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SPACE SHUTTLE HIGH PRESSURE AUXILIARY PROPULSION SUBSYSTEM DEFINITION STUDY

SUMMARY REPORT

Contract Number NAS 8-26248

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY • EAST

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CORPORATION

COPY NO. 68

SPACE SHUTTLE HIGH PRESSURE AUXILIARY PROPULSION SUBSYSTEM DEFINITION STUDY

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12 FEBRUARY 1971 REPORT MDC E0299

SUMMARY REPORT

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PREFACE

This report summarizes the effort conducted in support of the space shuttle high pressure auxiliary propulsion subsystem study and defines the preliminary design of the final subsystems selected. The study was performed for the National Aeronautics and Space Administration, Marshal Space Flight Center, Huntsville, Alabama, under contract NAS 8-26248.

This volume summarizes the program and highlights the study approach and results.

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1. INTRODUCTION

The NASA space shuttle vehicle system for future manned space operations requires development of a number of subsystems which are either new or significant extensions of state-of-the-art technology. Among these is the auxiliary propulsion subsystem (APS) used for control and maneuvering of the shuttle vehicle after main engine cut-off. The magnitude of APS control requirements is far in excess of those of previous vehicles. To provide a high performance APS and, at the same time, to take advantage of benefits in the areas of propellant logistics, safety, reuse, and performance, a gaseous hydrogen/oxygen auxiliary propulsion subsystem was identified as the most desirable type of subsystem.

There are two basic methods of implementing an APS of this type. These are:

(1) high pressure APS, in which propellants are stored at, or conditioned to, the most desirable thruster operating pressures;

(2) low pressure APS, in which propellants are supplied to the control thrusters from main ascent propellant tanks at normal ullage pressures.

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

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

To fulfill shuttle needs, NASA contracted for APS definition studies of both high and low pressure APS. These studies were divided into two phases. The first phase, Subtask A, was a conceptual subsystem definition to provide NASA with data sufficient for selection of the best means of APS implementation in both high and low pressure categories. The second phase, Subtask B, was 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 the analyses and design support necessary to define the active components for APS evaluation. NASA 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 was providing sufficient comparative data on various APS concepts to allow selection of the best high pressure approach for Subtask B preliminary design. The results of the Subtask A portion of the study are documented in detail in the Subtask A report (Reference (a)). Subtask B was initiated using concepts defined during Subtask A. Detailed component and assembly trade studies, and design analyses, were performed in parallel with supporting subsystem design and operating analysis to define the recommended baseline APS. Final baseline APS installation and preliminary design were accomplished. Results of the second phase of the high pressure APS study (preliminary APS design) are defined in the Subtask B report (Reference (b)). The high pressure APS Design Handbook (Reference (c)) defines the preliminary design, operating performance, and weight sensitivities for the selected APS for Orbiter B, Orbiter C and the Booster of Reference (d).

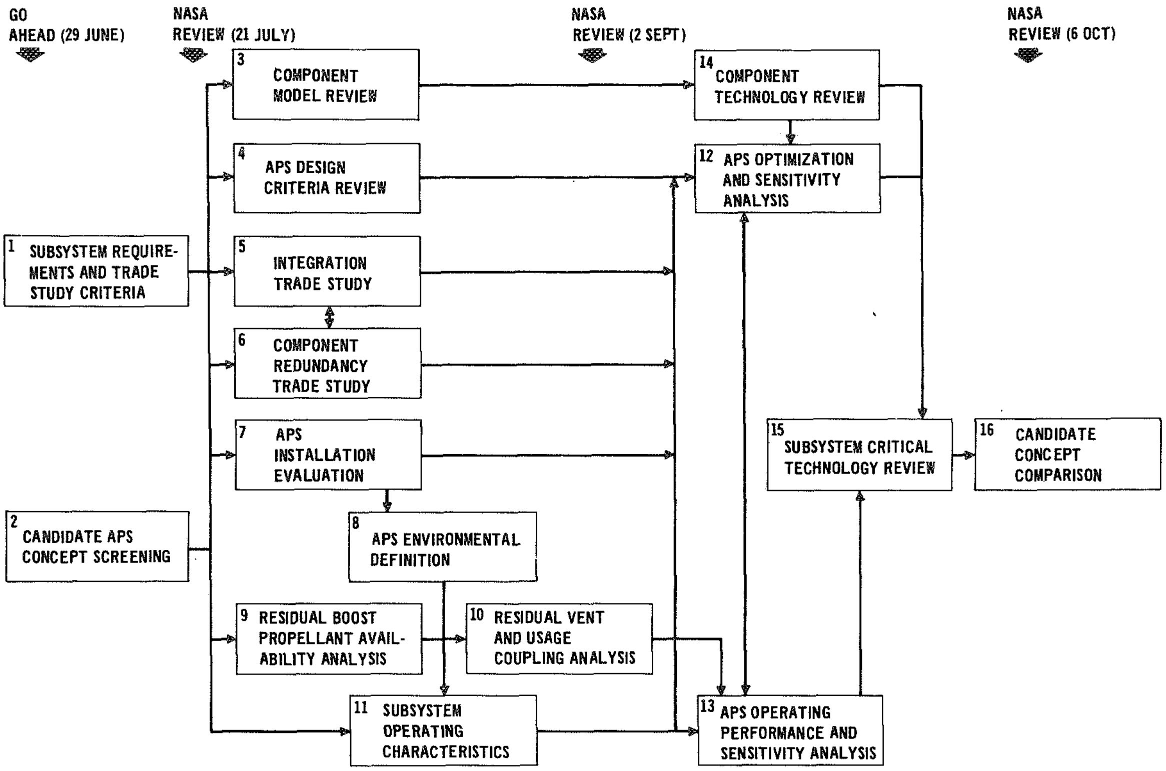
This report summarizes the tasks conducted in both Subtask A and Subtask B phases of the high pressure APS study, and defines (in summary form) the preliminary design of final APS configurations.

2. STUDY APPROACH

The high pressure APS study was conducted in two phases, Subtask A, Conceptual Subsystem Definition, and Subtask B, Preliminary Subsystem Design. Reference (e) provides a detailed program plan for the complete study, and defines in detail the task objectives and their relationship to the overall study. The tasks are shown in Figures 2-1 and 2-2 in flow chart form for the two subtasks. Figure 2-3 defines the program schedule.

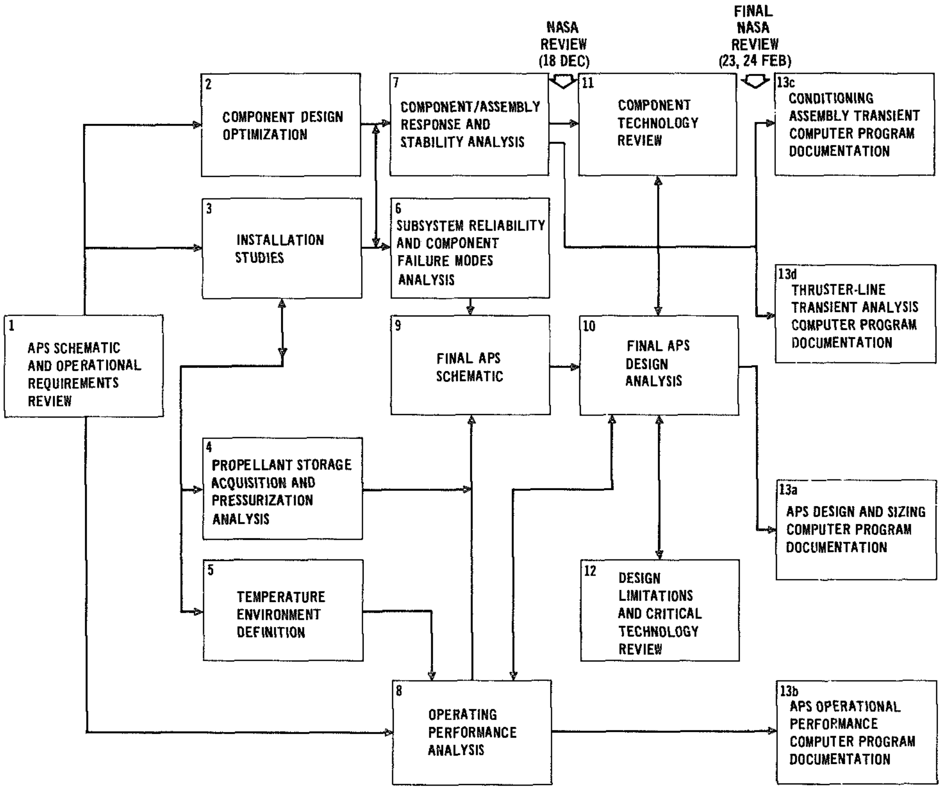
In Subtask A, the problem addressed was providing sufficient comparative data on the various high pressure APS concepts to allow selection of the best approach for Subtask B preliminary design. For this early study phase the predominant concern was the relative merit of various APS concepts, rather than their absolute performance levels. Component and assembly optimizations, within a given subsystem concept, were limited to those areas which could potentially impact subsystem selection. Thus, final data resulting from this phase of study 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. Vehicles considered in Subtask A were the two orbiters and boosters defined in Reference (f). Mission APS requirements for these shuttles were also defined in Reference (f).

Subtask B was initiated using APS concepts defined during Subtask A. Vehicles and requirements were redefined by NASA prior to Subtask B. Considered for the Subtask B APS installation were Orbiter B, Orbiter C, and the Booster defined in Reference (d). Tradeoff studies were performed to determine thruster arrangement and thrust level which would best meet maneuvering requirements and still provide the minimum weight configuration. To define the recommended baseline APS, in-depth component and assembly trade studies and design analyses were performed in parallel with supporting subsystem design and operating analyses. Final baseline APS installation and preliminary design studies including component definition were then accomplished.



SUBTASK A – TASK DESCRIPTION FLOW CHART

FIGURE 2–1



SUBTASK B – TASK DESCRIPTION FLOW CHART

FIGURE 2–2

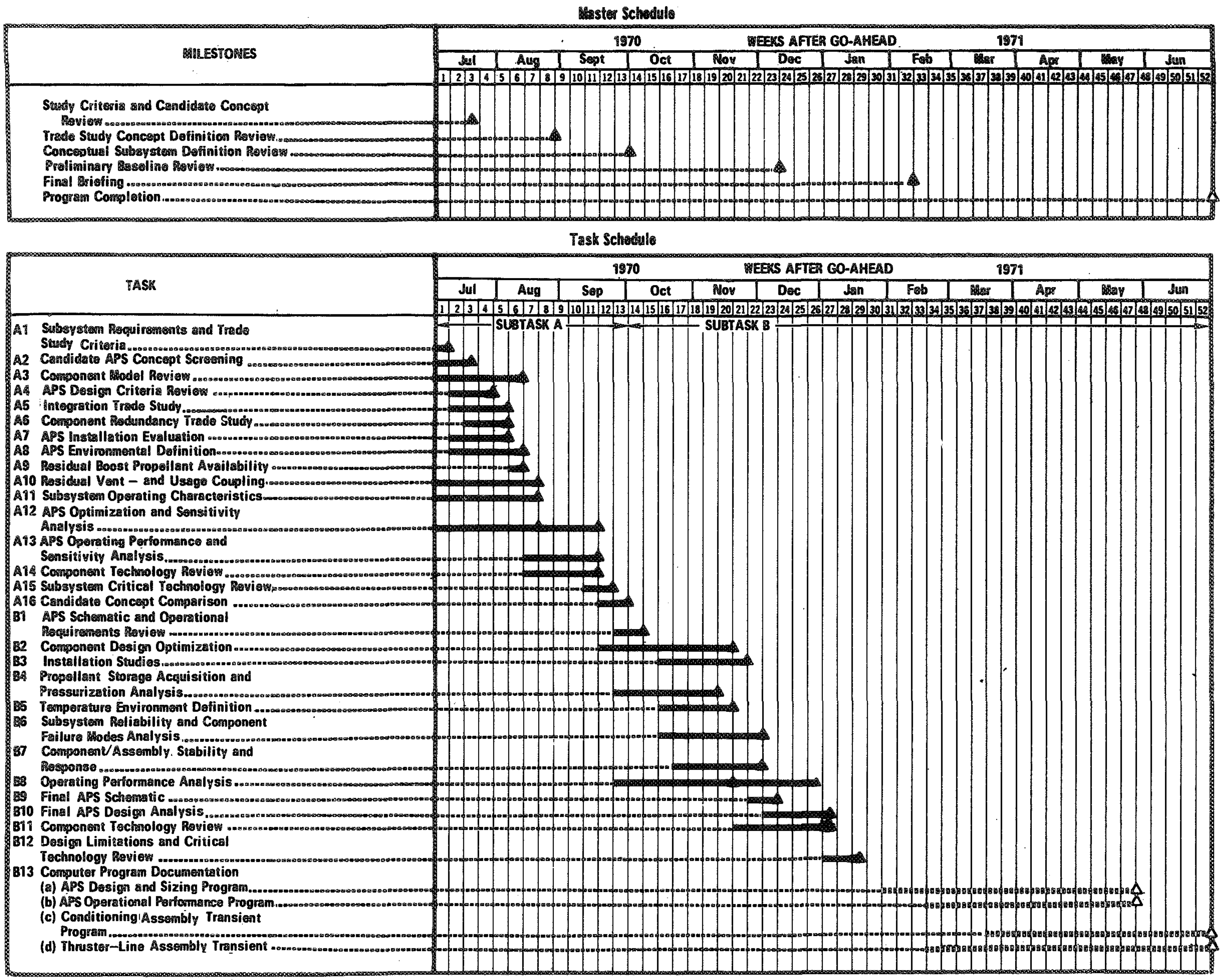

Master Schedule
MILESTONES
1970
WEEKS AFTER GO-AHEAD
1971
Jul
Aug
Sept
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52
Study Criteria and Candidate Concept Review
Trade Study Concept Definition Review
Conceptual Subsystem Definition Review
Preliminary Baseline Review
Final Briefing
Program Completion
Task Schedule
TASK
1970
WEEKS AFTER GO-AHEAD
1971
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52
SUBTASK A
SUBTASK B
A1 Subsystem Requirements and Trade Study Criteria
A2 Candidate APS Concept Screening
A3 Component Model Review
A4 APS Design Criteria Review
A5 Integration Trade Study
A6 Component Redundancy Trade Study
A7 APS Installation Evaluation
A8 APS Environmental Definition
A9 Residual Boost Propellant Availability
A10 Residual Vent – and Usage Coupling
A11 Subsystem Operating Characteristics
A12 APS Optimization and Sensitivity Analysis
A13 APS Operating Performance and Sensitivity Analysis
A14 Component Technology Review
A15 Subsystem Critical Technology Review
A16 Candidate Concept Comparison
B1 APS Schematic and Operational Requirements Review
B2 Component Design Optimization
B3 Installation Studies
B4 Propellant Storage Acquisition and Pressurization Analysis
B5 Temperature Environment Definition
B6 Subsystem Reliability and Component Failure Modes Analysis
B7 Component/Assembly Stability and Response
B8 Operating Performance Analysis
B9 Final APS Schematic
B10 Final APS Design Analysis
B11 Component Technology Review
B12 Design Limitations and Critical Technology Review
B13 Computer Program Documentation
(a) APS Design and Sizing Program
(b) APS Operational Performance Program
(c) Conditioning/Assembly Transient Program
(d) Thruster–Line Assembly Transient

FIGURE 2–3

3. SUBTASK A, CONCEPTUAL SUBSYSTEM DEFINITION

Subtask A sought, as its primary objective, to define the preferred high pressure APS approach. Concept screening studies were performed early in the program to define candidate APS concepts. Design analyses and intrasubsystem trade studies were performed to configure concepts to a parallel level of detail and to further screen the candidates to define the most attractive approaches. Resulting APS concepts were then compared on the basis of weight, simplicity, mission flexibility, and required new technology. The turbopump APS was selected for both orbiters and booster as the highest rated concept, and became the configuration defined for detail investigation during Subtask B.

3.1 Requirements - Subtask A APS requirements were defined by NASA prior to study initiation (Reference (f)). Four space shuttle vehicles were evaluated during this study phase. Both high and low crossrange orbiters and boosters were considered. These are illustrated in Figure 3-1. Included in Reference (f) were preliminary control and translation acceleration requirements. Various thruster sizing options were investigated for these acceleration requirements; then, APS control thrust levels and the number of control thrusters were established for each orbiter and booster. These are summarized in Figure 3-2. Shuttle mission timelines corresponding to the space station resupply/logistics mission were provided as a baseline mission for Subtask A comparisons.

Three modes of APS usage, representing varying degrees of +X maneuver capability, were investigated for the orbiter timeline. These were:

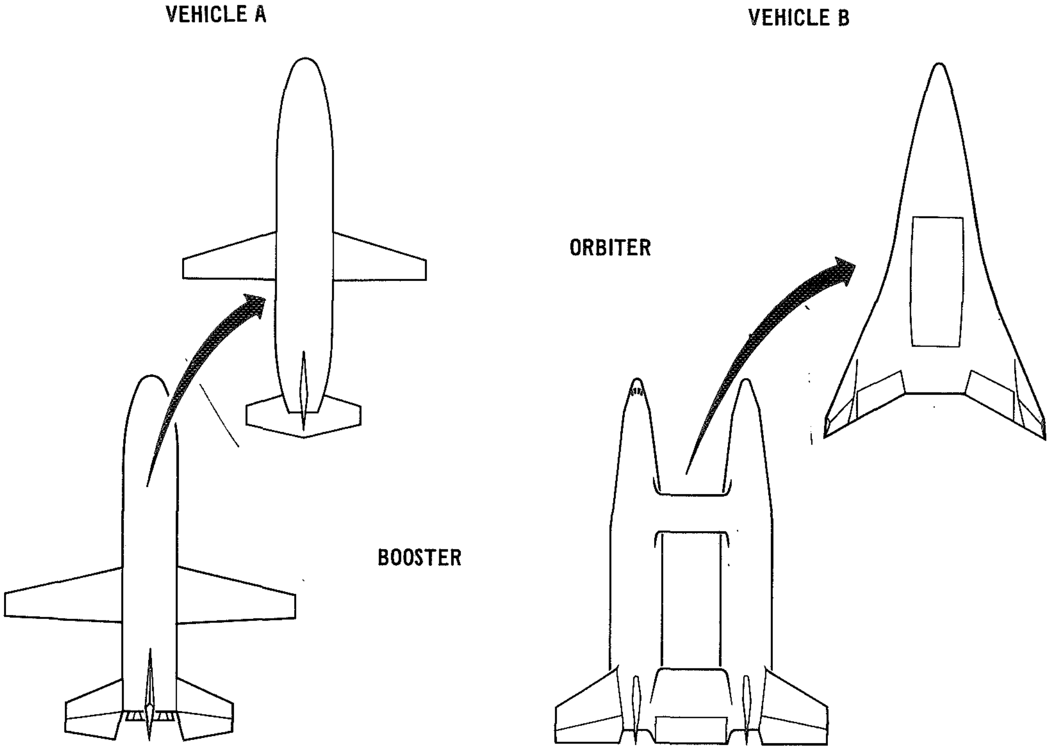
(1) APS capable of providing all maneuvers

(2) APS designed for +X maneuvers of $\leq$ 50 ft/sec only

(3) APS designed for +X maneuvers of $\leq$ 10 ft/sec only

For the last two operating modes, a separate orbit maneuvering subsystem (OMS) would be required for major +X maneuvers. Figure 3-3 illustrates the four vehicle configurations considred during this study phase, while Figure 3-2 summarizes APS total impulse requirements for both orbiters and boosters.

