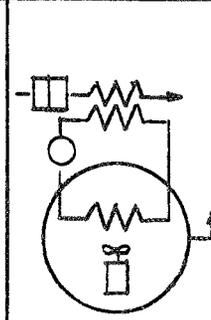
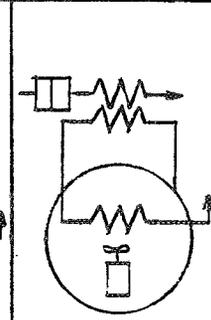
Concept 4 uses an intermediate helium loop to transfer heat from hot gas generator products to tank fluid. This concept provides a safety advantage over previous concepts, in that a leak in the heat exchanger on the O_2 side will not expose the hydrogen-rich gas generator products to the O_2 .

Concept 5 uses an external tube-in-shell heat exchanger to transfer heat from gas generator products to cold side fluid. This, in turn, transfers required heat to tank fluid and continues to the accumulator at a slightly elevated temperature.

A comparison of minimum weights for each concept showed that concept 3 is the lightest system. Relative weights of other concepts are shown in Figure E-38. Figures E-39 through E-42 show concept weights from which the minimum concept weights were selected. For concept weight comparison, a representative tank diameter of 5 feet was used for those concepts which depend upon propellant tank size.

Concept 2 is heavier than concept 3 because the pump must operate on a lower density fluid, resulting in a heavier pump assembly (due to higher volumetric flow rate and power requirement). Concept 1 is heavier because of the larger flow area through which the pump must circulate the fluids. Thus, to keep pump power requirements down, fluid velocity must be kept low. This results in a low cold side convective heat transfer coefficient and a heavy heat exchanger. Concept 4 must compromise between a high mean temperature differential at one heat exchanger and a low temperature differential at the other, resulting in relatively large heat exchangers. Resulting large wetted area produces a high frictional pressure drop, which requires increased pump power and (thus) pump weight. Concept 5, because of its relatively high design flow rate requirement, has a high temperature differential across the gas generator heat exchanger, but very low temperature differential across the in-tank heat exchanger. Thus, although the GG heat exchanger is

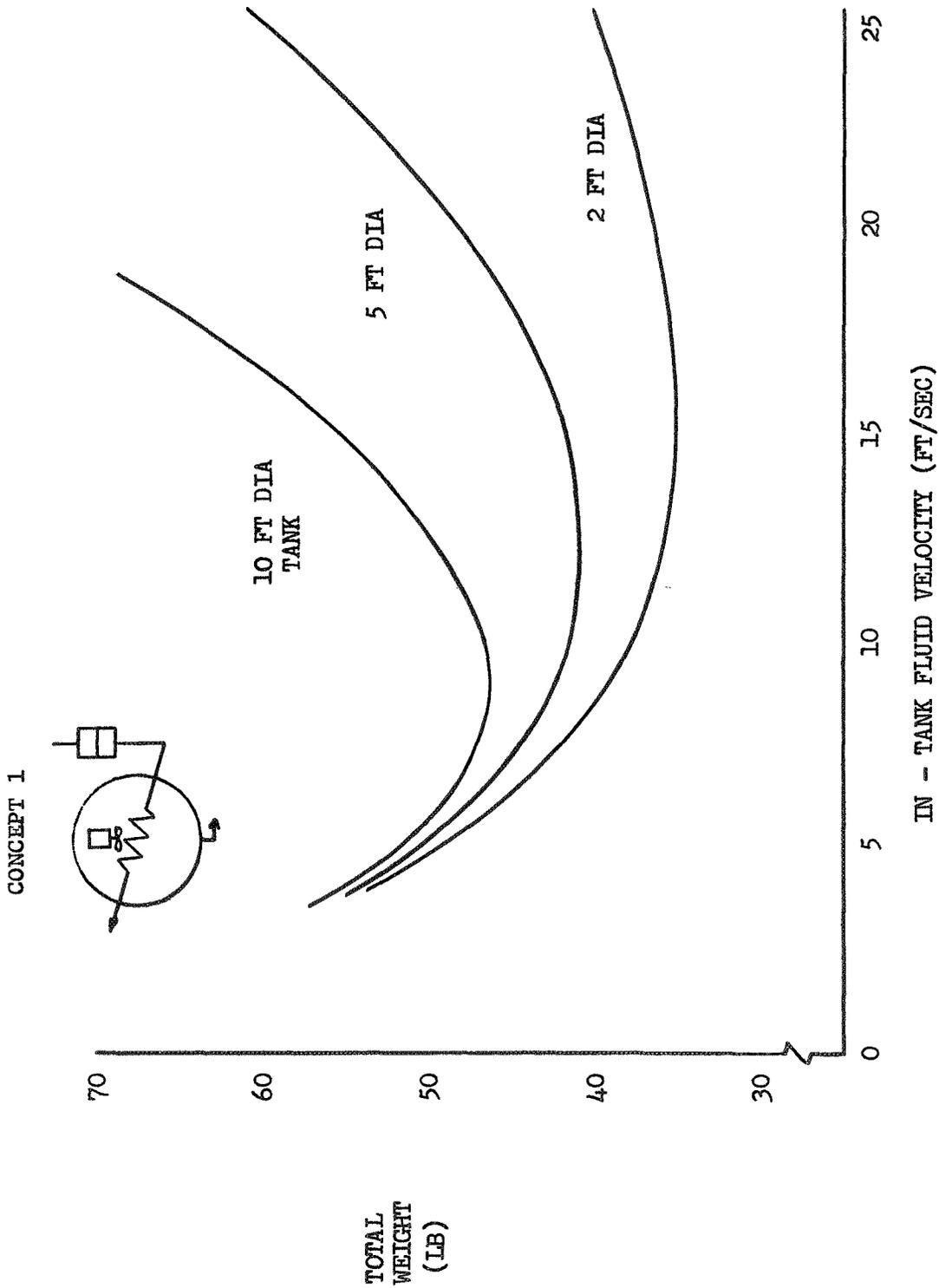
small, the in-tank heat exchanger is extremely large.

CONCEPT	DESIGN FEATURES	RELATIVE WEIGHT	COMMENTS
	IN TANK HEAT EXCHANGER - CIRCULATION DEVICE PROVIDES FORCED CONVECTION HEAT TRANSFER ON COLD SIDE	4.1	EXPLOSION HAZARD IN O ₂ TANK REDUNDANCY DIFFICULT TO IMPLEMENT HOT GAS TUBING PENETRATION THROUGH TANK
	EXTERNAL HEAT EXCHANGER - PUMP CIRCULATES FLUID THROUGH SHELL	1.8	ISOLATION PROVISIONS FOR REDUNDANCY PROVIDE EXPLOSION PROTECTION PUMP OPERATION WITH CONSTANT DENSITY FLUID
	EXTERNAL HEAT EXCHANGER - PUMP CIRCULATES FLUID THROUGH SHELL	1.0	ISOLATION PROVISIONS FOR REDUNDANCY PROVIDE EXPLOSION PROTECTION PUMP OPERATION WITH VARIABLE DENSITY FLUID
	INTERMEDIATE HELIUM LOOP - IN TANK HEAT EXCHANGER WITH CIRCULATION DEVICE - EXTERNAL HEAT EXCHANGER WITH PUMP	28.5	NO EXPLOSION PROTECTION REQUIRED REDUNDANCY DIFFICULT TO IMPLEMENT
	OPEN LOOP SYSTEM - IN TANK HEAT EXCHANGER WITH CIRCULATION DEVICE - EXTERNAL HEAT EXCHANGER NO PUMP	47.5	ISOLATION PROVISIONS FOR REDUNDANCY PROVIDE EXPLOSION PROTECTION

SELECTED

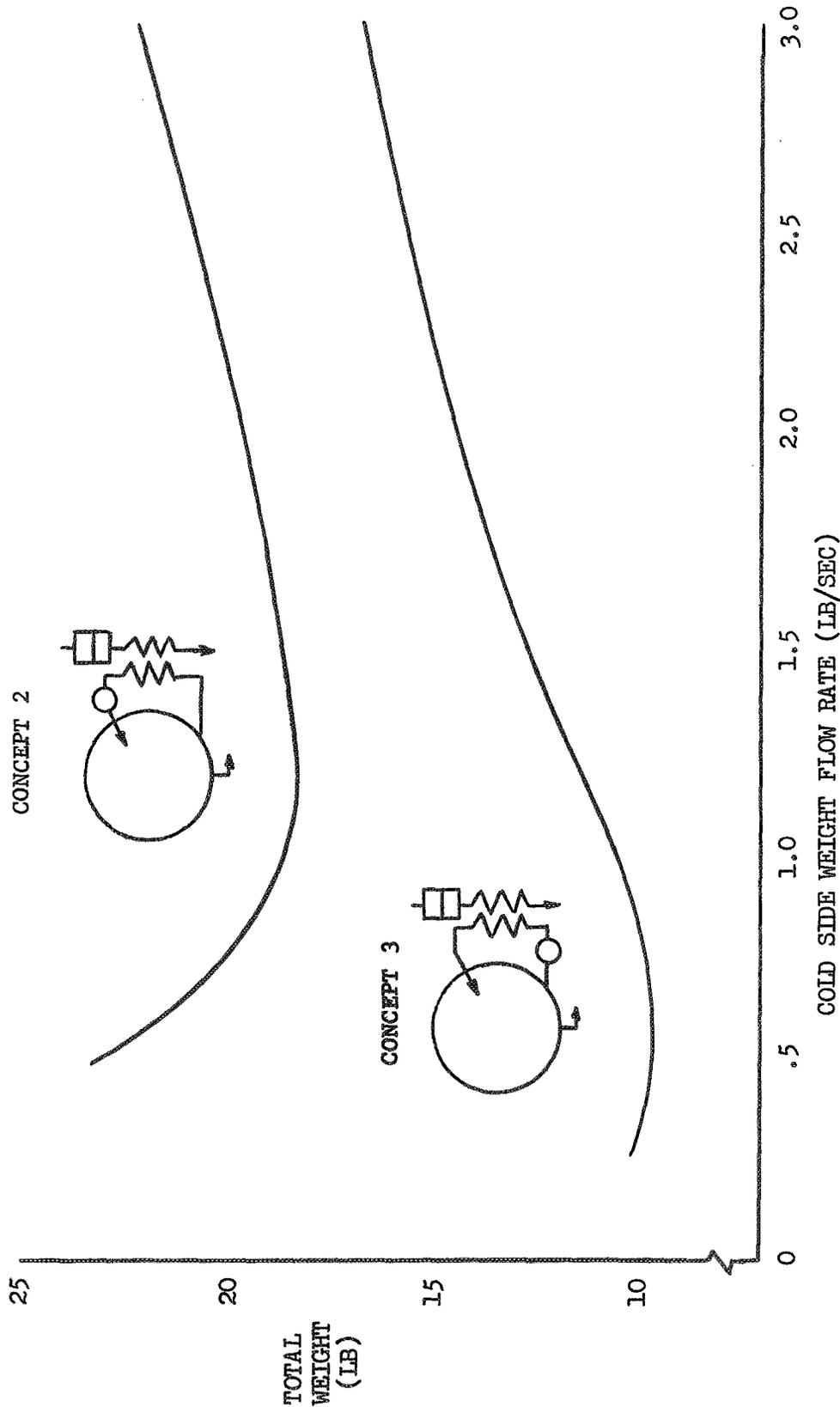
SUPERCRITICAL STORAGE TANK HEAT EXCHANGER COMPARISON

FIGURE E-38



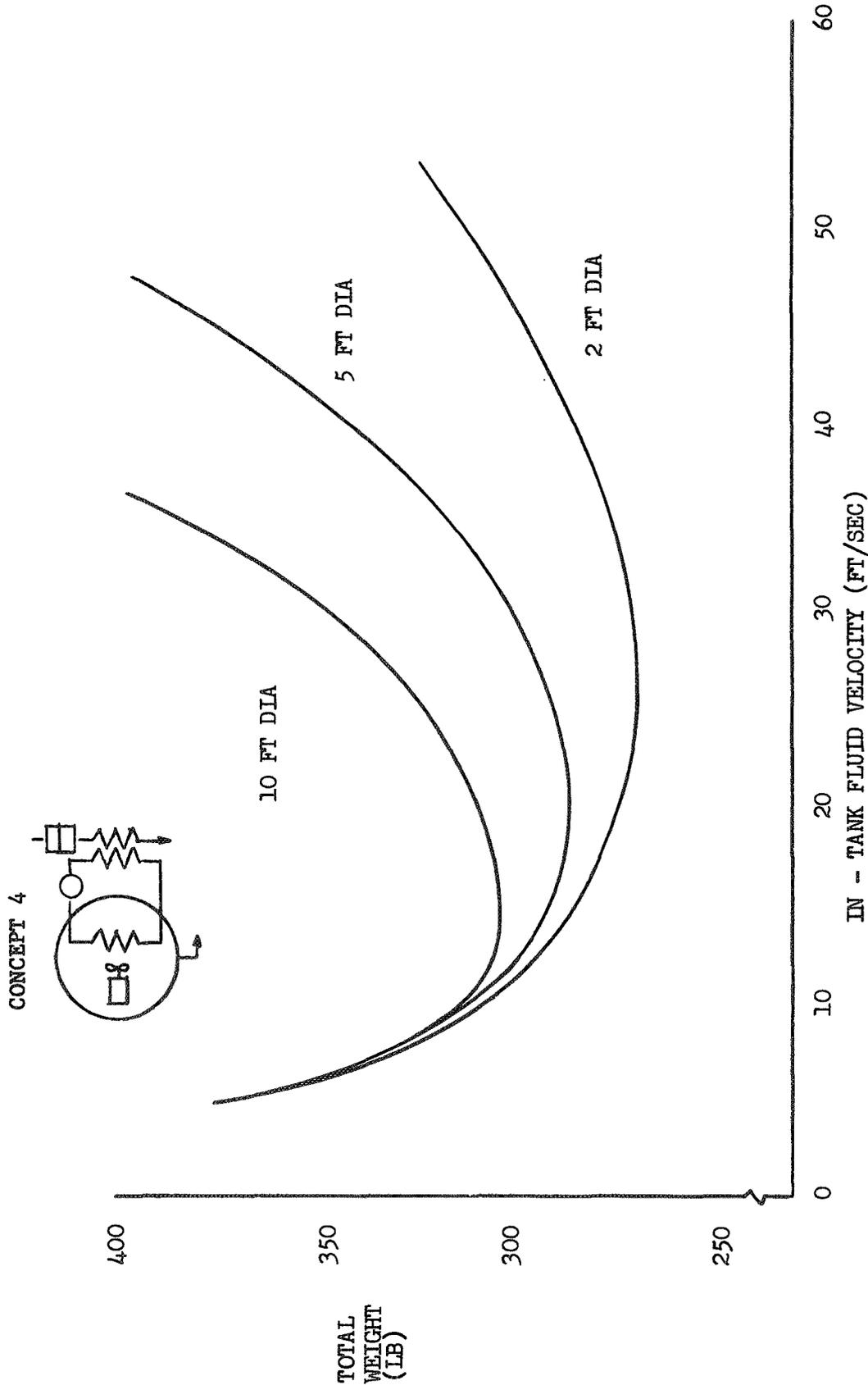
WEIGHT VARIATION OF SUPERCRITICAL HEAT EXCHANGER

FIGURE E-39



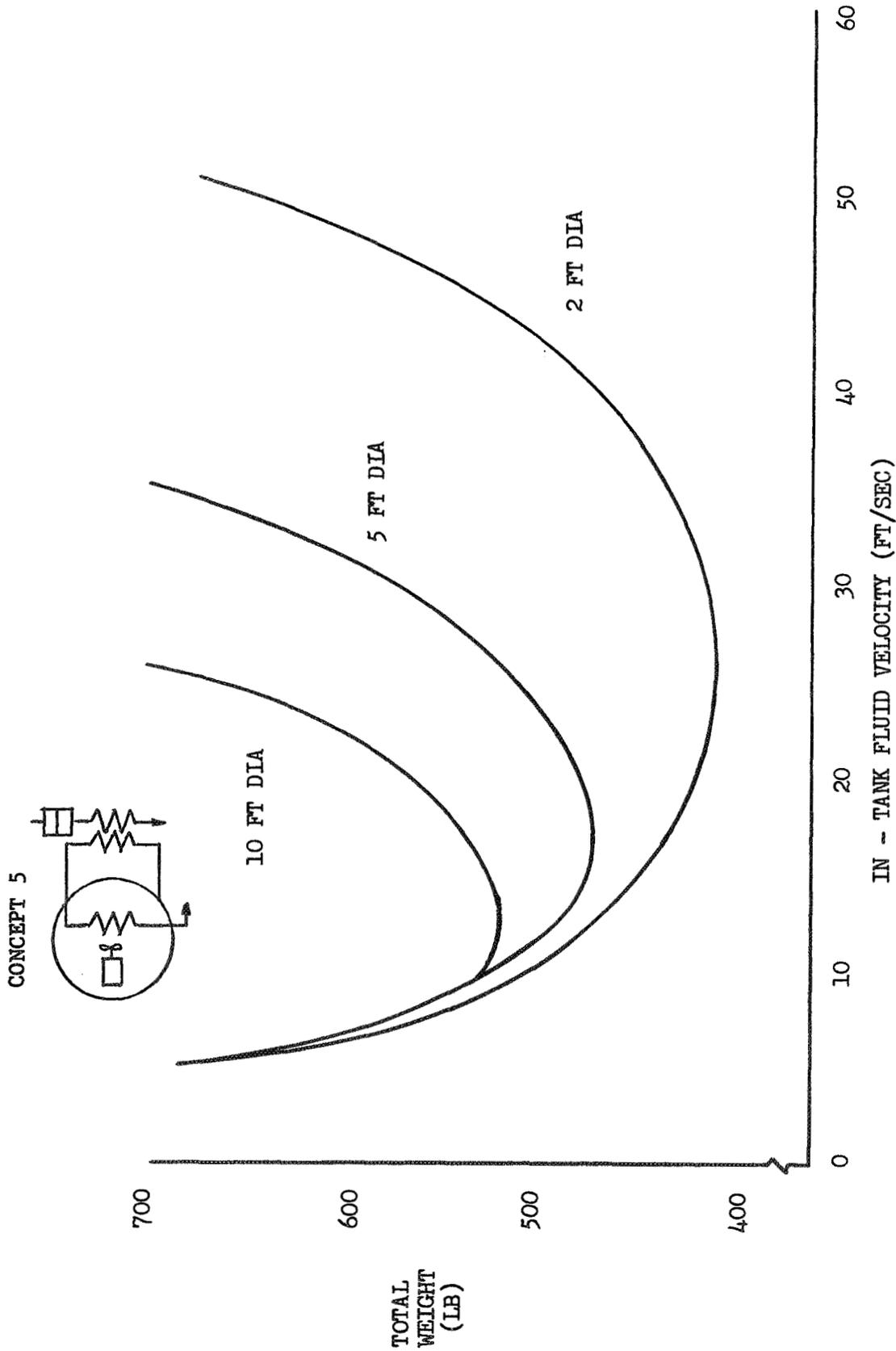
WEIGHT VARIATION OF SUPERCRITICAL HEAT EXCHANGER

FIGURE E-40



WEIGHT VARIATION OF SUPERCRITICAL HEAT EXCHANGER

FIGURE E-41



WEIGHT VARIATION OF SUPERCRITICAL HEAT EXCHANGER

FIGURE E-42

E-9. CONTROLS

APS concept requires several types of control components. This section provides weight data on the more significant APS controls, i.e., shutoff valves and regulators. Where possible, existing units served as a guideline for weight estimates.

E-9.1 Shutoff Valves - Fluid shutoff valves considered include ball, butterfly, poppet, blade, and diaphragm configurations. Valve weights are based on weight data compiled from previous valve designs. These data indicate that valve weight is primarily a function of flow area or line size and that the type of shutoff element does not appear to be significant. Figure E-43 presents weight data as a function of line diameter for both steel and aluminum valves. Actuation systems for shutoff valves included in weight analysis were determined from estimated response requirements, weight constraints, and envelope limitations.

E-9.2 Pressure Regulators - Factors that influence high pressure regulator design and fluid properties, maximum inlet pressure, minimum inlet pressure, required flow rate, range of flow rates, regulation pressure desired, regulation pressure tolerance, operating temperature range, and response. For low flow rates a thermally compensated staged or piloted poppet type regulator in current usage can be used. For high flow rates, no reference unit was located, but units having a regulated pressure below 50 lbf/in² a flow rates up to 50 lb/sec GO₂ have been made for space vehicles. In addition to the main flow control, a power actuator, bias regulator, and pilot valve are required.

Weight vs. flow rate curves shown in Figure E-44 were established by determining equivalent flow orifice size, obtaining weights from the shutoff valve curve, and adjusting weights upward as a function of size in order to allow for added complexity, a larger actuator, and compensation devices.

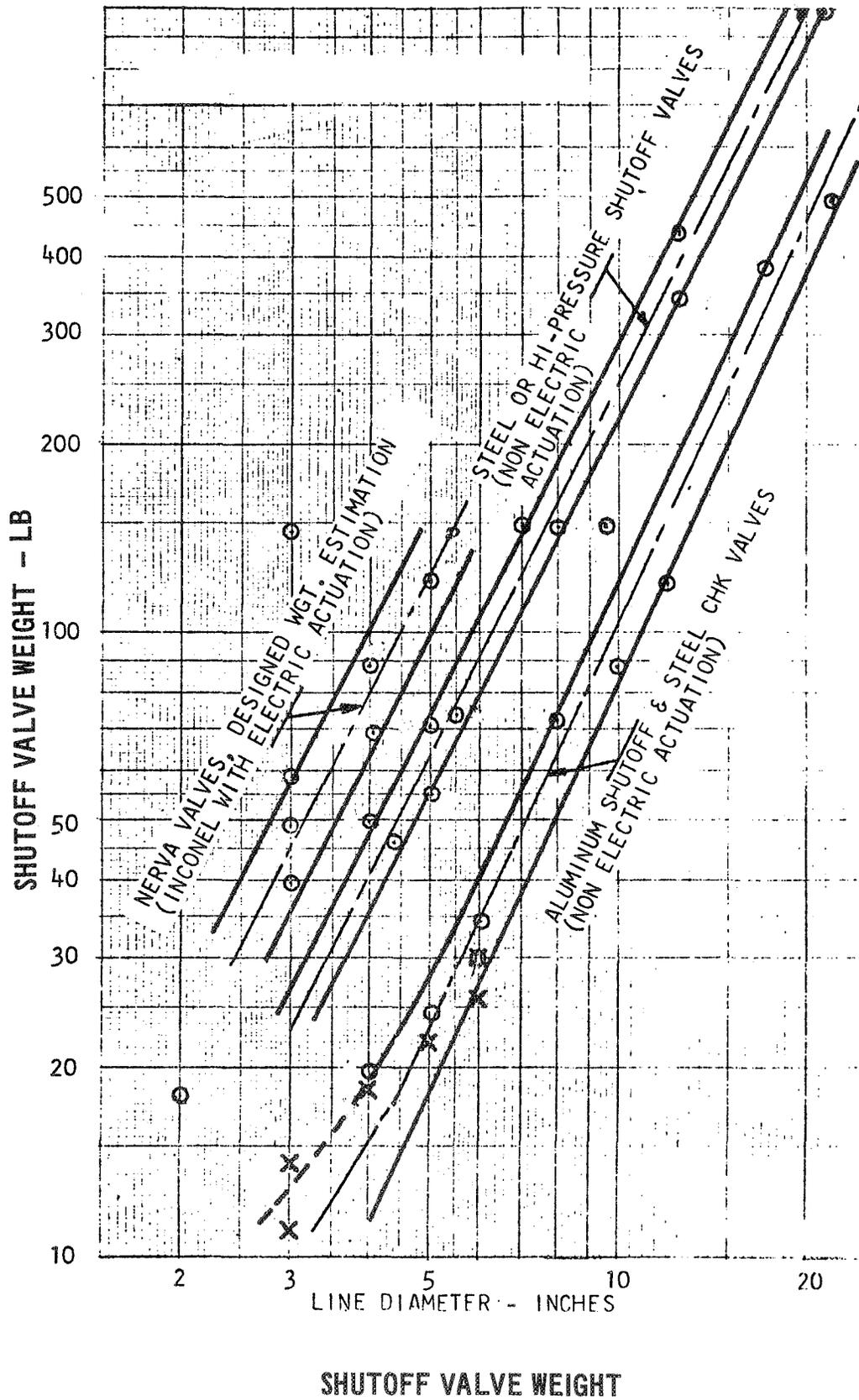
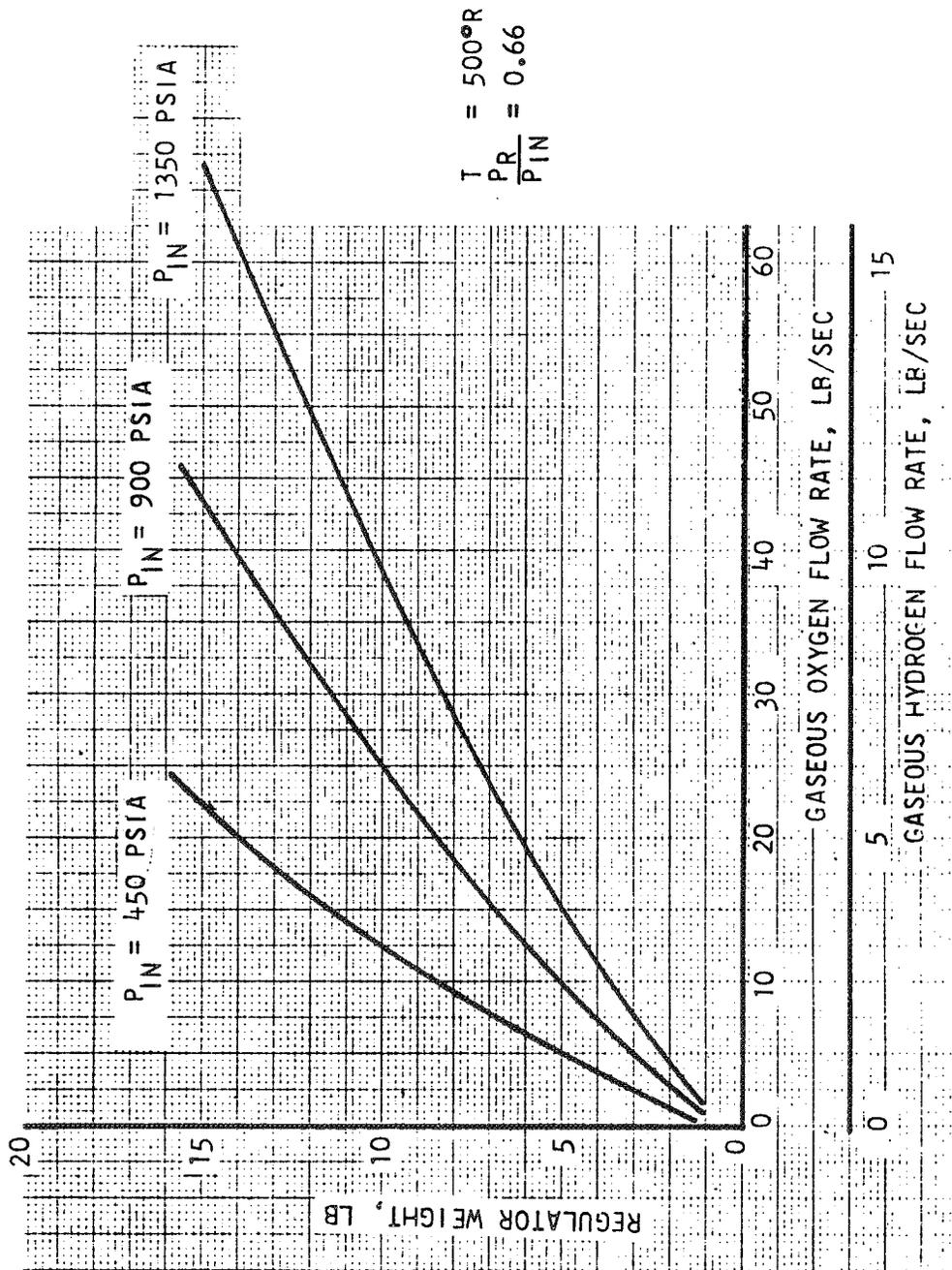


FIGURE E-43



HIGH PRESSURE REGULATOR WEIGHT

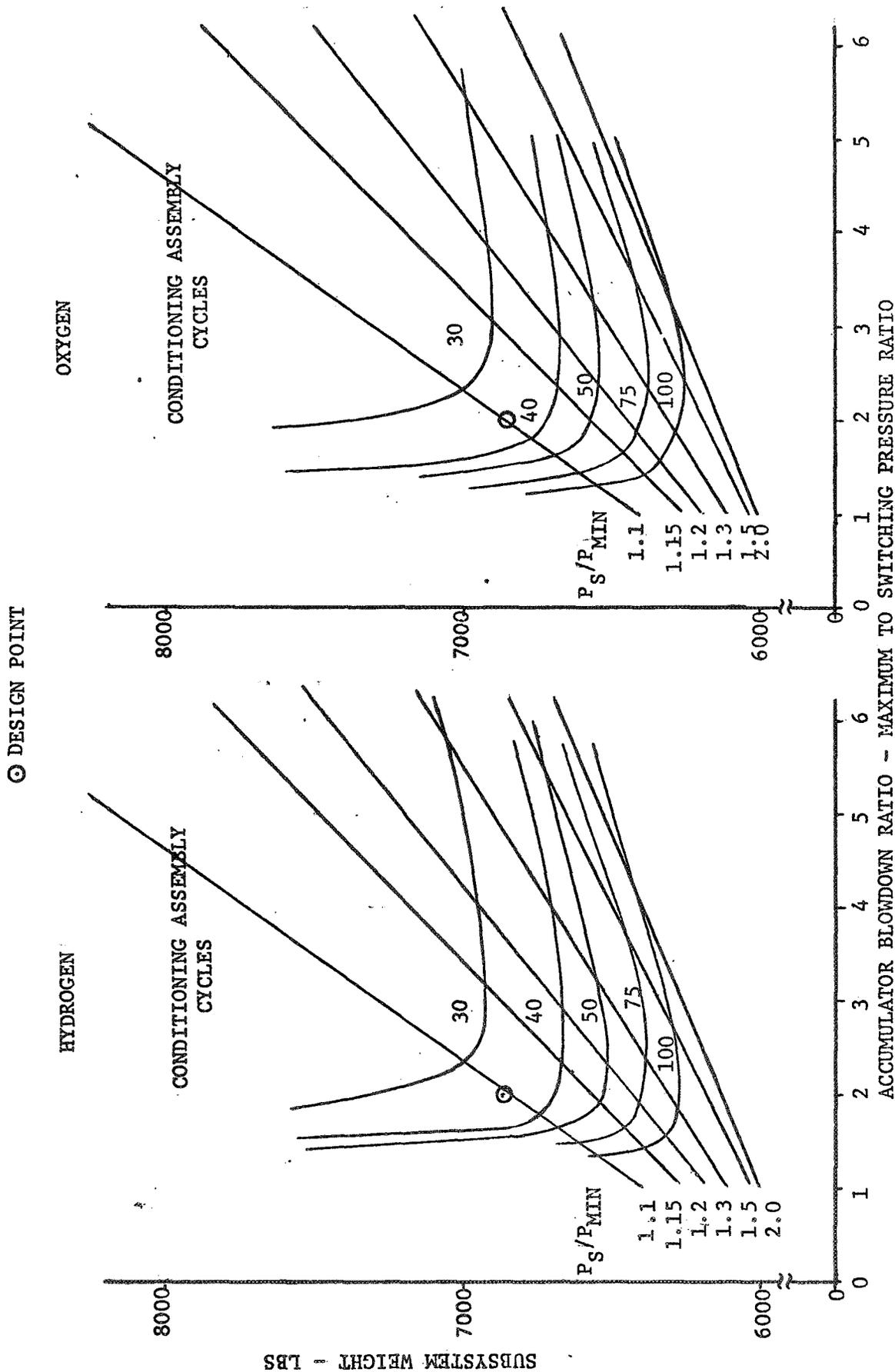
FIGURE E-44

E-10. ACCUMULATOR AND SUPPLY LINES

Efficient APS operation requires a propellant supply line assembly to each thruster and an accumulator to store conditioned gaseous propellant so that the conditioner assembly is not required to cycle for each thruster firing. APS analysis requires a representative component model to size accumulators and supply line. Models used in the study are described below.