3.2 Trade Study Concepts - The orbiter and booster concept matrices of Figures 3-4 and 3-5 were established based on preliminary concept screening defined in Reference (a). A total of 50 possible APS options are identified. However, many of these options are associated with vehicle requirements. The principal variations to to be observed occur in the basic APS concept definition. As shown in Figure 3-4, there were three basic APS concepts to be considered for the orbiters. Similarly,



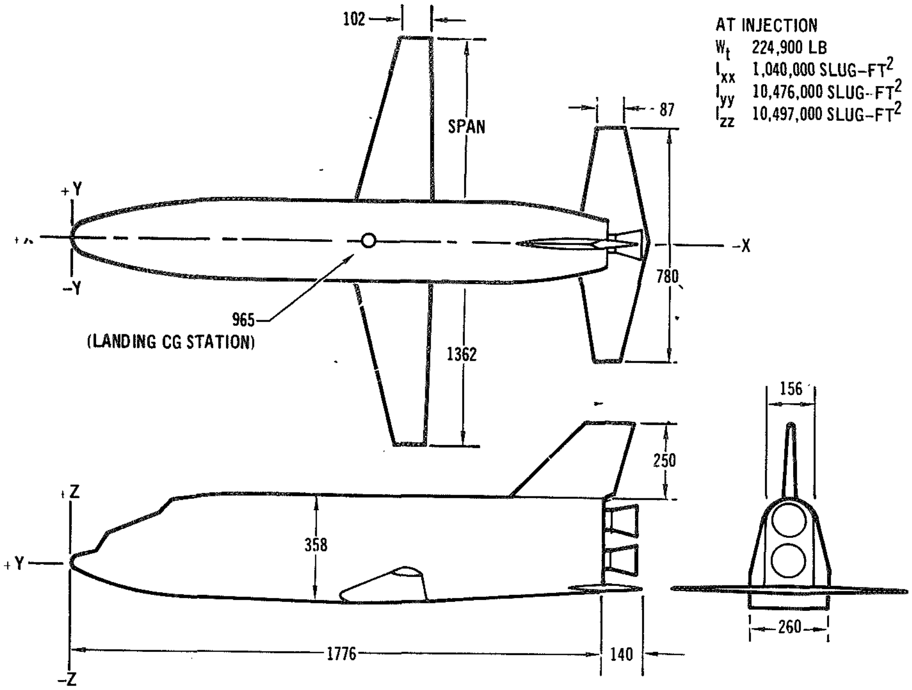
SUBTASK A VEHICLE CONFIGURATIONS

FIGURE 3-1

VEHICLE	THRUST LEVEL (LB)	NUMBER OF THRUSTERS	TOTAL IMPULSE (10^6 LB SEC)			
			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

REQUIREMENTS SUMMARY
Subtask A

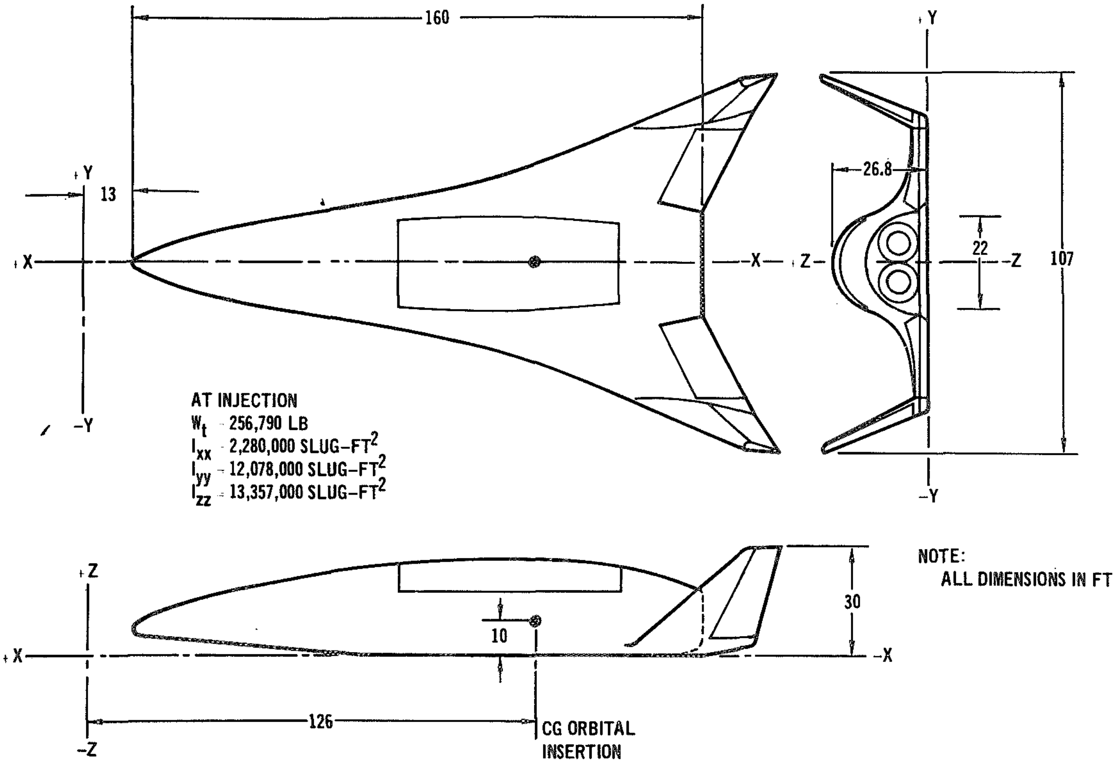
FIGURE 3-2



AT INJECTION
W_t 224,900 LB
I_{xx} 1,040,000 SLUG-FT^2
I_{yy} 10,476,000 SLUG-FT^2
I_{zz} 10,497,000 SLUG-FT^2

NOTE: ALL DIMENSIONS IN INCHES

ORBITER A – LOW CROSS RANGE

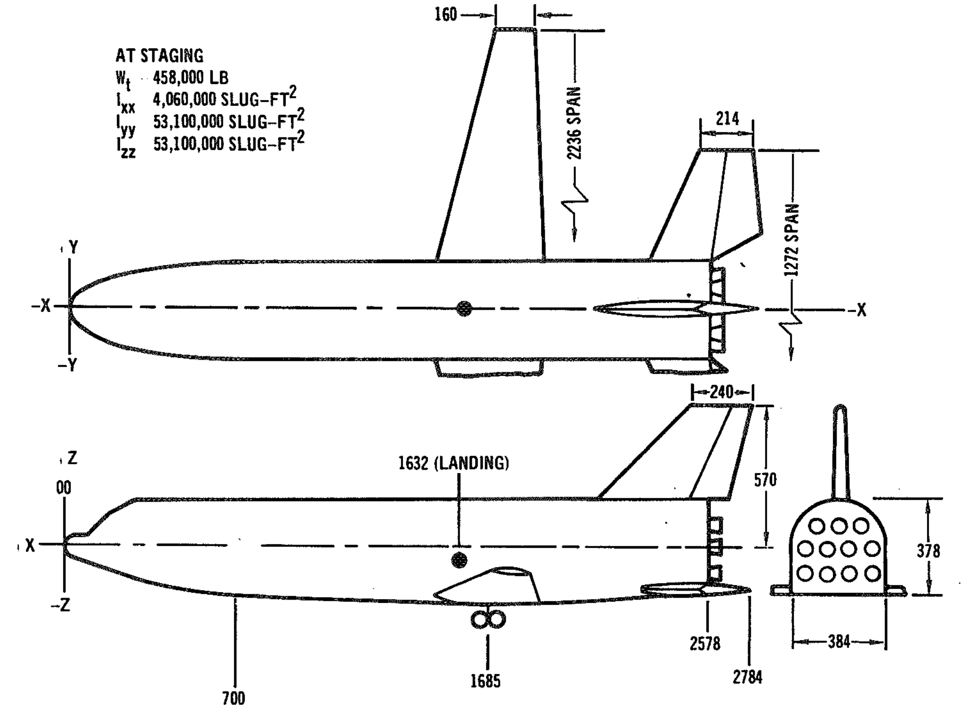


AT INJECTION
W_t 256,790 LB
I_{xx} 2,280,000 SLUG-FT^2
I_{yy} 12,078,000 SLUG-FT^2
I_{zz} 13,357,000 SLUG-FT^2

NOTE:
ALL DIMENSIONS IN FT

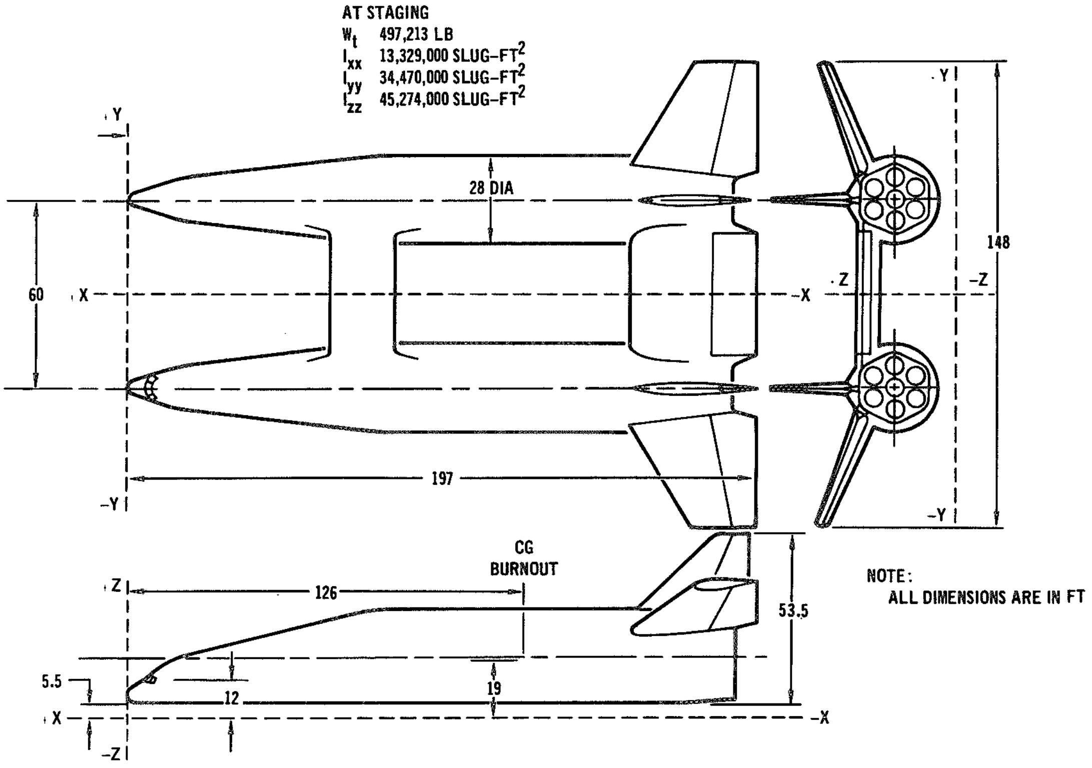
ORBITER B – HIGH CROSS RANGE

FIGURE 3-3



NOTE: ALL DIMENSIONS IN INCHES

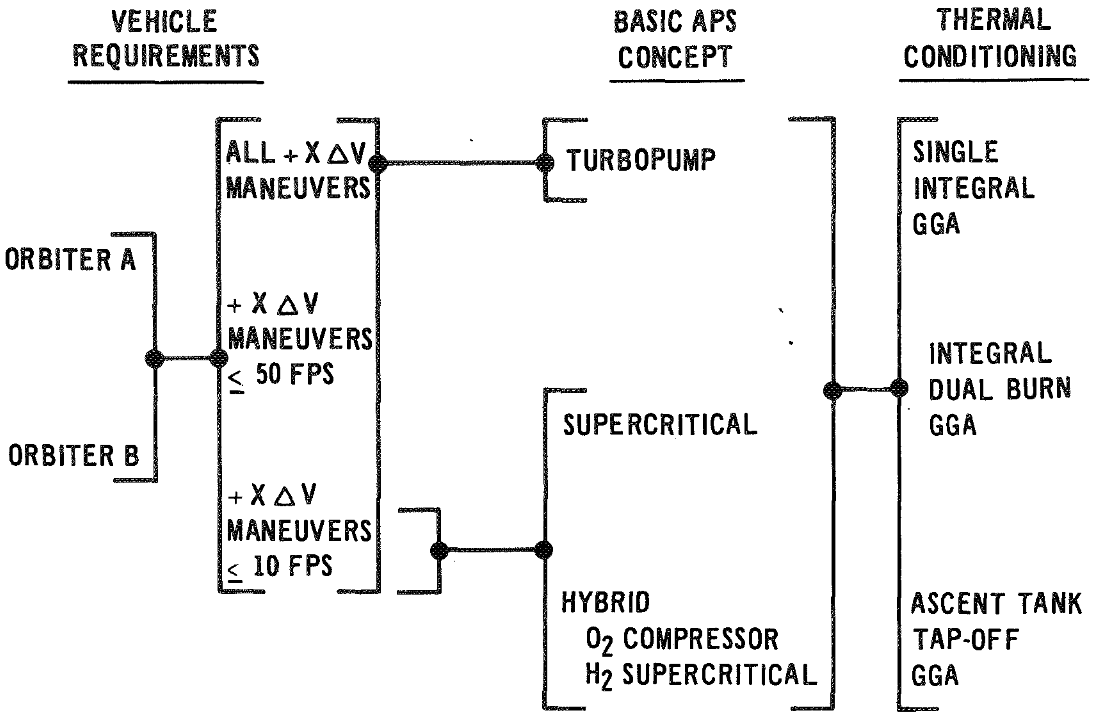
BOOSTER A - LOW CROSS RANGE



NOTE:
ALL DIMENSIONS ARE IN FT

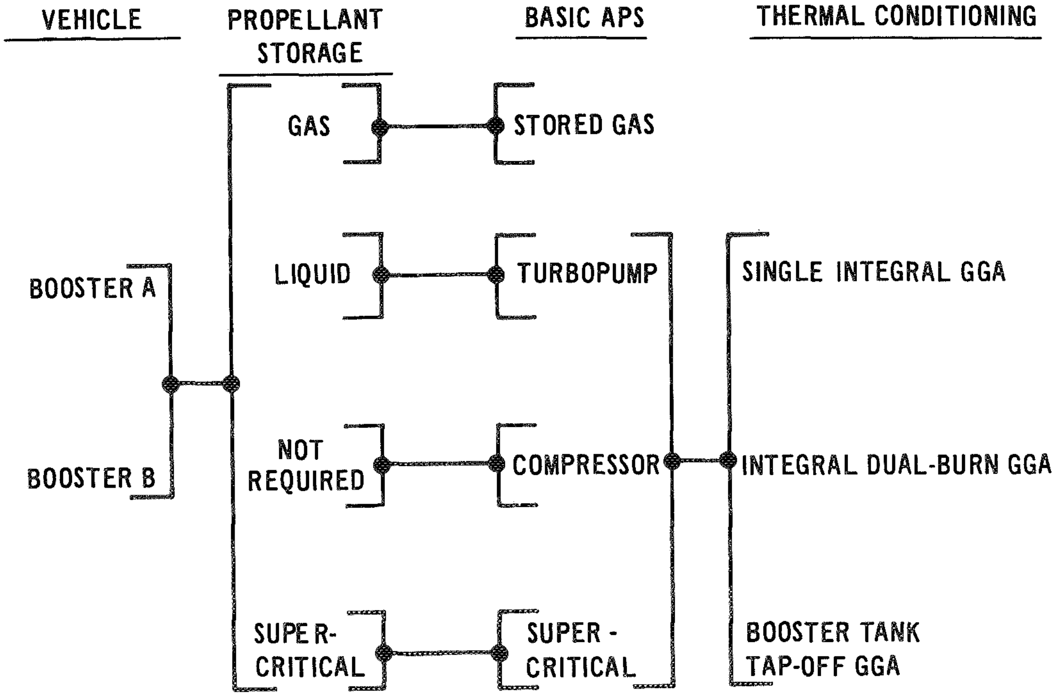
BOOSTER B - HIGH CROSS RANGE

FIGURE 3-3 CONTINUED



ORBITER CONCEPT MATRIX

FIGURE 3-4



BOOSTER CONCEPT MATRIX

FIGURE 3-5

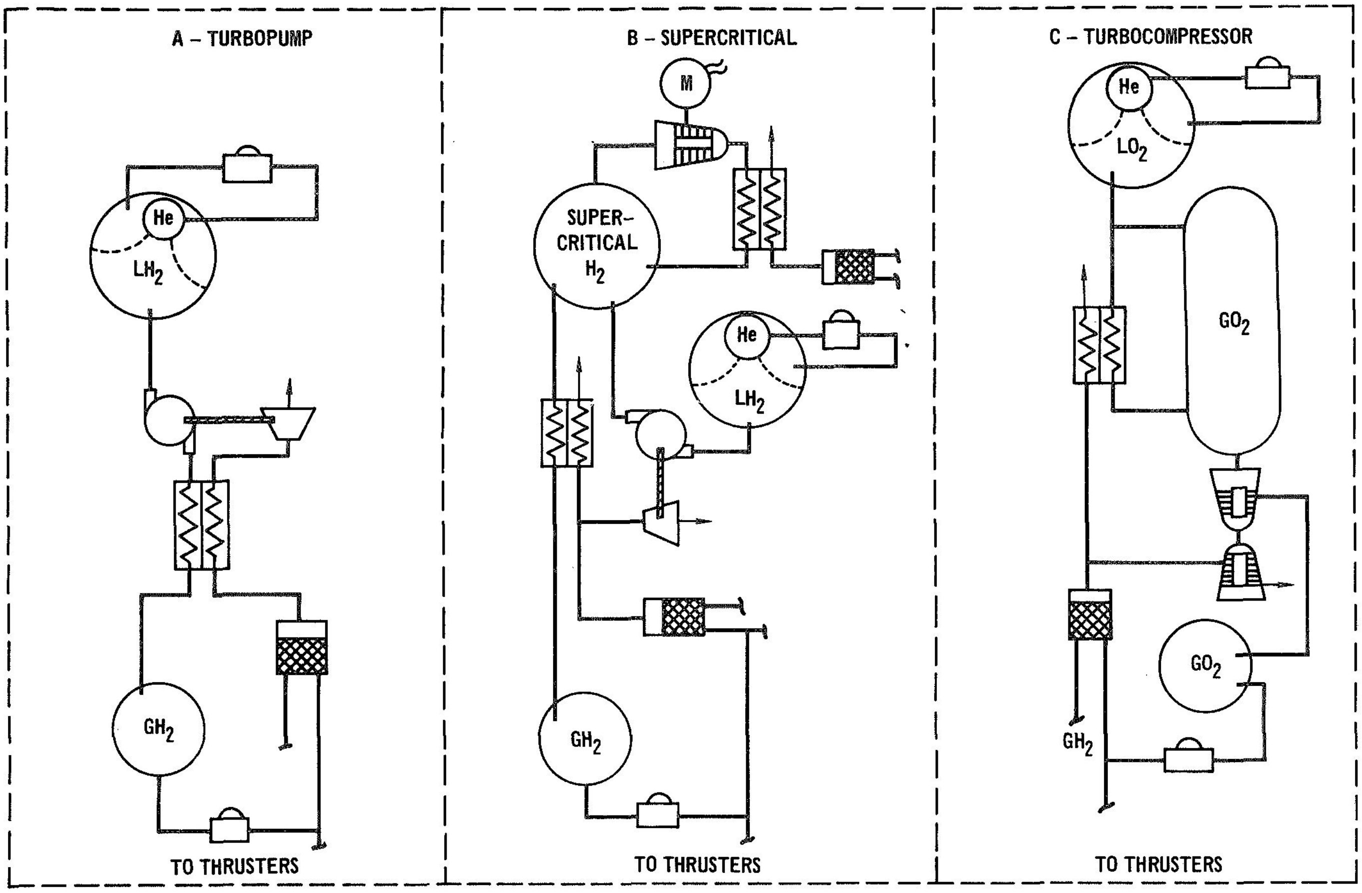
Figure 3-5 identifies four APS concepts considered for the boosters. For purposes of clarity, thermal conditioning was separated as an independent trade study, because alternate conditioner concepts have similar effects on the performance of different APS concepts.

Candidate orbiter concepts are illustrated in simplified schematics in Figure 3-6. For clarity, the schematics of Figure 3-6 have eliminated propellant control components such as valves and redundant components provided to satisfy failure criteria, and only one propellant side is shown. All concepts use accumulators to decouple conditioner assemblies from thrusters. These accumulators store a limited amount of gaseous propellants to allow thruster operation without starting the propellant conditioners (which operate only when accumulator pressure decays below a prescribed level).

3.2.1 Turbopump APS Concept - The basic turbopump APS concept is illustrated in Figure 3-6a. Propellant is stored as a liquid in a single tank containing both OMS and APS propellant supplies. Turbopump suction head requirements are provided by a cold helium pressurization subassembly. The turbopump subassembly increases propellant pressures to those required for subsystem operation, while the heat exchanger downstream of the turbopump provides thermal conditioning necessary to raise propellants to operating temperatures required for thruster operation. The conditioned propellant vapor is stored in an accumulator. A pressure regulator downstream of the accumulator controls pressure for both control thrusters and the gas generator. Energy for both thermal conditioning and turbopump operation are provided by a low mixture ratio, bipropellant gas generator.

3.2.2 Supercritical APS Concept - In the supercritical concept, the propellant is stored above critical pressures. Storage tank pressures in this subsystem concept are maintained by heat addition, which is provided by an external heat exchanger/circulation pump assembly (illustrated in Figure 3-6b). 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 from the low pressure liquid propellant storage tank. The subsystem incorporates a downstream heat exchanger to complete the thermal conditioning of the propellants to the temperatures required for thruster operation.

3.2.3 Hybrid APS Concept - 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 3-6c. In this concept, low pressure propellant vapor is extracted from



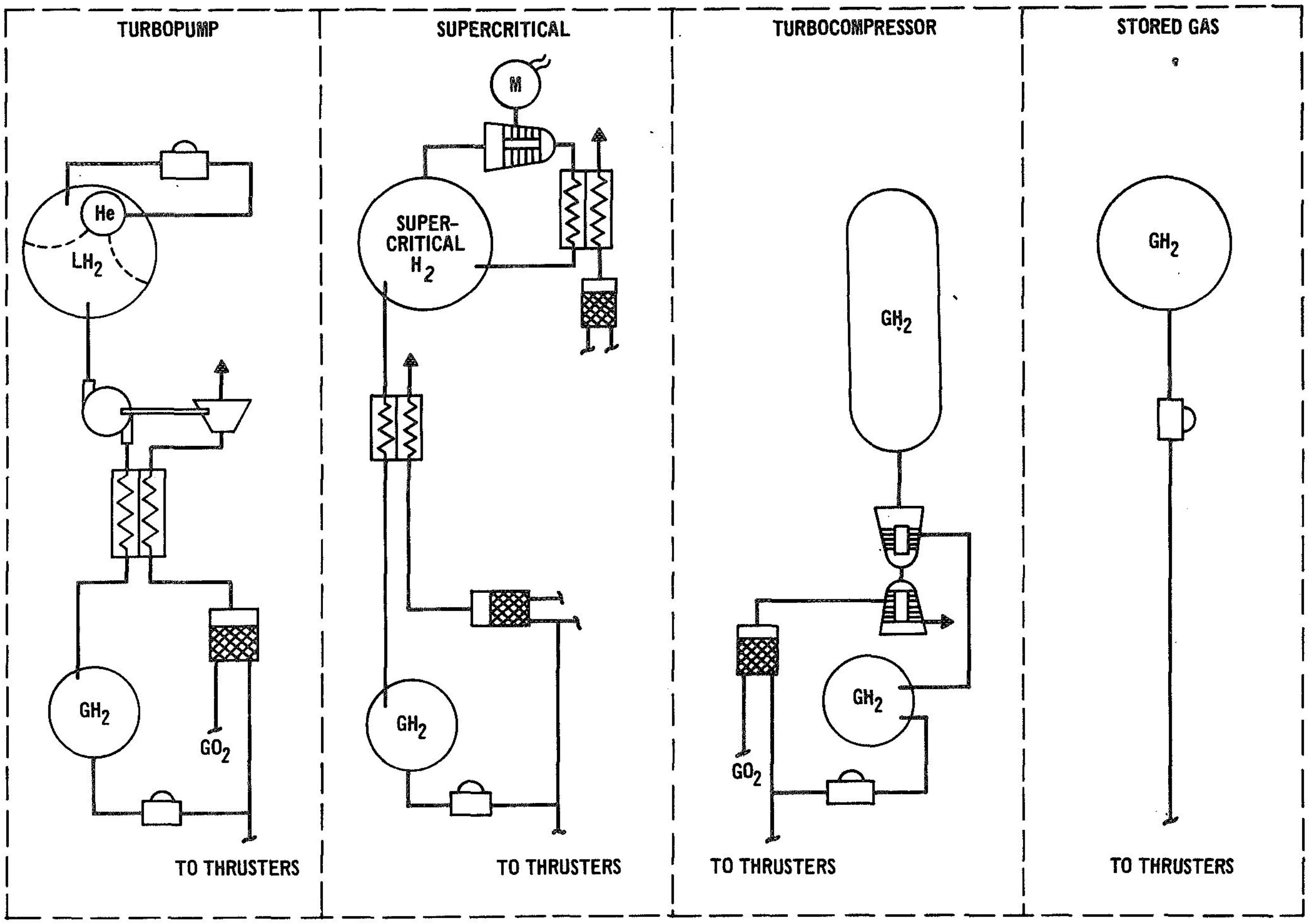
HYBRID SUBSYSTEM CONSISTS OF TURBOCOMPRESSOR O_2 SUBSYSTEM COMBINED WITH SUPERCRITICAL H_2 SUBSYSTEM

ORBITER APS CANDIDATE CONCEPTS

FIGURE 3-6

the main engine tanks and compressed in a turbocompressor to the pressure required for subsystem operation. No thermal conditioning downstream of the compressor is required since temperature rise due to compression is ample for thruster operation. The turbocompressor is powered by a gas generator similar to the turbopump concept design. Main engine propellant tanks do not contain sufficient propellant vapor for the entire mission, considering even the lowest total impulse requirement. Therefore, a separate propellant resupply tank is required to replenish the main engine tanks when pressure falls below a prescribed level. A gas generator provides energy required by the heat exchanger to precondition oxygen to a vapor state prior to main engine tank replenishment.

3.2.4 Booster APS Concepts - APS concepts considered for the booster are illustrated in Figure 3-7. The turbopump concept is identical for both boosters and orbiters. The supercritical concept for the booster is similar to that described for the orbiter with the exception that, since booster total impulse require-



BOOSTER APS CANDIDATE CONCEPTS FIGURE 3-7

ments are comparatively low, no resupply to the supercritical storage tank is required. In the booster, compressors were considered for both hydrogen and oxygen propellant supplies. The single difference between the booster and orbiter turbocompressor concepts is that the booster requires no auxiliary resupply propellant, since ample residual propellant vapors remain after booster main engine cutoff to satisfy mission total impulse requirements. Also considered for the booster was a simple stored gas bipropellant APS concept. In this concept, operation is similar to a conventional cold gas attitude control system, except that hydrogen and oxygen are burned as bipropellants. Gaseous propellants are stored at high pressure and regulated to the pressures required for thruster operation.

3.2.5 Conditioning Assembly Selection - As shown in Figures 3-4 and 3-5, there are a number of alternates available for conditioner implementation. Three thermal conditioning concepts are shown in Figure 3-4:

(1) single integral gas generator assembly

(2) integral dual burn or staged combustion gas generator assembly

(3) main ascent tank tap-off cycle

In addition, each concept can be implemented somewhat differently with regard both to their operating temperatures and to use of the vent gas from the conditioners for additional impulse. The total impulse required by the APS was the driving influence on selection of a conditioner approach. For those subsystems used in the all-maneuver case, a conditioning assembly tailored to provide the maximum possible performance was desirable, providing, as it did, very significant weight advantages. For this reason, an assembly using a high temperature single integral gas generator in conjunction with a propulsive vent was selected for both orbiters in the all-maneuver class. At the lower impulse levels, the advantages of high performance in the conditioner assembly were less significant and, since only a small fraction of the the impulse could be provided by a propulsive vent, the propulsive vent was not desirable. For the ≤ 50 ft/sec velocity allocation, a high temperature single integral gas generator without a propulsive vent was selected. For the ≤ 10 ft/sec class, a single integral gas generator operating at 2000°R without propulsive vent was selected.

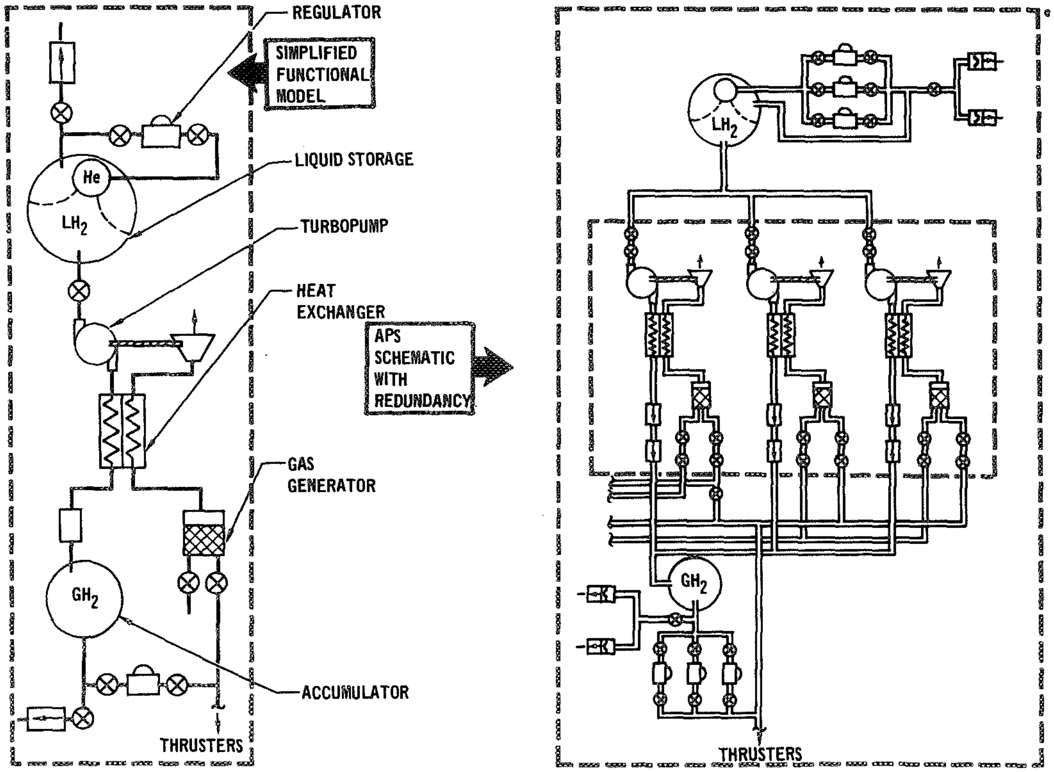
Using the conditioner concepts identified above, APS concept matrices of Figures 3-4 and 3-5 reduce to a total of 18 concept alternates. These alternates, together with their associated maneuver levels and vehicle elements, are tabulated in Figure 3-8. Figure 3-8 thus forms the complete list of subsystems compared in Subtask A after all screening had been completed.

3.3 <u>Trade Study Results</u> - The 18 concepts identified in Figure 3-8 were compared on the basis of subsystem weight, technology, simplicity, and flexibility to changes in requirements. Detail subsystem schematics were developed to identify the number of components within each subsystem, and to establish overall subsystem weight. Simple line schematics describing the concepts were expanded to incorporate component redundancy necessary to satisfy shuttle failure criteria. A typical example is shown in Figure 3-9 for a portion of a turbopump subsystem. Weight and performance models were developed over a parametric range for each component and subassembly. Using these parametric data, analyses defined subsystem weight and the most desirable design operating points. Figure 3-10 exemplifies weight sensitivity to design variables and Figure 3-11 shows weight sensitivity to APS requirements. Figure 3-12 provides a summary of APS design points and weights as developed by these analyses. When optimum or desired design points had been established, the subsystems were judged according to the study selection criteria. These criteria

IDENTIFIER:	VEHICLE/APS TYPE/VELOCITY LEVEL		
VEHICLE	APS TYPE	VELOCITY LEVEL	IDENTIFICATION
ORBITER A	TURBOPUMP	ALL +X MANEUVERS	OA/TP/ALL
		+X MANEUVERS ≤ 50 FPS	OA/TP/50 FPS
		+X MANEUVERS ≤ 10 FPS	OA/TP/10 FPS
	SUPERCRITICAL		OA/SC/10 FPS
	HYBRID		OA/HY/10 FPS
ORBITER B	TURBOPUMP	ALL +X MANEUVERS	OB/TP/ALL
		+X MANEUVERS ≤ 50 FPS	OB/TP/50 FPS
		+X MANEUVERS ≤ 10 FPS	OB/TP/10 FPS
	SUPERCRITICAL		OB/SC/10 FPS
	HYBRID		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

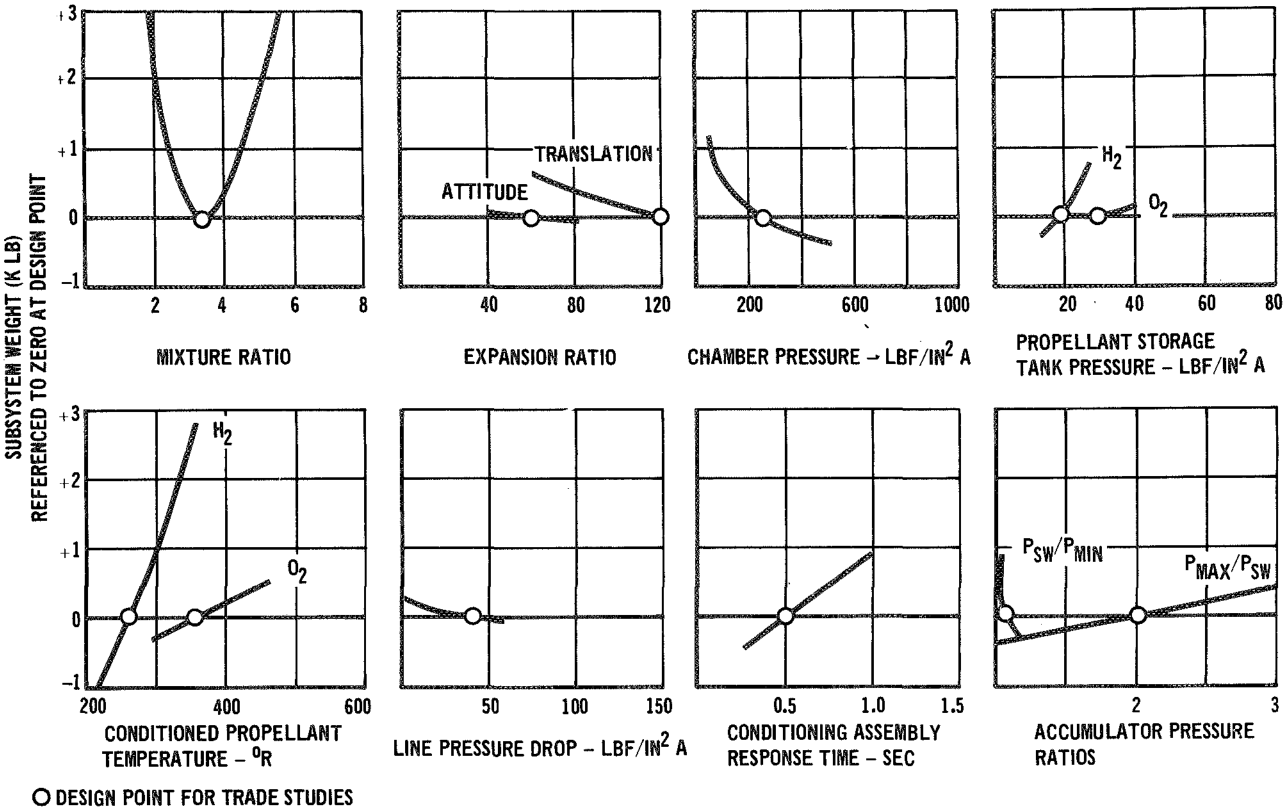
APS CONCEPT IDENTIFICATION

FIGURE 3–8



TYPICAL TURBOPUMP APS SCHEMATIC
(Hydrogen Side)

FIGURE 3–9



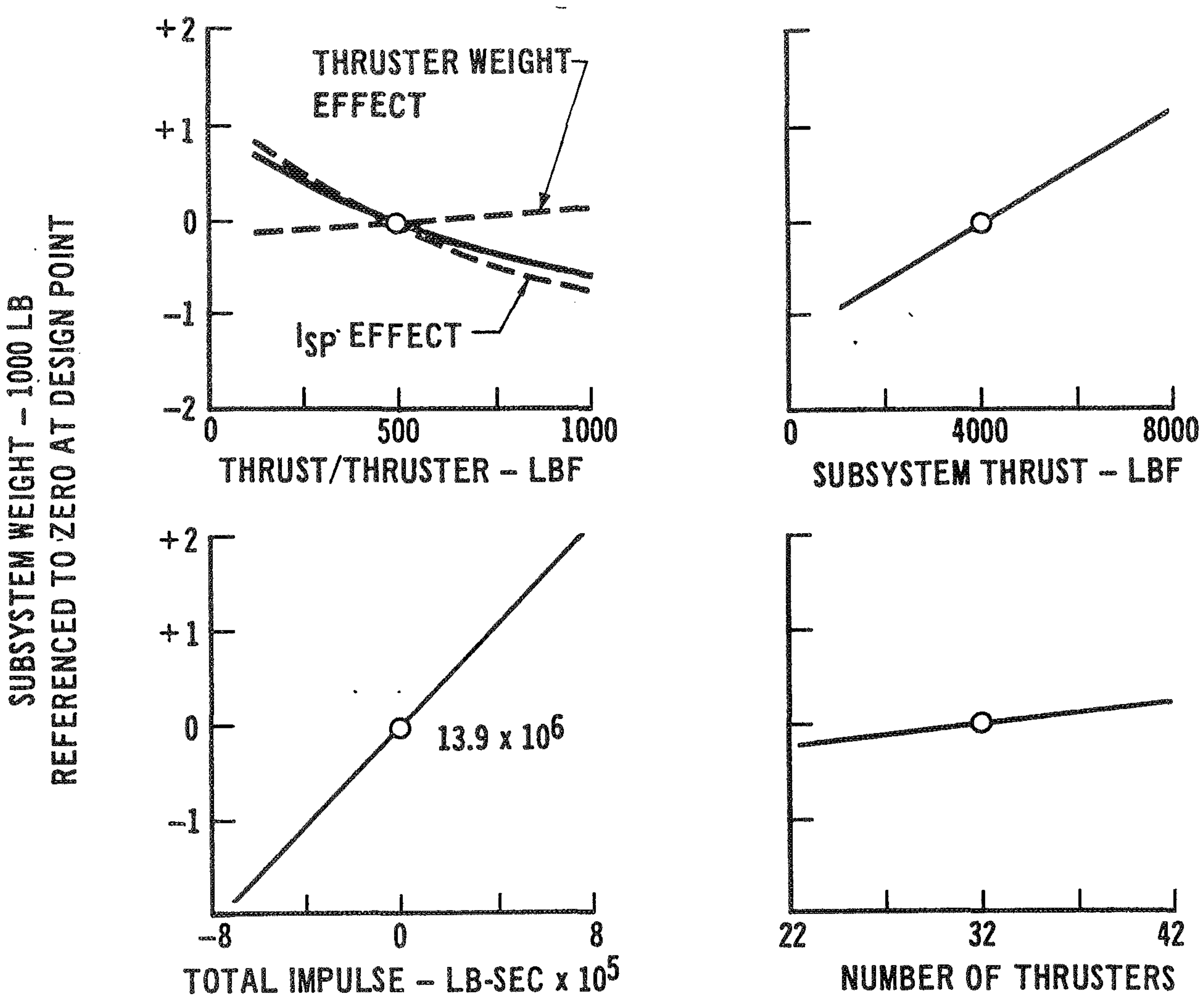
WEIGHT SENSITIVITY TO DESIGN VARIABLES

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

FIGURE 3-10

are identified in Figure 3-13, together with the weighting applied to each criterion and the assessment rationale. The following paragraphs provide a summary of this assessment, and paragraph 3.4 provides a comparison of alternate APS concepts.