Accumulators are spherical pressure vessels designed to blowdown in pressure in order to supply conditioned propellants for thruster operation. When the accumulators blowdown to a specified switching pressure, the conditioner assembly starts up and recharges the accumulator to maximum pressure, at which point the cycle starts again. Major requirements of an accumulator are that (1) during blowdown between maximum and switching pressure, it provides sufficient propellant to the thrusters so that a limited number of conditioner cycles are required, and that (2) between switching and minimum pressures, it provides continuous propellant flow to the thrusters while the conditioner assembly is starting up. To size an accumulator which will meet the requirements, minimum pressure must be calculated from thruster chamber pressure, injector pressure drop, supply line pressure drop, and regulator pressure drop. With this pressure and an assumed switching to minimum pressure ratio, a propellant density change in the accumulator can be calculated. This density change for specific conditioner assembly startup time and nominal system thrust will define accumulator volume. Standard pressure vessel relationships are then used to calculate accumulator weight for volume and maximum pressure (which was calculated using maximum-to-switching pressure ratio). In order to provide minimum subsystem weights, the maximum-to-switching and the switching-to-minimum pressure ratios must be optimized for response time and number of cycles required. An example optimum weight study is presented in Figure E-45 which reflects the use of aluminum (2014-T6) for the accumulator. As shown, there is a minimum weight for a specific response time and a specific number of cycles

The propellant supply line assembly is an aluminum (2014-T6) ducting system designed to carry gaseous propellant from accumulator to thruster injector manifold. Line section size is defined by line length and line diameters. Line lengths are obtained from scale vehicle drawings which present accumulator and thruster locations. Lines are laid out as a branch system originating from a main line from the accumulator. Line segment diameters are calculated to achieve a specified pressure drop per unit length. With line diameter and propellant



TURBOPUMP ACCUMULATOR SIZING CRITERIA
Orbiter A
Conditioning Assembly Response Time = 0.5 Second

FIGURE E-45

pressure, required wall thickness of line segment can be calculated using strength relationships. Two additional wall thickness criteria were used: wall thickness could not be less than diameter divided by 80, because of installation restrictions, and not less than 0.04 in. because of manufacturing restrictions. Having determined line lengths, diameters, and wall thickness, total supply line assembly weight was calculated.

**APPENDIX F
RESIDUAL PROPELLANT AVAILABILITY**

F-1. INTRODUCTION

At the time of orbiter main engine shutdown, there is a significant quantity of oxygen and hydrogen propellants remaining, as residual liquids and gases, in engine propellant tanks. Typically there are, as a minimum, approximately 2500 lb of residual propellants in Orbiter A. These residual propellants are entirely assessed against the main engine system and, if they could be used by the APS, would be considered as free in APS weight accounting. The quantity of propellant available as residuals would constitute a significant item in the APS weight, and hence is of considerable importance in concept selection. In the high pressure APS concepts, there are two means of using these residual propellants:

- (1) Turbocompressor APS concepts which extract their propellant from the main engine tanks.
- (2) Tap-off conditioner concepts which operate the gas generator with main engine propellants.

All residual propellant, however, is not available for APS usage. After main engine shutdown, heat transfer from external structure and/or vaporization of residual liquids will increase main engine tank pressures to vent levels, and

residuals will be lost through venting unless they are used by the APS. Boil-off and vent rates are independent of APS usage; thus, to determine the amount of residuals that can be credited to the APS, requires an analysis coupling combined effects of heat transfer and vaporization rates associated with residual liquids in the tank. Since vaporization occurs in a very low g environment, evaluation of actual vaporization rates would require modeling of fluid motion and heat transfer characteristics in a low gravity environment. These analytical techniques were not available. The approach selected for this study was to correlate liquid vaporization rates experienced on previous boosters, and thereby to define a model which would predict equivalent propellant motion and heat transfer effects for a known mission and vehicle characteristics. This model was then applied to shuttle vehicle design and mission in order to identify vaporization rates that could be expected during the shuttle mission.

This appendix defines the correlation of booster vaporization rate data and its application to the shuttle vehicle. The following paragraphs provide a definition of the Saturn vehicles examined and a discussion of data and results for both oxygen and hydrogen. A summary of the equivalent models which best approximate fluid motion and heat transfer is provided and finally, these results are applied to the space shuttle vehicle to predict the availability of liquid residuals for the APS.

F-2. SATURN DATA EVALUATION

Low gravity, orbital data were available for three booster configurations. These were: (a) Saturn-IV, (b) Saturn IVB/IB, and (c) Saturn-IVB/SV. The Saturn-IV vehicle was the upper stage of the Saturn I, two-stage, launch vehicle. This vehicle performed a single burn to earth orbit. The Saturn-IVB/IB vehicle was the upper stage of the Saturn IB, two-stage, launch vehicle. The Saturn IVB flight numbers for this booster configuration were in the 200 series. The Saturn IVB/SV vehicle was the third stage of the Saturn V, three-stage, launch vehicle. This vehicle performed a two-burn mission; the first burn was to earth orbit, followed by an earth orbital coast, then a second burn for translunar orbit insertion. The flight numbers for this booster configuration were in the 500 series. The S-IVB/IB and S-IVB/SV stages were basically of the same configuration.

All S-IV and S-IVB flights were examined to obtain applicable data for the oxygen. Eight flights provided data suitable for study. Segments from 11 flights were examined to obtain data applicable to the hydrogen propellant. Six groups of these data were analyzed in depth using one particularly well instrumented group to correlate the other data. The following paragraphs provide a summary of the data obtained and a discussion of its interpretation.

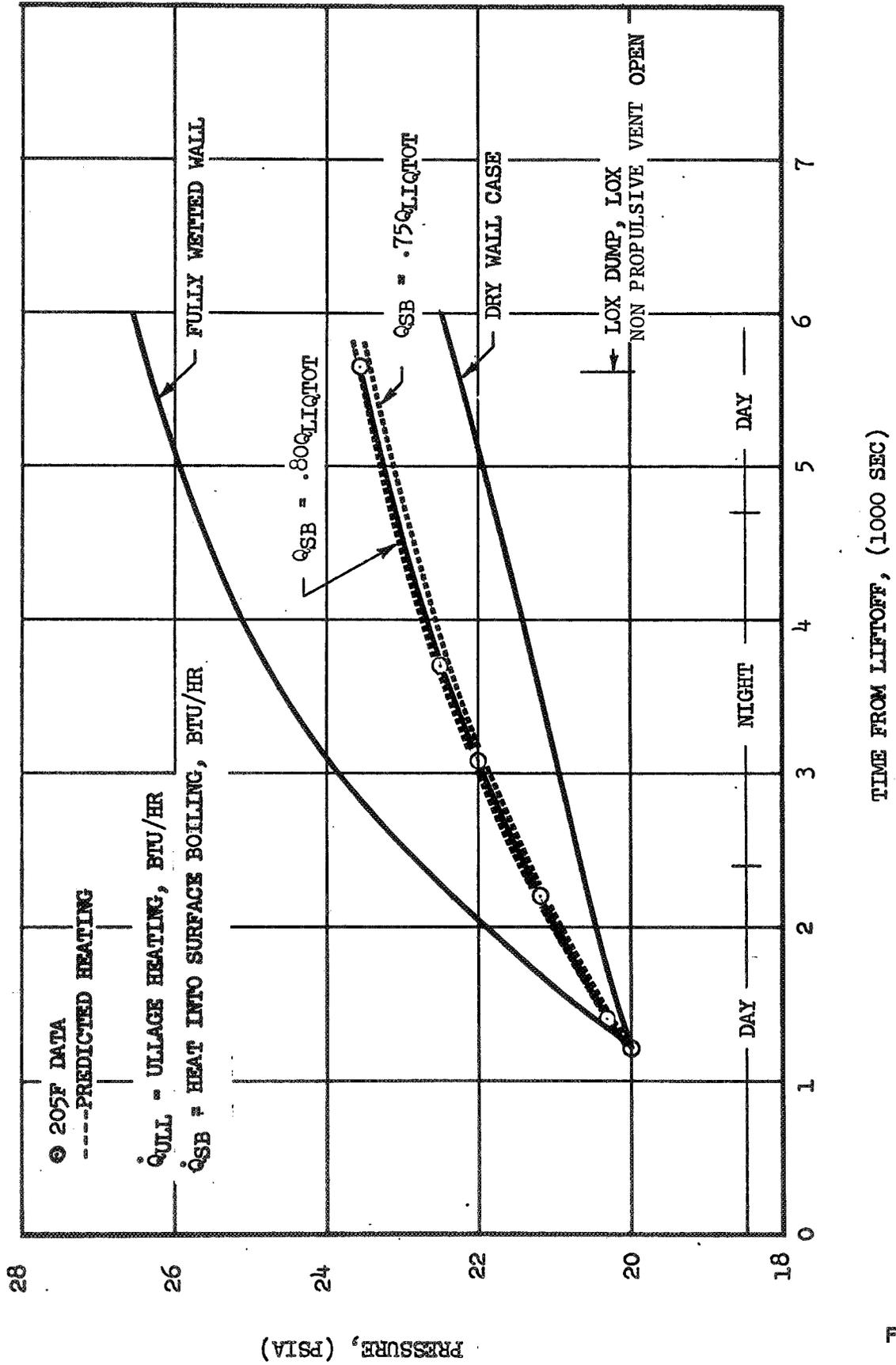
F-2.1 Liquid Oxygen Evaluation - For the eight flights which provided LO₂ data suitable for study, heating was divided into two regimes. These were: (1) ullage gas heating, or heating characterized by a vapor interface at the propellant tank wall, and (2) liquid heating, or heating characterized by a liquid interface at the propellant tank wall. This latter heating regime was further subdivided to identify the amount of liquid heating that should be allocated to propellant boil off and the amount associated with bulk liquid heating. The applicable data were evaluated to determine amount of liquid/gas heating, wetted wall surface area, and percentage of liquid heat transfer associated with propellant boiloff.

To evaluate liquid oxygen tank conditions during low g coast, the tank conditions at the beginning and end of the coast were established as closely as

possible. For example, for one typical flight (vehicle 204), the following conditions were established. After main engine cutoff, the stage was pitched for alignment with the local horizontal. Subsequent to this, the following tank conditions were achieved: LO_2 bulk temperature 161° to 162°R , ullage gas temperature 160°R and ullage pressure $19 \text{ lbf/in}^2\text{a}$. These were used as the initial conditions for evaluation of LO_2 characteristics. The conditions at the end of a two hour coast were: LO_2 bulk temperature 164° to 165°R , ullage gas temperature 165° to 170°R and ullage pressure $26.3 \text{ lbf/in}^2\text{a}$. The observed pressure rise could not be due to ullage heating alone as it would require an ullage temperature of 180°R . Bulk boiling of the liquid also could not have occurred, because bulk liquid temperature never reached saturated conditions. Thus, a combination of liquid heating, liquid vaporization, and ullage gas heating was required to explain the measurements. To determine the appropriate balance between vaporization and ullage heating, a computer program was utilized to investigate the influence of the various parameters affecting pressure and temperature within the vehicle. Using this approach, the balance between ullage heating, and vaporization which best satisfied end conditions was deduced. For the data point in question, the average bulk heating rate for the residual liquid was approximately 1500 BTU/hr. The heat input rates required to vaporize sufficient liquid for the observed pressure rise rates were also determined. These varied between 5,000 and 15,000 BTU/hour. These results indicated that between 75 to 90 percent of the total heat transferred from the tank to liquid oxygen resulted in vaporization, while the remainder was associated with bulk liquid heating.

As another example, Figure F-1 shows pressure rise as a function of time for flight 205. Calculations of the pressure rise rate for two extreme cases are also shown. The extreme cases considered were: (1) A fully wetted wall in which all of the heating was directly applied to the liquid, (2) a dry wall case in which all heat transfer was delivered to the ullage gas. These extremes are shown to bound the actual data. A curve which best satisfied the observed data was deduced for this flight, the same manner as described above, by assuming that 75 percent of the total liquid heating was associated with surface boiling. As shown this provides a very good model of the results.

Other flight data indicated different pressure profiles during coast. For example, the rate of pressure rise as a function of time from insertion was observed to vary from flight to flight. This was partially correlated with the



LOX TANK ULLAGE PRESSURE
(S-IVB-205, LOW-G COAST)

FIGURE F-1

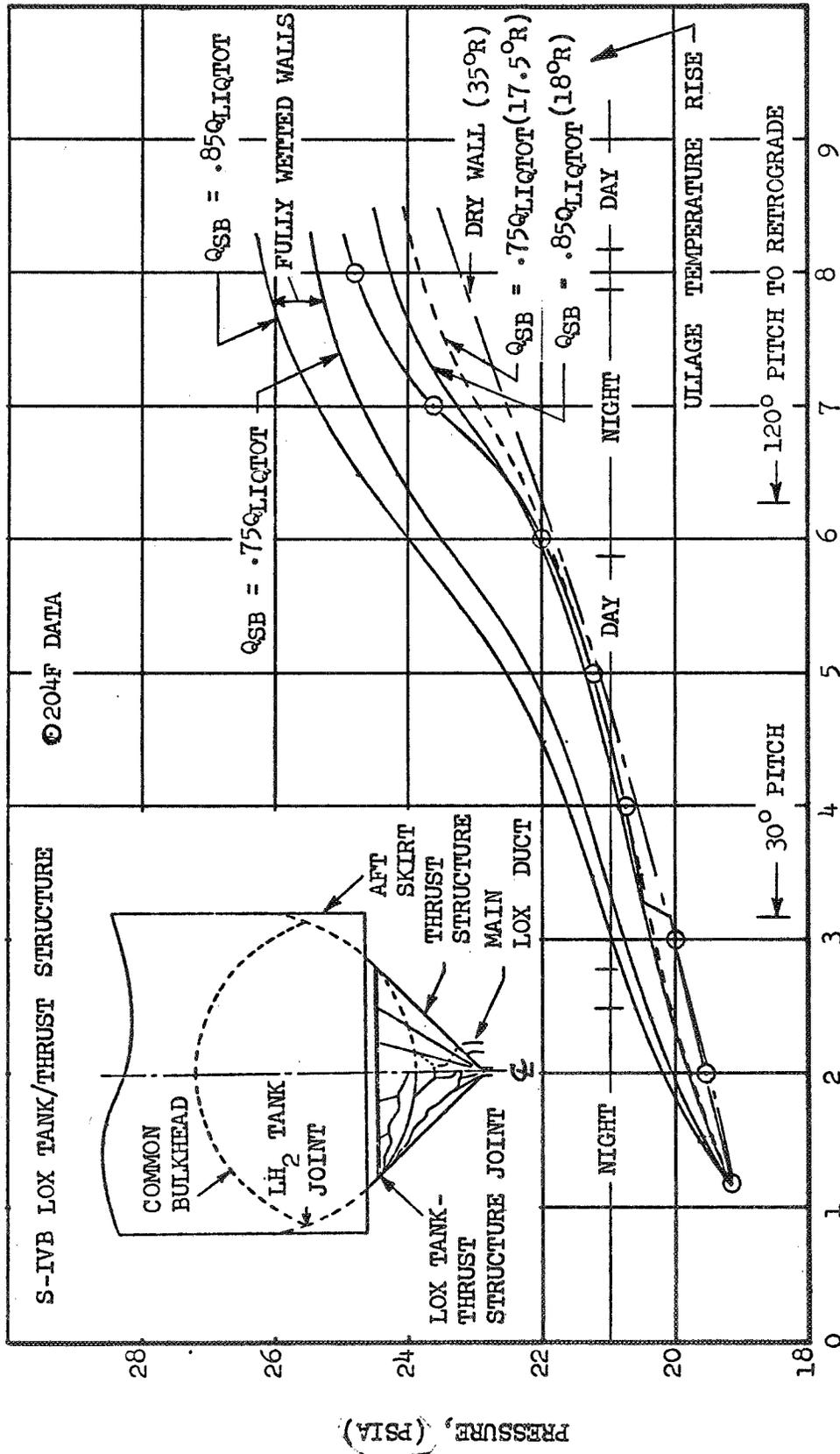
sun angle, which varied for different vehicles because of their different launch times during the day. Other factors contributing to differences were amount of liquid residuals, ullage mass composition (helium and oxygen), ullage temperature, and extent of orbital maneuvers.

The pressure history of flight 204, shown in Figure F-2, clearly shows the singular effect of orbital maneuvers. Pitch maneuvers were executed at 3200 and at 6300 seconds. These are believed to have positioned liquid over tank support structure which provided high heat shorts with the resultant increases in heat transfer and vaporization. Also shown in Figure F-2 are the analytical results for various proportions of liquid heating associated with surface boiling. To illustrate the range of differences needed to explain the various flights, the data for five flights are shown in Figure F-3. These curves have been fitted with various allocations of heating between the liquid and ullage. Here again, the range of conditions is bracketed by wetted and dry wall calculations.

Based on evaluation of oxygen data, a range of values for the amount of liquid heating that should be allocated to surface boiling was observed to range from 75 to 90 percent. The flight data also indicated that the residual oxygen liquid appeared to remain settled. That is, the most accurate model for definition of equivalent liquid wall contact area was a completely settled liquid mass.

F-2.2 Liquid Hydrogen Evaluation - Segments from 11 flights were examined to obtain data applicable to the residual hydrogen propellant. Six sets of these data were analyzed in depth, using one particularly well-instrumented set to correlate the other data. For the hydrogen, an approach somewhat different to that used for oxygen was employed. Emphasis was placed on long steady state periods with a constant low g level applied to the vehicle. These conditions were selected to minimize the influence of the high heat capacity of the hydrogen tank insulation. Periods of no venting or periods with measured vented gas quantities were chosen to determine the total mass in the tank so that an accurate accounting of energy could be achieved. Energy balances for the hydrogen tank were carried out for a number of tank conditions on both the S-IVB and S-IV stages. The purpose of these was to determine the heat flux to the liquid and gas, and the percentage of tank wall wetted by liquid during low g operations.

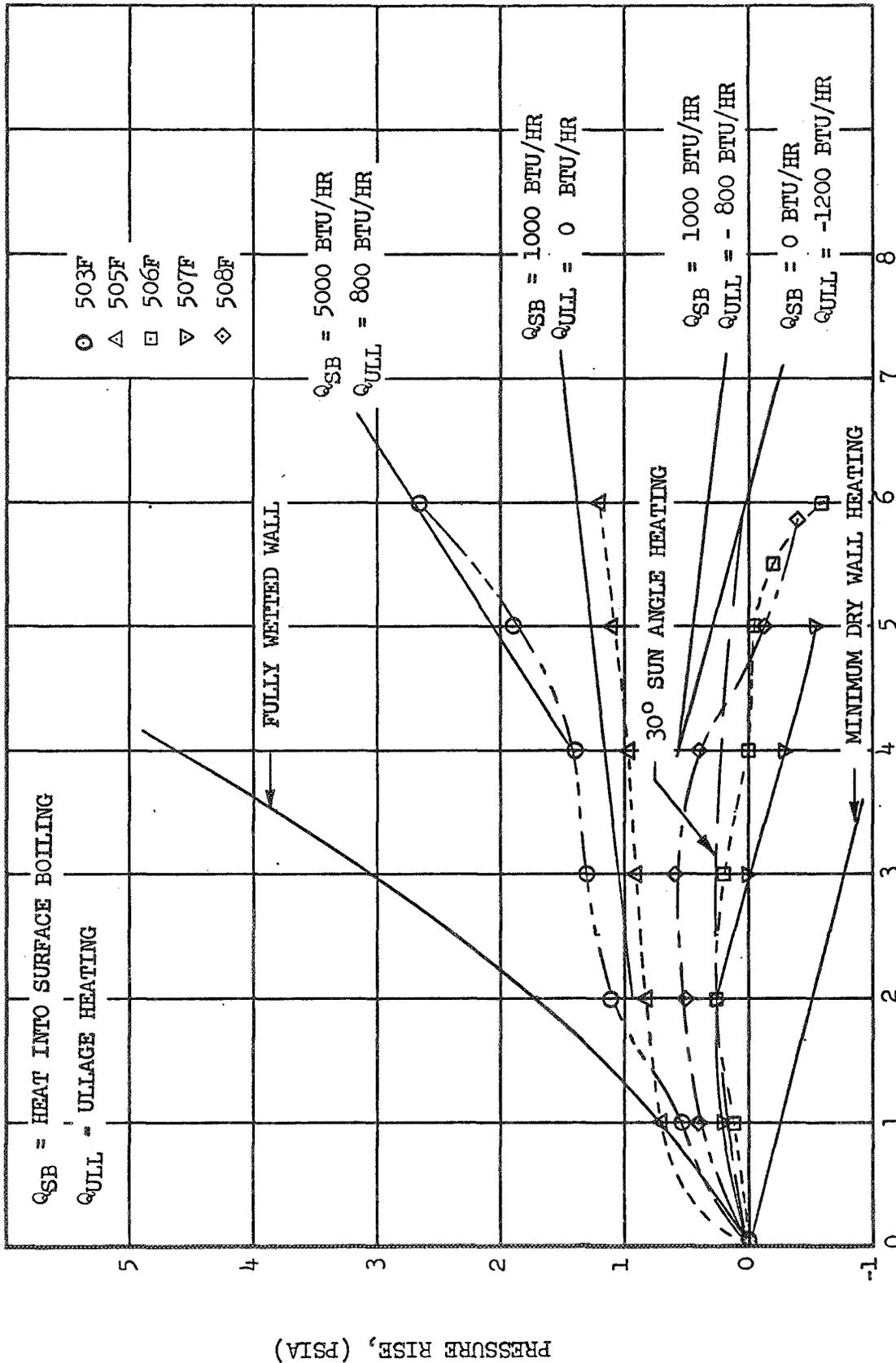
Results of seven energy balances which were applicable to the orbiter are tabulated in Figure F-4, and calculations related to these data are shown in Figure F-5. Figure F-5 presents the observed heat transfer rate as a function of



TIME FROM LIFTOFF, (1000 SEC)

LOX TANK ULLAGE PRESSURE
(204 FLIGHT, LOW-G COAST)

FIGURE F-2



TIME AFTER S-IVB/CSM SEPARATION, (1000 SEC)

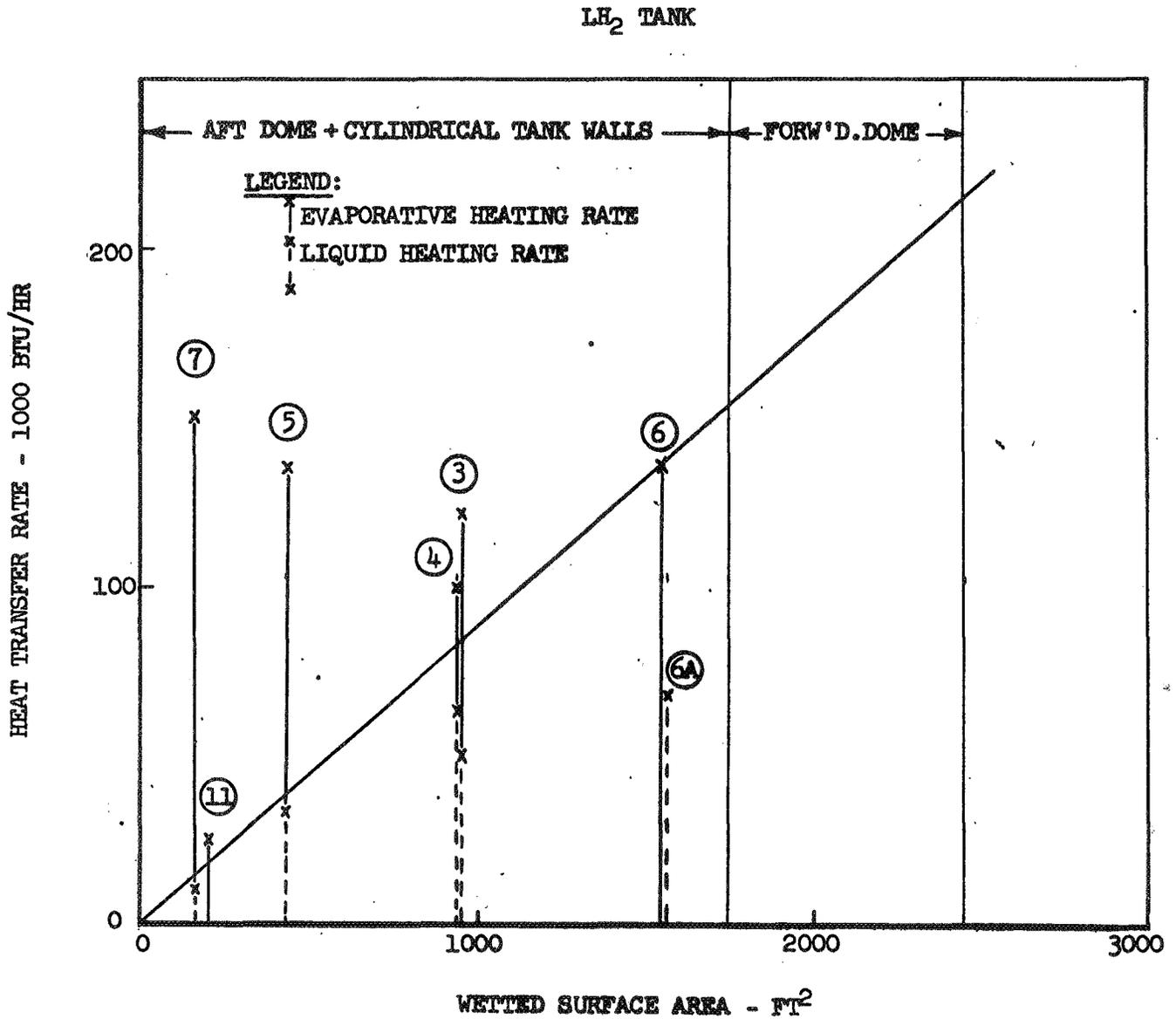
LOX TANK ULLAGE PRESSURE CHANGES
FOR TRANSLUNAR COASTS OF THE INDICATED FLIGHTS

FIGURE F-3

EVALUATION POINT	ϵ - LEVEL	$\dot{Q}_{\text{BOILLOFF}}$ BTU/HR	$\dot{Q}_{\text{LIQUID HEATING}}$ BTU/HR	\dot{Q}_{GULLAGE} BTU/HR	WETTED WALL AREA OF SETTLED RESIDUAL, FEET ²
③	1×10^{-5}	72,500	APPROX. 50,000	25,200	955 (38.6%)
④	$1-3 \times 10^{-4}$	37,000	62,700	25,000	935 (37.8%)
⑤	-10^{-8}	101,800	33,000	0	425 (17.2%)
⑥	4×10^{-5}	136,000	0	23,500	1550 (68.8%)
⑦	-4×10^{-6}	140,000	10,300	0	160 (6.5%)
⑪	$2-7 \times 10^{-4}$	25,000	0	68,200	EQUIVALENT 190 (7.7%)
⑥A	4×10^{-5}	TRANSIENT	57,000	TRANSIENT	1550 (68.8%)