3.3.1 APS Weight Comparison - Figures 3-14, 3-15 and 3-16 show the weights developed for each APS concept at the design points listed in Figure 3-12. Figure 3-14 shows a comparison of the turbopump subsystems at the various maneuver levels for both oribiters. Obviously additional weight, to account for an OMS subsystem, must be included before a rational decision based on weight could be made regarding the best maneuver velocity allocation for the APS. Evaluation of OMS weight was not a part of this contract effort, and comparison of APS for different velocity levels is made exclusive of weight. Only technology, simplicity and flexibility are compared. Figure 3-15 provides a comparison of the three alternate orbiter concepts at a common maneuver level, and forms a valid weight comparison for the alternate APS concepts. As shown, the turbopump subsystem is the lightest weight for both orbiters. Figure 3-16 compares the four alternate booster concepts for both boos-



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

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

FIGURE 3-11

ters. Again, as is true for the orbiters, the turbopump subsystem is the lightest weight for both boosters.

3.3.2 APS Technology Critique - Each of the candidate APS concepts was evaluated to provide an assessment of the technology considerations which would influence concept selection. Figure 3-17 identifies the common technology considerations, associated with a turbopump subsystem, which apply to all maneuver levels. It also identifies those factors which would impact concept selection at the various maneuver levels. The principal difference between maneuver levels is the conditioner assembly design. At high maneuver velocity levels, performance advantages of high performance conditioner assemblies are quite pronounced, and technology extensions are warranted.

	THRUSTER		ϵ	FEED ASSEMBLY		CONDITIONER		NO. OF CYCLES	ACCUMULATOR		WEIGHT
	M_R	P_C		ΔP_{LINE}	$P_{T_{H_2}}/P_{T_{O_2}}$	T_{H_2}/T_{O_2}	ΔT		$\frac{P_{MAX}}{P_S}$ O_2/H_2	$\frac{P_S}{P_{MIN}}$ O_2/H_2	
ORBITER A: (32 THRUSTERS – 500 LB THRUST)											
ALL MANEUVERS – TURBOPUMP (13,912,000 LB-SEC)	3.5	250	60/120	40	19/30	260/360	0.5	35 + 15 = 50	2	1.09/1.11	38,157
≤ 50 FPS – TURBOPUMP (2,968,000 LB-SEC)	3.8	250	60	40	19/30	260/360	0.5	50	2	1.09/1.11	10,511
≤ 10 FPS – TURBOPUMP (1,485,000 LB-SEC)	4.0	250	60	40	19/30	260/360	0.5	50	2	1.09/1.11	6,915
– SUPERCRITICAL	4.0	200	60	25	25/30	260/360	0.5	120 + 15 = 135	1.5/1.4	1.3	8,164
– HYBRID	4.0	100	60	35	19/45	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)	3.5	500	60/120	50	19/35	260/360	0.5	50	2	1.15/1.21	42,782
≤ 50 FPS – TURBOPUMP (3,449,000 LB-SEC)	3.8	500	60	50	19/35	260/360	0.5	50	2	1.15/1.21	11,771
≤ 10 FPS – TURBOPUMP (1,707,000 LB-SEC)	4.0	500	60	50	19/35	260/360	0.5	50	2	1.15/1.21	7,670
– SUPERCRITICAL	4.0	200	60	25	25/30	260/360	0.5	120 + 15 = 135	1.5/1.4	1.3	9,918
– HYBRID	4.0	100	60	35	19/40	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	5.0	500	40	40	25/35	260/360	0.5	50	2	1.6	3,929
– SUPERCRITICAL	5.5	200	40	25	N/A	260/360	0.5		1.5/1.4	1.3	6,696
– TURBO-COMPRESSOR	6.0	17.5	10	3	N/A	N/A	1.5		1.2	2.2	5,000
– STORED GAS	6.0	100	60	30	N/A	210/350 (FINAL TEMP AFTER BLOWDOWN)	N/A	N/A	5	N/A	11,541
BOOSTER B: (16 THRUSTERS – 2000 LB THRUST 475,000 LB-SEC)											
– TURBOPUMP	5.0	500	40	40	25/35	260/360	0.5	50	2	1.6	3,316
– SUPERCRITICAL	5.5	200	40	25	N/A	260/360	0.5		1.5/1.4	1.3	5,543
– TURBO-COMPRESSOR	6.0	13.5	10	3	N/A	N/A	1.5		1.2	2.2	6,100
– STORED GAS	6.0	125	60	30	N/A	210/350	N/A	N/A	6	N/A	10,248

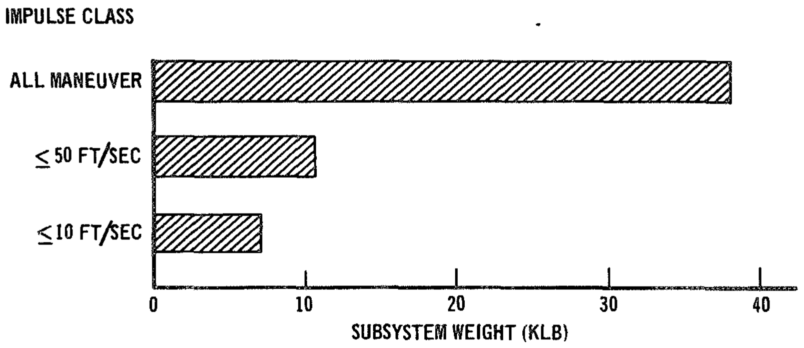
HIGH PRESSURE APS SUMMARY

FIGURE 3–12

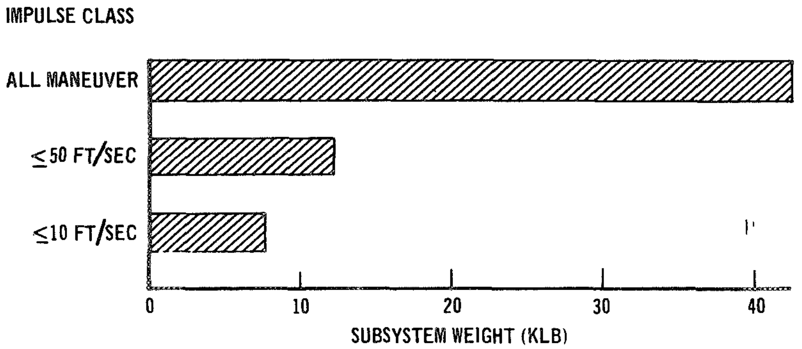
SELECTION CRITERIA	WEIGHTING (% OF TOTAL)	RATIONALE TO BE USED FOR WEIGHTING
TECHNOLOGY REQUIRED	0 – 25	WEIGHTING BASED ON ENGINEERING JUDGMENT OF DEVELOPMENT RISK, SCALING FROM STATE-OF-THE-ART THROUGH EXTENSION OF AN EXISTING TECHNOLOGY BASE TO COMPLETELY NEW CONCEPTS OR APPROACHES, AND ON DEVELOPMENT 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 3–13



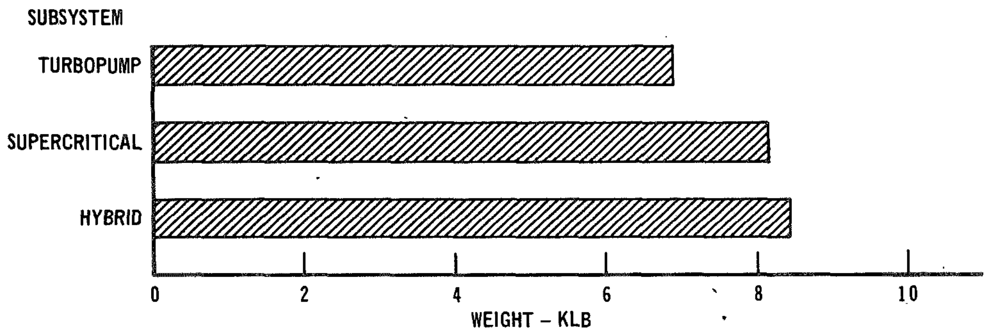
Orbiter A



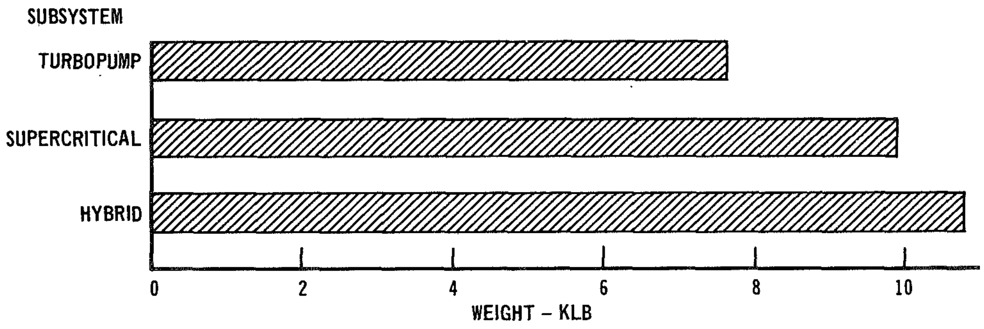
Orbiter B

TURBOPUMP APS WEIGHT COMPARISON

FIGURE 3–14



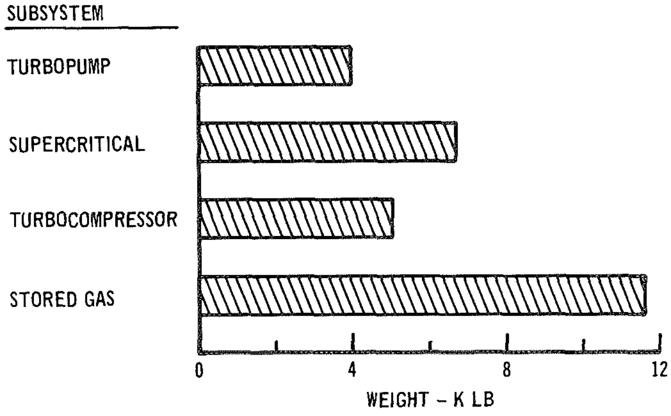
ORBITER A



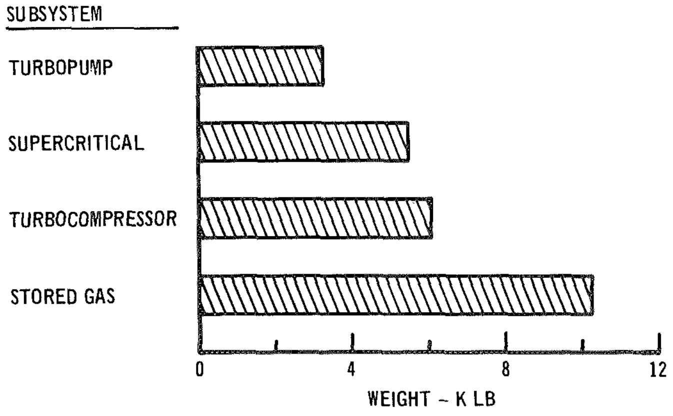
ORBITER B

APS WEIGHT COMPARISON ($\leq$10 FT/SEC)

FIGURE 3–15



Booster A



Booster B

APS WEIGHT COMPARISON
BOOSTERS

FIGURE 3–16

<table>
<tr><th>ALL MANEUVERS</th><th>≤ 50 FPS</th><th>≤ 10 FPS</th></tr>
<tr><td colspan="2">FACTORS WHICH IMPACT CONCEPT SELECTION</td><td></td></tr>
<tr><td>• 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</td><td>• HIGH TEMPERATURE – COOLED GAS GENERATOR DESIGN
• HEAT EXCHANGER SHELL AND TUBE SUPPORT COOLING DESIGN
• GG PROPELLANT SEQUENCING AND CONTROL DURING CONDITIONER TRANSIENTS</td><td></td></tr>
<tr><td colspan="3">COMMON TECHNOLOGY CONSIDERATIONS
• 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)</td></tr>
</table>

TECHNOLOGY CRITIQUE
Orbiters/Turbopump
FIGURE 3-17

Figure 3-18 compares different APS concepts at a fixed maneuver velocity level. Again, tehcnology is separated into common technology considerations and factors which impact APS concept selection. For the turbopump, the primary technology differences are associated with design of a rapid spin-up, multi-cycle turbopump, and design of the liquid positive propellant positioning device. For the supercritical subsystem, no propellant positioning is required, but this subsystem does require a more complex conditioner assembly design. The conditioner inlet temperatures vary markedly, and the conditioner must be highly throttleable to accommodate varying conditioning requirements. The hybrid concept has a number of technological disadvantages. All considerations applicable to the supercritical concept apply to the hybrid. In addition, it requires technology improvements in turbocompressor design and performance, as well as the additional technology associated with the propellant resupply assembly.

TURBOPUMP	SUPERCRITICAL	HYBRID
FACTORS WHICH IMPACT CONCEPT SELECTION		
• 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	• CONDITIONER CONTROL AND SENSORS TO MAINTAIN ACCUMULATOR INLET TEMPERATURE • HIGHLY THROTTABLE GG • HOT GAS VALVE DESIGN FOR MULTI-CYCLE OPERATION	• SAME COMMENTS AS SUPER-CRITICAL • CONTROL OF THRUSTER O/F • WARM GAS THRUSTER VALVE AND REGULATOR DESIGN FOR GO_2 • TURBOCOMPRESSOR DESIGN FOR FAST RESPONSE, MULTICYCLE OPERATION AND WIDE VARIANCE IN OPERATING CONDITIONS • TURBOCOMPRESSOR INLET DESIGN • MAIN ASCENT TANK PRESSURE CONTROL ASSEMBLY DESIGN • DESIGN OF PASSIVE TWO – PHASE HEAT EXCHANGER ASSEMBLY FOR OXYGEN RESUPPLY
COMMON TECHNOLOGY CONSIDERATIONS		
• 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, $\leq$ 10 FPS

FIGURE 3–18

Figure 3-19 compares the various booster APS concepts. In all cases, technology requirements are relaxed for the boosters. Turbopump cycle life is significantly reduced, as is propellant tank size and (hence) the size of the propellant positioning device. With the supercritical concept, no resupply is required; hence, technology requirements are also relaxed. In the case of the turbocompressor, 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 as all components are state-of-the-art.

3.3.3 <u>APS Simplicity Critique</u> - Figures 3-20 and 3-21 summarize unique advantages and disadvantages of various APS concepts, in relation to inherent subsystem simplicity and management of subsystem development. Comparing turbopump subsystem simplicity (Figure 3-20) across maneuver levels shows that there are only minimal differences in the subsystems. Figure 3-20 also compares the three orbiter con-

TURBOPUMP	SUPERCRITICAL	TURBOCOMPRESSOR	STORED GAS
FACTORS WHICH IMPACT CONCEPT SELECTION			
• RAPID SPIN-UP CRYOGENIC COOLED/LUBED BEARING LIFE • TURBOPUMP DYNAMIC SEAL LIFE • DESIGN AND TEST OF MODERATE SIZE, LOW G POSITIVE PROPELLANT POSITIONING DEVICE	• CONDITIONER CONTROLS AND SENSORS TO MAINTAIN ACCUMULATOR INLET TEMPERATURE • HIGHLY THROTTABLE GAS GENERATOR	• LARGE TURBOCOMPRESSOR DESIGN FOR FAST RESPONSE • TURBOCOMPRESSOR INLET DESIGN	
COMMON TECHNOLOGY CONSIDERATIONS • ACCURATE, HIGH FLOW, LOW PRESSURE DROP PRESSURE REGULATORS			

BOOSTER TECHNOLOGY CRITIQUE

FIGURE 3–19

SUBSYSTEM	UNIQUE DISADVANTAGES	UNIQUE ADVANTAGES
TURBOPUMP ALL MANEUVER	• CONTROL AND SEQUENCING OF GG DURING CONDITIONER TRANSIENTS • CONTROL OF PROPULSIVE VENT FOR +X MANEUVERS	• –
≤ 50 FPS	• CONTROL AND SEQUENCING OF GG DURING CONDITIONER TRANSIENTS	• –
≤ 10 FPS	• –	• –
≤ 10 FPS TURBOPUMP	• CONTROL AND SEQUENCING DURING PUMP STARTUP • COMPLEXITY ASSOCIATED WITH PUMP COOLING DURING SHUTDOWN AND NON-USE PERIODS	• MINIMUM NUMBER OF SUBSYSTEM COMPONENTS • MOST STRAIGHT FORWARD COMPONENT INTEGRATION AND MANAGEMENT OF DEVELOPMENT • SIMPLEST CONTROL REQUIREMENT
SUPERCRITICAL	• 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	• NO PROPELLANT POSITIONING • SIMPLIFIED DYNAMIC COMPONENT OPERATION
HYBRID SUPERCRITICAL H_2 TURBOCOMPRESSOR O_2	• SAME AS ABOVE SUPERCRITICAL • PROPELLANT POSITIONING REQUIRED • COMPLEX VEHICLE INTERFACE • PRECONDITIONING OF PROPELLANT RESUPPLY INCREASES CONTROL AND OPERATIONAL COMPLEXITY	• SAME AS ABOVE SUPERCRITICAL

ORBITER SIMPLICITY CRITIQUE

FIGURE 3–20

SUBSYSTEM	DISADVANTAGES	ADVANTAGES
TURBOPUMP	• CONTROL AND SEQUENCING DURING PUMP STARTUP	• STRAIGHTFORWARD COMPONENT INTEGRATION AND MANAGEMENT OF DEVELOPMENT
SUPERCRITICAL	• MAXIMUM NUMBER OF SUBSYSTEM COMPONENTS • MAXIMUM CONDITIONER ASSEMBLY CONTROL COMPLEXITY • MOST COMPLEX COMPONENT INTEGRATION • VERY COMPLEX IN TERMS OF DEVELOPMENT MANAGEMENT	• NO PROPELLANT POSITIONING • SIMPLIFIED DYNAMIC COMPONENT OPERATION
TURBOCOMPRESSOR	• PROPELLANT POSITIONING REQUIRED • COMPLEX VEHICLE INTERFACE	• PROPELLANT STORAGE NOT REQUIRED
STORED GAS		• MINIMUM NUMBER OF SUBSYSTEM COMPONENTS • MINIMUM OF COMPONENT INTEGRATION • SIMPLEST CONTROL REQUIREMENT

BOOSTER SIMPLICITY CRITIQUE

FIGURE 3-21

cepts at a fixed maneuver velocity level. Relative to other APS concepts, the turbopump concept is appreciably simpler and offers the 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, it is by far the most complex in terms of subsystem management during development. However, the supercritical subsystem offers significant advantages in that there is no rotating machinery and no propellant positioning required. Figure 3-21 provides a critique of simplicity considerations for the boosters. As is clear from the figure, the stored gas subsystem is the simplest, and has an appreciable number of advantages relative to the other subsystems.

3.3.4 APS Flexibility to Changes in Requirements - APS flexibility to requirement changes was adjudged on the basis of data similar to those shown in Figure 3-11. Considered were changes in subsystem weight associated with changes in thruster thrust, total subsystem thrust, total impulse and number of APS thrusters. Quantitative sensitivities were determined for each APS concept and ratings were based on these values. The turbopump subsystems are the least sensitive to changes in requirements, and provide the greatest flexibility potential. Point ratings are summarized on the final rating charts shown in Figures 3-22, 3-23, and 3-24.

3.4 Concept Comparisons and Selections - Using the data provided in Paragraph 3.3 total point ratings were established for each of the 18 candidate concepts. These results are summarized in Figures 3-22, 3-23, and 3-24. Figure 3-22 provides a comparison of turbopump subsystems at the three maneuver velocity levels. Weight is not considered, for reasons noted in Paragraph 3.3.1. Based on the other selection criteria, the all-maneuver class APS provides the highest total point rating and, since the other criteria would only be degraded by addition of an OMS system, it is the best maneuver velocity application from the standpoints of technology,

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 3-22

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 3–23

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 3–24

simplicity and flexibility. Figure 3-23 compares 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 the boosters (as shown in Figure 3-24). Thus, on the basis of all selection criteria, the turbopump subsystem was shown by this study to be the best candidate for Subtask B preliminary design. The all-maneuver class APS was also selected for the orbiters.

4. SUBTASK B - PRELIMINARY DESIGN

4.1 APS Requirements - APS thrust level and total impulse were defined during Subtask A effort for the vehicle configurations, design characteristics, and acceleration requirements defined in the Space Shuttle Vehicle Description and Requirements Document (Reference (d)). Subsequently, revisions were made to this document, requiring an updating of the APS requirements for Subtask B. These revisions included changes to vehicle configuration, increased acceleration requirements, and refined mission timelines. Three vehicle configurations, two orbiters, and one booster were evaluated during Subtask B. These vehicles are illustrated in Figures 4-1 through 4-3.

A detailed evaluation of APS thrust level, total impulse, and number of thrusters for the Subtask B study phase was made. Options available within the constraints imposed by the vehicle acceleration requirements and vehicle configuration were compared to establish those installation and thruster characteristics which would provide minimum APS weight. Thrust levels and number of thrusters resulting are summarized in Figure 4-4. As shown, a common thrust level of 1850 lb was selected for both orbiters and the booster.

In Subtask A, three levels of APS +X maneuvering capability were investigated for the orbiters. These were:

(1) APS designed to perform all orbiter +X maneuvering functions
(2) APS designed to perform +X velocity changes $\leq$ 50 ft/sec
(3) APS designed to perform +X velocity changes of $\leq$ 10 ft/sec.

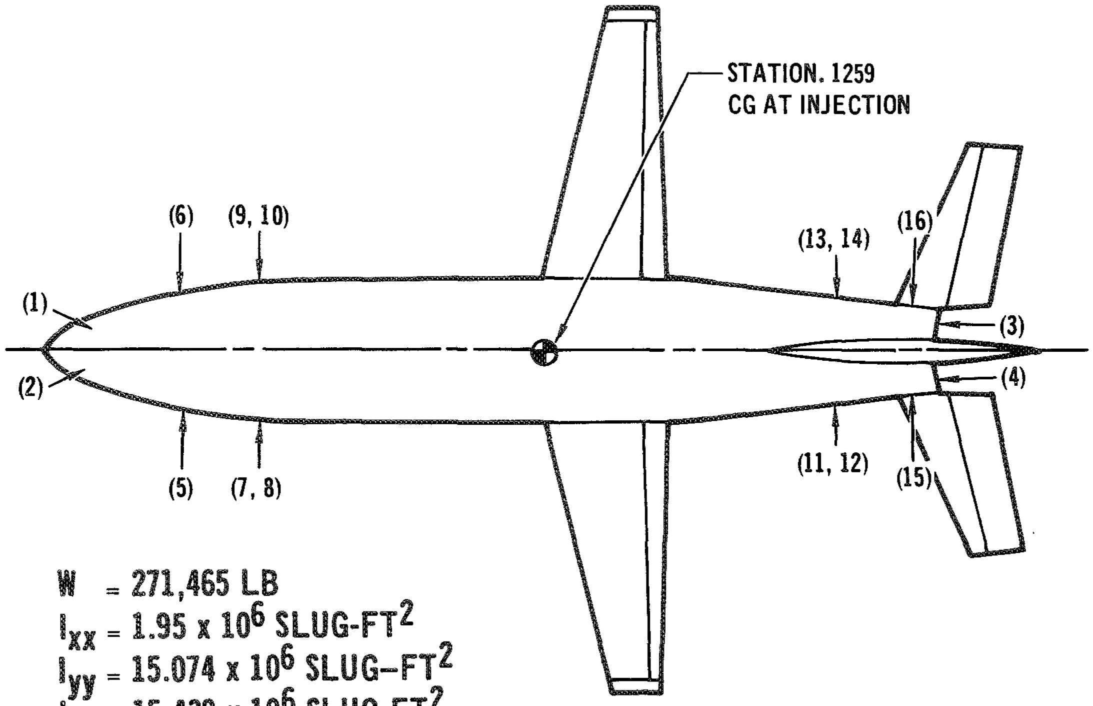
In the last two cases, a separate orbit maneuvering subsystem (OMS) would be required for major +X translation maneuvers with velocity changes greater than those provided by the APS. For Subtask B, a single APS operational approach (in which the APS performs all +X maneuver functions) was selected by NASA. This eliminated the requirement for a separate OMS to perform major translation maneuvers. Two different mission timelines for the Space Station/Base Logistics Mission were considered for Subtask B:

(1) an early, or third, orbit rendezvous
(2) a late, or seventeenth, orbit rendezvous.

The maximum APS total impulse requirements resulted for the seventeenth orbit case and are shown in Figure 4-4 for both orbiters, together with booster total impulse requirements.

THRUSTER ASSEMBLY SUMMARY – ORBITER B

THRUSTER ASSEMBLY NUMBER	NUMBER OF 1850 LB_F THRUSTERS	PURPOSE
1	1	– X
2	1	– X
3	3	+ X
4	3	+ X
5	2	+ Y, + YAW
6	2	– Y, – YAW
7	1	– Z, – PITCH, – ROLL
8	1	+ Z, + PITCH, + ROLL
9	1	– Z, – PITCH, + ROLL
10	1	+ Z, + PITCH, – ROLL
11	1	– Z, + PITCH, – ROLL
12	1	+ Z, – PITCH, + ROLL
13	1	– Z, + PITCH, + ROLL
14	1	+ Z, – PITCH, – ROLL
15	2	+ Y, – YAW
16	2	– Y, + YAW

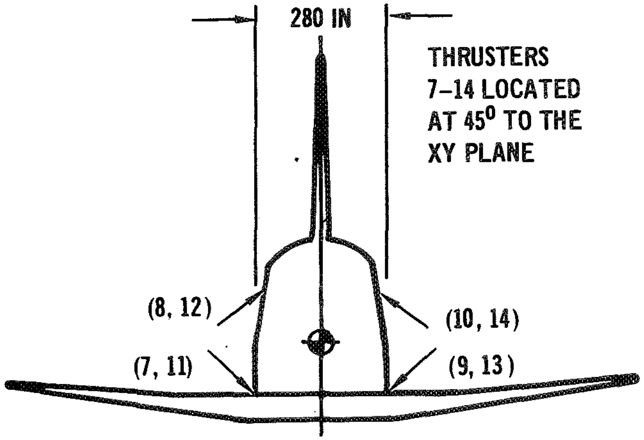


W = 271,465 LB

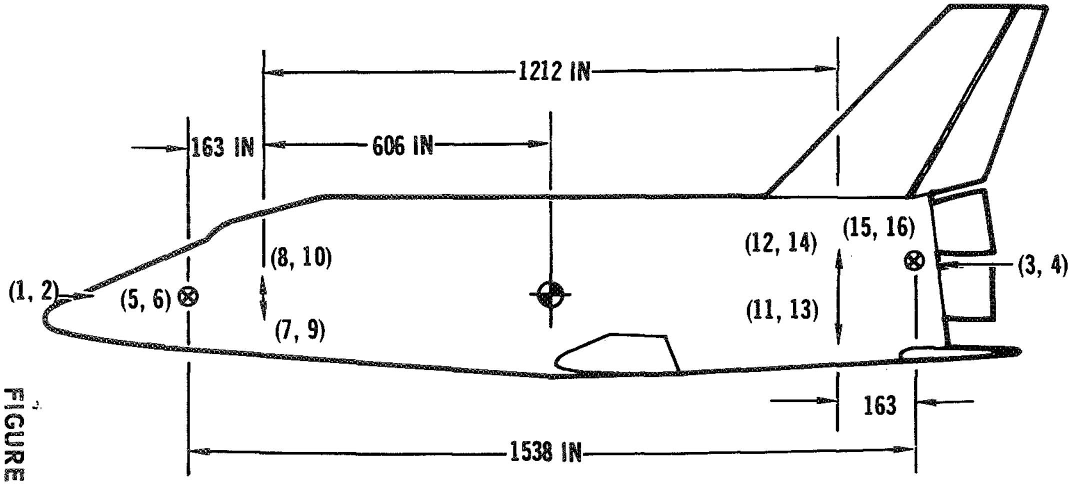
I_{xx} = 1.95 x 10^6 SLUG-FT^2

I_{yy} = 15.074 x 10^6 SLUG–FT^2

I_{zz} = 15.438 x 10^6 SLUG-FT^2

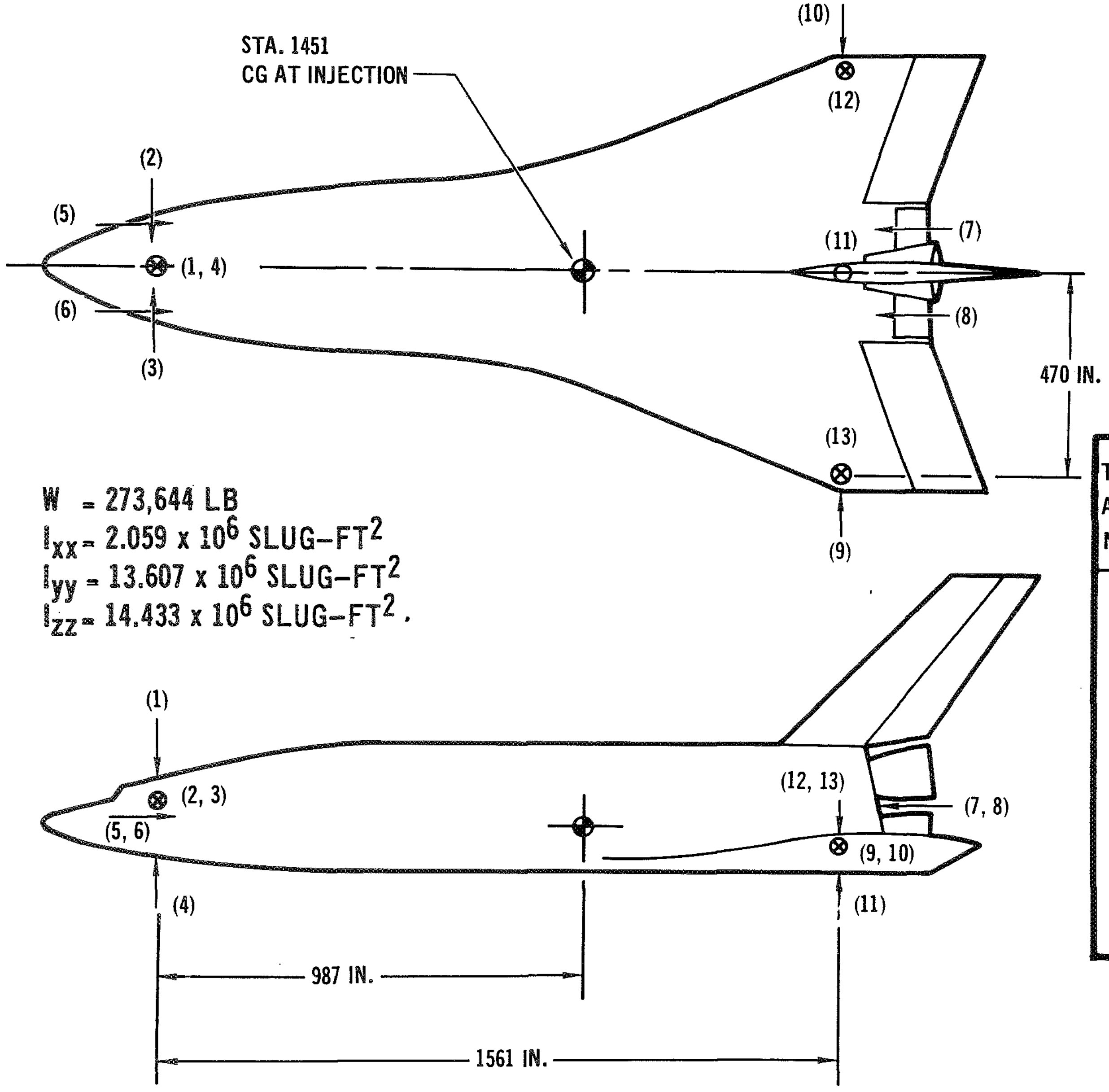


THRUSTERS 7–14 LOCATED AT 45^0 TO THE XY PLANE



ORBITER B THRUSTER LOCATIONS

FIGURE 4–1



W = 273,644 LB

I_{xx} = 2.059 x 10^6 SLUG–FT^2

I_{yy} = 13.607 x 10^6 SLUG–FT^2

I_{zz} = 14.433 x 10^6 SLUG–FT^2.

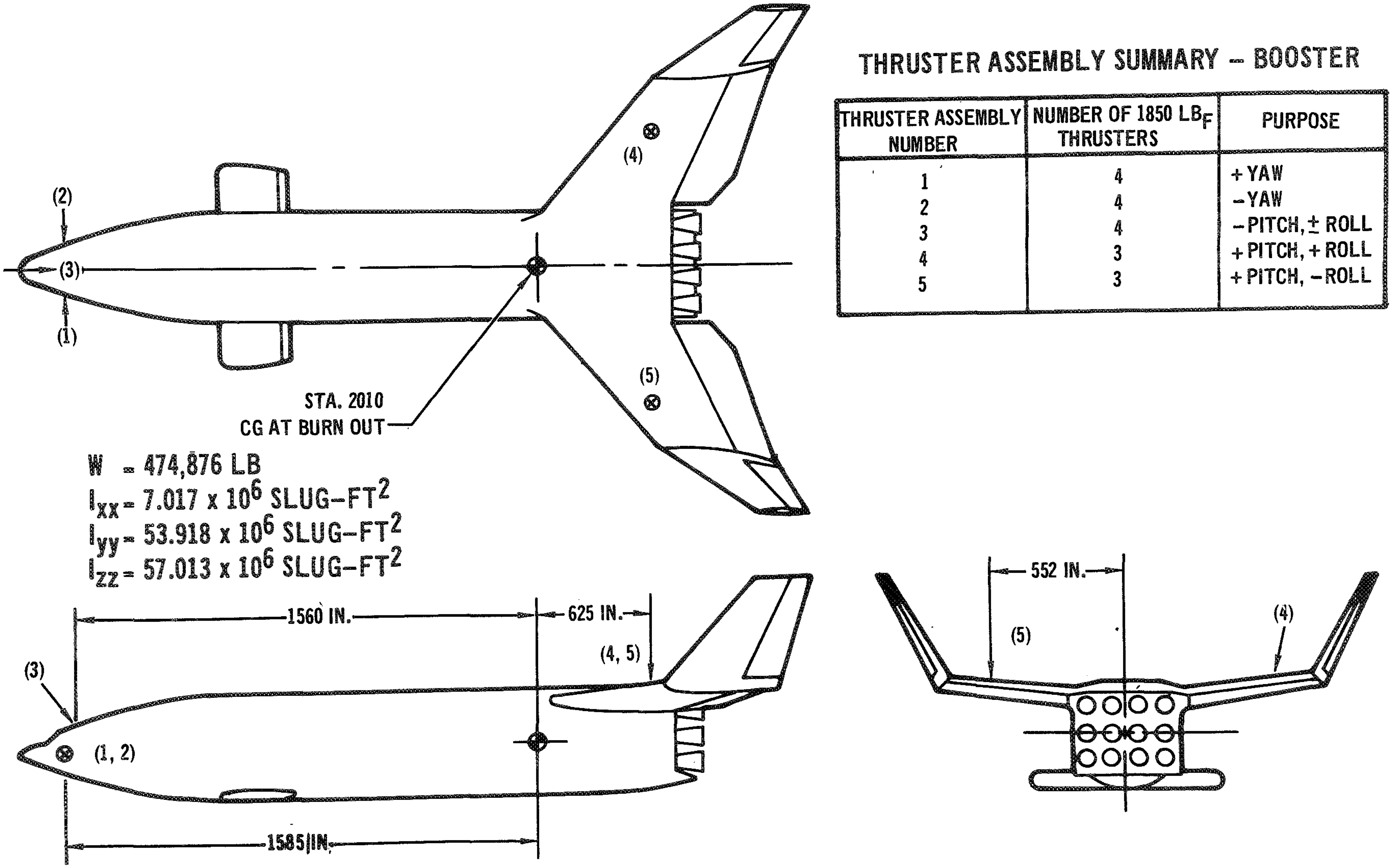
ORBITER C THRUSTER LOCATIONS

THRUSTER ASSEMBLY SUMMARY – ORBITER C

THRUSTER ASSEMBLY NUMBER	NUMBER OF 1850 LBF THRUSTERS	PURPOSE
1	3	–Z, – PITCH
2	2	–Y, – YAW
3	2	+ Y, + YAW
4	3	+ Z, + PITCH
5	1	– X
6	1	– X
7	3	+ X
8	3	+ X
9	3	+ Y, – YAW
10	3	– Y, + YAW
11	3	+ Z, ± ROLL, – PITCH
12	3	– Z, + ROLL, + PITCH
13	3	– Z, – ROLL, + PITCH

THRUSTER ASSEMBLY SUMMARY – BOOSTER

THRUSTER ASSEMBLY NUMBER	NUMBER OF 1850 LB_F THRUSTERS	PURPOSE
1	4	+ YAW
2	4	– YAW
3	4	– PITCH, ± ROLL
4	3	+ PITCH, + ROLL
5	3	+ PITCH, – ROLL



$W = 474{,}876$ LB
$I_{xx} = 7.017 \times 10^6$ SLUG–FT^2
$I_{yy} = 53.918 \times 10^6$ SLUG–FT^2
$I_{zz} = 57.013 \times 10^6$ SLUG–FT^2

BOOSTER THRUSTER LOCATIONS

FIGURE 4–3

	THRUST LEVEL	NUMBER OF THRUSTERS	TOTAL IMPULSE (10^6 LB SEC)	
			BOOSTER	ORBITER
ORBITER B	1850	24		12.666*
BOOSTER	1850	18	0.860	
ORBITER C	1850	33		12.766*

* 100 LB-SEC MINIMUM IMPULSE BIT
17TH ORBIT RENDEZVOUS

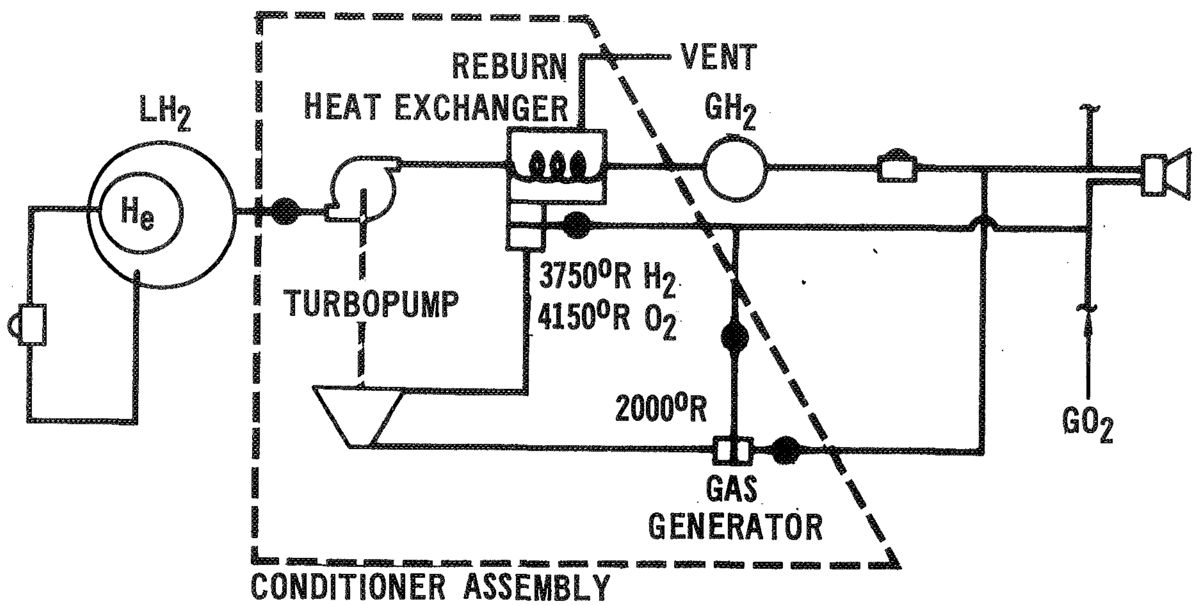
REQUIREMENTS SUMMARY
Subtask B

FIGURE 4-4

4.2 <u>APS Preliminary Design Description</u> - The conceptual subsystem definition or Subtask A effort defined the turbopump subsystem as the most attractive approach for a high pressure APS. APS components and assemblies making up the turbopump APS were reevaluated in detail during this preliminary design phase to reflect updated requirements, as well as to ensure a design capable of the required performance. These more detailed studies and tradeoffs resulted in selection of a new design approach for the conditioner assembly and provided the additional detail necessary to refine the designs for other subsystem components and assemblies. A simplified schematic for the hydrogen side of the resulting subsystem is presented in Figure 4-5. The schematic for the oxygen side is similar. In overall approach, the selected APS design is similar to that described in Subtask A.