SUMMARY OF HEATING RATES

FIGURE F-4



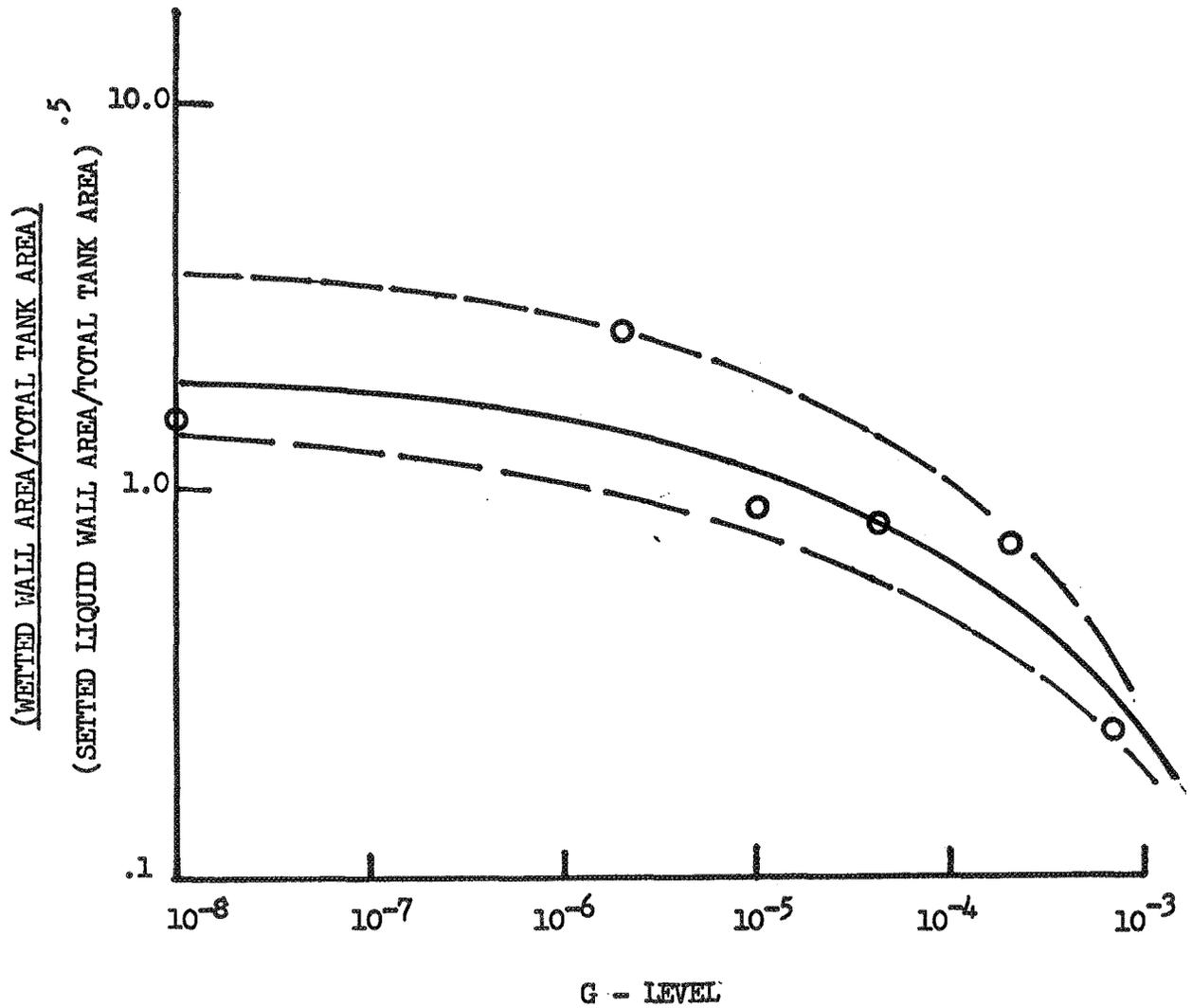
S-IVB, LIQUID AND EVAPORATIVE HEATING RATES VS
WETTED SURFACE AREA OF SETTLED RESIDUAL

FIGURE F-5

calculated wetted wall area, assuming the residuals to be completely settled in the base of the tank. A key point in Figure F-5 is point number 6. For this set of conditions, an evaluation of heat transfer fully independent of ullage and liquid temperature measurements was obtained. Point 6 corresponds to a steady state, continuous venting period, and represents data from several S-IVB/SV flights. The results of an energy balance under the conditions represented by point 6 are reliable, since the hydrogen tank has reached an equilibrium condition with saturated liquid and a stratified ullage gas. Under these conditions, boiloff and ullage heating could be derived directly from measured flow rate and enthalpy. Also, the wetted wall area during this process was relatively well known. For these reasons point 6 is considered to be the most reliable data of Figure F-5, and all data should approach the linear curve through point 6 as heat transfer rate should be proportional to surface area.

For the other points in Figure F-5, there was significantly more uncertainty regarding the amount of wall-wetted by liquid; however, one major factor neglected in Figure F-5 was the influence of acceleration level on liquid configuration and wetted wall area. From Figures F-4 and F-5, it may be observed that the points which are most distant from the linear relationship between liquid/ullage heat input versus wetted wall area as described by the line through point 6 (for example points 5 and 7) represent those with the lowest gravity environment. In order to investigate the influence of gravity, correlated data from Figure F-4 expresses an effective wetted wall, defined as that which would be wetted assuming the data for point 6 provided a linear curve as a function of wetted wall. The effective wetted wall fraction thus obtained is shown in Figure F-6 and was translated to the linear curve at a constant heat transfer rate. The area defined by the linear curve provided the effective wetted wall area and its ratio of effective to settled wall area.

Application of Saturn data to definition of a liquid hydrogen model indicate that the position of the liquid hydrogen is strongly acceleration dependent. Correlation of Saturn data with the space shuttle indicated that approximately 65 percent of the hydrogen tank would initially be wetted even if only small amounts of residual were present. The analysis shows that hydrogen liquid is maintained near saturation conditions, and effectively 100 percent of the liquid heating will go into vaporization.



LH₂ WALL - WETTING DEPENDENCE ON G - LEVEL

FIGURE F-6

F-3. RESIDUAL AVAILABILITY FOR APS

Available residual propellants were evaluated, using the previous equivalent models for liquid vaporization, for the high pressure APS concepts which potentially use liquid residuals. Simulated missions were analyzed for four specific cases coupling liquid boiloff, vapor heating, and APS usage during the mission. The analysis techniques used to accomplish this coupling were the same as those for low pressure APS operational analysis as defined in Reference (a).

The hybrid APS considered for the orbiter utilized a turbocompressor for the oxygen propellant. Analysis of the oxygen residuals for this APS concept clearly indicated that a resupply assembly was required to make up propellant in the oxygen tank. That is, there were not sufficient liquids and gas residuals on board to satisfy the entire APS mission, and supplemental oxygen must be provided by the APS; however, an appreciable quantity of oxidizer could be saved by utilizing as much of the residuals as possible. Analysis of the less than or equal to 10 ft/sec velocity mission, where the hybrid concept is applied, indicated that if liquids were considered, approximately 417 pounds of oxidizer could be obtained free for the APS from main engine residuals.

Also of interest for high pressure APS concepts was the tap-off conditioner approach. In this conditioner approach, the gas generators for pump power and propellant heating are powered by propellant extracted from the main engine tanks. This concept was evaluated for each maneuver level. Analysis of the orbiter turbo-pump APS for the ≤ 10 ft/sec case indicated that for the tap-off cycle, an oxygen resupply assembly would not be required. During the mission, the oxygen tank pressure decayed to approximately 30 lbf/in². The hydrogen tank held pressure until the entry phase. During entry, hydrogen tank pressure dropped rapidly and approximately 43 lb of hydrogen resupply was required to complete the mission. Thus, for the ≤ 10 ft/sec case, the total conditioning requirements would be only 43 lb of hydrogen. For both of the other missions, i.e., ≤ 50 ft/sec and all-maneuver, both hydrogen and oxygen boost tanks required resupply to maintain pressure. This was also the case for the turbocompressor APS. For the all-maneuver case, the use of residuals resulted in a reduction of APS propellants of 840 lb of oxygen and 335 lb of hydrogen. For the ≤ 50 ft/sec mission, the APS loading was reduced by 533 lb of oxygen and 161 lb of hydrogen.

The "free" propellants described above were credited to the APS in the weight accounting for subsystem comparisons in the body of this report and for conditioner concept comparisons in Appendix D. Also of interest for the high pressure APS was the use of residuals in the booster stage. Analysis of low pressure booster APS concepts (Reference (a)) clearly showed that there were ample residual propellant vapors in the main engine tanks for the entire booster mission, i.e., accounting of residual liquids was not required. Thus, for the booster turbocompressor concept, no APS propellant was required as all necessary gas could be extracted from the booster tanks without resupply. Based on these results, no additional analyses were undertaken for the booster residuals in this APS study.

REFERENCES:

- (a) Kendal, A. S., McKee, H. B., Orton, G. F., Low Pressure Auxiliary Propulsion Subsystem Definition Study Subtask A Report: McDonnell Douglas Report No. MDCEO303, dated 29 January 1971.

APPENDIX G

APS REQUIREMENTS

G-1. INTRODUCTION

In order for the APS study to be of maximum use to the space shuttle effort, it was necessary to establish the impact of vehicle configuration on APS selection and design. To accomplish this, two typical space shuttle vehicle concepts (orbiters and boosters of both high and low cross range type) were investigated. These represented typical configurations under investigation by vehicle contractors and provided a relatively broad range of APS design requirements. Study vehicles were defined by Reference (a) which was provided as part of the APS study contract to serve as a guideline for vehicle and APS interfacing and to establish APS requirements. Reference (a) provided both mission characteristics and control acceleration requirements. Using these, it was necessary to conduct analyses to define APS thrust level and number of thrusters, as well as to define APS propellant capacity necessary to satisfy all vehicle control and maneuvering requirements. This appendix describes the approach taken for these analyses, and summarizes the results.

G-2. APS THRUST LEVEL

APS were required to provide both translation and attitude control capability for orbiters in all axes, while only attitude control was required for boosters. Vehicle translation and control acceleration requirements (as specified in Reference (a)) are tabulated in Figures G-1 and G-2 for orbiters and boosters, respectively. Minimum, nominal minimum, nominal maximum, and maximum accelerations are listed for all axes. The primary design requirement was to provide a safe return of the vehicle in the event of two thruster failures. Under this operating condition (i.e., with two thrusters inoperative), the APS was required to meet or exceed specified minimum accelerations. While not a requirement, an acceleration level between nominal minimum and nominal maximum when all thrusters were operative was a desired design goal, as was a common thrust level for all thrusters (i.e., common thrusters). In establishing APS thrust levels, consideration was given to minimizing control cross-coupling in both the normal APS operating mode and in the presence of thruster failures. The following paragraphs define the approach and results of a study performed to determine thrust levels of APS thrusters and number of thrusters necessary to satisfy the above criteria. Baseline study vehicles and APS thruster locations were defined by Reference (a) and are presented in Figures G-3 through G-6. Vehicle weight and balance characteristics at time of injection were used for thrust requirements analysis.

Thrust levels for the four study vehicles were defined by determining total thrust levels for each axis, based on specified minimum, nominal minimum, nominal maximum, and maximum specified acceleration levels. Total thrust level identified the number of thrusters required in each axis for a specified thruster thrust level. Using several values of thrust level, the number of thrusters required was determined using the criteria that nominal minimum thrust would be provided with all thrusters operative, and minimum thrust would be provided with two thrusters failed. Several combinations of thrust level and number of thrusters resulted. Design thrust level and total number of thrusters were subsequently selected on minimum subsystem weight and number of thrusters. The following paragraphs identify the results of this effort for the four study vehicles.

G-2.1 Orbiter A - The various thrust level/number of thruster options which satisfied Orbiter A requirements are shown in Figure G-7. The selected design point of 32 thrusters at 500 lb thrust provides a minimum number of thrusters and

EVENT ^a		2ND STAGE BOOST ENGINE OUT			1 TO 28 46 TO 53			29 TO 45			54		
		X	Y	Z	X ^b	Y	Z	X	Y	Z	X	Y	Z
TRANSLATION ACCELERATION FT 'SEC ²	MIN	NO			0.07	0.07	0.07	SAME AS			NO		
	NOM MIN	REQUIREMENT			0.1	0.1	0.1	EVENT 1			REQUIREMENT		
	NOM MAX				0.5	0.25	0.25						
	MAX				1.0	1.0	1.0						
ANGULAR ACCELERATION DEG 'SEC ²	MIN NOM MIN NOM MAX MAX	R	P	Y	R	P	Y	R	P	Y	R	P	Y
		NO			0.3	0.3	0.3	SAME AS			0.3	0.3	0.3
		REQUIREMENT			0.5	0.5	0.5	EVENT 1			1.0	0.5	1.00
					2.0	2.0	2.0				1.75	1.0	1.75
					4.0	4.0	4.0				4.0	4.0	4.0
FINE ATTITUDE LIMITS - DEG		NO			0.5	0.5	0.5	0.5	0.5	0.5	2.0	2.0	2.0
COARSE ATTITUDE LIMITS - DEG		NO			45	45	45	5.0	5.0	5.0			
		REQUIREMENT											

- a. REFERENCE (a) PRESENTS DESCRIPTIONS OF THE EVENTS.
- b. MAXIMUM LIMITS FOR EVENTS 5, 8, 11, 14, 17, 20, 23, 26, AND 53 MAY BE INCREASED WHEN THE APS IS USED TO PERFORM THE MAJOR PLUS X TRANSLATION.

**SPACE STATION/BASE LOGISTICS MISSION – ORBITER
MANEUVERING CAPABILITY REQUIREMENTS**

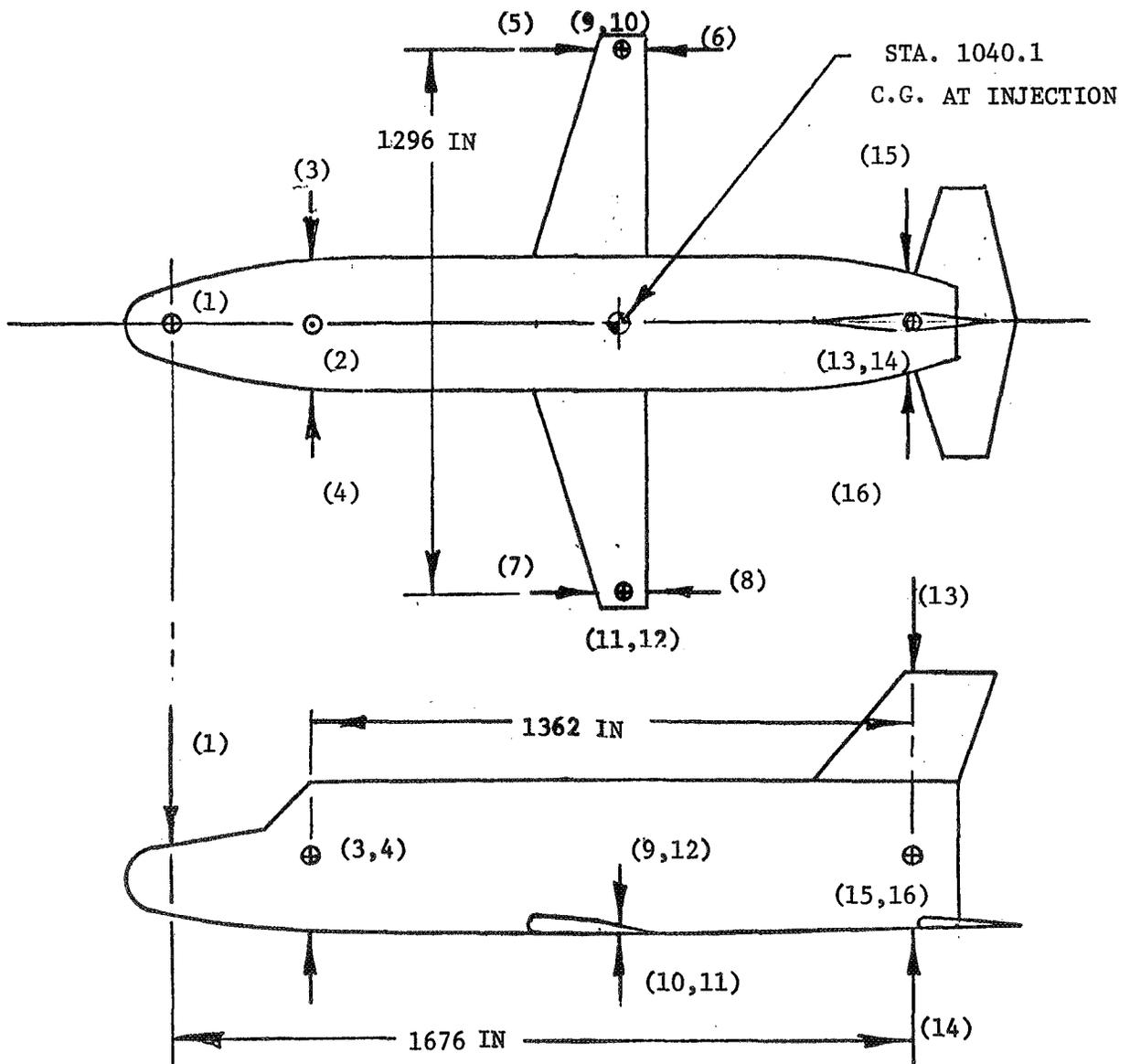
FIGURE G-1

EVENT ^a		2			3			4			5		
		X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
TRANSLATION ACCELERATION FT/SEC ²	MIN	NO			NO			NO			NO		
	NOM MINZ	REQUIREMENT			REQUIREMENT			REQUIREMENT			REQUIREMENT		
	NOM MAX												
	MAX												
ANGULAR ACCELERATION DEG/SEC ²	MIN NOM MIN NOM MAX MAX	R	P	Y	R	P	Y	R	P	Y	R	P	Y
		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
		1.0	0.5	1.0	0.5	0.5	0.5	0.5	0.5	0.5	1.0	0.5	1.0
		1.75	1.0	1.75	1.0	1.0	1.0	1.0	1.0	1.0	1.75	1.0	1.75
		2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
ANGULAR RATE DEG/SEC	MIN NOM MIN NOM MAX MAX				2.0	2.0							
ATTITUDE LIMITS - DEG		2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

- a. REFERENCE (a) PRESENTS DESCRIPTIONS OF THE EVENTS.

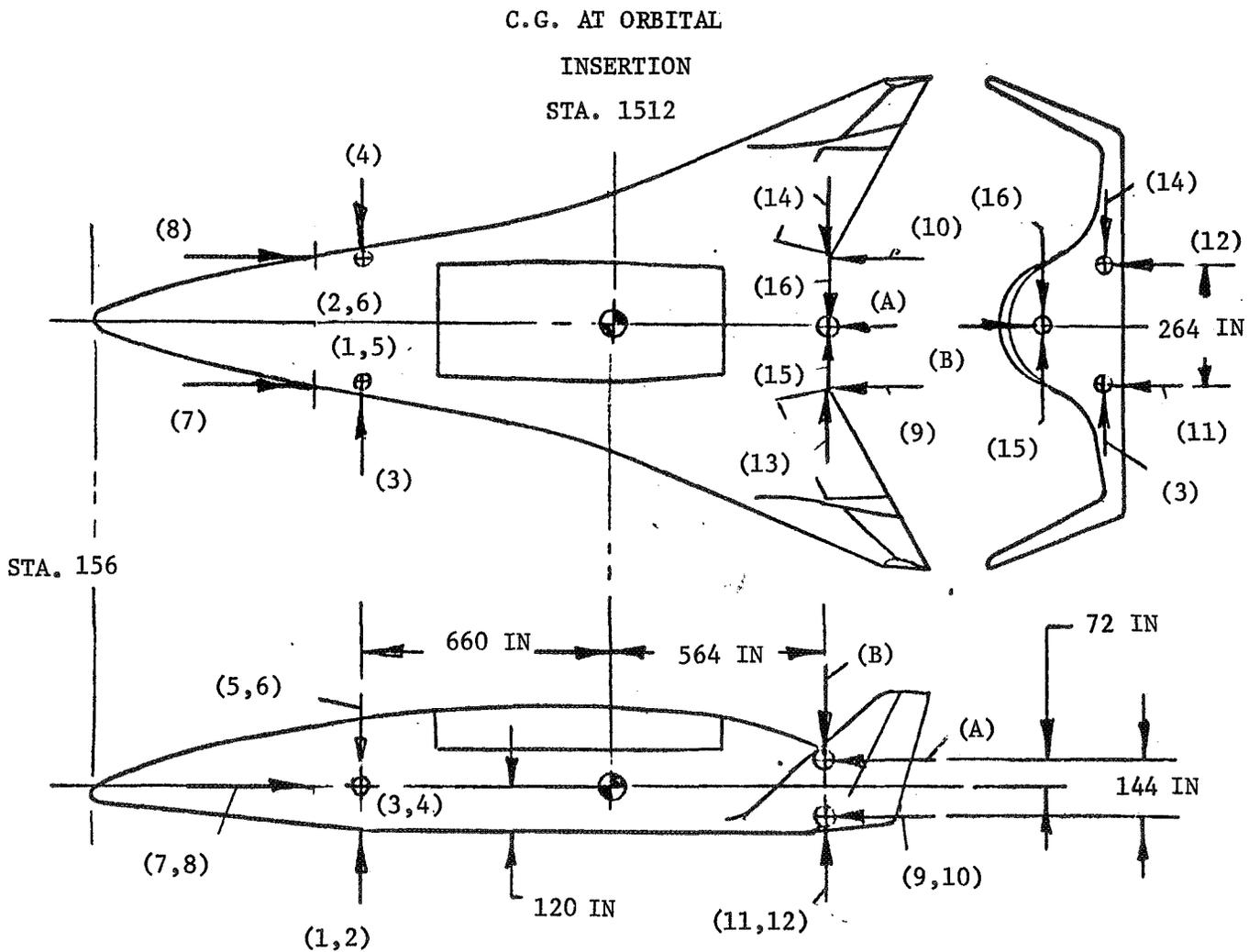
**SPACE STATION/BASE LOGISTICS MISSION – BOOSTER
MANEUVERING CAPABILITY REQUIREMENTS**

FIGURE G-2



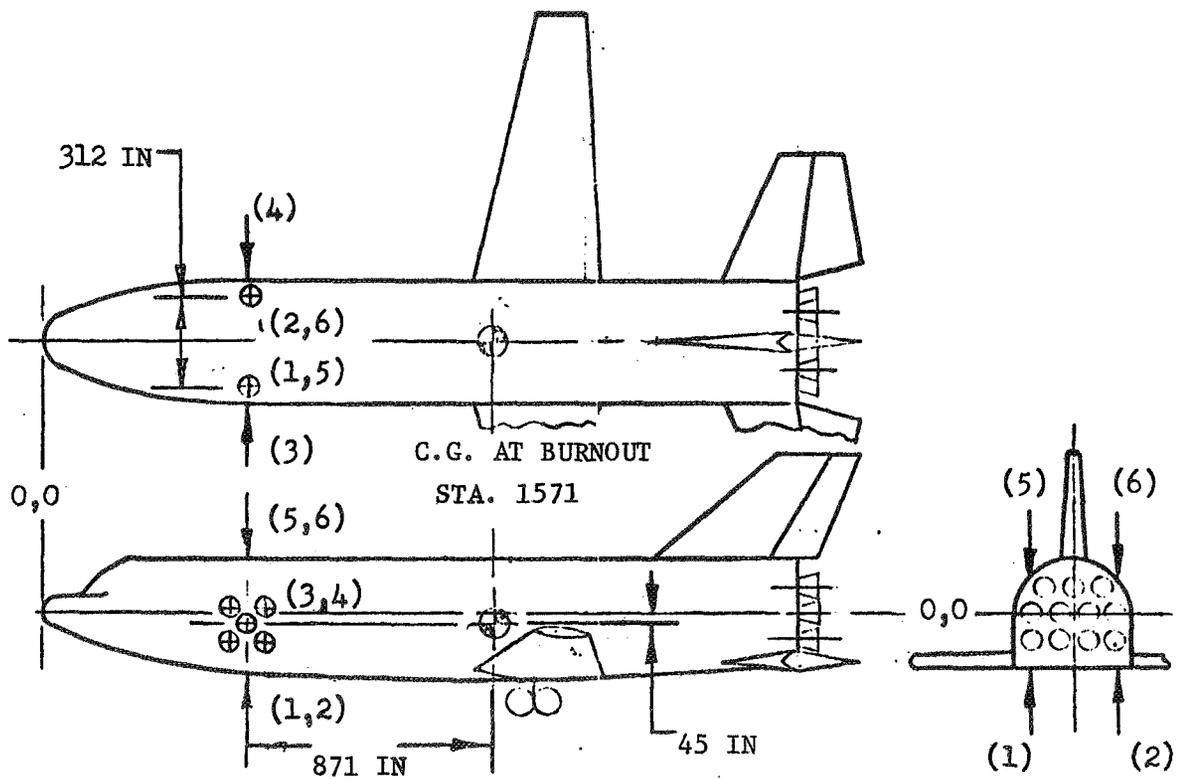
THRUSTER LOCATIONS - ORBITER A

FIGURE G-3



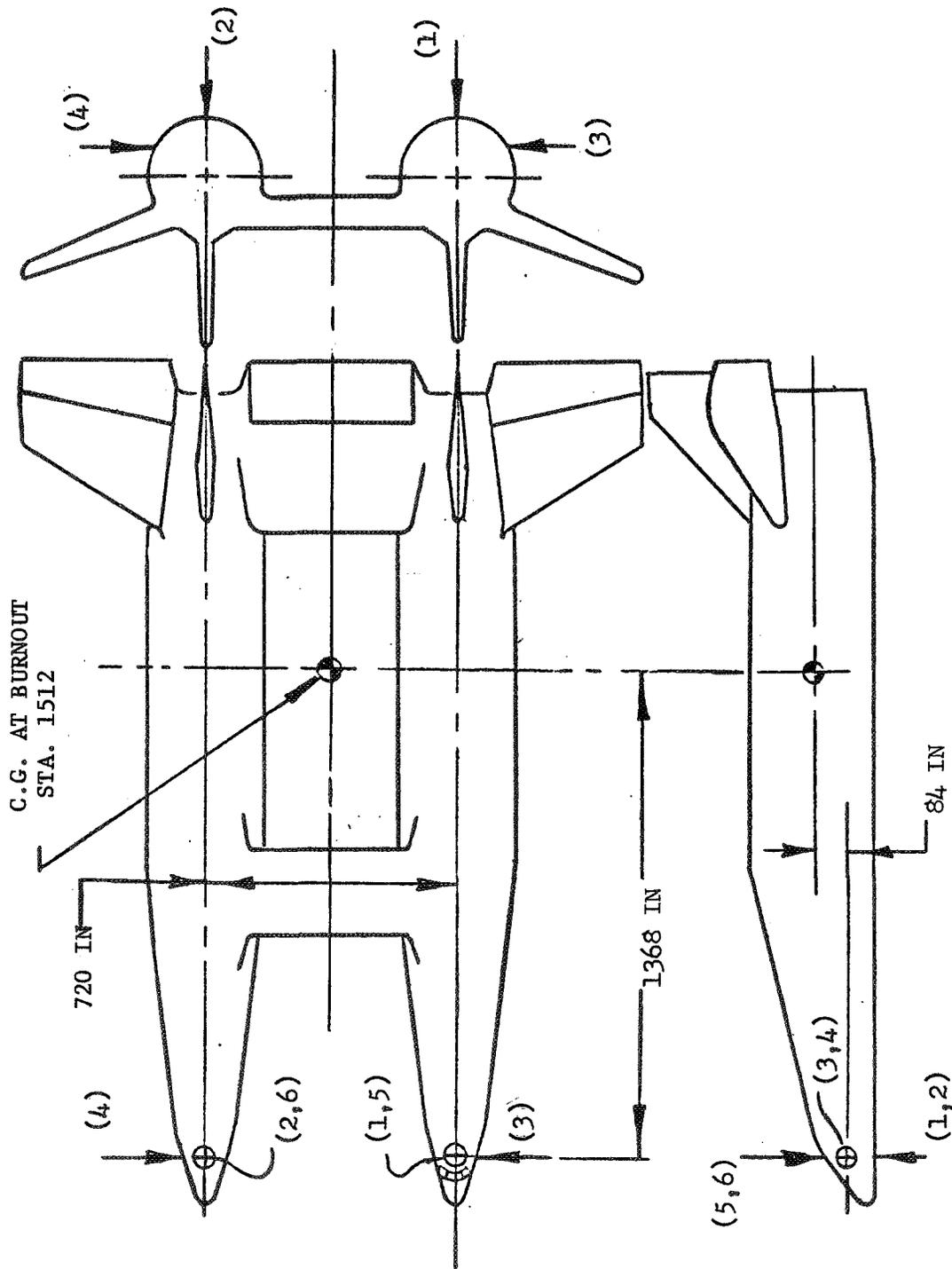
THRUSTER LOCATIONS - ORBITER B

FIGURE G-4



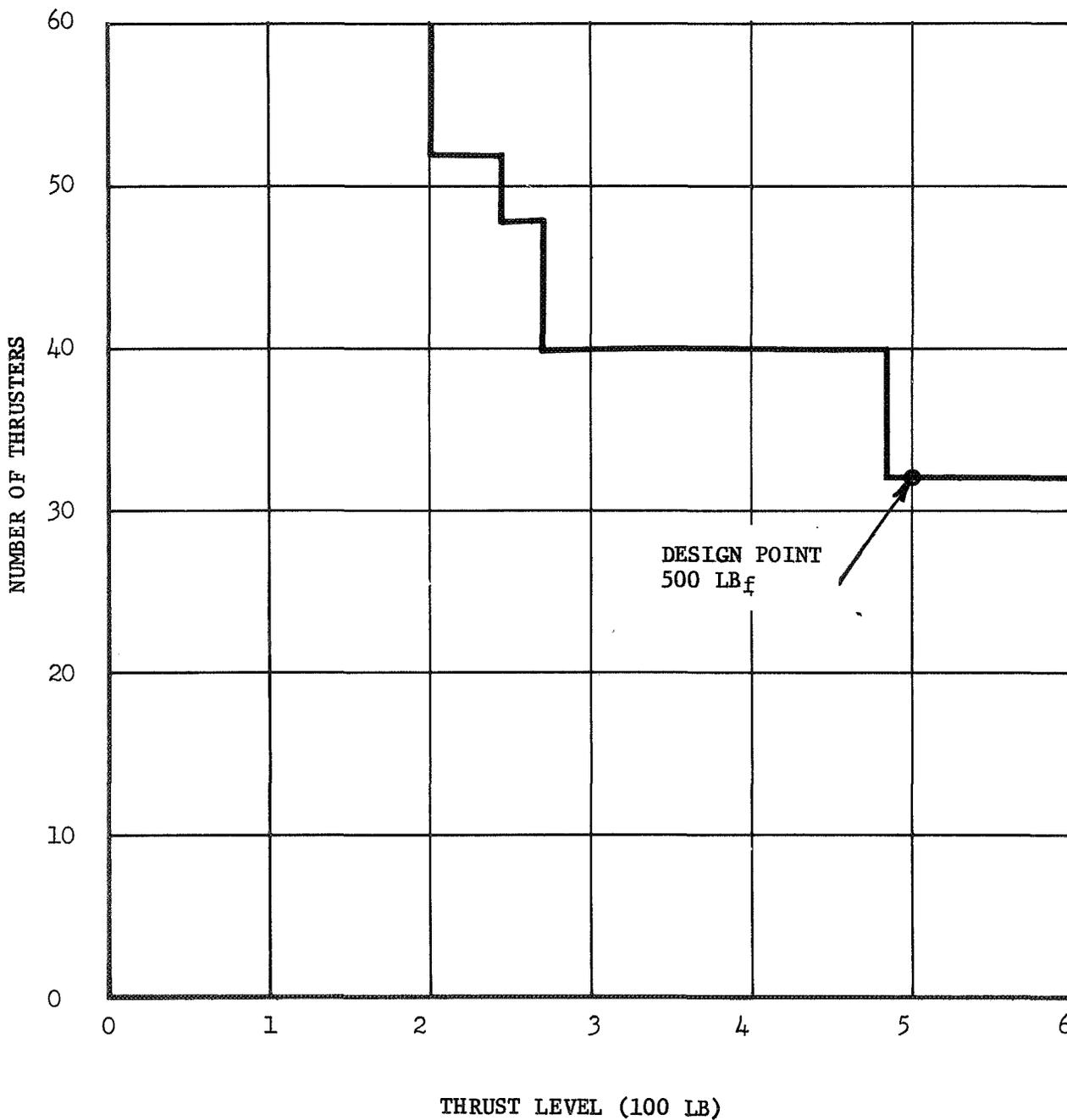
THRUSTER LOCATIONS - BOOSTER A

FIGURE G-5



THRUSTER LOCATIONS - BOOSTER B

FIGURE G-6



ORBITER A THRUST REQUIREMENTS

FIGURE G-7

nearly minimum subsystem weight. Two thrusters are located at each of the thrusters assembly locations, as shown in Figure G-8. Thrust levels associated with acceleration requirements of Figure G-1 are shown in Figure G-9. The shaded areas correspond to the desired thrust level or desired control acceleration in each axis. The total thrust identified by two arrows is the nominal thrust condition, representing APS operation under normal operating conditions. The single arrow (or minimum thrust point) identifies a total thrust capability in each axis in the presence of two thruster failures. Inspection of the results of Figure G-9 shows that, with the exception of the roll axis, desired acceleration goals are satisfied. In roll, however, acceleration capability is above that desired. In order to satisfy the desire for thruster commonality, this increased roll acceleration capability was considered satisfactory. Also shown by Figure G-9 is the minimum acceleration capability of the APS with two thruster failures which exceeds that required in all axes.

G-2.2 Orbiter B - The various thrust level/number of thruster combinations available for Orbiter B are shown in Figure G-10. The selected design point of twenty-eight 1,000 lb thrusters provides the minimum number of thrusters, and, as with Orbiter A, a nearly minimum subsystem weight. Figure G-11 summarizes thruster locations for Orbiter B and thruster functions. Orbiter B maneuvering requirements and APS capability are shown in Figure G-12. Results here are somewhat different than those for Orbiter A. Under nominal conditions, translation acceleration capability is above the desired range in both the Y and Z axes; however, again in the interest of thruster commonality, this level was necessary in order to satisfy minimum acceleration requirements with two thruster failures. For this design constraint, the critical axis was roll. With two thruster failures, minimum roll acceleration requirements are satisfied, but further reductions in thrust level would mean that this requirement could not be met.

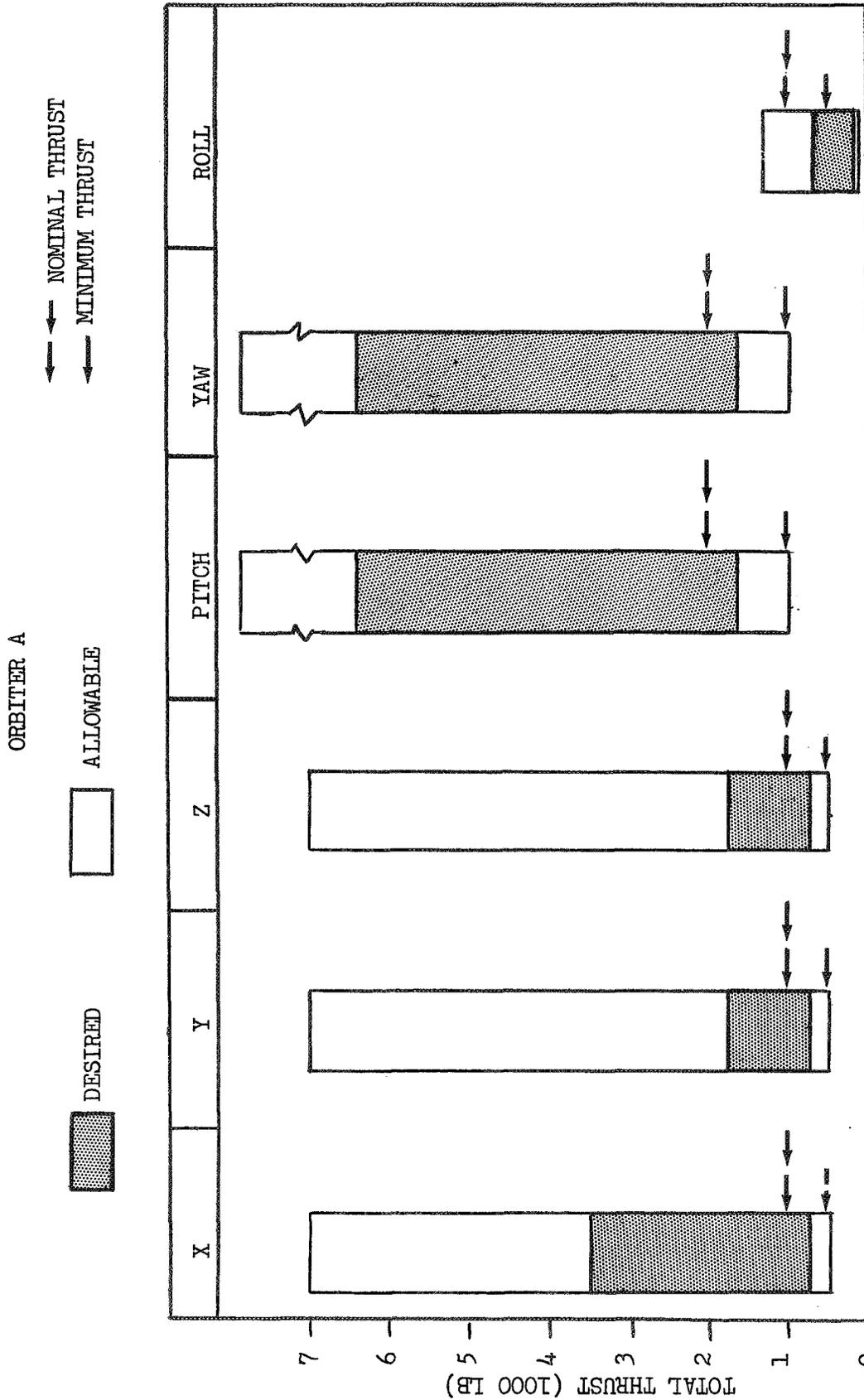
G-2.3 Booster A - The various thrust level/number of thruster options for Booster A are presented in Figure G-13. A design point of 18 thrusters, operating at a design level of 2600 lb thrust was selected. The selected design point provides nearly minimum subsystem weight. Figure G-14 presents a summary of thruster locations and their functions. Thrust required to satisfy control acceleration requirements in each axis for the boosters is shown in Figure G-15. As shown for Booster A, selected design point exceeds minimum requirements with two thruster failures and provides desired acceleration levels in both pitch and yaw axes. The desired acceleration is somewhat exceeded under nominal conditions in roll, but

ORBITER A

THRUSTER ASSEMBLY NUMBER	NUMBER OF 500 LB THRUSTERS	PURPOSE
1	2	- PITCH, - Z
2	2	+ PITCH, + Z
3	2	- YAW, - Y
4	2	+ YAW, + Y
5	2	- X
6	2	+ X
7	2	- X
8	2	+ X
9	2	+ ROLL
10	2	- ROLL
11	2	+ ROLL
12	2	- ROLL
13	2	+ PITCH, - Z
14	2	- PITCH, + Z
15	2	+ YAW, - Y
16	2	- YAW, + Y

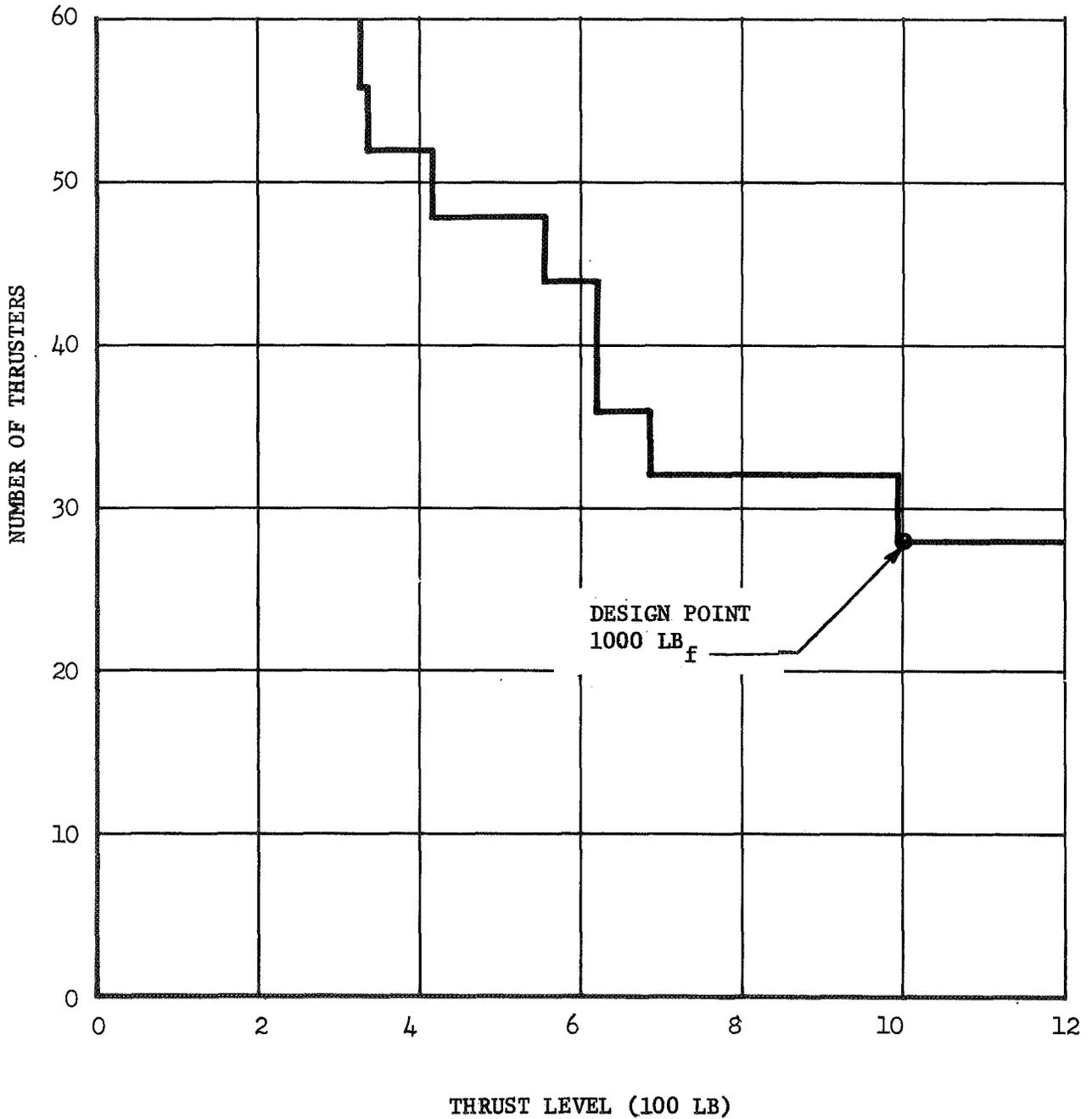
THRUSTER ASSEMBLY SUMMARY

FIGURE G-8



MANEUVER REQUIREMENTS AND CAPABILITY

FIGURE G-9



ORBITER B THRUST REQUIREMENTS

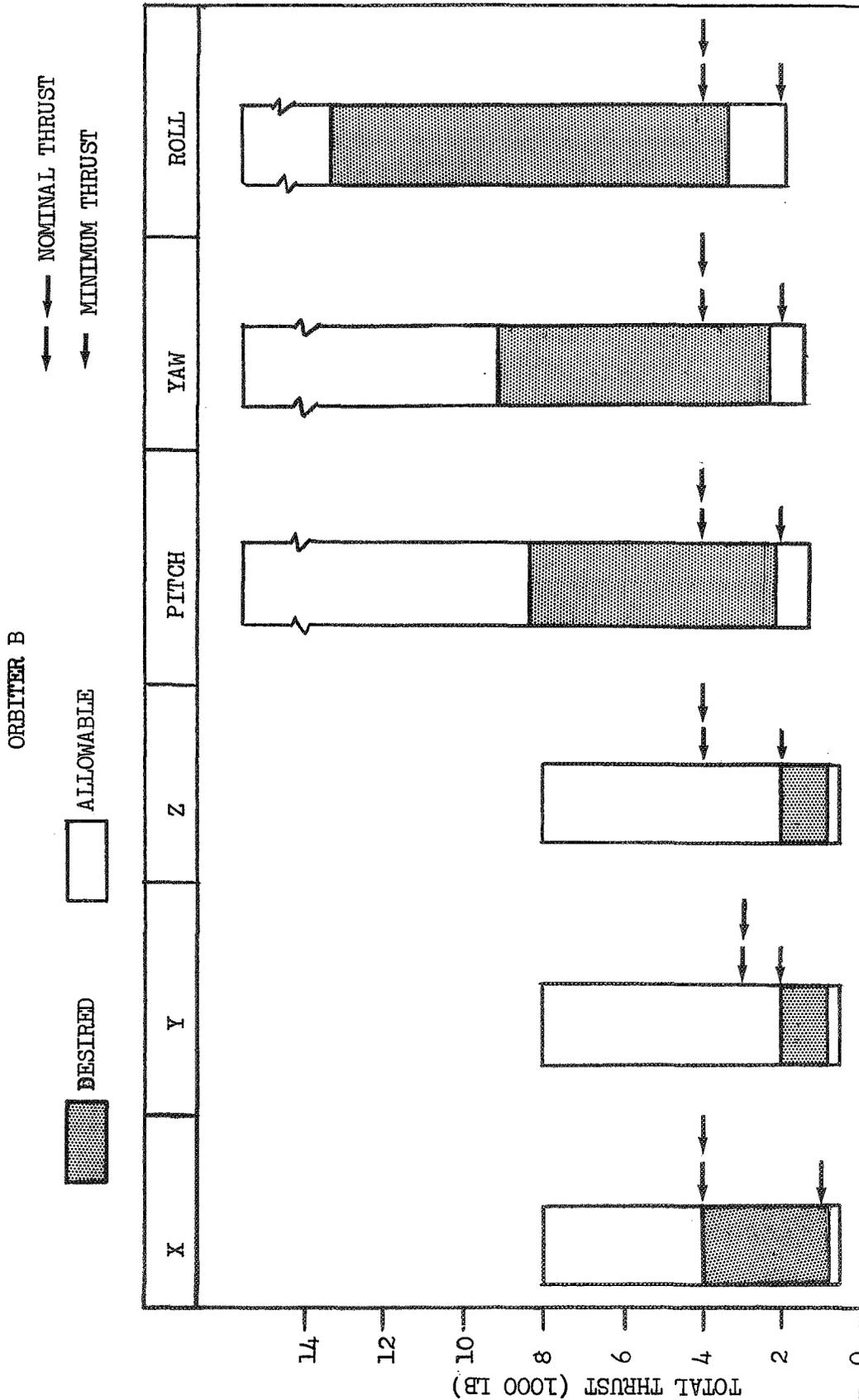
FIGURE G-10

ORBITER B

THRUSTER ASSEMBLY NUMBER	NUMBER OF 1000 LB THRUSTERS	PURPOSE
1	1	+ PITCH, + Z (+ROLL)
2	1	+ PITCH, + Z (-ROLL)
3	2	+ YAW, + Y
4	2	- YAW, - Y
5	1	- PITCH, - Z (-ROLL)
6	1	- PITCH, - Z (+ROLL)
7	2	- X
8	2	- X
9	1	+ X
10	1	+ X
11	1	- PITCH, + Z
12	1	- PITCH, + Z
13	2	- ROLL, - YAW, + Y
14	2	+ ROLL, + YAW, - Y
15	2	+ ROLL, - YAW, + Y
16	2	- ROLL, + YAW, - Y
A	2	+ X
B	2	+ PITCH, - Z

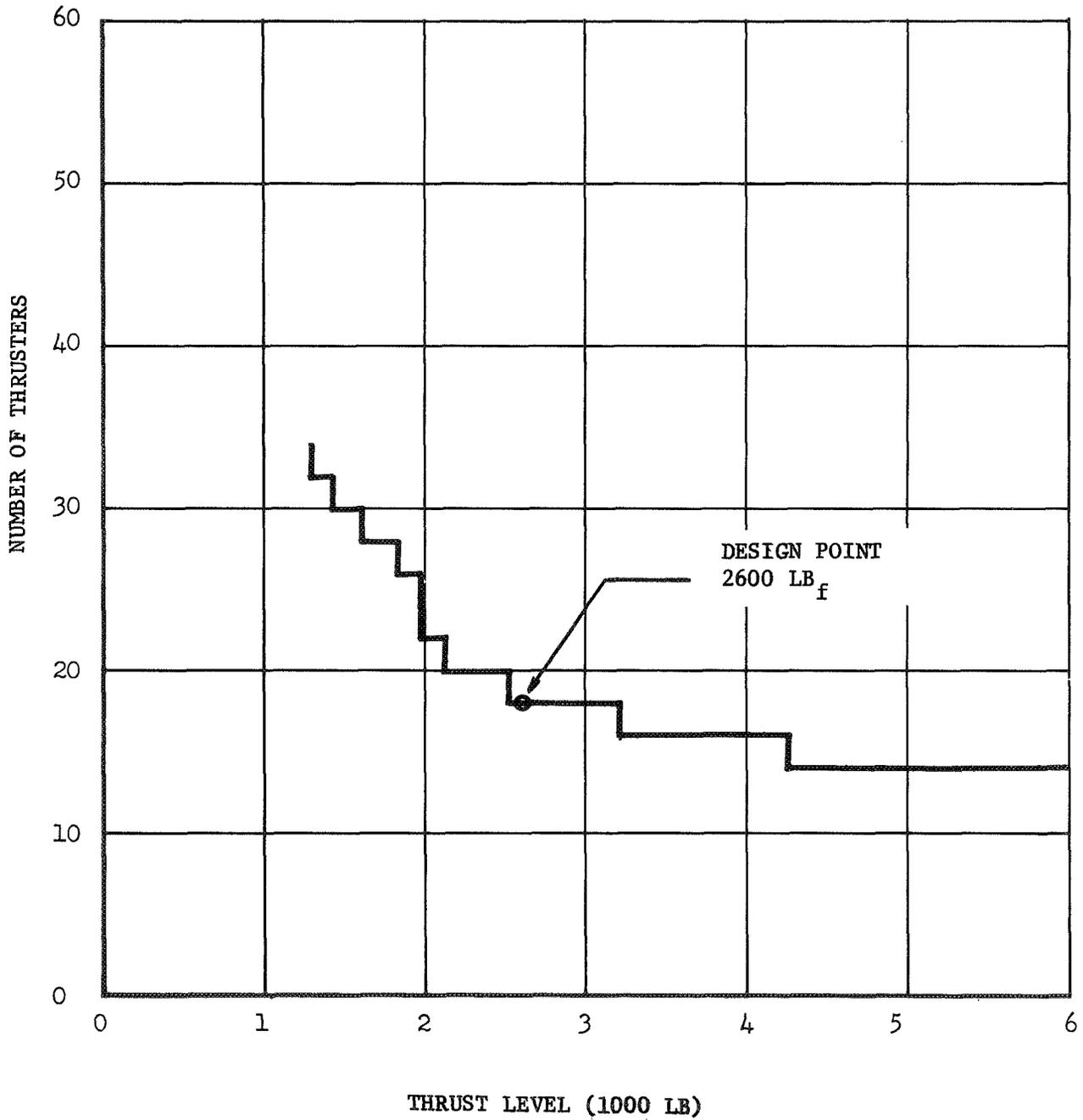
THRUSTER ASSEMBLY SUMMARY

FIGURE G-11



MANEUVER REQUIREMENTS AND CAPABILITY

FIGURE G-12



BOOSTER A THRUST REQUIREMENTS

FIGURE G-13

BOOSTER A

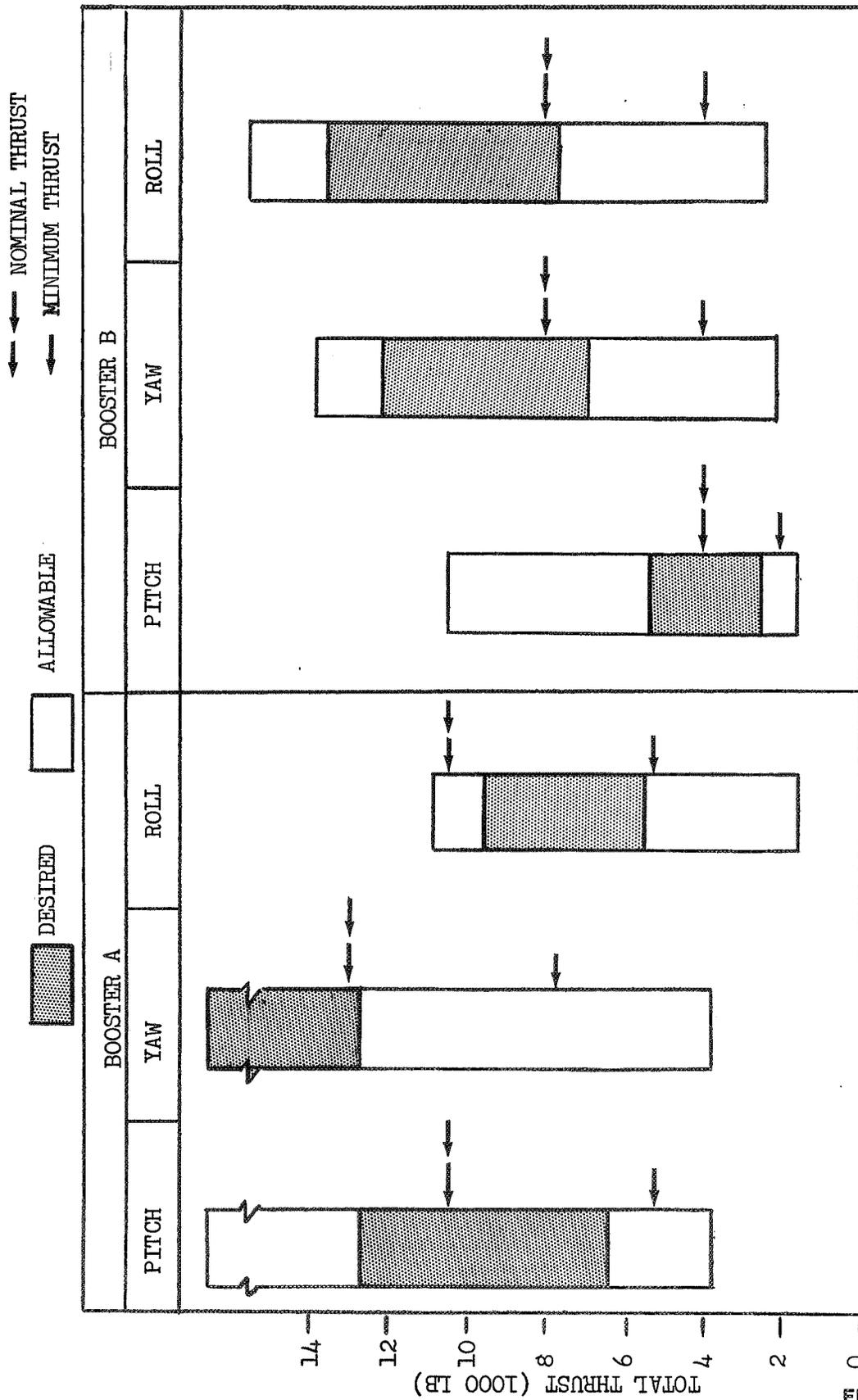
THRUSTER ASSEMBLY NUMBER	NUMBER OF 2600 LB THRUSTERS	PURPOSE
1	2	+ PITCH, + ROLL
2	2	+ PITCH, - ROLL
3	5	+ YAW
4	5	- YAW
5	2	- PITCH, - ROLL
6	2	- PITCH, + ROLL

BOOSTER B

THRUSTER ASSEMBLY NUMBER	NUMBER OF 2000 LB THRUSTERS	PURPOSE
1	2	+ PITCH, + ROLL
2	2	+ PITCH, - ROLL
3	4	+ YAW
4	4	- YAW
5	2	- PITCH, - ROLL
6	2	- PITCH, + ROLL

THRUSTER ASSEMBLY SUMMARY

FIGURE G-14

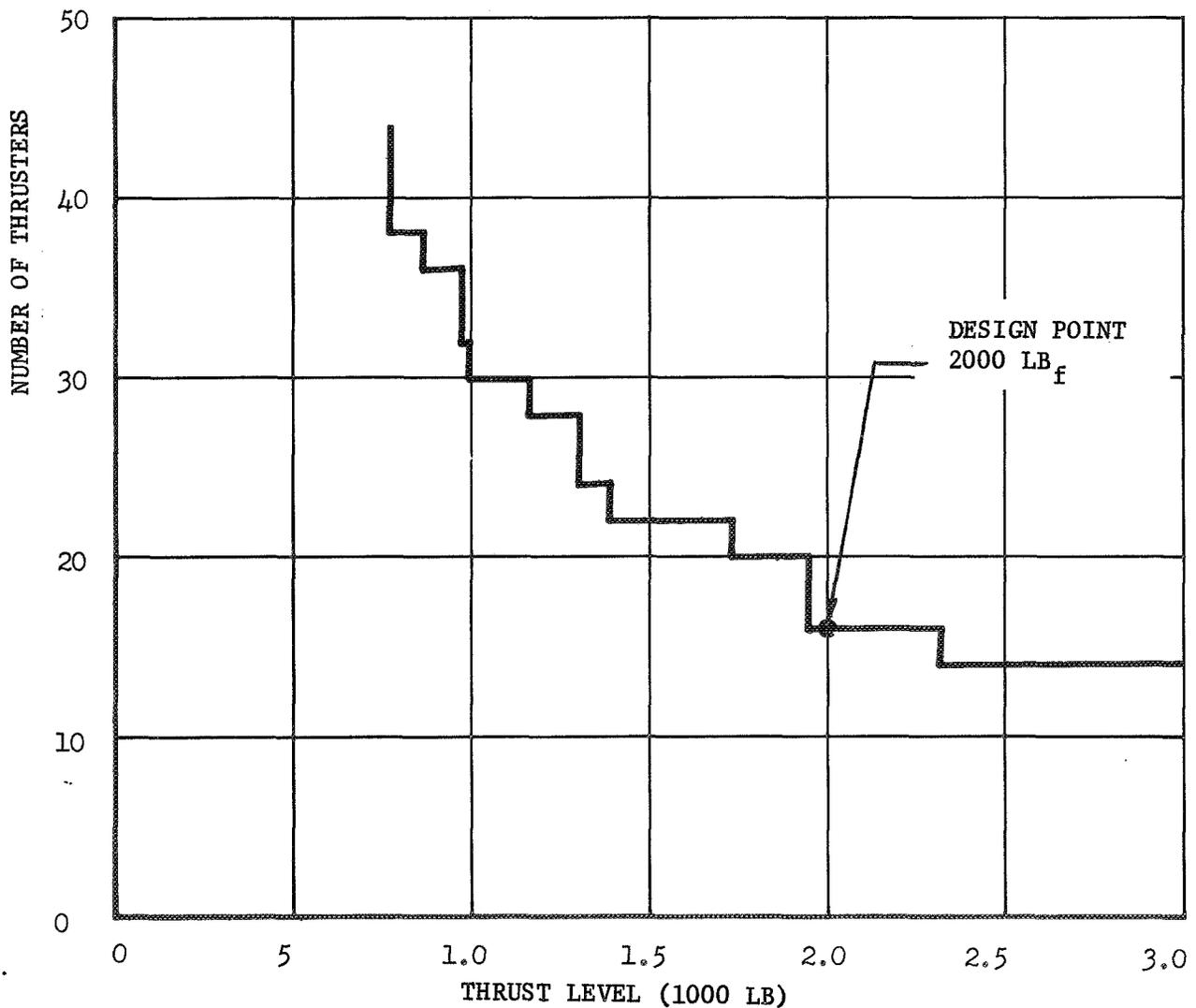


MANEUVER REQUIREMENTS AND CAPABILITY

FIGURE G-15
G-17

roll and pitch control was provided by common thrusters in this vehicle configuration. Roll thrust level could not be reduced without also reducing pitch control below required levels.