The principal difference between the final APS design and that resulting from Subtask A is the conditioner assembly. In the final Subtask B design, a single gas generator, operating at 2000°R, is used for each propellant conditioner. The exhaust products from these generators drive the turbopumps and provide a portion of the energy necessary to condition the propellants to the required temperatures. All gas generator products are first passed to the turbopump turbine, then directed to the heat exchanger, where supplemental oxygen is added to increase heat release and improve overall APS performance. The heat exchanger is connected directly to a vehicle vent assembly. In the vent assembly, heat exchanger exhaust

REGENERATIVE/FILM COOLED THRUSTER



FINAL APS CONFIGURATION
TURBOPUMP WITH REBURN HEAT EXCHANGER

FIGURE 4-5

products are discharged from the vehicle through opposing nozzles, to eliminate disturbance forces, or if a +X axis maneuver is in process, through an aft directed nozzle to provide useful impulse.

The subsystem is most clearly described by considering it as made up of four primary assemblies:

(1) thruster assemblies
(2) accumulators and feedline assembly
(3) propellant conditioning assembly
(4) propellant storage assembly.

The following paragraphs provide a summary of alternate design approaches considered for each primary APS assembly. Also provided is a description of the designs selected, their operation, and the analysis and rationale behind their selection.

4.2.1 APS Thruster Assemblies - The APS uses gaseous hydrogen-oxygen thrusters to provide both vehicle control and maneuvering impulse. In Subtask A, a film-cooled thruster assembly was assumed as the baseline for concept trade studies. During Subtask B, the applicability of fully regeneratively cooled thrusters to the APS was evaluated. As expected, these comparisons showed that the increased specific impulse afforded by a regeneratively cooled thruster would significantly reduce APS weights. However, the evaluation also showed that the installation constraints, which require nozzle scarfing, are not practical for a fully regeneratively cooled engine, and that the cycle life requirement of approximately 50,000 cycles could not be met. The selected chamber configuration, a partial regeneratively cooled design (as shown in Figure 4-6), represented a compromise to meet these two discrepancies with minimum performance sacrifice. The selected chamber is a single up-pass regenerative design, with an area ratio of 11 to 1. The scarfing required by various installations in the vehicle is easily accommodated by the fabricated nozzle attached at the 11 to 1 area ratio. The nozzle is film-cooled by employing approximately 5.5 percent of the hydrogen flow. The cycle life requirement is met by the addition of approximately 7.5 percent film cooling at the injector face along the chamber wall.

The igniter subassembly consists of a separate high response bipropellant valve, a cooled ignition chamber, and the spark plug. Primary propellant flow to the thruster is controlled by a linked, parallel poppet valve with pneumatic actuation.

Performance estimates based on the selected injector and on the film cooling requirements are illustrated in Figure 4-7 for two different thruster expansion ratios.

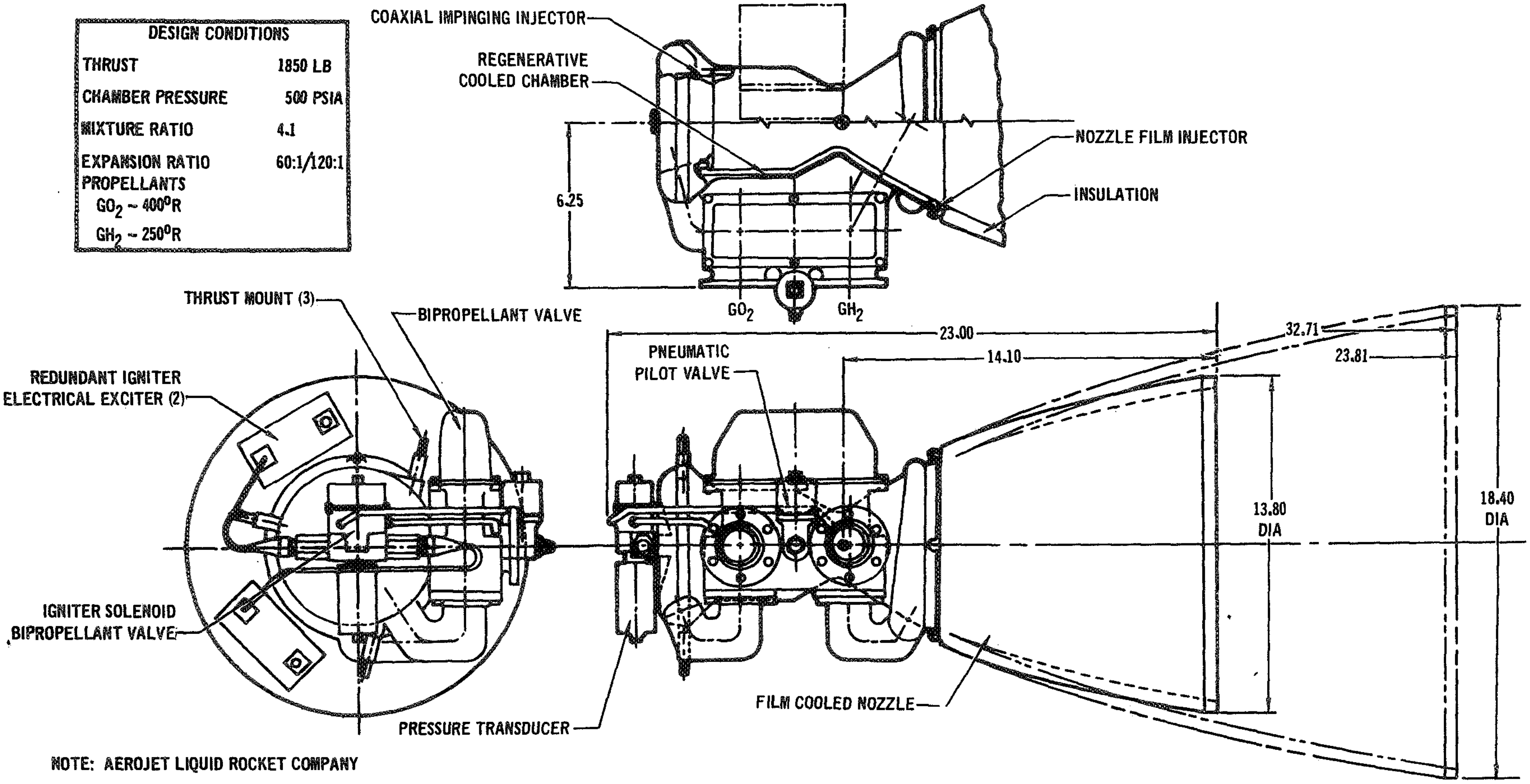
Since approximately 90 percent of the APS total impulse is expended for +X translation, a separate study was conducted in conjunction with thruster design selection to explore the advantages of using different thrusters individually designed for translation and for attitude control. The designs evaluated were:

(1) APS thrusters designed with an increased nozzle expansion ratio
(2) thrusters designed to operate with liquid hydrogen and gaseous oxygen as the propellants
(3) thrusters designed to operate with liquid hydrogen and liquid oxygen.

These options represent a continuous improvement in subsystem specific impulse, at the expense of progressively greater design deviation from the common attitude control thrusters. All three options increased thruster specific impulse while performance improvement for the last two options also resulted from a reduction in propellant conditioning requirements.

Based on comparison of APS weights and complexity of using these alternates, it was concluded that, while the concepts using liquid propellants could provide

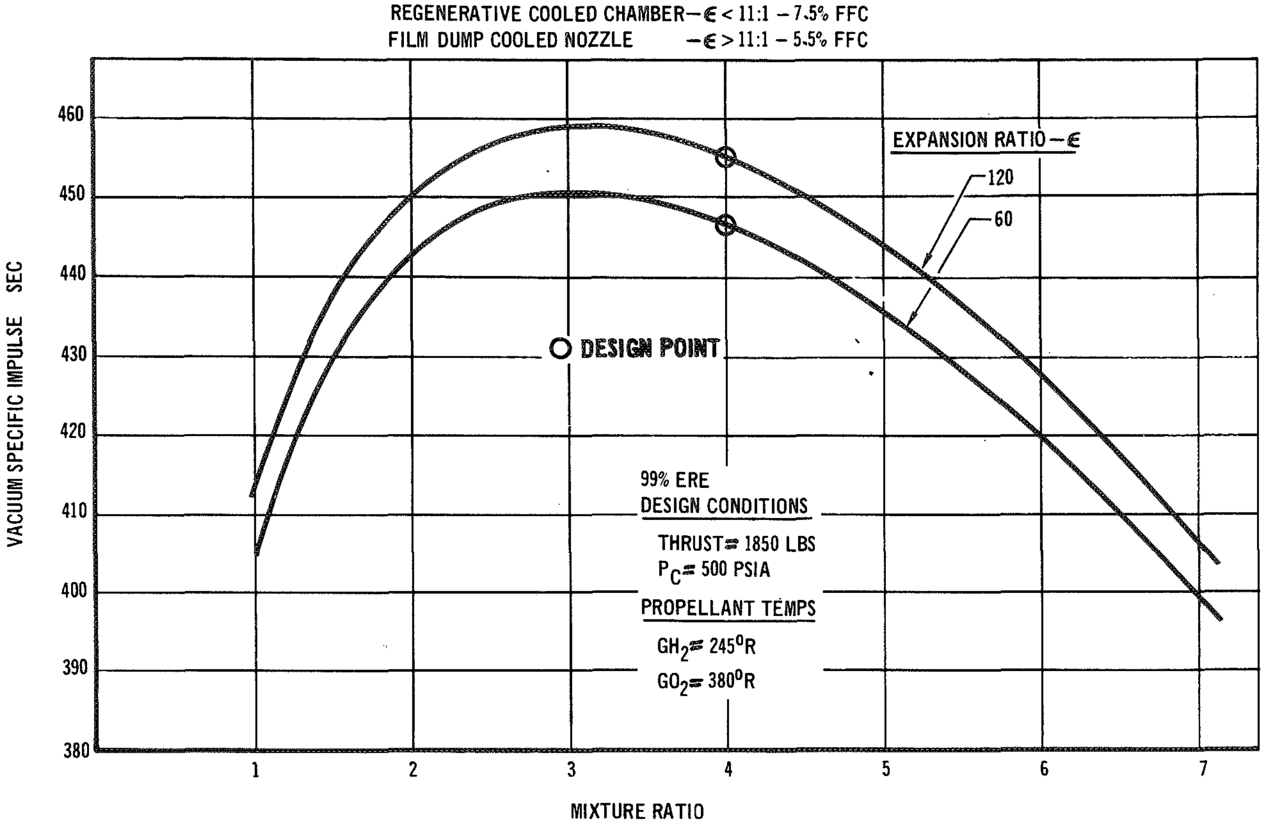
DESIGN CONDITIONS	
THRUST	1850 LB
CHAMBER PRESSURE	500 PSIA
MIXTURE RATIO	4.1
EXPANSION RATIO	60:1/120:1
PROPELLANTS	
GO_2 ~ 400°R	
GH_2 ~ 250°R	



NOTE: AEROJET LIQUID ROCKET COMPANY

HIGH PRESSURE APS THRUSTER

FIGURE 4–6



HIGH PRESSURE APS THRUSTER PERFORMANCE FIGURE 4-7

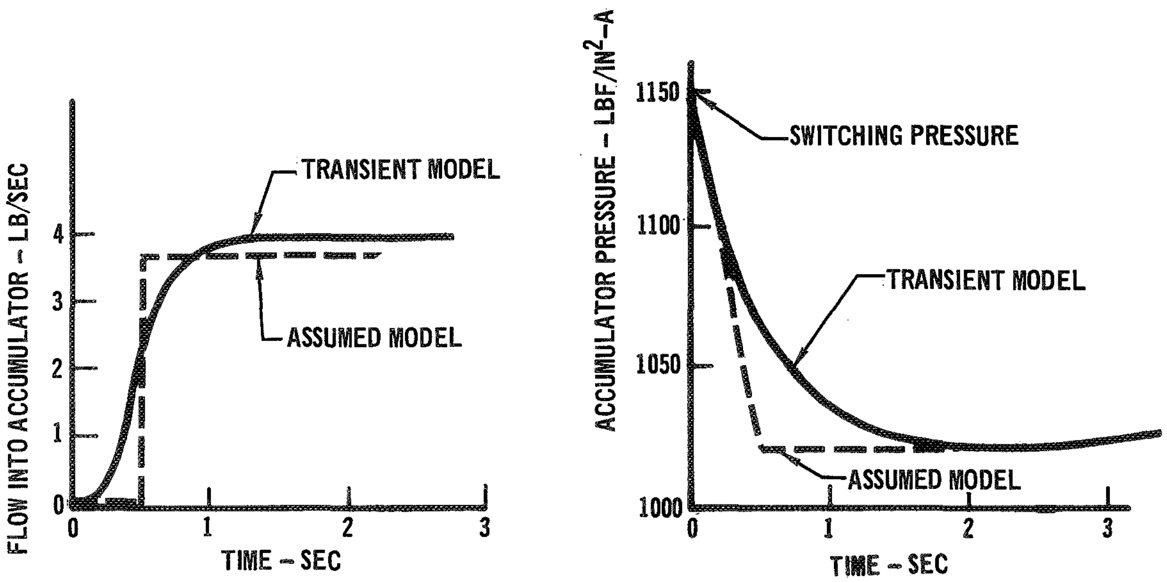
weight savings, the advantage was offset by the need for development of two different thruster assemblies (i.e., both gas and liquid propellant engines). However, the first option represented only a minimal change to the basic design, as it used gaseous propellants, and no changes were required in the combustion/cooling portions of the thruster assembly. Weight gains that could be realized by a simple change in nozzle skirt size were considered to outweigh the small penalties associated with a thruster commonality deviation, and this approach was selected for the APS design. Based on overall APS weight exchanges expansion ratios of 120 to 1 and 60 to 1 provided the most favorable design points; these were selected for the translation and attitude control thrusters, respectively.

4.2.2 <u>Accumulators and Feedline Assembly</u> - The accumulators are simple, spherical gas storage vessels which operate in a blowdown pressure mode and are recharged periodically by the conditioner assemblies. The accumulators serve two functions in the APS:

(1) they provide a ready supply of conditioned propellant for thruster operation

(2) they limit the number of conditioner assembly operating cycles during the mission.

Operation is illustrated in Figure 4-8. From a fully recharged condition (maximum pressure), accumulator pressure will decay at a rate dictated by thruster demands. When the pressure level has decayed to nearly minimum (switching pressure) the conditioner is signaled to start. The accumulator pressure will continue to decay until the conditioner equipment has accelerated to the point where flow into the accumulator exceeds outflow. The amount of pressure decay from the switching pressure to the minimum pressure condition satisfactory for thruster operation is dependent on both thruster usage rate and conditioning assembly transient response characteristics. Maximum thruster usage rate is set by the vehicle requirements, in this case four thrusters firing simultaneously. Conditioner response is a function of hardware design and its control system. Analysis of the preliminary design APS transient response was made, resulting in characteristics shown in Figure 4-8. From these characteristics, an equivalent start time,



ACCUMULATOR SIZING RESPONSE MODEL

FIGURE 4-8

(defined as the time to produce the same accumulator pressure decay with no conditioner flow) was established as 0.5 sec. This equivalent start time was then used in accumulator size optimization.

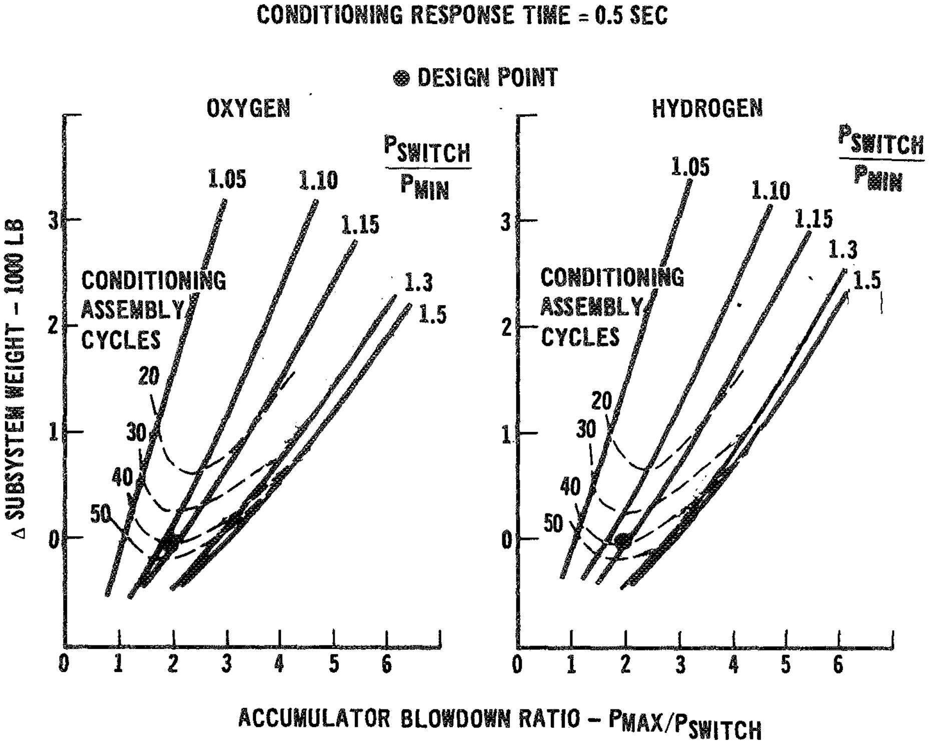
For the defined conditioner start time and maximum thruster flow demand, accumulator volume is discretely defined by the accumulator switching to minimum pressure ratio since this defines the propellant mass available for thruster operation during startup. This volume, and the maximum pressure define the total propellant mass storage capacity of the accumulator and hence it also defines the number of conditioner operating cycles for any prescribed amount of APS total impulse expended under nonsteady-state conditions. Accumulator weight is defined by the maximum pressure in the accumulator and the volume. Thus, selection of the two accumulator pressure ratios (switching and blowdown) uniquely describes weight and the number of conditioner cycles. During preliminary design, parametric data were developed to map the influence of accumulator pressure ratios and allow design point selection. Figure 4-9 provides these results for the selected APS conditioner. As shown, for any desired number of cycles a minimum subsystem weight occurs at a blowdown ratio of approximately 2. The associated design value for switching pressure ratio is 1.13 for 41 operating cycles (based on 50 conditioner cycles per mission with nine required for major translation maneuvers). These values were used for APS design and the resulting accumulator volumes are 29 and 12 ft^3 for hydrogen and oxygen, respectively.

The feedline assembly configurations used for APS design were representative of actual installations so that their weight and influence on APS design could be realistically assessed. Line diameters were based on tradeoffs between weight reductions for smaller lines, and weight penalties in the accumulators and conditioners with increased pressure loss. Line lengths and routing were determined from installation layout studies.

Thermal analysis of the feedline assembly showed that insulation was required on the lines to minimize heat transfer to lines between the accumulators and thruster assemblies. Heat transfer into the gaseous propellant results in differences in thruster-inlet propellant density with attendant thrust and mixture ratio variations. Two alternate means of insulation were considered:

(1) vacuum jacketed lines

(2) lines insulated with high performance multilayer Mylar insulation protected by a flexible cover.



ACCUMULATOR SIZING - ORBITER B

FIGURE 4-9

The weights for these two alternate approaches and the complexity of their installation were compared and the result showed that vacuum jacketing would result in high weight penalties, a very complex installation, and only marginal performance advantages. For this reason, the flexible jacket approach was selected for the feedline installation. Transient heating analyses were conducted for the selected installation approach to evaluate the rates of temperature rise within the supply lines. These results show that an insulation thickness of approximately 0.3 in. for the hydrogen lines and 0.2 in. for the oxygen lines would satisfactorily limit temperature changes during APS operation.

To determine transient characteristics of the feed subassembly and thruster pulse mode performance, a digital computer program was developed to simulate APS thruster start and shutdown transients. Transient models were developed for lines, valves, orifices, regulators, and thrusters. These components were integrated into a transient analysis computer program to model the feed subassembly downstream of accumulators, accurately simulating line lengths, diameters, and component locations. The study was confined to the feed subassembly and thrusters, because the relatively large volume of the accumulators effectively decouples this portion of the subsystem from the conditioner assembly.

The thruster model analyzes the transient flow and combustion processes in the injector and thrust chamber. Combustion and performance parameters are calculated assuming an equilibrium combustion process. Program output includes a time history of temperature, pressure, and weight flow at any desired location. In addition, performance parameters, such as specific impulse, total impulse, mixture ratio, and thruster chamber temperature are calculated. Results from this program verified thruster/supply line compatibility, and minimum impulse bit (MIB) characteristics during pulse mode operation.

4.2.3 Conditioner Assembly - The baseline conditioner concept selected in Subtask A uses a 3500°R gas generator to provide the energy required for turbopump operation and propellant conditioning. In the Subtask A configuration, gas generator products were routed first to the heat exchangers, where cooling occurred, and then used to drive the pump turbine. A more detailed evaluation during Subtask B showed that hydrogen pump power requirements could not be matched without significant increases in conditioner bypass flow and/or reductions in chamber pressure. Both changes would result in increased APS weight. Therefore, to ensure minimum APS weight, the conditioner concept selection of Subtask A was reevaluated. Concepts considered are illustrated in Figure 4-10, where four general approaches are shown. The first is the Subtask A baseline. A number of modifications to this baseline were investigated. These included increases in bypass flow requirements, reductions in conditioning temperature, and reduced operating pressures. The second approach (Concept F) is a more significant modification of the Subtask A concept. In this concept, conditioner flow is first routed through a heat exchanger (where a portion of the energy is removed and temperature of the exhaust was reduced), then through a turbine to drive the turbopump, and, finally, through a second heat exchanger to complete energy removal. The third alternate approach shown in Figure 4-10 relocates the turbine in the cycle with respect to the heat exchanger. In this approach, it is necessary to operate the gas generator at a reduced temperature compatible with turbine blade materials, but performance levels are restored to those of the Subtask A concept by adding supplemental oxygen to the fuel-rich turbine exhaust in the downstream heat exchanger. The fourth approach uses a cold turbine concept, in which the turbine is located in the primary propellant flow line downstream of the heat exchanger similar to an expander cycle engine. The various conditioner concepts were investigated to establish their design points, weights, and the technology required for development. Figure 4-11 summarizes results from this

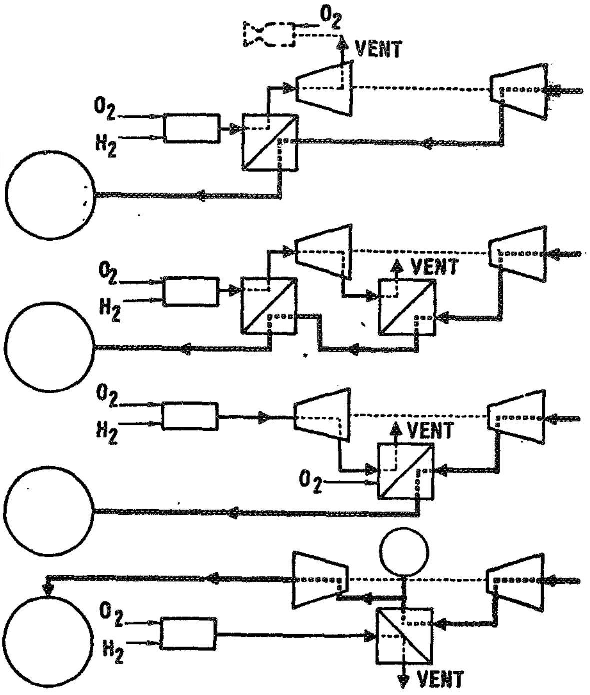
CONCEPT

A THRU E SUBTASK A CONDITIONER CONFIGURATION
- GAS GENERATOR TEMPERATURES VARIED
- ACTIVE PROPULSIVE VENT INVESTIGATED

F SUBTASK A HYBRID-CONFIGURATION
- TURBINE LOCATED IN MID-CYCLE

G SUPPLEMENTAL O_2 CONFIGURATION
- TURBINE EXHAUST REBURNED IN HEAT EXCHANGER

H & I COLD TURBINE CONFIGURATIONS
- HIGH AND LOW PRESSURE START ACCUMULATORS



ALTERNATE CONDITIONING ASSEMBLY CONCEPTS

FIGURE 4-10

CONCEPT	OPERATING CONDITIONS HYDROGEN TEMP °R	GAS GENERATOR TEMP °R	ACCUMULATOR PRESSURE– LBF/IN^{2}A MAX MIN	CHAMBER PRESSURE LBF/IN^{2}A	WEIGHT CHANGE LB	TECHNICAL CONSIDERATIONS RELATIVE TO SELECTION
A	200	3500	2000/915	500	REFERENCE	• NOT FEASIBLE DUE TO TURBINE REQUIREMENTS.
B	145	3500	880/400	200	+ 260	• HIGH TEMPERATURE-COOLED GG/HX REQUIRED. • MAXIMUM TURBOPUMP EFFICIENCY CRITICAL TO DESIGN.
C	120	2500	1150/520	270	+ 320	• SAME AS B BUT COOLING PROBLEM MUCH RELAXED.
D	105	2000	1450/600	350	+620	• MAXIMUM TURBOPUMP EFFICIENCY REQUIRED FOR PERFORMANCE.
E	105	2000/2000	1450/600	350	+170	• TURBOPUMP EFFICIENCIES CRITICAL TO DESIGN. • REQUIRES DEVELOPMENT OF ACTIVE VENT GG
F	200	3500	2200/915	500	+100	• REQUIRES DEVELOPMENT OF 2 HEAT EXCHANGERS. • SUBSYSTEM MATCHING AND CONTROL WILL BE COMPLEX. • TURBOPUMP EFFICIENCIES ARE CRITICAL TO DESIGN. • HIGH TEMPERATURE TURBINE BLADE DESIGN.
G	100	(2000/XXXX) 3500 EQ.	1570/655	350	−580	• SAME AS F EXCEPT MINIMUM CONDITIONING TEMPERATURE AND DEVELOPMENT OF SECONDARY INSTEAD OF 2 HEAT EXCHANGERS IS REQUIRED.
H	260	260	970/400 3000/800	200	+1270	• REQUIRES REDUNDANT START ACCUMULATORS • O_2 TURBINE THRUST BEARING LIFE BEYOND STATE-OF-THE-ART.
I	260	260	970/200 970/400	100	+2750	• SAME AS H

COMPARISON OF ALTERNATE CONDITIONER CONCEPTS

FIGURE 4-11

evaluation. The reburn heat exchanger (Concept G) was selected as the Subtask B baseline.

The revised conditioner concept uses a single 2000°R gas generator in each conditioner. Generator exhaust products are used first to drive the turbopump. Then, the fuel-rich turbine exhaust is directed to the heat exchanger, where supplemental oxygen is added to increase heat release and improve overall assembly performance.

Conditioner control is required during accumulator recharge, during steady-state (+X translation) operation, and during conditioner start transients. Since the control method selected would affect both overall APS performance and the design points for the conditioner components, it was necessary to evaluate the alternates and define their effect on overall APS weight and component requirements, considering first accumulator recharge.

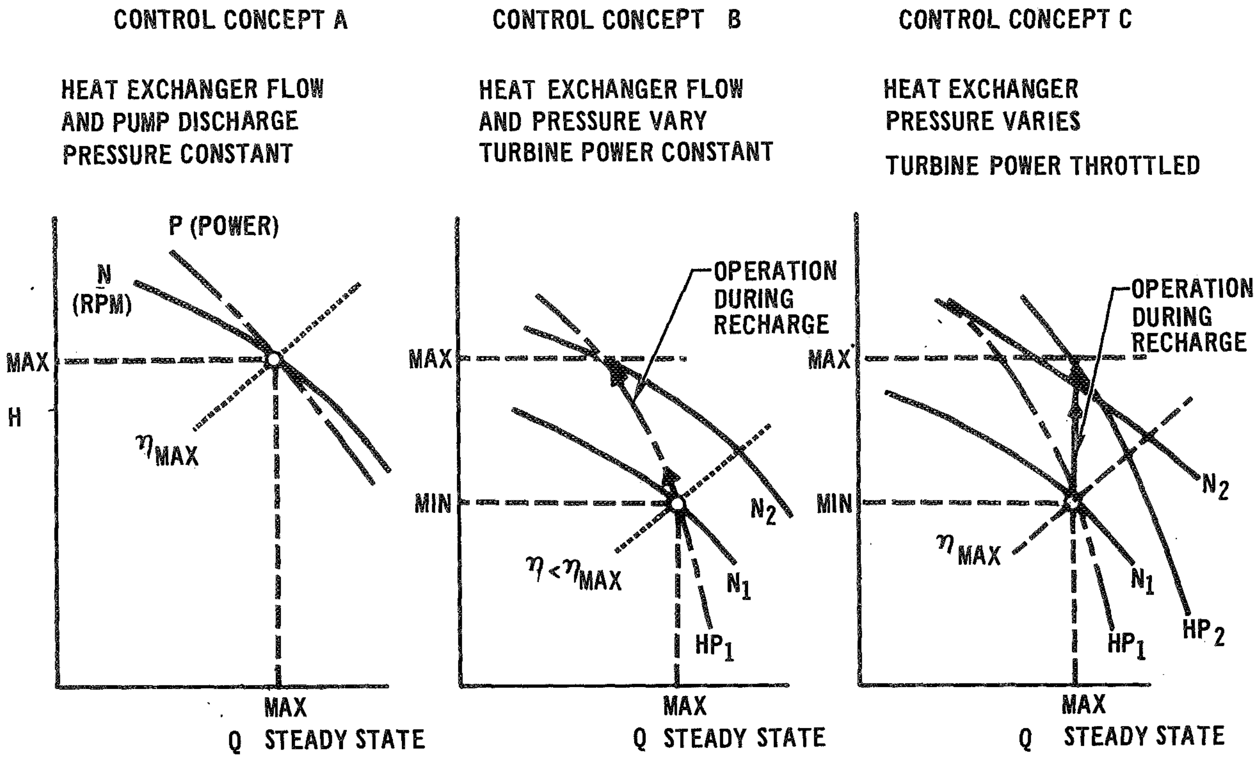
Accumulator Recharge - The conditioner must be capable of providing maximum accumulator pressure during recharge operations, and must also be capable of sustaining minimum accumulator pressure with maximum thruster flow. Several alternatives were available for control of the conditioner during accumulator recharge. These differed both in the manner in which heat exchanger flow and pressure were controlled during recharge, and in overall performance levels. The approaches considered were:

(1) The simplest control approach would be to design the conditioner for a fixed point. Always operating at maximum pressure and maximum flow would satisfy both requirements, while providing nearly constant component operating conditions. However, the amount of gas generator flow required during steady-state operation directly affects APS specific impulse; it was desirable to operate at reduced pressure under steady-state conditions to minimize weight.

(2) A concept requiring somewhat more difficult component design involves controlling to a fixed conditioner flow rate. In this approach, turbine power was reduced for steady-state operation, and was increased to provide the pressures required for accumulator recharge.

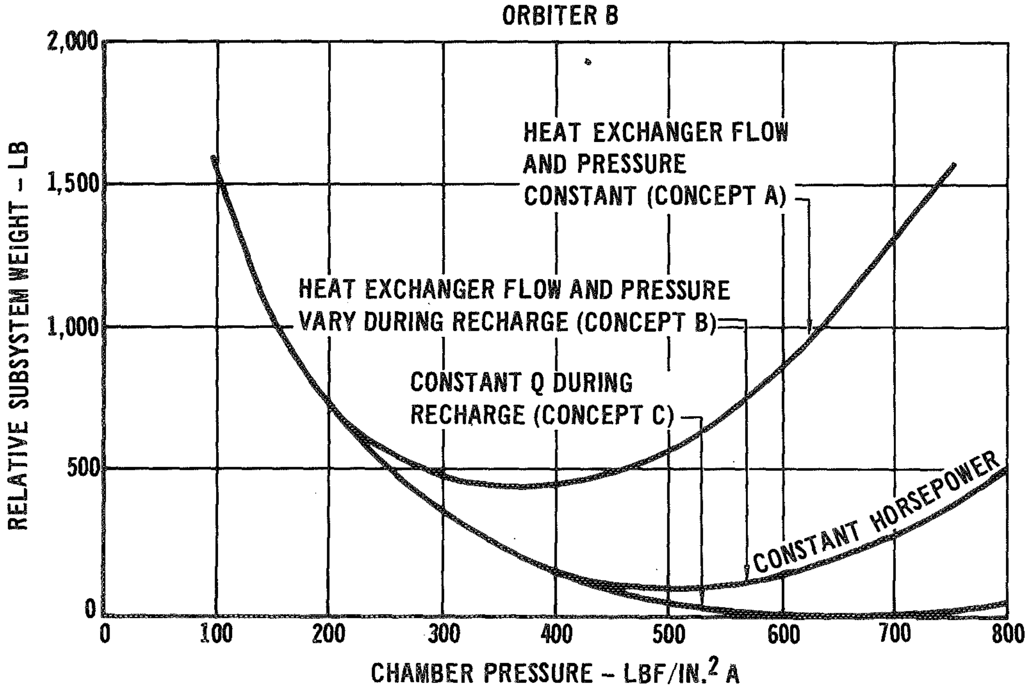
(3) Equally complicated is the fixed turbine power approach. In this concept, turbine power was maintained constant, and conditioner flow was allowed to decrease during the recharge cycle.

Figure 4-12 illustrates each of the control concepts on pump head-flow curves. Figure 4-13, the results of this comparison, shows APS weight as a function



TURBOPUMP OPERATING CONDITIONS

FIGURE 4-12



SUBSYSTEM WEIGHT COMPARISON FOR VARIOUS CONTROL CONCEPTS

FIGURE 4-13

of chamber pressure for the three control concepts.

In this analysis the amount of supplemental oxygen was varied to satisfy two constraints:

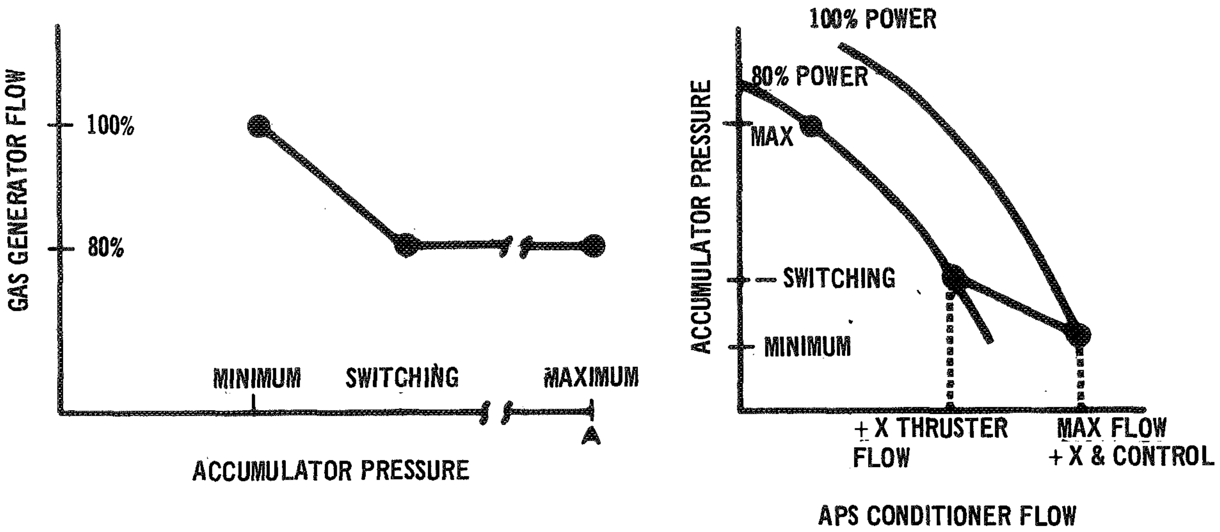
(1) provide a minimum pressure of 30 lbf/in^2a in the heat exchanger to allow sea level development testing

(2) provide a heat exchanger discharge temperature of 800°R minimum to preclude H_2O condensation in the heat exchanger assembly.

The constant power level approach was selected for APS design. This approach provided a simple control, nearly minimum subsystem weight, and required only a minimum variation in gas generator operating characteristics during the cycle. With this selected recharge approach, the APS optimized at a value of 500 lbf/in^2a chamber pressure, and overall conditioner mixture ratios of 2.43 and 2.7 for the hydrogen and oxygen conditioners, respectively.

Steady-State Operation - During steady-state +X translation maneuvers, an undefined, and variable, amount of propellant will be required for attitude control. Conditioners could be designed with excess flow capability, but conditioners could then cycle on/off during steady-state firings, requiring additional life capability or increased accumulator weight. Also, it was recognized in the conditioner design that variations in gas generator inlet pressure or temperature would necessitate control of gas generator oxygen flow to limit gas generator temperatures to levels acceptable for turbine operation. This requirement, together with the unattractiveness of additional conditioner cycling, led to selection of a control operating point that provided the capability for turbine power variation over a small range. Power variation is provided by throttling gas generator flow over a 20 percent range to maintain minimum accumulator pressure. Valve operation and the resulting pump characteristics are shown in Figure 4-14. At any pressure above switching pressure, gas generator flow is constant providing near constant power to the turbines during recharge. Between switching and minimum pressure, gas generator flow is modulated as shown. Resulting pump operation is shown on the pump map. When APS demands are only those required for +X thruster operation, power is at the lowest level. When demands increase, due to attitude control thruster demands, accumulator pressure will decrease and turbine power increase along the path shown (to bring accumulator pressure back to the control point).

Start Transients - Conditioner response time is a primary factor in accumulator sizing, since it is directly related to accumulator volume. Slow conditioner



PUMP AND GAS GENERATOR VALVE OPERATION

FIGURE 4-14

response characteristics result in excessive accumulator weight penalties. Conditioner assembly start time can be improved either by increasing conditioner steady-state design flow (oversizing) or by increasing turbine power level. As described above, the first of these options was undesirable because of the additional operating life or accumulator weight that would be imposed. The effect of increased turbine power was investigated by analytically simulating conditioner assembly transient characteristics under varying power conditions. Evaluation of pressure decay and, thus, of equivalent lag time required mathematical modeling of the dynamic behavior of the individual conditioner assembly components and their respective interfaces.