G-2.4 Booster B - The various thrust level/number of thrusters options for Booster B are presented in Figure G-16. A design point of 16 thrusters, operating at 2,000 lb thrust best satisfied vehicle requirements. Figure G-14 summarizes Booster B thruster locations and their functions. The maneuvering thrust level requirements for Booster B are presented in Figure G-15. As shown, under nominal conditions desired thrust levels and control accelerations are satisfied and, with two thruster failures, control acceleration is above the minimum required.



BOOSTER B THRUST REQUIREMENTS

FIGURE G-16

G-3. APS TOTAL IMPULSE

APS total impulse requirement consists of the impulse expended in three different types of maneuvers; translation, attitude, and attitude control.

The translation maneuver requirements are primarily +X velocity change requirements, such as orbit circularization, orbit transfer, and deorbit. The +X maneuvering requirements could be fulfilled by the APS alone, or by the APS in conjunction with a separate orbit maneuvering subsystem (OMS). During Subtask A, three different +X maneuver requirements were defined for the APS. These approaches required the APS to perform

- (1) all +X maneuvers
- (2) all +X maneuvers equal to, or less than, 50 ft/sec
- (3) all +X maneuvers equal to, or less than, 10 ft/sec

This section provides a summary of analyses to define APS total impulse requirements for each of these three maneuver requirements.

The mission timelines, presented in Reference (a) describe the orbiter and booster missions in terms of a series of events relevant to the auxiliary propulsion subsystem, Figures G-17, G-18. These events describe translation and attitude maneuvers and attitude control requirements for a typical mission. During attitude control periods, pitch, roll, and yaw attitudes must be held within a specified tolerance or deadband. The mission timeline defines the width of deadband required and the time duration for which the deadband must be maintained at the various stages of the mission. Using these data, mission impulse requirements were determined based on the vehicle mass, center of gravity, and inertial characteristics at the time of orbital injection. In these analyses, effects of cross-coupling, installation tolerances, and effects of aerodynamic and gravity gradient torques were not considered.

The impulse requirement for translational maneuvers accounts for the majority of mission total impulse requirements. Translational maneuvers include both large maneuvers (such as the deorbit burn) and small maneuvers (such as docking). The impulse requirement for translational maneuvers was determined for a constant mass body:

$$\text{total impulse} = I = \frac{W}{g} \Delta V$$

Where W is the vehicle weight at orbital injection, and ΔV is the required change in velocity as defined for the various translation maneuvers in Reference (a).

<u>EVENT COMPLETION TIME*</u>	<u>EVENT</u>	<u>PROPULSION REQ'T DESCRIPTION</u>
1. -165 sec.	Staging	Separation of booster and orbiter (No APS requirement)
2. 0	Insertion into nominal 50 x 100 N.M. orbit	Damping of main engine cutoff transients.
3. -	Manual attitude hold	±45° deadband
4. -	Orient to burn attitude and estab- lish Fire Attitude Hold	±0.5° deadband
5. 44-46 min.	Circularization at 100 N.M.	100 - 130 fps Δ V
6. -	Manual attitude hold	±45° deadband
7. -	Orient to burn attitude and establish Fine Attitude Hold	±0.5° deadband
8. 59-524	Dispersion on 100 N.M. cir- cularization burn	0 - 32 fps Δ V

* Time is referenced to Event 2 in minutes unless otherwise stated. Both minimum and maximum cumulative times are shown.

SPACE STATION/BASE LOGISTICS MISSION TIMELINE - ORBITER

FIGURE G-17

	<u>EVENT COMPLETION TIME</u>	<u>EVENT</u>	<u>PROPULSION REQ'T DESCRIPTION</u>
9.	-	Drifting flight	No deadband
10.	-	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband
11.	74-1005	Plane change burn	0 - 200 fps ΔV
12.	-	Manual attitude hold	$\pm 45^\circ$ deadband
13.	-	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband
14.	84-1165	Dispersion on plane change burn	0 - 50 fps ΔV
15.	-	Drifting flight	No deadband
16.	-	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband
17.	94-1326	Transfer to 100 x Phasing Orbit Altitude	279 - 290 fps ΔV
18.	-	Manual attitude hold	$\pm 45^\circ$ deadband
19.	-	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband

MISSION TIMELINE-ORBITER

FIGURE 17 CONTINUED

G-21

<u>EVENT COMPLETION TIME</u>	<u>EVENT</u>	<u>PROPULSION REQ'T DESCRIPTION</u>
20. 116-1349	Dispersions on transfer burn	0 - 72 fps ΔV
21. -	Manual attitude hold	$\pm 45^\circ$ deadband
22. -	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband
23. 138-1372	Circularization at Phasing Orbit Altitude	253 - 297 fps ΔV
24. -	Manual attitude hold	$\pm 45^\circ$ deadband
25. -	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband
26. 195-1429	Dispersions on circularization burn	0 - 74 fps ΔV
27. -	Manual attitude hold	$\pm 45^\circ$ deadband
28. -	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband
29. 253-1487	TPI	30-37 fps ΔV
30. -	Coarse automatic attitude hold	$\pm 5^\circ$ deadband

MISSION TIMELINE--ORBITER

FIGURE 17 CONTINUED

	<u>EVENT COMPLETION TIME</u>	<u>EVENT</u>	<u>PROPULSION REQ'T DESCRIPTION</u>
31.	—	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband
32.	275-1510	MCC-1	0 - 36 fps ΔV
33.	—	Coarse automatic attitude hold	$\pm 5^\circ$ deadband
34.	—	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband
35.	286-1522	MCC-2	0 - 19 fps ΔV
36.	—	Coarse automatic attitude hold	$\pm 5^\circ$ deadband
37.	—	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband
38.	297-1533	TPF	28 - 30 fps ΔV
39.	—	Stationkeeping and attitude hold	0-10 fps Multiaxis Translation ΔV and 0-10 fps Multiaxis Attitude ΔV ($\pm 0.5^\circ$ deadband)
40.	312-1593	Docking	0-10 fps Multiaxis Translation ΔV and 0-10 fps Multiaxis Attitude ΔV ($\pm 0.5^\circ$ deadband)
41.	7277-8505	On Orbit	(TBD)
42.	7227-8508	Undock	0.5 fps ΔV
43.	—	Fine Attitude Hold	$\pm 0.5^\circ$ deadband

	<u>EVENT COMPLETION TIME</u>	<u>EVENT</u>	<u>PROPULSION REQ'T DESCRIPTION</u>
44.	7242-8523	Orient to burn attitude and establish Fine Attitude Hold and Separation	$\pm 0.5^\circ$ deadband 10 fps ΔV
45.	-	Course attitude hold	$\pm 45^\circ$ deadband
46.	-	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband
47.	7279-9267	Ground track adjust #1	0-27 fps ΔV
48.	-	Manual attitude hold	$\pm 45.0^\circ$ deadband
49.	-	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband
50.	7297-9639	Ground track adjust #2	0-28 ΔV
51.	-	Manual attitude hold	$\pm 45^\circ$ deadband
52.	-	Orient to burn attitude and establish Fine Attitude Hold	$\pm 0.5^\circ$ deadband
53.	7317-10012	De-orbit	450-530 fps ΔV
54.	7359-10057	Entry	25-60 fps ΔV

MISSION TIMELINE-ORBITER

FIGURE 17 CONTINUED

<u>EVENT COMPLETION TIME*</u>	<u>EVENT</u>	<u>PROPULSION REQUIREMENT DESCRIPTION</u>
1. 0	Staging	Separation of booster and orbiter (No APS requirement)
2. 0+	Post Separation	Damping of main engine cutoff and separation transients.
3. 0.7-0.8	Orientation	Maneuver vehicle to reentry attitude.
4. 0.9-1.1	Attitude hold	$\pm 2^\circ$ deadband
5. 1.9-6.1	Entry	$\pm 2^\circ$ deadband

*Time is referenced to Event 1 in minutes unless otherwise stated. Both minimum and maximum cumulative times are shown.

SPACE STATION/BASE LOGISTICS MISSION TIMELINE — BOOSTER

FIGURE G-18

The impulse requirement for rotational maneuvers is a function of vehicle inertia and thruster moment arms with respect to the center of gravity for each axis. Several criteria were used to define impulse requirements for rotational maneuvers. The maximum maneuvering rate was 0.5 deg/sec, and whenever possible, maneuvers were performed at a slower rate. The basis used to define the minimum rate was that the maneuver (including acceleration and deceleration) would be completed in two minutes. The impulse requirement for rotational maneuvers about a given axis was determined by applying the following relationship:

$$\text{impulse} = I = \frac{J}{L} \dot{\Delta\theta}$$

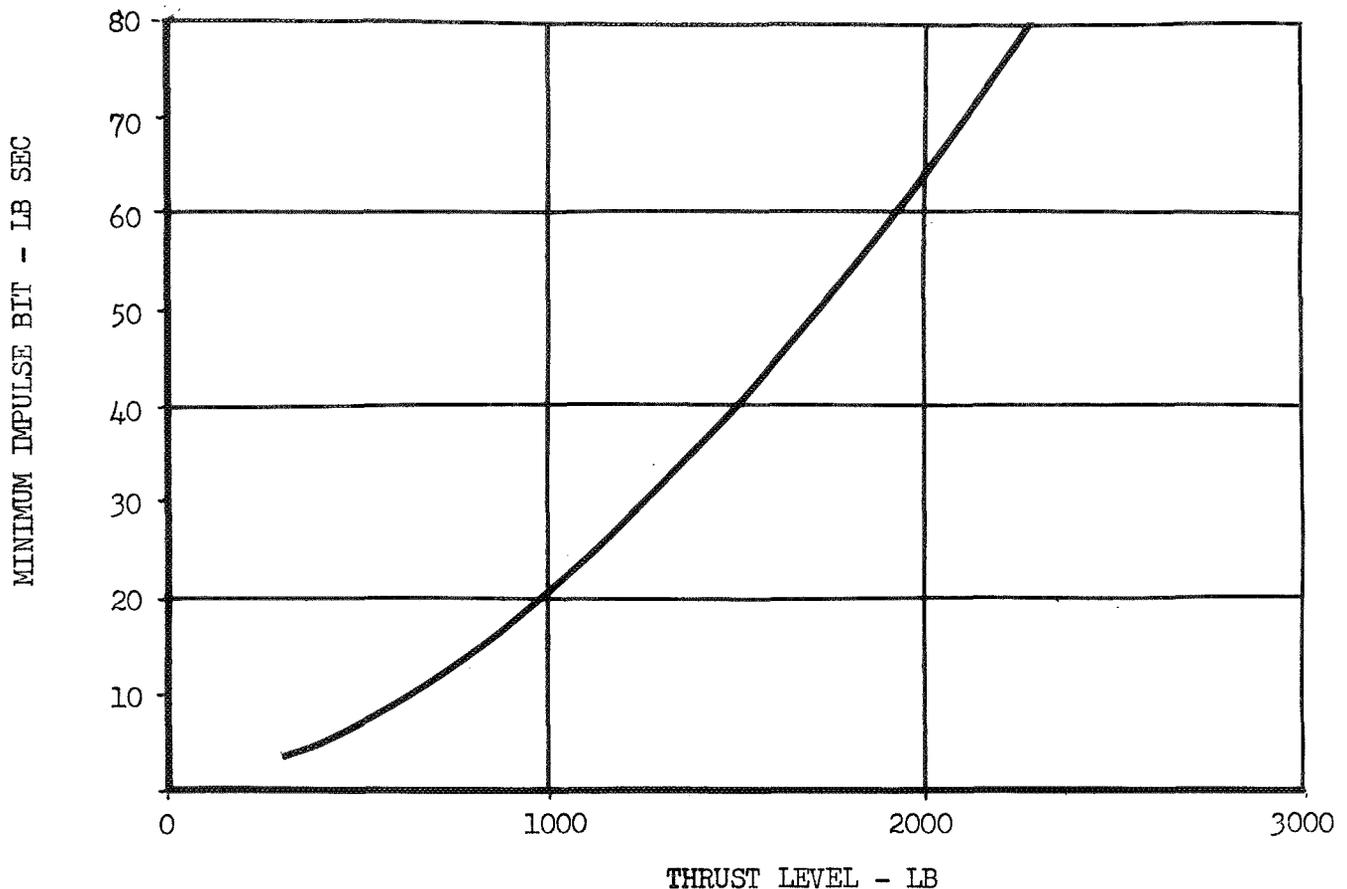
Where J is the moment of inertia about the given axis, L is the thruster moment arm length corresponding to the given axis, and $\dot{\Delta\theta}$ is the angular velocity imparted about that axis. An angular velocity increment, $\Delta\theta$, is imparted to initiate and terminate each maneuver. The total impulse requirement for rotational maneuvers is based upon summation of impulse requirements of pitch, yaw, and roll axes.

Attitude control maneuvers ensure that the vehicle orientation remains fixed within specified angular limits, i.e., deadband. During attitude control the vehicle is continuously cycled in pitch, yaw, and roll between specified deadband limits. Since propellant usage will be smaller if rate of vehicle oscillation is slow, it is advantageous to apply small-impulse corrections to the vehicle during deadband operation. The number of thrusters used to perform these corrections was the minimum number which could be fired without incurring excessive attitude cross-coupling. Each thruster used imparts a minimum impulse bit (MIB), defined as the smallest unit of impulse a single thruster can deliver. MIB is dependent on thrust level and thruster design. For these analyses, an estimate of the achievable minimum impulse bit was made from a correlation of data on existing rocket engines. Figure G-19 shows estimates used as a function of thrust level.

The impulse expended by attitude control firings is a function of deadband limits and MIB. The impulse expended in this limit cycle operation about a given axis was determined by the following relationship:

$$I = \frac{t \dot{\theta} N \text{ MIB}}{D}$$

Where t is the time duration of the attitude control period, D is the deadband width, $\dot{\theta}$ is the average rate of travel between the deadband limits, and N is the number of attitude correcting thrusters fired. The drift between limits was



PRELIMINARY MINIMUM IMPULSE BIT DEFINITION

FIGURE 19

assumed to be due to over correction imparted by MIB firings. Cross-coupling effects were neglected. The average drift rate about a given axis due to the attitude control firings was determined by the following relationship:

$$\dot{\theta} = \frac{1}{2} \frac{N \text{ MIB } L}{J}$$

Where N is the number of engines firing, L is the thruster moment arm, and J is the moment of inertia with respect to the given axis. The total impulse requirement for attitude control operation is determined by summing impulse expended in pitch, yaw, and roll attitude control for all deadbands and times specified in the mission timeline.

Mission total impulse requirements were determined for Orbiters A and B and the Boosters using the approaches and assumptions discussed above. Results are presented in Figure G-20.

References:

- (a) Space Shuttle Vehicle Description and Requirements Document:
NASA-MSFC, dated July 15, 1970.

	APS MANEUVER REQUIREMENTS	ORBITER A	ORBITER B	BOOSTER A	BOOSTER B
ATTITUDE* MANEUVERING AND CONTROL	< 10 FPS	732,000	923,000		
	< 50 FPS	732,000	923,000		
	ALL	735,000	929,000		
TRANSLATION MANEUVERING	< 10 FPS	753,000	784,000		
	< 50 FPS	2,236,000	2,526,000		
	ALL	13,177,000	15,060,000		
TOTAL	< 10 FPS	1,485,000	1,707,000		
	< 50 FPS	2,968,000	3,449,000		
	ALL	13,912,000	15,989,000	4,830,000	4,600,000

* USAGE DUE TO ERRORS IN ATTITUDE SENSORS NOT INCLUDED

IMPULSE TOTALS (LB-SEC)

APPENDIX H

PRELIMINARY APS CONCEPT SCREENING

H-1. INTRODUCTION

The objective of Subtask A was to select from the many available APS alternates that concept or approach best suited to the shuttle application. To accomplish this, it was necessary to compare candidate subsystems in parallel (i.e., each subsystem considered in Subtask A must be treated at parallel levels of design sophistication). Thus, one of the first tasks of Subtask A was to screen from the many APS concepts those approaches which were not truly viable candidates and which, by their presence, would dilute the effort on the more competitive subsystem approaches. In order to accomplish this, concepts to be eliminated had to be shown as clearly noncompetitive. In other words, there could not be a fine line drawn between competitive and non-competitive subsystems because the preliminary nature of this subtask would introduce a gray area in concept selection. Only those concepts which were clearly non-competitive could be screened, and those which did not satisfy this criteria would be retained for further study. Fortunately, there was a good baseline available against which to make this preliminary comparison of candidate concepts. Prior to award of the study contract, an Internal Research and Development (IRAD) program

had been conducted at McDonnell Douglas which provided data and analytical techniques applicable to this screening. Specifically, a low cross range orbiter had been used as a base for comparison of alternate APS concepts and requirements for this vehicle were sufficiently close to those of the present space shuttle study that results could be implemented with confidence, using sensitivity data for individual APS concepts. The MDAC IRAD study was based on preliminary component models as described in Reference (a). These models, while unsophisticated and not satisfactory for Subtask A of the program in its entirety, were entirely adequate for this preliminary screening.

This appendix describes the techniques used to apply these precontract study results to the vehicle requirements of Subtask A, and compares the weight of various alternate subsystems. Candidate concepts are compared on the basis of their weight and other unique advantages or disadvantages. The basic philosophy and the rationale for concept selection are presented, and, finally, candidate concepts for both boosters and orbiters are defined for Subtask A analysis.

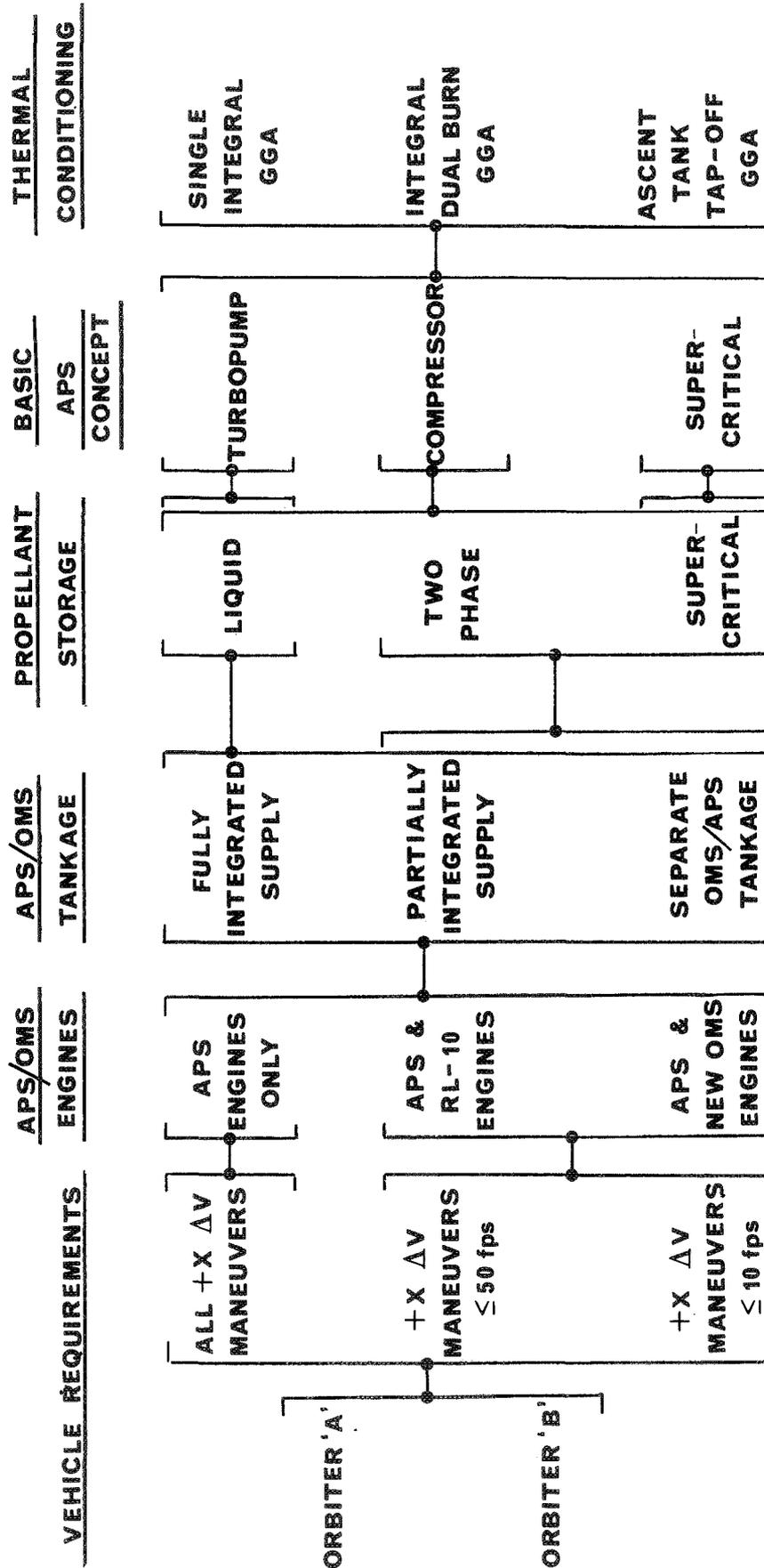
H-2. ORBITER CONCEPT ALTERNATIVES

Candidate auxiliary propulsion subsystems can be synthesized by combining one of the options shown in the different columns of Figure H-1. All options can effect APS selection. For example, alternate APS concepts are formulated by variations in vehicle requirements which effect size of APS concepts, hence, the relative merit of the various concepts. Propellant tankage interaction also plays an important role in concept selection, (i.e., for a liquid storage subsystem, integrated tankage is perhaps the most attractive approach). Conversely, for a supercritical subsystem, in which the propellant is stored at high pressure, a large tank is extremely undesirable from a weight standpoint. The basic APS alternates, such as turbopump, turbocompressor, or supercritical storage form the fundamental difference in concept and hence, the primary selection to be made. The options illustrated by Figure H-1 make up a total of 387 separate subsystem concepts. This, of course, is a highly unrealistic number and significant screening was required to reduce this matrix to a manageable number and provide the depth required for subtask A.

As noted previously, data were available from a precontract IRAD Program at McDonnell Douglas. This program provided APS design and weight data for a single low cross range orbiter at three different total impulse levels, corresponding to three different APS +X maneuvering velocity allocations. These velocity allocations corresponded to designs where the APS, besides performing all other post-separation maneuvering and attitude control functions:

- (1) performs all post separation +X maneuvering;
- (2) performs +X translation maneuvers ≤ 50 ft/sec;
- (3) performs +X translation maneuvers ≤ 10 ft/sec.

In the latter two cases an orbit maneuvering subsystem (OMS) provides the remainder of the +X translation maneuvers. Figure H-2 shows the IRAD total impulse levels associated with the three velocity allocations and, for comparison purposes, shows Subtask A impulse and thrust level requirements. Comparison of the requirements shows that impulse levels for the IRAD effort are very similar to those of Orbiter A, but were significantly less than those of Orbiter B. Comparison of thrust levels and numbers of engines indicates thrust levels used for the IRAD effort were



HIGH PRESSURE SUBSYSTEM SYNTHESIS

FIGURE H-1

TOTAL IMPULSE

VEHICLE	STUDY REQUIREMENTS - 10 ⁶ LB-SEC	IRAD REQUIREMENTS - 10 ⁶ LB-SEC
BOOSTER A	.48	-
BOOSTER B	.46	-
VEHICLE	STUDY REQUIREMENTS - 10 ⁶ LB-SEC ≤10 FT/SEC	IRAD REQUIREMENTS - 10 ⁶ LB-SEC ≤50 FT/SEC
ORBITER A	1.48	1.54
ORBITER B	1.71	1.54
	ALL	ALL
	13.91	13.0
	15.99	13.0

THRUST LEVEL

VEHICLE	THRUSTER NUMBER AND THRUST LEVEL REQUIREMENTS	
	STUDY CONFIGURATION	IRAD CONFIGURATION
BOOSTER A	18 @ 2600 LB	-
BOOSTER B	16 @ 2000 LB	-
ORBITER A	32 @ 500 LB	24 @ 1500 LB
ORBITER B	28 @ 1000 LB	24 @ 1500 LB

COMPARISON OF STUDY AND IRAD REQUIREMENTS

FIGURE H-2

appreciably greater than those of either Subtask A orbiter. Therefore, the IRAD study results required adjustment to accommodate changes in thrust level, number of engines, and total impulse.

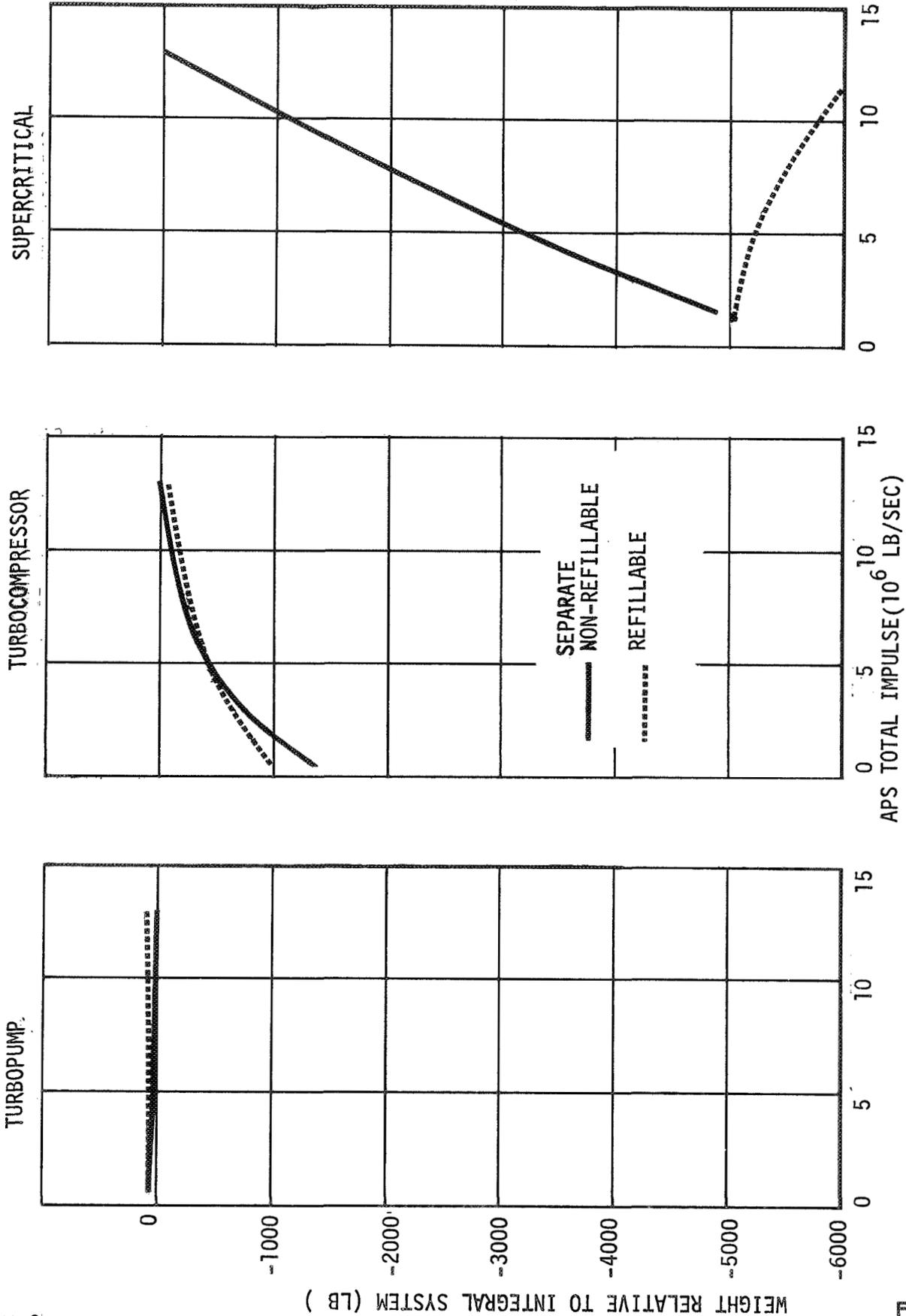
H-3. ORBITER CONCEPT SCHEMATICS

Figure H-3 shows IRAD study results comparing weight of various tankage options for the three basic APS alternates. In this figure, weights of three propellant storage options are compared for each candidate concept. A single integral tank, in which both OMS and APS propellant supplies were stored, was used as a reference for data shown. Two other cases were compared with the weight of this reference. Both had separate APS and OMS tankage. In one, all APS propellant was stored in a separate APS propellant tank. In the second, only the amount of APS propellant that would be used between major OMS burns was stored in the separate tank, which required refilling during each major OMS burn.

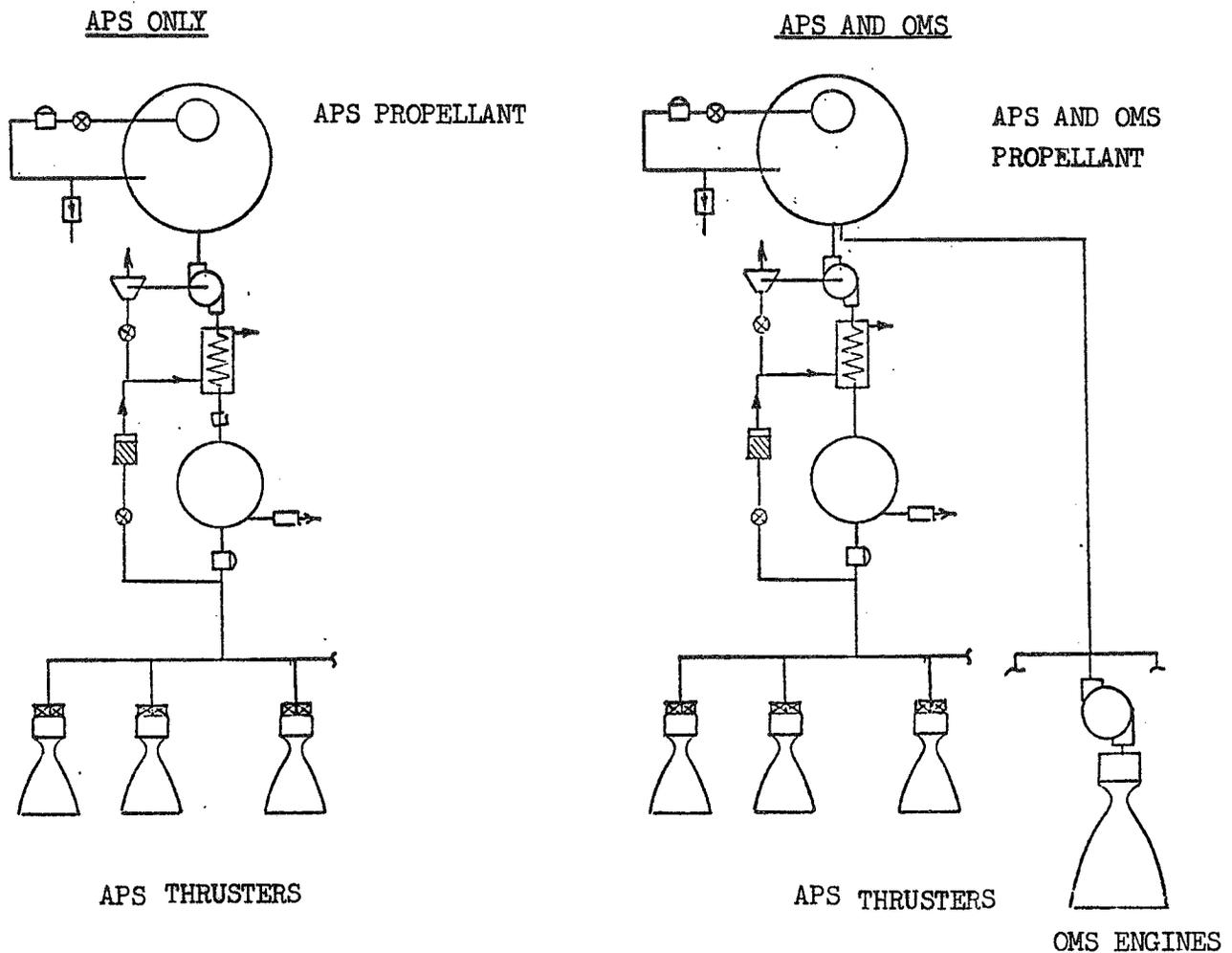
Inspection of the data shown in Figure H-3 for the turbopump subsystem shows that there is very little weight difference in any of the three approaches at any of the total impulse levels of interest. Based on this, a single integral tank was selected for the turbopump system, as this approach was the simplest and most flexible of the three. With this propellant integration approach, the turbopump subsystem schematic shown in Figure H-4 was defined. For clarity this schematic does not include the redundant components necessary to satisfy shuttle failure criteria; however, for the turbopump and for all other subsystems analyzed during this effort the required component redundancy was included in the weight and sizing analysis. The schematic refinement shown in Figure H-5 for the turbopump system is typical. Here, compared to the line schematic of Figure H-4, is the actual number of components used for APS design and sizing and for APS weight evaluation.

Figure H-3 shows that for the turbocompressor subsystem, a single integral tank is not as attractive as separate tanks. This is due primarily to the fact that in the turbocompressor subsystem, APS propellant is injected into main ascent tanks; thus, APS tanks must operate at relatively high pressures to allow propellant transfer and injection. In this subsystem type, it is attractive to use small tanks, and separate tankage was selected for the turbocompressor subsystem, shown in the schematic of Figure H-6. A separate OMS is shown for the cases where the APS does not provide all postseparation +X maneuvering.

The necessity of separate tankage is even more pronounced in the supercritical subsystem and results in an extreme weight advantage. Storage tank pressures in the supercritical subsystem are quite high, and it is desirable to use as



TANKAGE INTEGRATION EFFECTS
APS & OWS Total Impulse = 13 x 10⁶ Lb/Sec

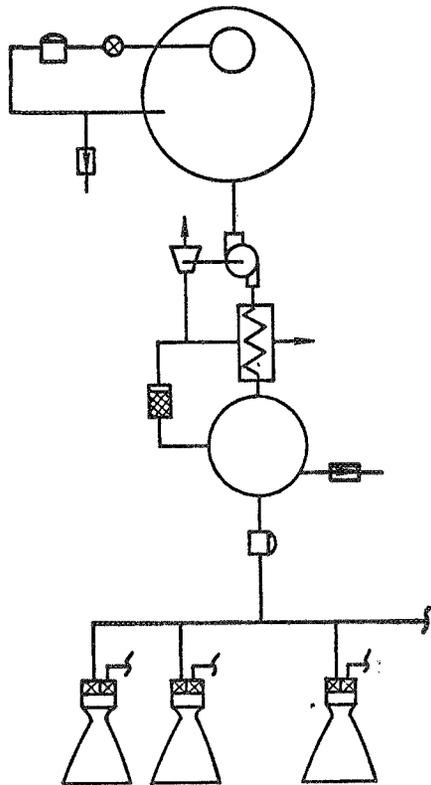


TURBOPUMP APS SCHEMATICS
One Propellant Side

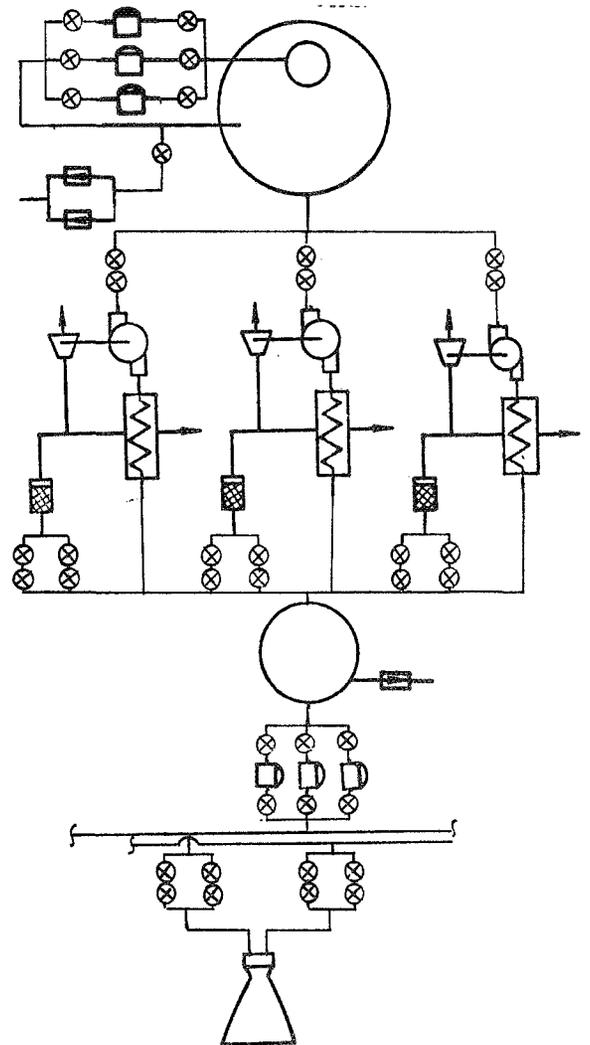
FIGURE H-4

small a propellant tank as possible. For this reason, separate, refillable propellant tanks were selected for the supercritical APS (illustrated in the schematic of Figure H-7). With this subsystem, a separate OMS tank is always provided, and liquid is transferred from this tank to the high pressure APS tank during each major translation maneuver.

SINGLE LINE SCHEMATIC
OF PUMP APS

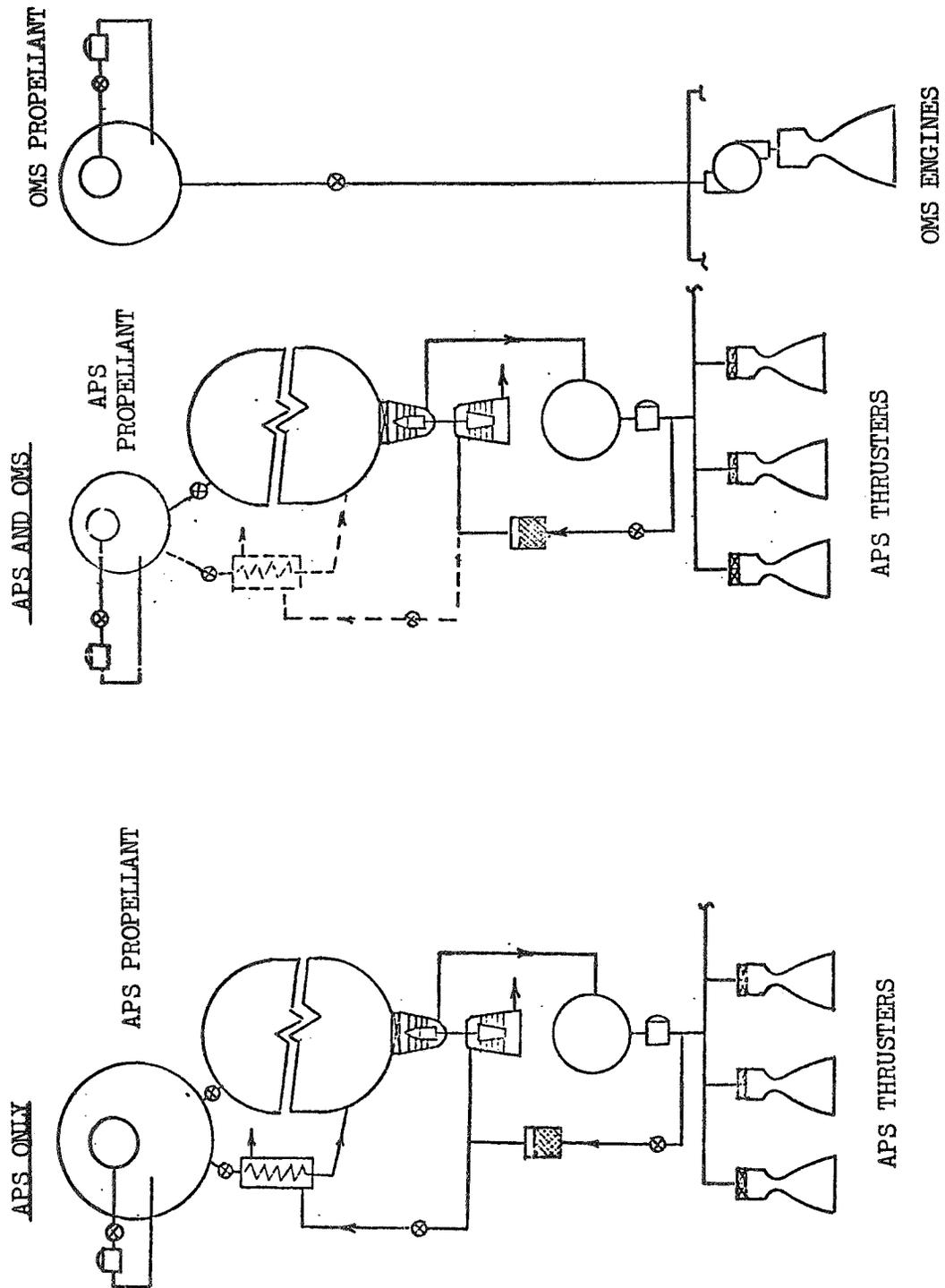


PUMP APS WITH REDUNDANCY



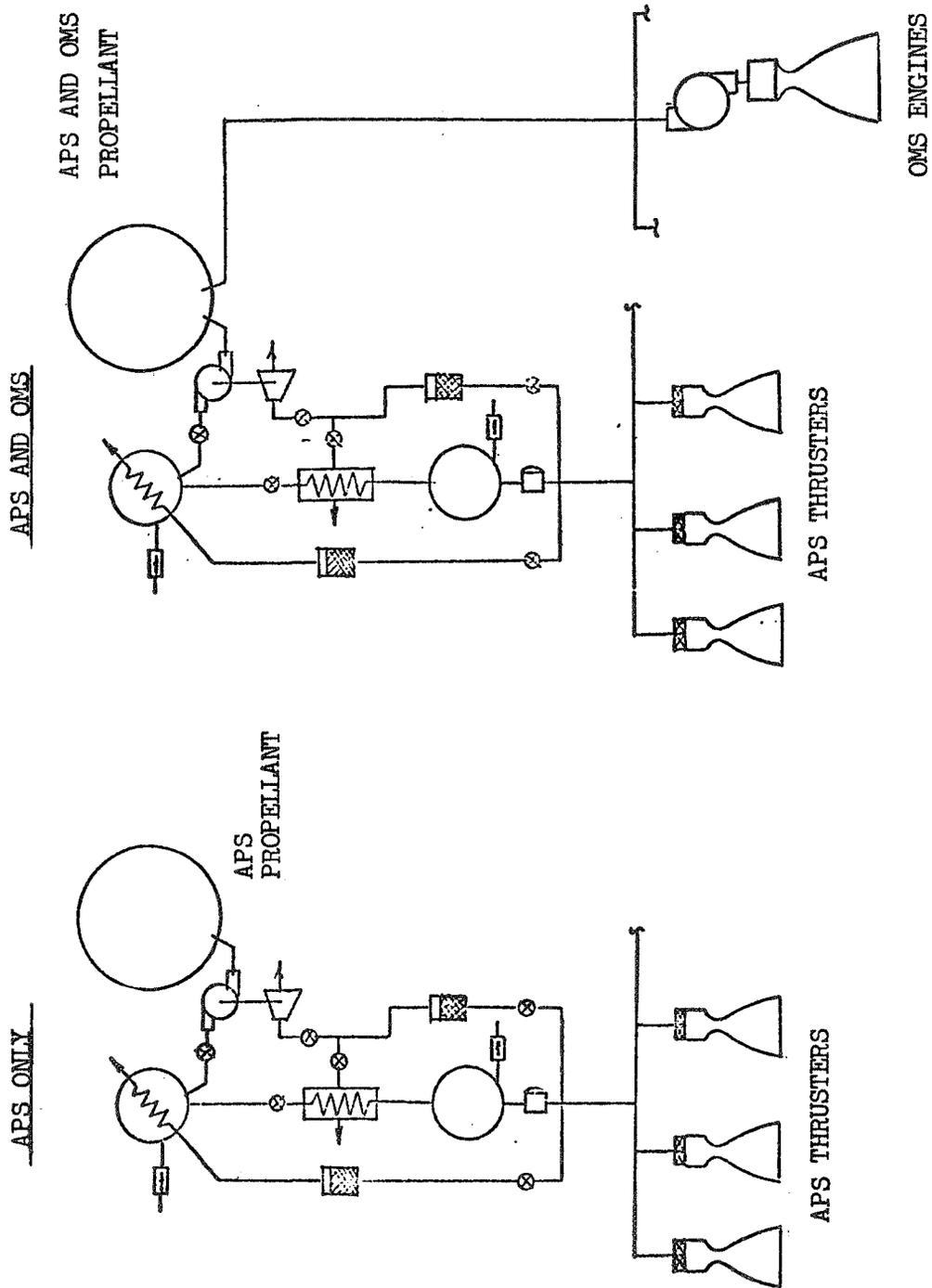
REDUNDANCY

FIGURE H-5



TURBOCOMPRESSOR APS SCHEMATIC
One Propellant Side

FIGURE H-6



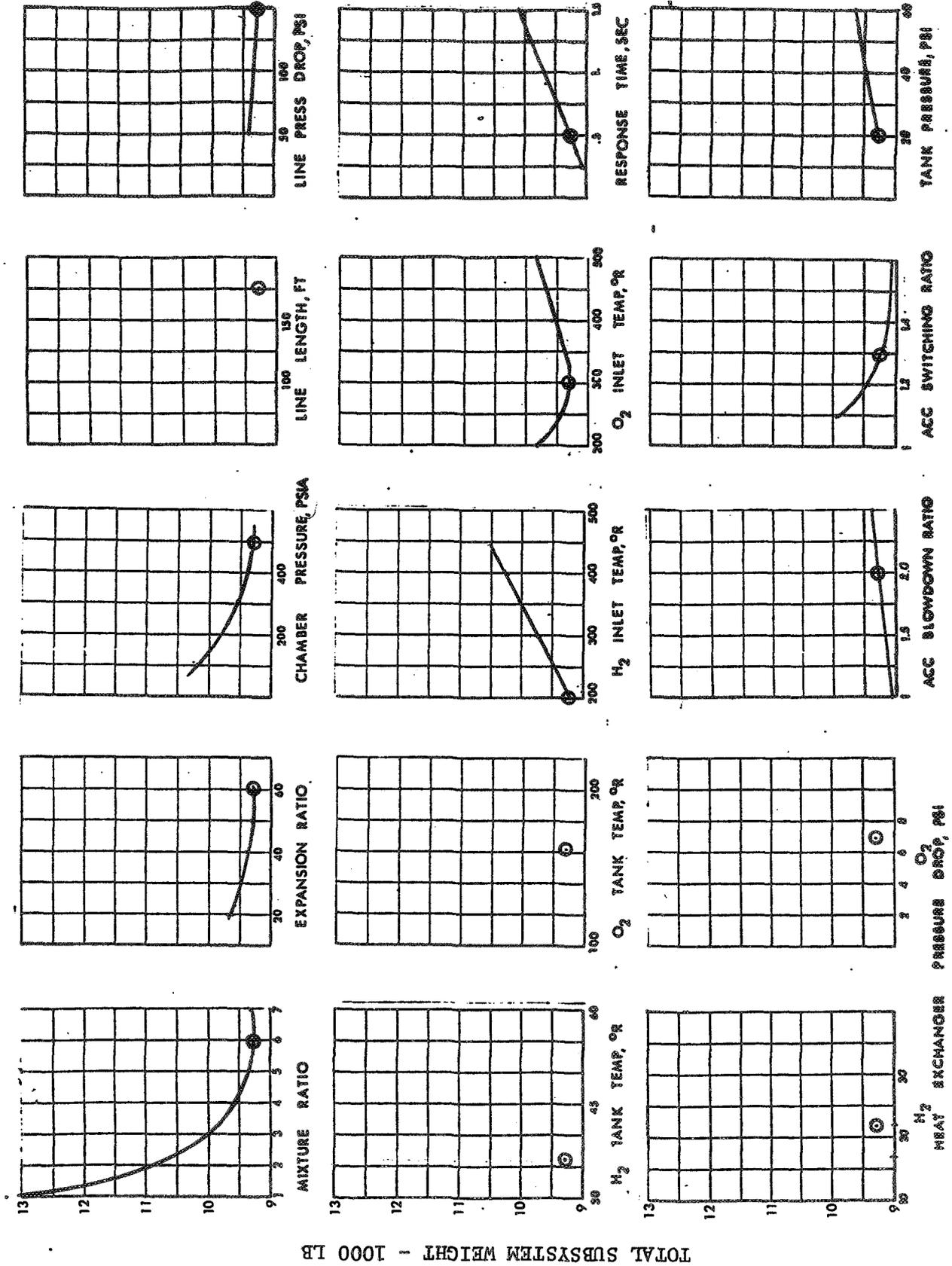
SUPERCritical APS SCHEMATIC
One Propellant Side

H-4. CONCEPT DESIGN POINTS

Using the schematics defined in Section H-3, each subsystem concept was analyzed to determine its weight sensitivity to various design features. From this analysis, design points which defined a minimum subsystem weight were selected. Component models used for these analyses were those defined in Reference (a). Figure H-8 shows the results of these analyses for the turbopump APS concept at a total impulse corresponding to the ≤ 50 ft/sec APS velocity allocation. As shown, mixture ratio for the subsystem optimizes at approximately 6:1 using shifting equilibrium thruster performance from Reference (a). Thruster expansion ratio is 60:1 and design chamber pressure is 500 lbf/in²a. Hydrogen and oxygen conditioning temperatures of 200° and 300°R respectively were selected and, based on the analysis of Reference (a), a subsystem response time of 0.5 sec was used. Switching and blow-down pressure ratios for the accumulators of 1.3 and 2, respectively, were used. As shown in Figure H-8, these design points resulted in nearly minimum subsystem weight. Further weight reductions could have been potentially achieved through design refinements, but the values used were considered realistic and were the best available at that phase of the study program.

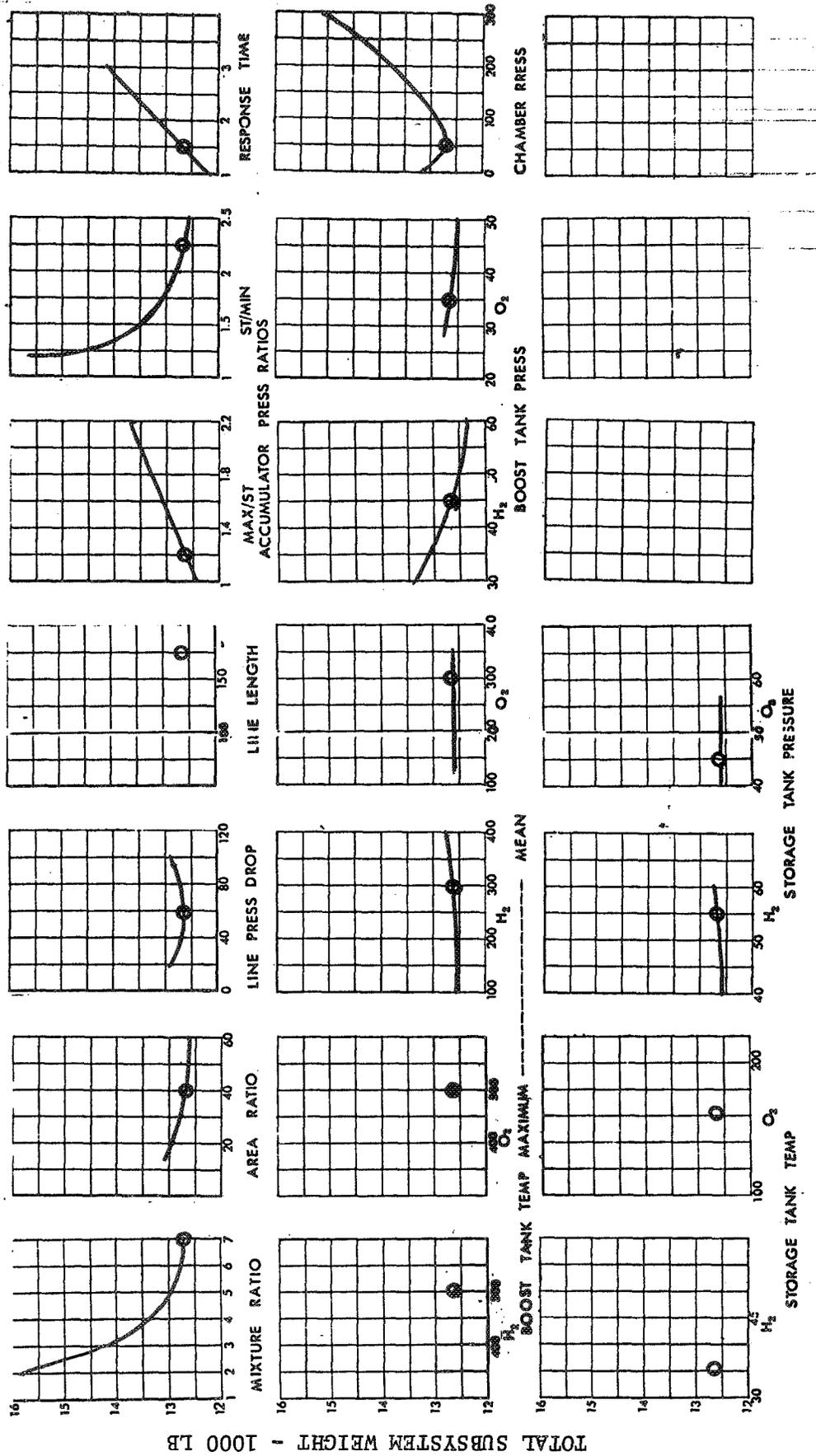
Similar results are shown in Figure H-9 for the turbocompressor APS. This subsystem optimized at a somewhat higher mixture ratio because of the relatively high hydrogen compression conditioning requirements. Because of increased conditioner flow for compression, this subsystem optimized at a relatively low chamber pressure of 50 lbf/in²a as shown. Other design values for this subsystem are indicated on Figure H-9.

Figure H-10 shows the supercritical APS design values. This subsystem, like the turbocompressor, favored operation at relatively low chamber pressure. This resulted primarily from the fact that the propellant storage tank must supply sufficient pressure for all subsystem pressure drops. Thus, an increase in chamber pressure results in an increase in storage tank pressure and, hence, in storage tank weight. For this APS, a total impulse of 700,000 lb-sec was used as the amount that will be stored in the supercritical tank prior to usage. This amount of impulse is the maximum required to allow APS usage between major +X translation burns during which the APS supercritical tank is refilled. Additional propellant to satisfy the mission requirements was considered to be stored as a liquid in the OMS tankage.



TURBOPUMP APS

FIGURE H-8

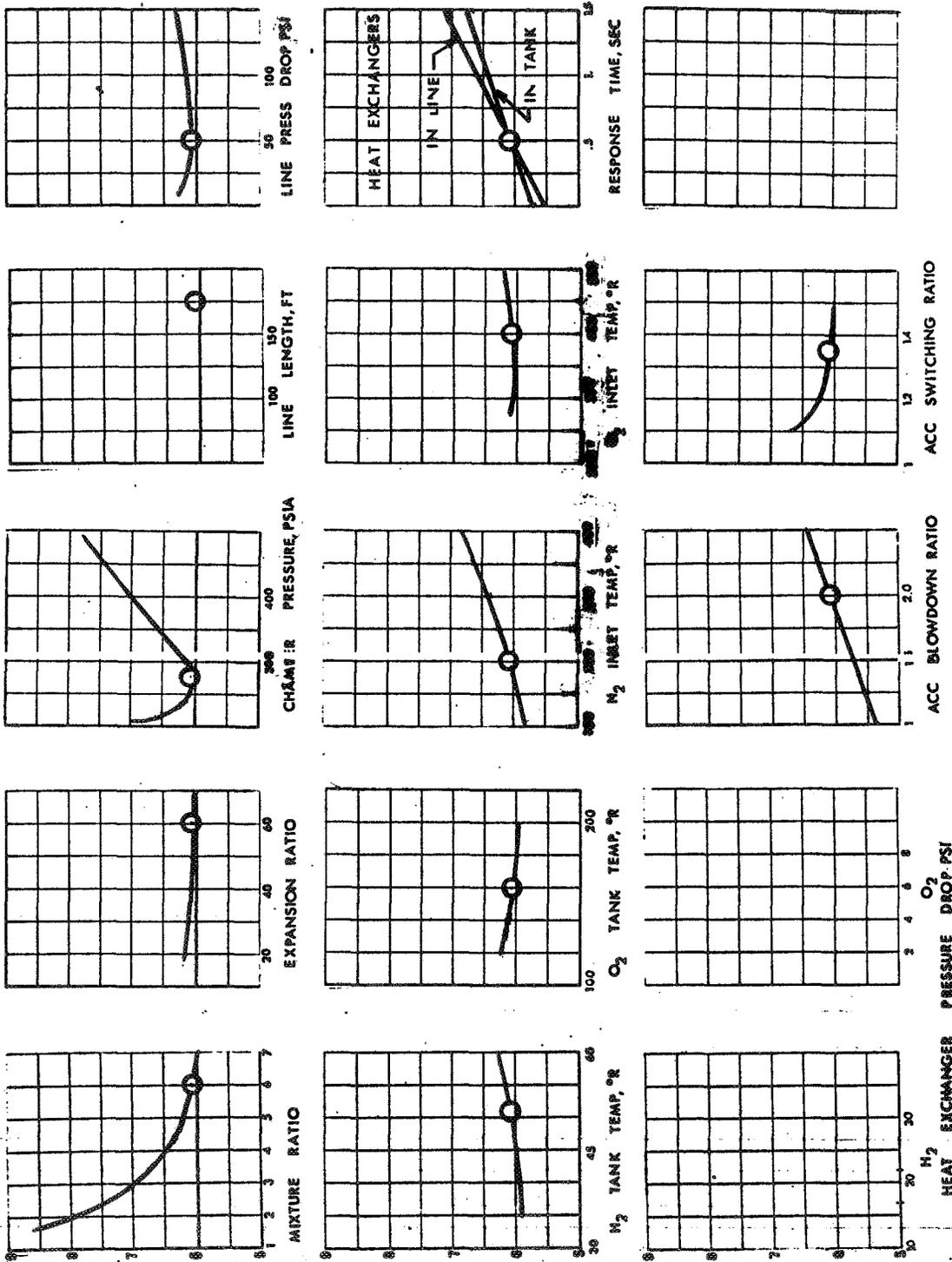


TOTAL SUBSYSTEM WEIGHT - 1000 LB

o TOTAL IMPULSE = 2.92×10^6 LB-SEC

TURBOCOMPRESSOR APS

FIGURE H-9



TOTAL SUBSYSTEM WEIGHT - 1000 LB

○ TOTAL IMPULSE = 700×10^3 LB-SEC

SUPERCritical APS

FIGURE H-10

DESIGN VARIABLE	TURBOPUMP	SUPERCRITICAL	TURBOCOMPRESSOR		
			≤ 10	≤ 50	ALL
THRUSTER MIXTURE RATIO	6:1	6:1	7:1	6:1	
EXPANSION RATIO	60:1	60:1	40:1	60:1	
CHAMBER PRESSURE (PSIA)	500	150	50	20	
LINE PRESSURE DROP (PSI)	150	50	60	25	
TANK TEMPERATURE (°R) - H ₂ O ₂	36 160	51 160	36 160		
PROPELLANT CONDITIONED TEMPERATURE (°R) - H ₂ O ₂	200 300	200 400	474 544	352 400	
CONDITIONING ASSEMBLY RESPONSE TIME - (SEC)	.5	.5	1.5		
ACCUMULATOR PRESSURE RATIO - MAX/SWITCH SWITCH/MIN	2.0 1.3	2.0 1.35	1.2 2.2		
PROPELLANT TANK PRESSURE (PSIA)	20	372 (H ₂) 750 (O ₂)	55 (H ₂) 45 (O ₂)		

APS DESIGN POINTS

FIGURE H-11

Figure H-11 summarizes all the APS design points for the different maneuver levels. As shown for the turbopump and supercritical subsystems, maneuver levels did not introduce differences in subsystem design point. For the turbocompressor subsystem a somewhat different design chamber pressure is desirable in the all maneuver case as, when total impulse is high, it is even more desirable to reduce bypass flow losses for propellant compression.

H-5. APS WEIGHT SENSITIVITY TO REQUIREMENTS

Using the design points of Section H-4, APS weight sensitivity to impulse and thrust level requirements was developed to allow adjustment of APS weights developed during the IRAD program to the requirements for study Subtask A. These results are shown in Figures H-12 and H-13. Figure H-12 shows APS weight sensitivity to total impulse for the three subsystem types. These data are based on the design points shown in Figure H-11 and cover the range of interest for all APS impulse levels. Similarly, the data of Figure H-13 were developed using design points of Figure H-11 with the exception that the number of APS engines was changed to correspond to the requirements of Orbiters A and B (as presented in Figure H-2). Shown in Figure H-13 is the sensitivity of APS weight to variations in thrust level for the two orbiters. Each APS concept is shown.

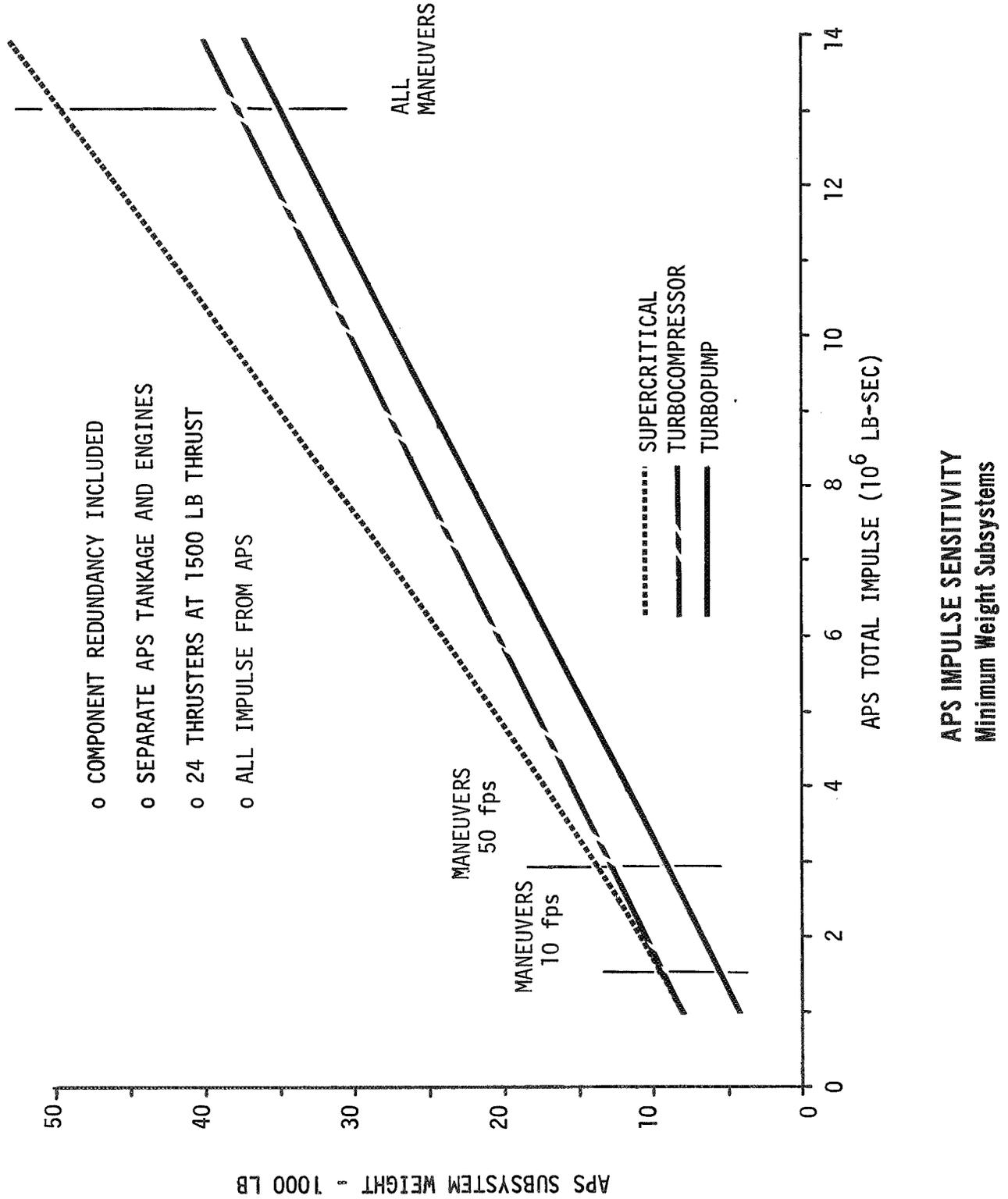
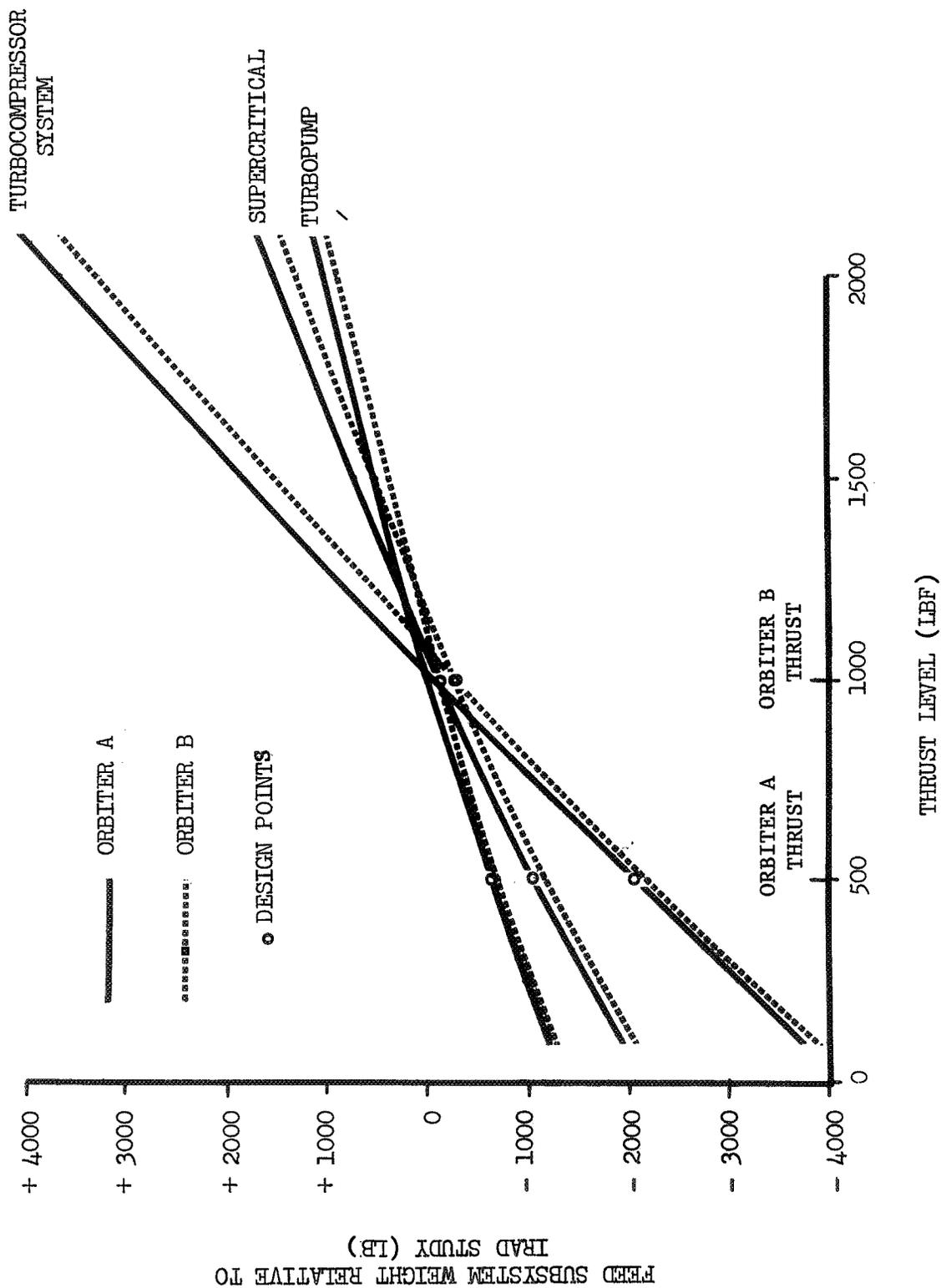


FIGURE H-12



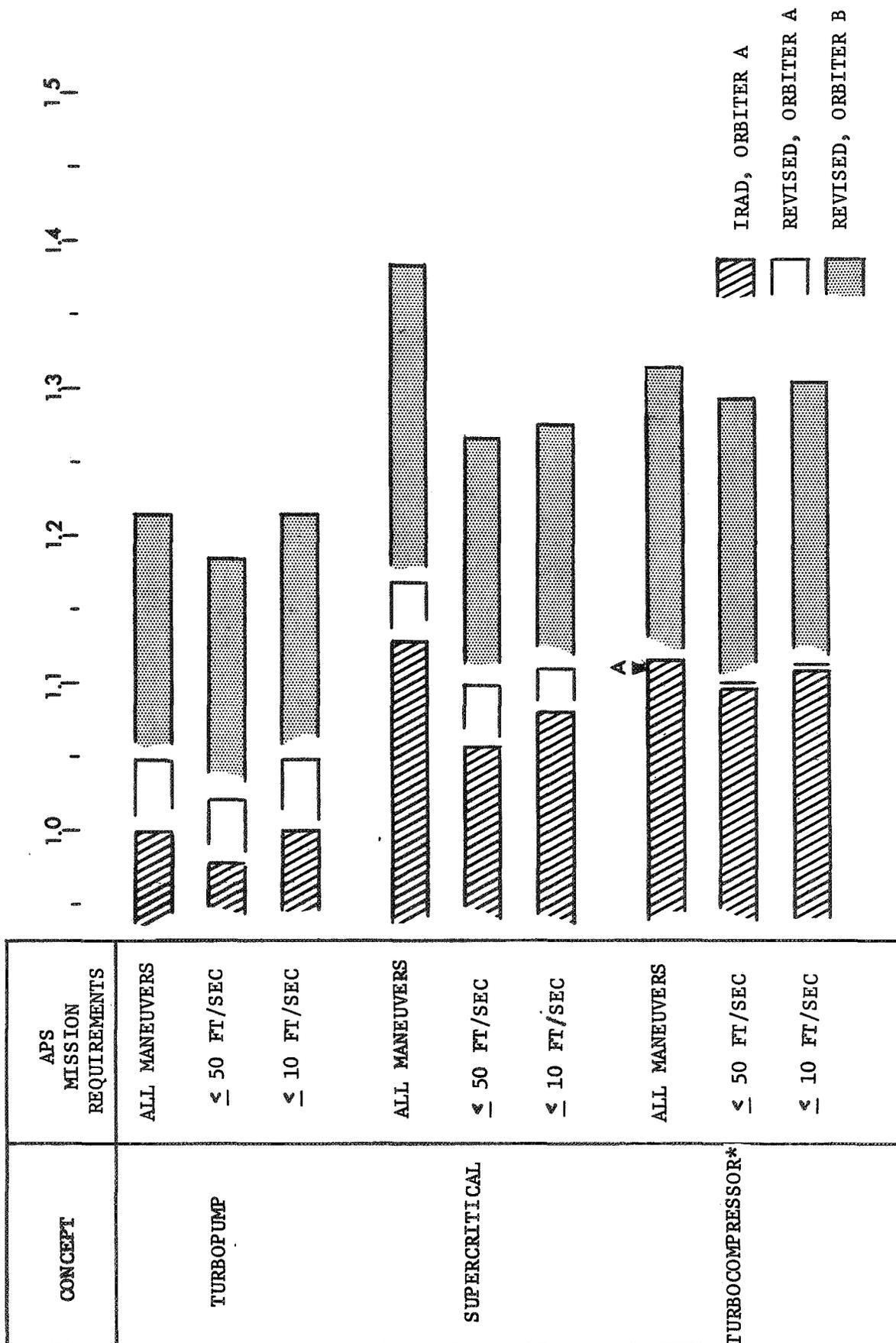
FEED SUBSYSTEM WEIGHT CHANGE
Maneuvers ≤ 10 & ≤ 50 Ft/Sec

FIGURE H-13

H-6. COMPARISON OF ORBITER APS WEIGHTS

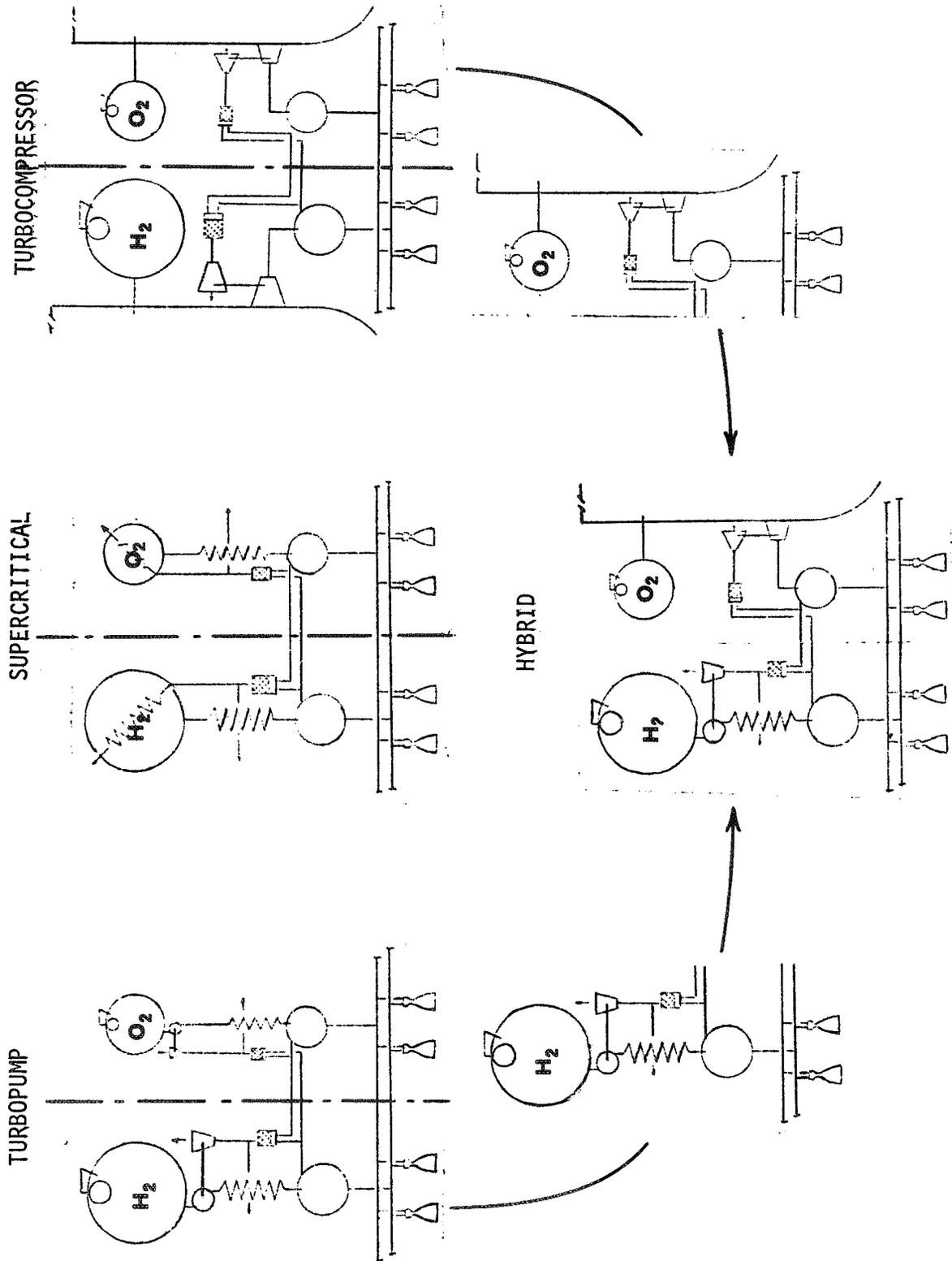
Figure H-14 is a bar chart showing the weight of the various APS concepts for different maneuver velocity levels. Shown are weights corresponding to requirements of Orbiters A and B, along with the IRAD subsystem weights for reference. Comparing Orbiter A from the IRAD program with its revision for this study, a slight increase in weight resulted from changes in thrust level and impulse requirements for both turbopump and supercritical subsystem, however, weights are approximately equal for the turbocompressor APS. The difference is principally due to the fact that the IRAD program did not account for the available residual propellants in the main engine tanks, and this reduced the weight of the turbocompressor subsystem. Weights of all subsystems for Orbiter B are significantly above those for Orbiter A, due, primarily, to increases in APS total impulse. Comparing the three different types of subsystems, it is clear that the turbopump is the lightest for all vehicles and for all velocity allocations.

In order to provide complete coverage of the various APS types, it was necessary to evaluate the impact of using different APS concepts for the different propellants (for example, using a turbopump concept for hydrogen delivery while using a compressor approach for oxygen). The result is a hybrid subsystem, as illustrated in Figure H-15. Since hybrids could potentially offer a better overall design than that afforded by using the same approach for both propellants, hybrids were examined for different impulse levels. These results are shown in Figures H-16, H-17, and H-18. These figures show the APS conceptual approach used for the different propellants and the resulting subsystem weight for the total impulse levels indicated. Inspection of Figures H-16, H-17, and H-18 shows that none of the hybrid concepts offers a weight advantage over the basic turbopump concept. In the analysis of hybrid subsystems, supercritical approaches were again considered to use separate refillable tanks and the compressor subsystems were credited with the weight of residuals in the main engine tanks.



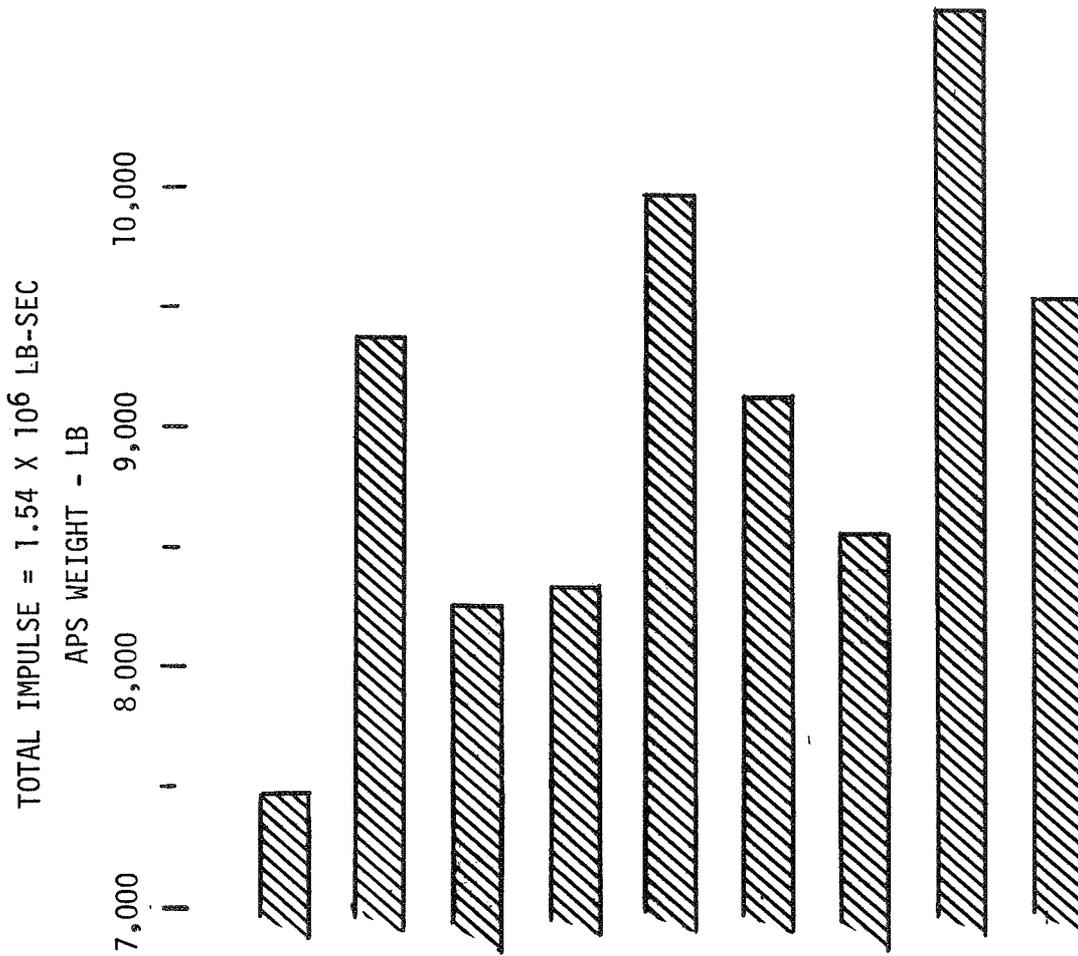
* WEIGHT INCLUDES RESIDUALS

REVISED REQUIREMENTS EFFECT UPON SUBSYSTEM WEIGHTS



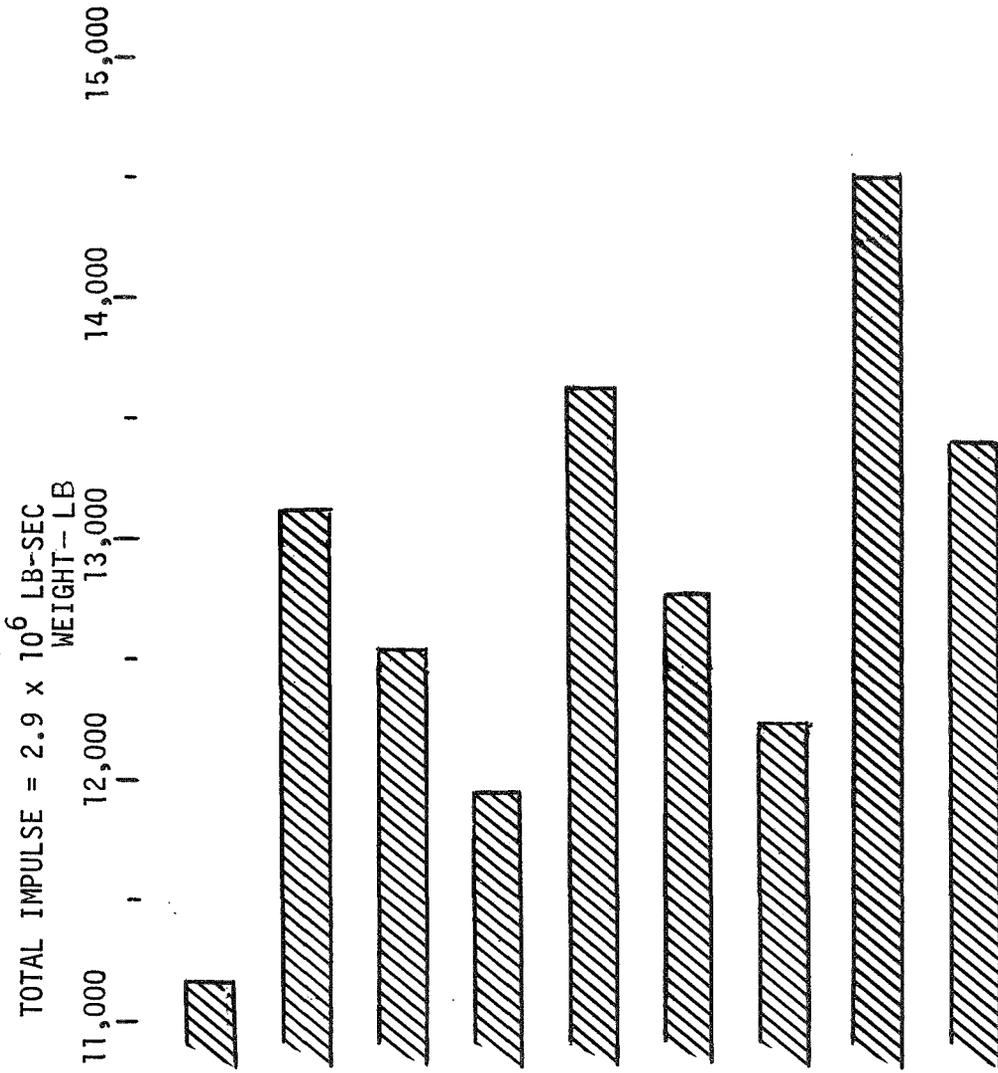
HYBRID DESIGN CONCEPT

FIGURE H-15



CONCEPT	
HYDROGEN	OXYGEN
PUMP	PUMP
COMPRESSOR	PUMP
SUPERCritical	PUMP
PUMP	COMPRESSOR
COMPRESSOR	COMPRESSOR
SUPERCritical	COMPRESSOR
PUMP	SUPERCritical
COMPRESSOR	SUPERCritical
SUPERCritical	SUPERCritical

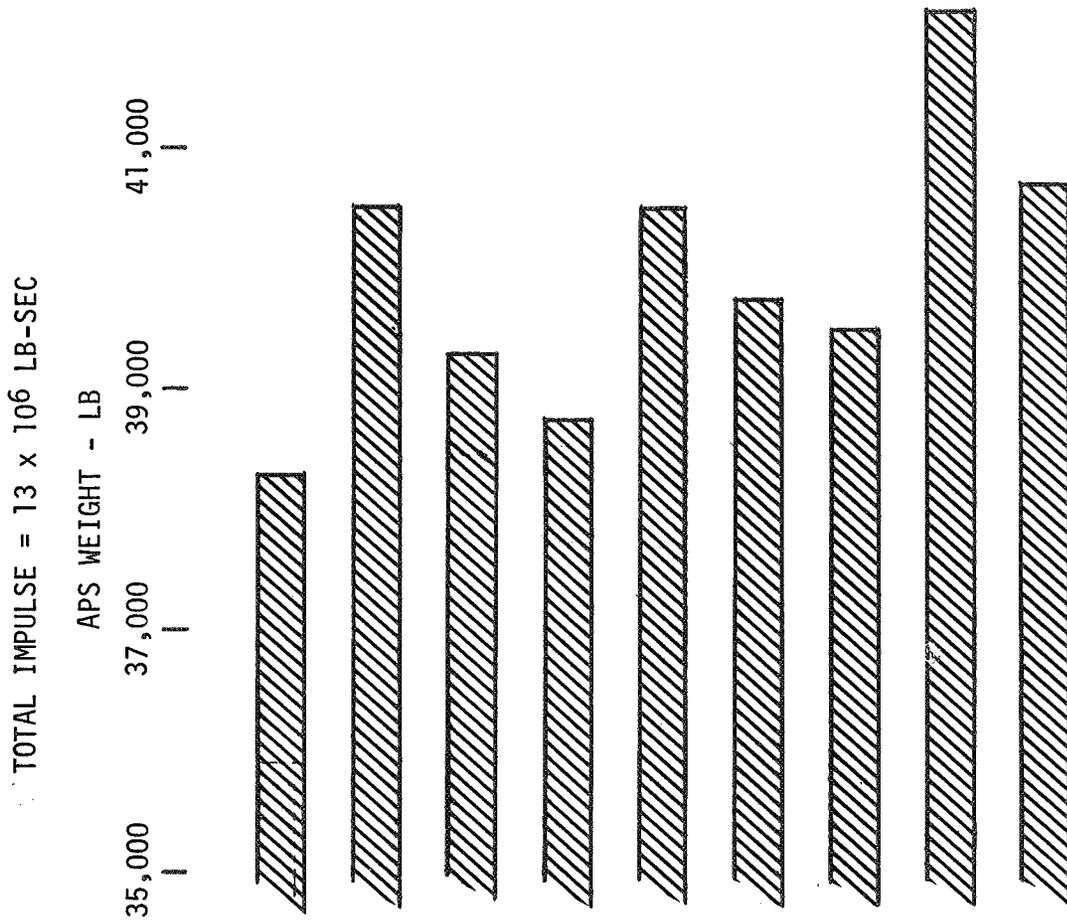
HYBRID SUBSYSTEM WEIGHTS



CONCEPT	
HYDROGEN	OXYGEN
PUMP	PUMP
COMPRESSOR	PUMP
SUPERCRITICAL	PUMP
PUMP	COMPRESSOR
COMPRESSOR	COMPRESSOR
SUPERCRITICAL	COMPRESSOR
PUMP	SUPERCRITICAL
COMPRESSOR	SUPERCRITICAL
SUPERCRITICAL	SUPERCRITICAL

HYBRID SUBSYSTEM WEIGHS

FIGURE H-17



CONCEPT	
HYDROGEN	OXYGEN
PUMP	PUMP
COMPRESSOR	PUMP
SUPERCRITICAL	PUMP
PUMP	COMPRESSOR
COMPRESSOR	COMPRESSOR
SUPERCRITICAL	COMPRESSOR
PUMP	SUPERCRITICAL
COMPRESSOR	SUPERCRITICAL
SUPERCRITICAL	SUPERCRITICAL

HYBRID SUBSYSTEM WEIGHTS

H-7. ORBITER CONCEPT SELECTION

Figure H-19 provides a comparison of the three basic APS concepts, and shows advantages or disadvantages unique to each approach.

H-7.1 Concept Summaries

H-7.1.1 Turbopump - This concept has been shown in Section H-4, to be the lightest approach for both orbiters, at any velocity level. It has the greatest flexibility to change in mission profile, since all propellant is stored in a single tank, and, therefore, can be used in any desired manner. Finally, it has the firmest technology base. Components in this subsystem are comparable in most respects to components available in industry today. Disadvantages of the turbopump are that propellants must be maintained in the liquid state, and must be positioned at all times in a zero g environment. This is particularly of concern for the hydrogen tank, as this tank is far larger than any that has been previously built. By its nature, hydrogen is difficult to maintain in a liquid state throughout the tank. In this subsystem approach, the pumps must be maintained at liquid temperatures throughout the mission in order to achieve required conditioner response times.

H-7.1.2 Supercritical - This subsystem has the unique advantage of not requiring propellant positioning because the gas or propellant is maintained in a single phase state throughout the mission. In the supercritical approach no rotating machinery is required. The disadvantages of the supercritical subsystem are that tankage is more complex because of the need for refill during mission. A tankage and heater technology base has not been established.

The tankage heater, required to maintain pressure within the supercritical tank, has only a very limited technology background. Heaters have been used in previous programs, but in these cases the extraction rates have been several orders of magnitude below those required for this assembly. Typically, previous programs have required heat inputs in the order of 40 to 100 watts. Approximately a 1,000,000 watt input is required to maintain pressure in the supercritical hydrogen tank during maximum APS usage. As hydrogen is withdrawn the energy input raises the temperature and pressure of the hydrogen remaining to maintain a constant supply pressure. Hence a totally new approach to heat addition would be required. Propellant is stored initially at near-liquid conditions, and, as the tankage approaches depletion, the propellant approaches the conditions required for engine operation. Thus, the amount of heat supplied in the downstream heat exchanger varies widely, and the downstream gas generator heat exchanger assembly

<u>BASIC CONCEPT</u>	<u>UNIQUE ADVANTAGES</u>	<u>UNIQUE DISADVANTAGES</u>
TURBOPUMP	<ul style="list-style-type: none">o LOWEST WEIGHT/VOLUMEo FLEXIBILITY IN MISSION PROFILEo FIRMIEST TECHNOLOGY BASE	<ul style="list-style-type: none">o PROPELLANT POSITIONING REQUIREDo PUMPS MUST BE KEPT CHILLED
SUPERCRITICAL	<ul style="list-style-type: none">o PROPELLANT POSITIONING NOT REQUIREDo NO ROTATING MACHINERY	<ul style="list-style-type: none">o MORE COMPLEX TANKAGE DUE TO REFILL FOR HIGH IMPULSE LEVELSo TANKAGE/HEATER TECHNOLOGY BASE NOT ESTABLISHEDo HIGHLY THROTTLEABLE GGA REQUIRED FOR CONDITIONING
TURBOCOMPRESSOR	<ul style="list-style-type: none">o USE OF BOOST RESIDUALS	<ul style="list-style-type: none">o COMPLEX SYSTEM WHEN PRECONDITIONING IS REQUIREDo COMPLEX VEHICLE INTERFACEo LARGE-HIGH POWER-FAST RESPONSE TURBOMACHINERY TECHNOLOGY BASE NOT AVAILABLEo HIGHER COMPONENT LIFE REQUIREMENTS

BASIC CONCEPT CRITIQUE

FIGURE H-19

would require a high degree of throttling for control.

H-7.1.3 Turbocompressor - The only unique advantage of this subsystem concept is that it can make use of the residual propellants remaining in booster engine tanks after main engine cutoff. A number of disadvantages, however, are evident. The subsystem is complex when preconditioning prior to injection into the main propellant tanks is required. Inspection of the schematics of Figure H-6 shows the increased subsystem complexity associated with the preconditioning loop. Vehicle interface with this subsystem type is more complex. Heat transfer into the propellants prior to compression is a key design factor; hence, this vehicle interface is much more critical to subsystem operation. The turbocompressors required are large, high power, fast response units, and, for such units, a technology base is not available. Finally, due to the somewhat longer response time associated with the large turbocompressors, accumulators must be undersized to avoid excessive weight penalties, resulting in an increase in the number of compressor starts during the mission. This last factor, of course, increases component life requirements.

H-7.2 Concepts Selected for Further Study - The basic philosophy which was applied to orbiter concept selection is shown in Figure H-20. As stated in Section 1 of this Appendix, the primary desire was to reduce the number of systems to a manageable level, so that the overall trade study could be accomplished with the highest confidence, but to temper this by retention of any subsystems for which there were doubts about the validity of screening. Following this philosophy, three basic subsystems were selected:

- (1) The turbopump was selected for both orbiters at all APS impulse levels. The rationale for this selection was that the turbopump subsystem offered the lowest weight at all impulse levels and provided the best technology base
- (2) The supercritical subsystem was retained for both orbiters but would be investigated at the low velocity allocation only. The primary rationale for this was that, at the low impulse levels, the supercritical subsystem was weight competitive and had the distinct advantage of requiring no propellant positioning. At the low impulse level, refill complexity could potentially be eliminated with a minimal weight penalty, thus simplifying the supercritical subsystem
- (3) A hybrid subsystem was also to be investigated. This hybrid used a supercritical hydrogen propellant supply and a turbocompressor oxygen supply.

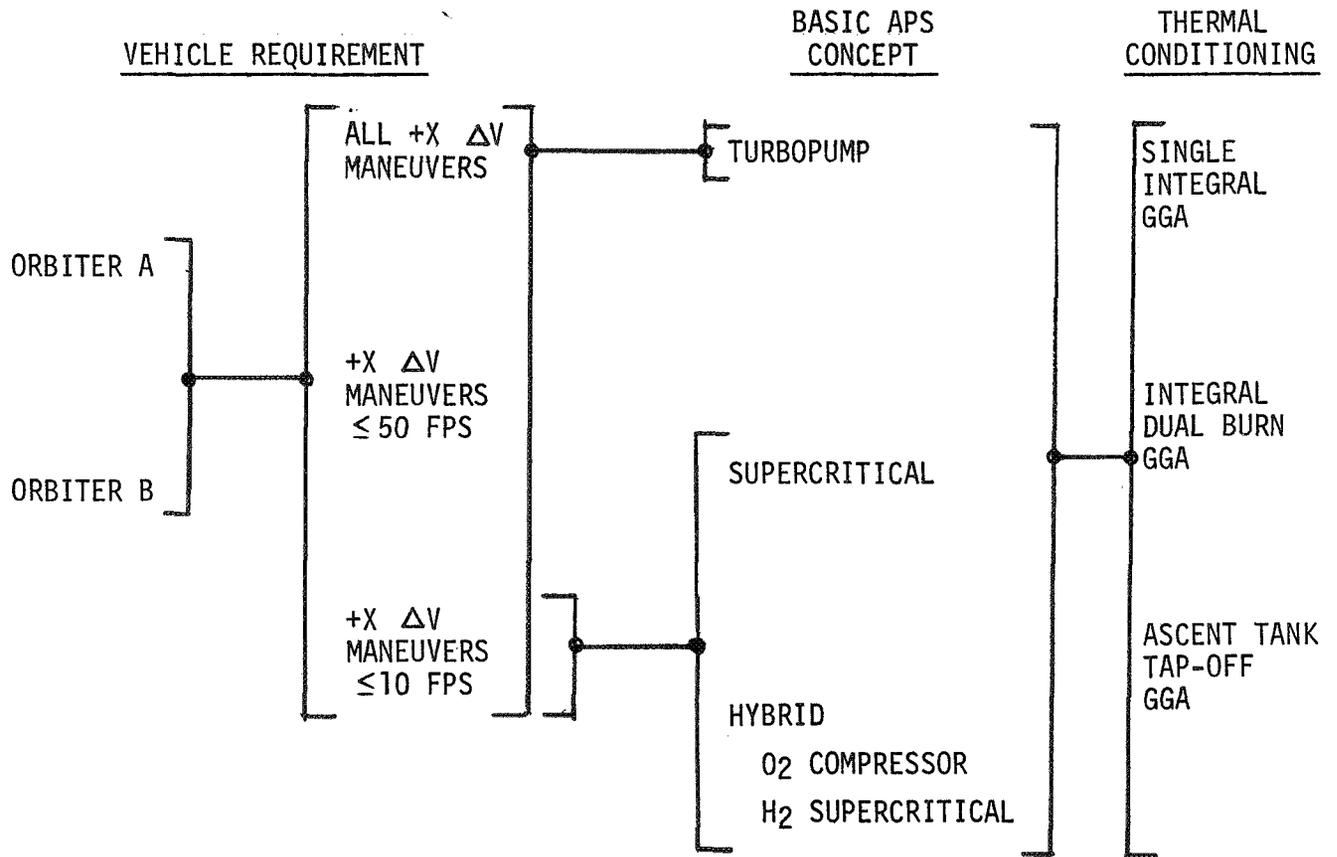
BASIC PHILOSOPHY: PROVIDE BEST OVERALL STUDY RESULTS BY CONCENTRATING EFFORT ON APPROACHES WHICH ARE MOST ATTRACTIVE, BUT PROVIDE SUFFICIENT EFFORT ON OTHER CONCEPTS TO THOROUGHLY CONFIRM SCREENING CONCLUSIONS.

- o TURBOPUMP
 - o BOTH ORBITERS
 - o ALL APS IMPULSE LEVELS
 - o LOWEST SUBSYSTEM WEIGHT
 - o BEST TECHNOLOGY BASE
- o SUPERCRITICAL
 - o BOTH ORBITERS
 - o LOW APS IMPULSE LEVEL ONLY
 - o NO PROPELLANT POSITIONING
 - o AT LOW IMPULSE REFILL CAN BE ELIMINATED WITH LOW WEIGHT PENALTY
- o HYBRID -
 - SUPERCRITICAL H₂
 - COMPRESSOR O₂
 - o BOTH ORBITERS
 - o LOW APS IMPULSE LEVEL ONLY
 - o SIMPLIFIED PROPELLANT POSITIONING
 - o ALLOWS MORE DEPTH FOR COMPRESSOR ANALYSES IN AREA WHERE COMPRESSOR IS MOST ATTRACTIVE - I.E., O₂
 - o SAME AS ABOVE FOR H₂

CANDIDATE ORBITER CONCEPT SELECTION

The hybrid was selected for both orbiters at the low impulse level only. This hybrid was selected by the rationale shown in Figure H-20. Specifically, it simplified the propellant positioning problem by eliminating need for hydrogen propellant positioning (clearly the more difficult of the two propellants). It allowed more depth for compressor analysis in the area where the compressor was most attractive, i.e., the oxygen side. With oxygen, the power required for gas compression is much lower than for hydrogen, and turbomachinery sizes are correspondingly much smaller. Since the compressor concept can take advantage of residuals, it allows use of a compressor where maximum residuals are available, i.e., in the oxygen tank of the main engine subsystem. For the hydrogen side of the hybrid subsystem, advantages are the same as those identified previously for the supercritical APS.

Based on the above rationale, the recommended orbiter concept matrix shown in Figure H-21 was developed. As shown, the original 387 orbiter concepts were reduced to 30. First, the turbopump subsystem would be investigated for all maneuver levels. This would provide a comparison of differences in subsystem design when subsystems were tailored from low to high impulse levels. Secondly, candidates would provide a comparison of the three basic (generic) types of subsystem at a common impulse allocation. Finally, each of the subsystem concepts would be evaluated to determine the thermal conditioning approach best suited to the concept design.



RECOMMENDED ORBITER CONCEPT MATRIX

FIGURE H-21

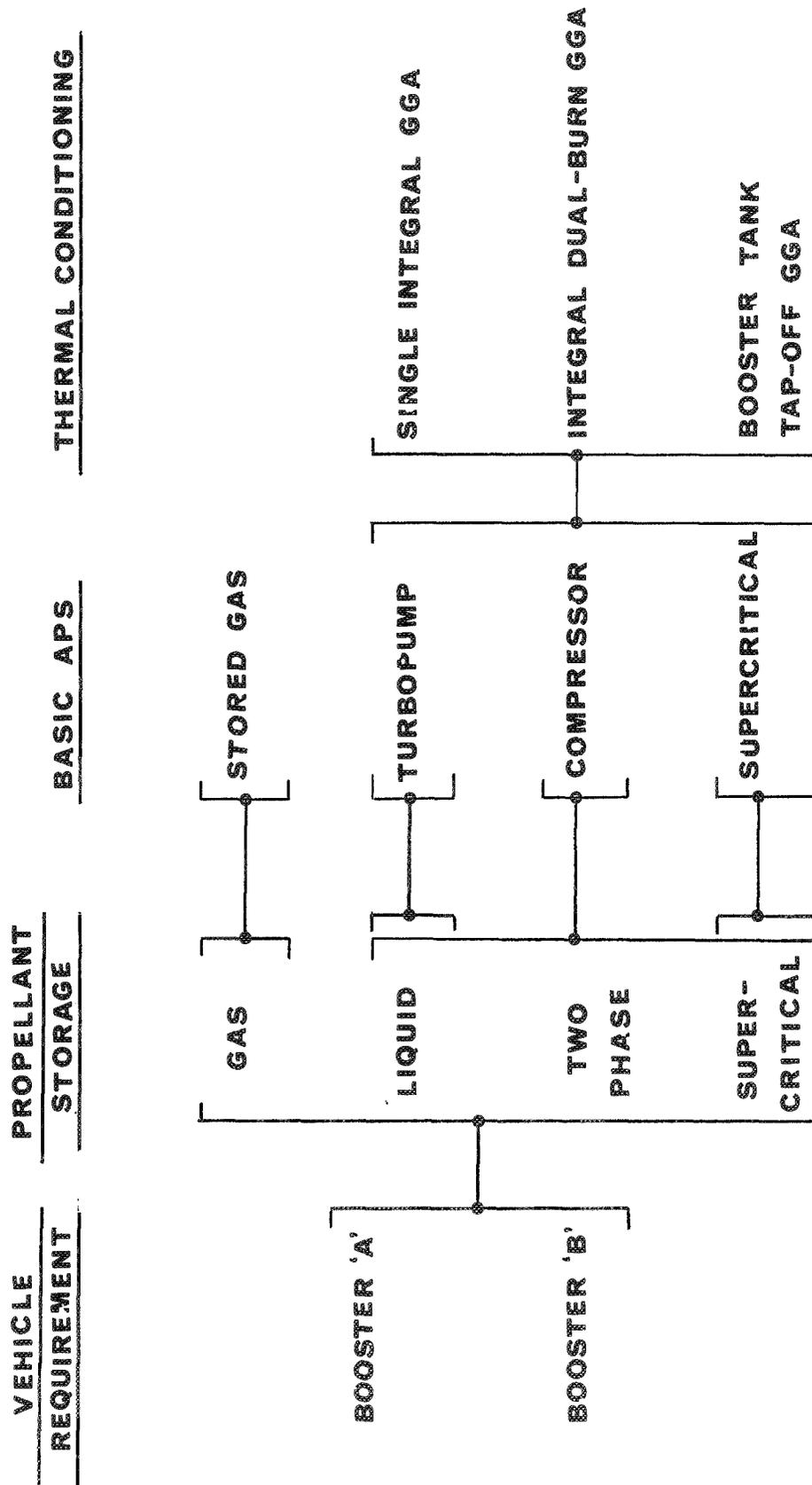
H-8. BOOSTER CONCEPT SELECTION

Booster concept selection approach was similar to that described above for the orbiters; however, selection and evaluation were much simplified, since the number of possible concepts was far more limited. Figure H-22 shows the possible means of subsystem synthesis for boosters. Again, as with the orbiters, APS concepts can be formulated by selection of one of the options from each column in Figure H-22. For purposes of screening, design points determined for the orbiter turbopump, compressor, and supercritical subsystems were applied to boosters. In addition to these three systems, however, a fourth generic option was available for the boosters. This was a simple stored gas bipropellant system in which the propellants for the entire mission are stored in large, high pressure accumulators, and no conditioning or liquid propellant storage is required. Weight sensitivity data for the stored gas APS are shown in Figure H-23, along with design points selected for subsystem comparison.

Comparison of the four APS concepts for the boosters is shown in Figure H-24. As observed for the orbiter, the turbopump subsystem is the lightest weight approach; however, each of the other concepts has certain advantages. Figure H-25 summarizes the rationale used for booster APS concept selection. As shown, even though the turbopump was the lightest, each of the candidates had sufficient doubt associated with its design and/or technology to warrant retention in the study. The compressor potentially eliminates the need for all propellant storage, with that associated simplification. The supercritical concept eliminates the need for propellant positioning, all rotating machinery, and, at the low impulse levels required for the booster, the need for refill. Finally, stored gas is by far the simplest overall subsystem, and the technology required for the other systems could warrant the weight penalty of the stored gas, especially for the booster, where a payload exchange ratio makes weight penalties far less important than in the orbiter. Thus, the recommended booster concept matrix shown in Figure H-26 is unchanged from the options identified in Figure H-22.

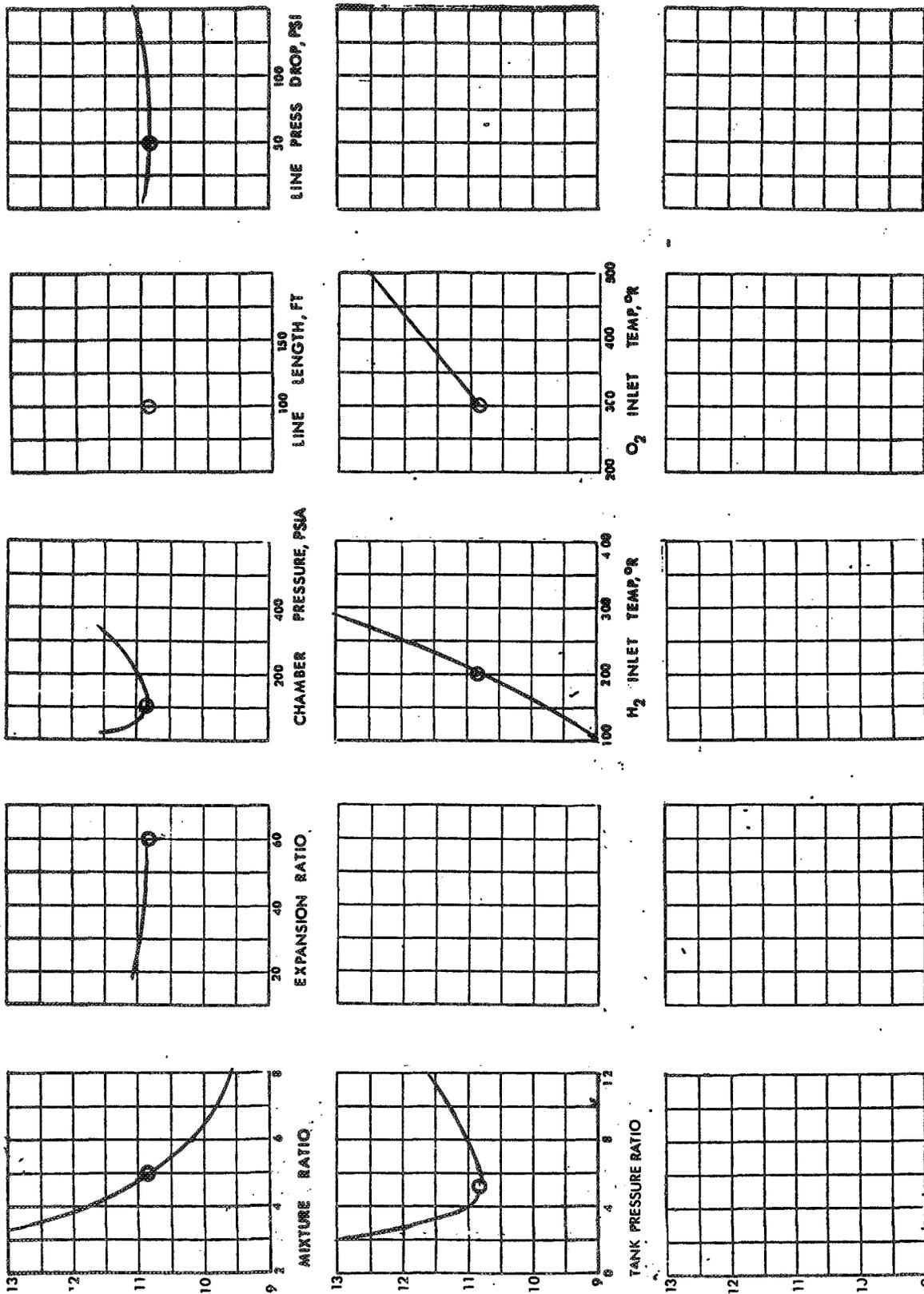
References:

- (a) Preliminary Comparison of Gaseous Oxygen/Hydrogen Propulsion Systems:
McDonnell Douglas Engineering Note EN-762, dated 26 January 1970.



HIGH PRESSURE SUBSYSTEM SYNTHESIS

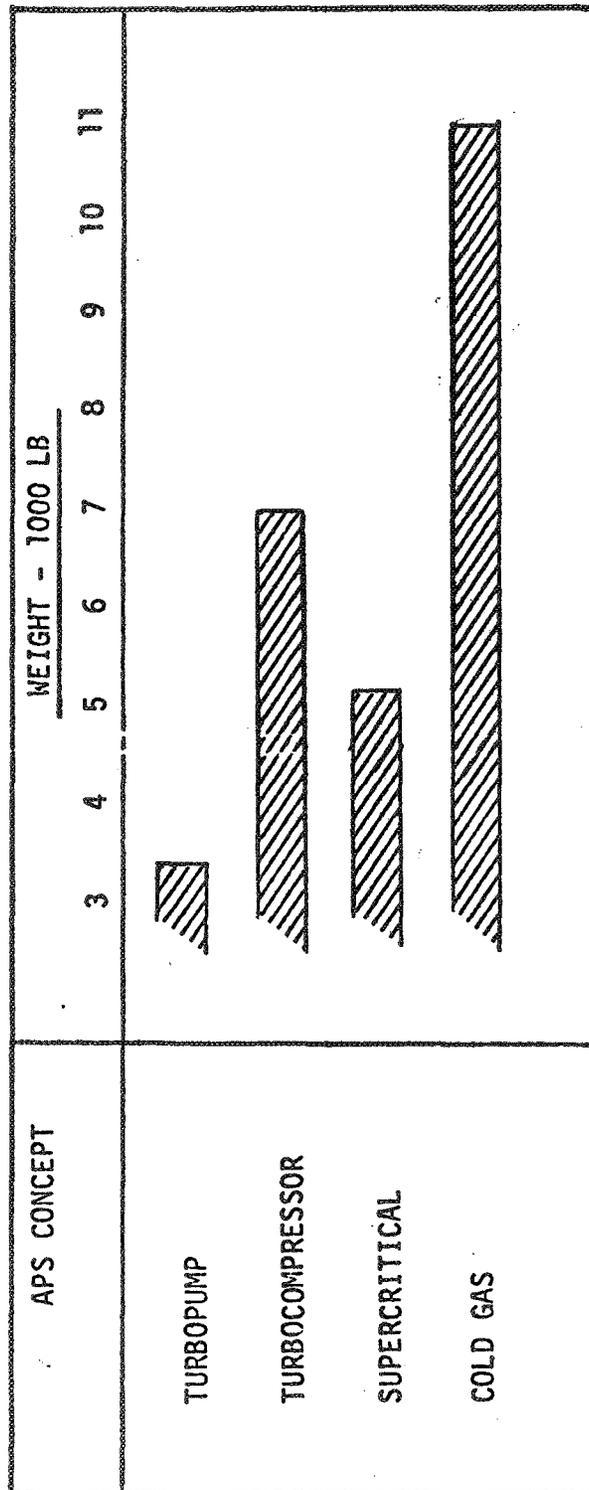
FIGURE H-22



TOTAL SUBSYSTEM WEIGHT = 1000 LB

COLD GAS APS

FIGURE H-23



COMPARISON OF BOOSTER APS CONCEPTS

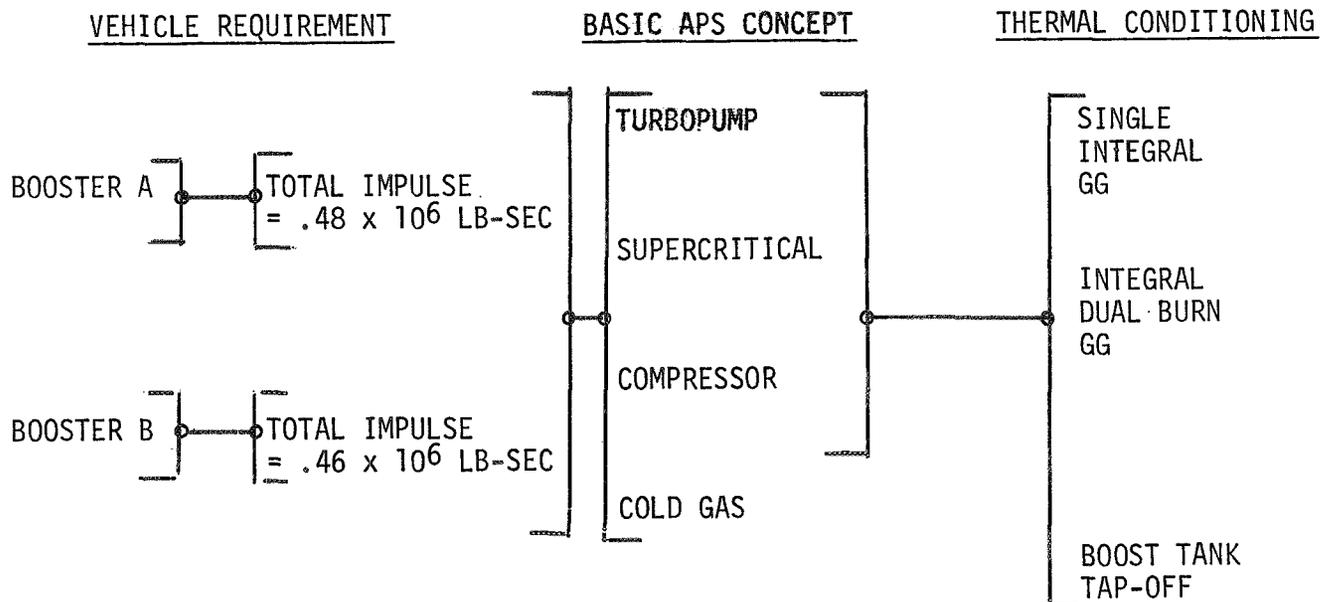
FIGURE H-24

BASIC PHILOSOPHY: PROVIDE BEST OVERALL STUDY RESULTS BY CONCENTRATING ON APPROACHES WHICH ARE MOST ATTRACTIVE, BUT PROVIDE SUFFICIENT EFFORT ON OTHER CONCEPTS TO PROVIDE A THOROUGH SCREENING.

- | | | |
|-------------------|-----------------|---|
| o TURBOPUMP | o BOTH BOOSTERS | o LOWEST SUBSYSTEM WEIGHT |
| o TURBOCOMPRESSOR | o BOTH BOOSTERS | o ALLOWS POSSIBLE USE OF RELATIVELY LARGE RESIDUAL MASS AVAILABLE FROM BOOST TANK |
| o SUPERCRITICAL | o BOTH BOOSTERS | o NO PROPELLANT POSITIONING
o NO ROTATING MACHINERY
o REFILL CAN BE ELIMINATED |
| o COLD GAS | o BOTH BOOSTERS | o SIMPLEST OVERALL SYSTEM
o NO ROTATING MACHINERY
o NO PROPELLANT POSITIVE EXPULSION OR POSITIONING |

CANDIDATE BOOSTER CONCEPT SELECTION

FIGURE H-25



RECOMMENDED BOOSTER CONCEPT MATRIX

FIGURE H-26

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY - EAST
Saint Louis, Missouri 63166 314-232-0232