Equations governing the dynamic behavior of these components were based upon:

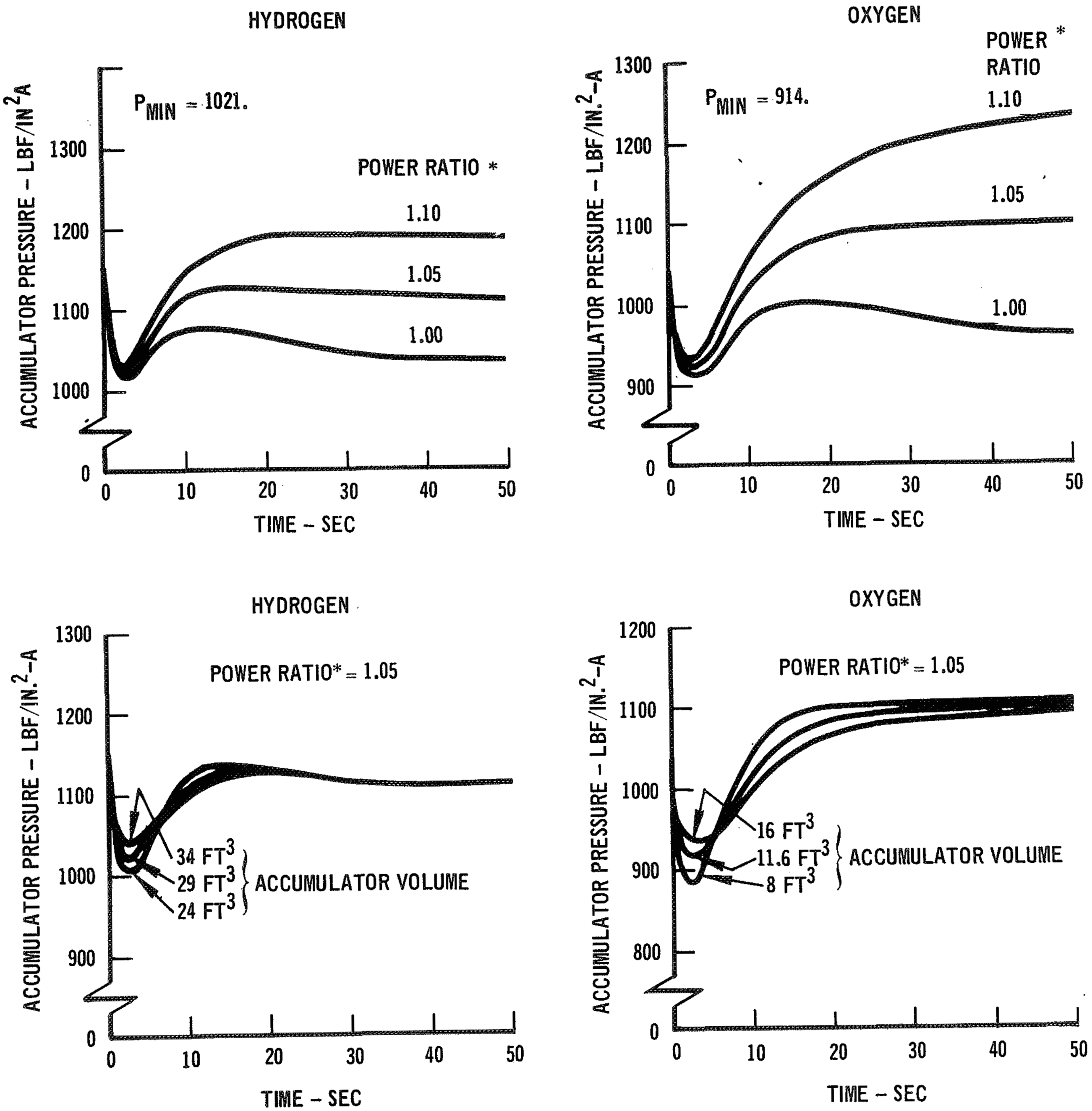
(1) turbopump equations of motion, where the rate of change of turbopump angular momentum is equal to turbine torque minus pump torque

(2) heat exchanger energy balance, where rate of change of heat exchanger internal energy is equal to rate of heat inflow on the hot side, minus rate of enthalpy outflow on the cold side

(3) accumulator energy balance, where accumulator temperature and pressure rate of change were derived from simultaneous solution of energy and mass conservation equations.

When applied to the APS conditioning assembly, these basic equations express the relationships between turbopump speed, heat exchanger wall temperature, accumulator temperature and pressure, and their respective time derivatives.

Results from these analyses are shown in Figure 4-15. As illustrated, when power is increased above that required for steady-state operation, the amount of accumulator pressure decay is reduced; hence, equivalent conditioner response time is improved. Reduction in pressure decay during startup is significant with only small increases in turbine power (5-10 percent) but further gain, by continued



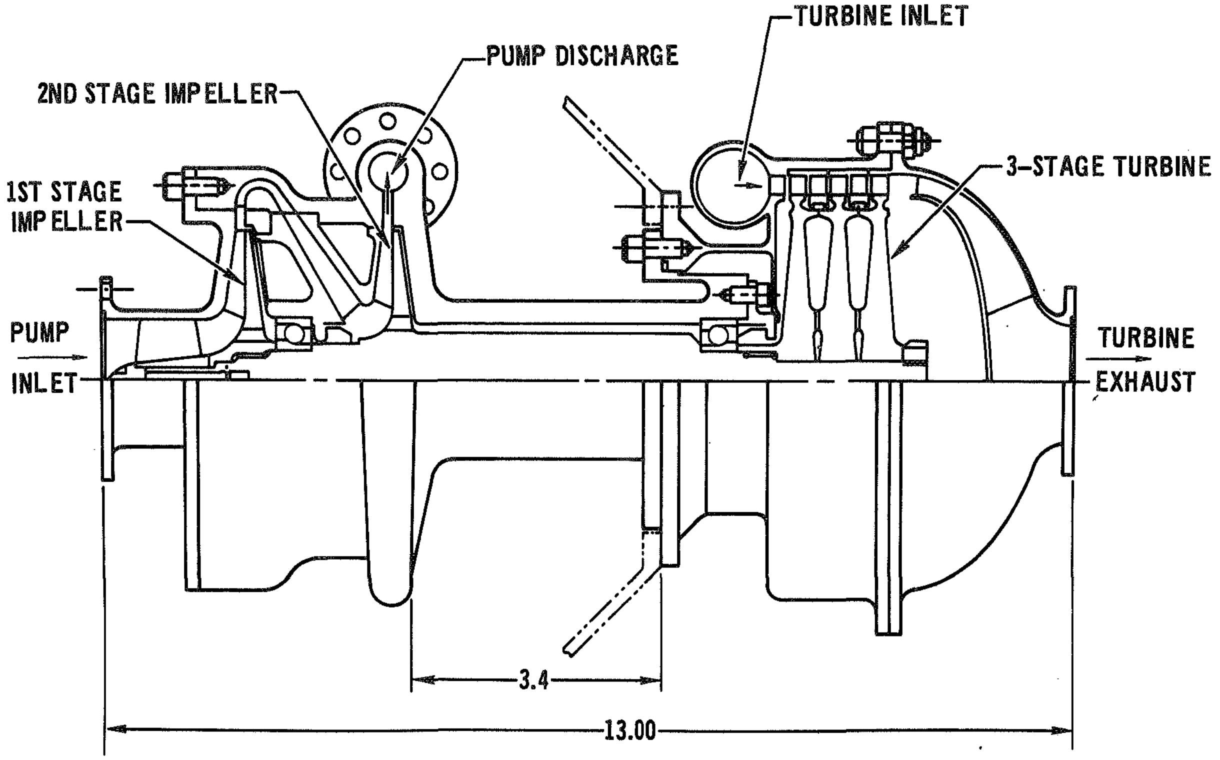
* POWER USED/POWER REQUIRED AT P_{MIN}

CONDITIONING ASSEMBLY STARTUP ACCUMULATOR PRESSURE TRANSIENTS

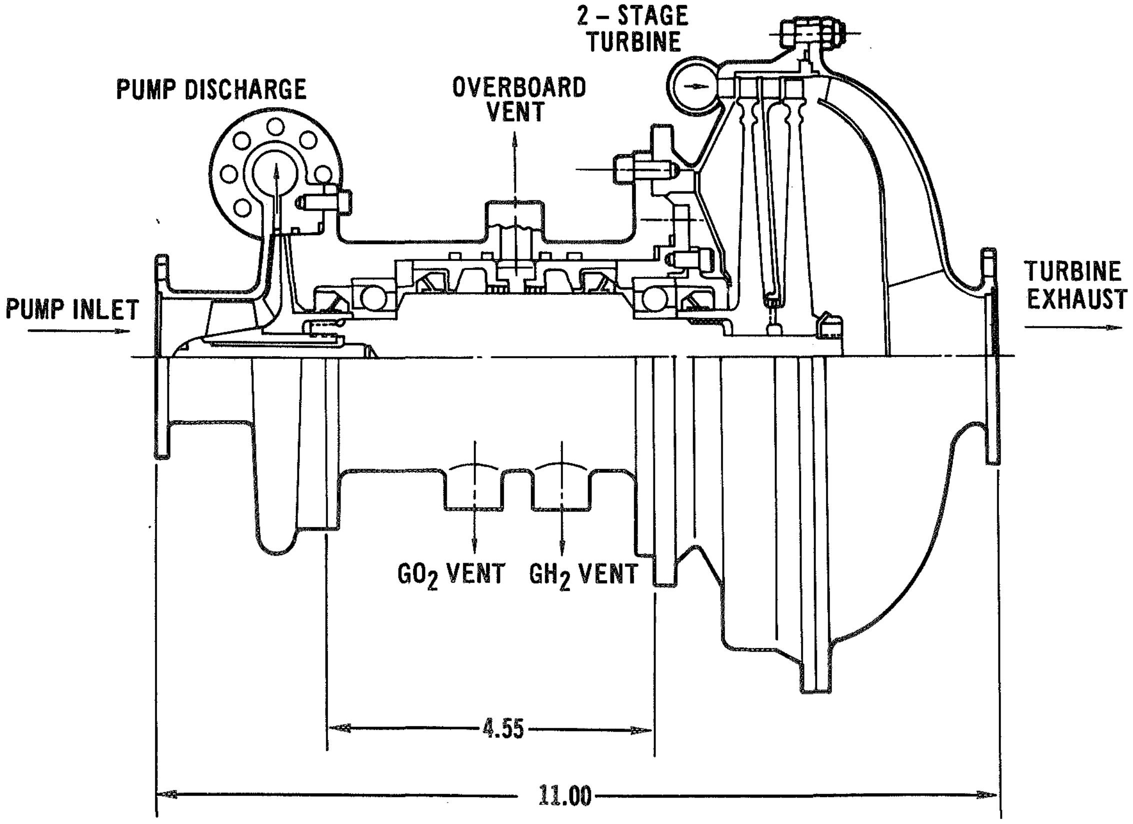
FIGURE 4-15

power increase, is limited. Based on these results, it was concluded that small power increases during conditioner start transients were desirable. The power increase is achieved by the sequencing characteristics of the gas generator valves which provide a high flow rate when they are initially commanded open. Flow is then subsequently throttled to the level commanded by accumulator pressure (as described above). For purposes of accumulator sizing, an average power ratio of 1.05 was used to define equivalent conditioner start time. Analytical results simulating accumulator pressure decay for a range of accumulator volumes are shown in Figure 4-15. From the volume/pressure decay data presented, an equivalent conditioner response time of 0.5 sec was derived for accumulator sizing.

Turbopump Subassembly - In the selected conditioner design, turbopump assemblies are required to operate at maximum flow and minimum accumulator pressure during nominal operation. However, the pumps must also provide the head rise necessary for conditioner recharge, and, since turbine power is maintained constant during recharge, pump flow is reduced and speed increased during the recharge cycle. The turbopumps selected for these requirements use pressure compounded, axial flow turbines, and centrifugal pumps. The oxygen assembly uses a single-stage pump and a two-stage turbine. The hydrogen assembly uses an additional stage on both pump and turbine. Pump impellers and turbine rotors are mounted on a common shaft, supported by propellant cooled/lubricated bearings. Figure 4-16 presents sketches of the turbopump assemblies. Turbopump design and performance were established after a detailed evaluation comparing the capability of several designs. Pump and turbine steady-state efficiency were investigated in detail, since these effect bypass flow requirements and, therefore, overall APS performance. An efficiency of 40 percent for the pump at steady-state operating conditions was selected as a design value for both pumps. This efficiency is less than the maximum available at the steady-state operating point, but was used to provide a design margin, and also allow pump operation at a higher overall efficiency during the recharge, thereby limiting heat exchanger flow reduction during recharge. The APS requires both high cycle life and fast response from the turbopump assemblies. Designs selected are based on criteria which do not stress material margins, and which provide rapid spin-up capability. In the APS design, in order to provide fast response, the turbopump assemblies are maintained at liquid temperatures throughout the mission. This is accomplished by providing both the operating and standby (redundant) turbopumps with a cooling loop using hydrogen coolant to intercept heat leak from the surroundings, and from conduction



APS LH_2 TURBOPUMP

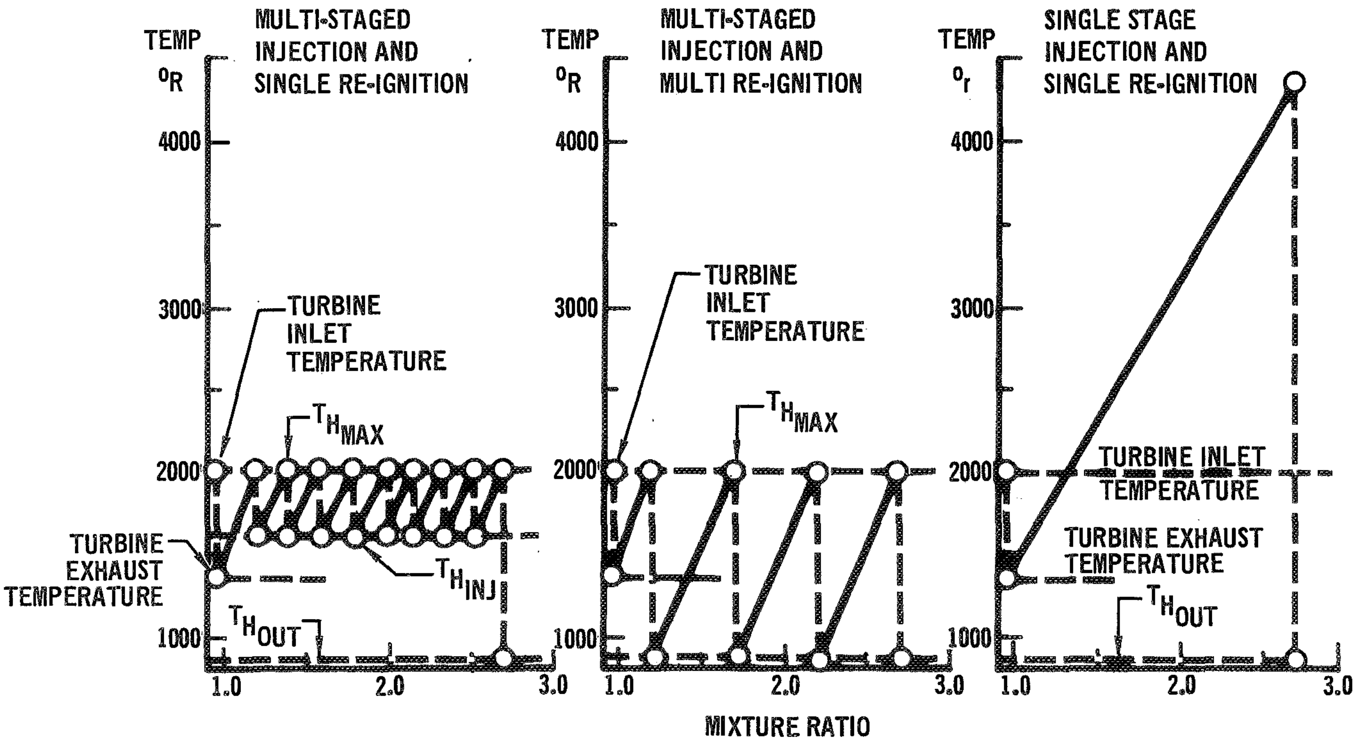


APS LO_2 TURBOPUMP

FIGURE 4-16

through the pump shaft and housing. Paragraph 4.2.4 (following) discusses the hydrogen coolant loop used to maintain the pumps in a chilled condition.

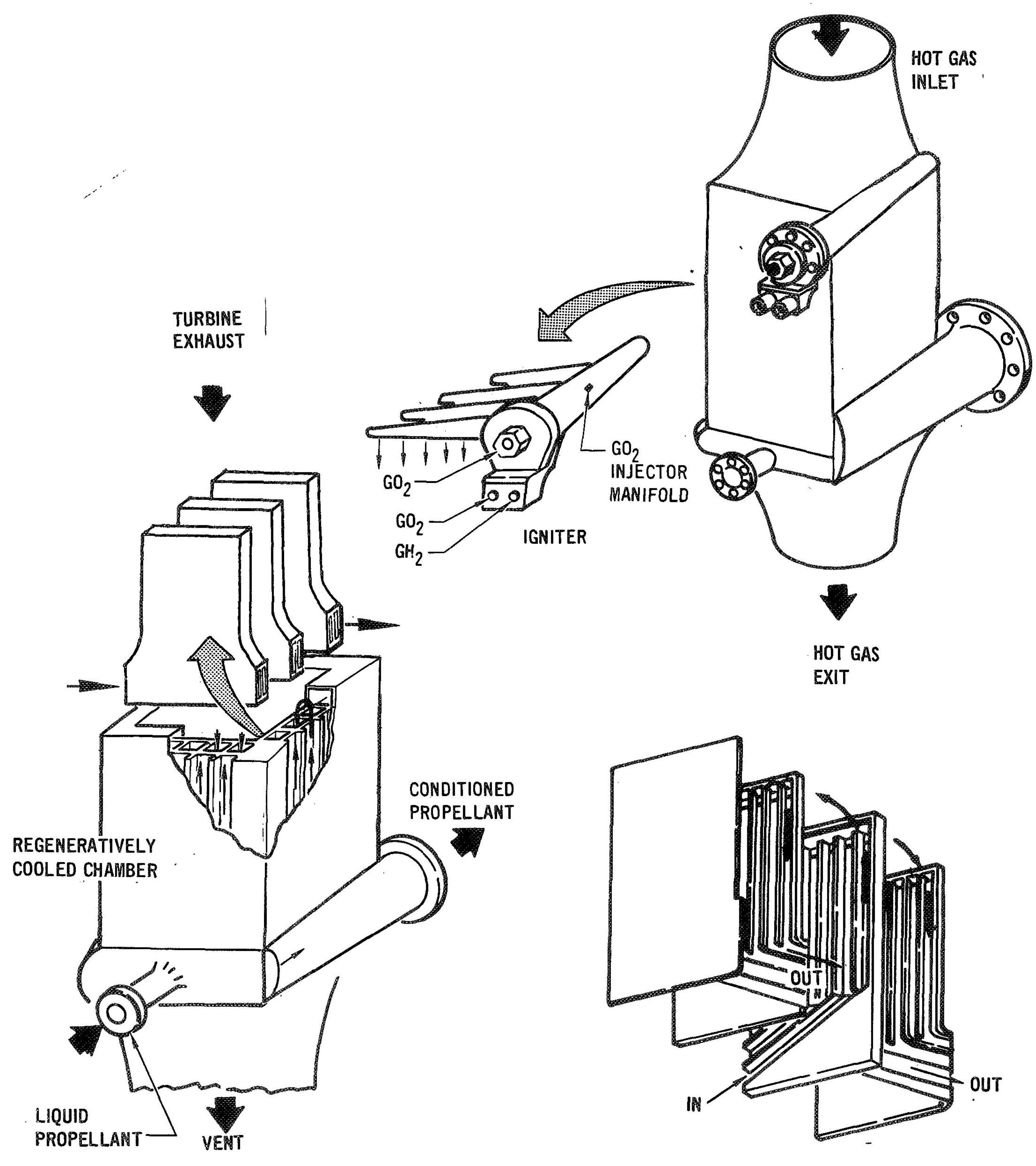
Heat Exchanger Subassembly - The APS uses a reburn heat exchanger subassembly to heat propellant to temperatures required for reliable thruster ignition. In this assembly, combustion products from the gas generator and turbine upstream are directed to APS heat exchangers, where supplemental oxygen is added to the fuel-rich turbine exhaust, and reburned to supply the energy necessary for propellant conditioning. The heat exchanger must operate in a relatively high hot-side temperature environment, and must provide high cycle life capability with large cold to hot side temperature gradients. Three types of heat exchangers were considered for this function, illustrated in Figure 4-17. Two heat exchanger concepts using staged oxygen addition to reduce and maintain outside gas temperatures to relatively low levels were considered. In the first, the fuel-rich gas and a small amount of oxygen are ignited in the heat exchanger inlet. The resulting temperature of the hot gas is approximately 2000°R. Heat exchange with the cold propellant cools the gas and when cooled to approximately 1500°R, additional oxygen is supplied to reestablish the higher temperature. In this manner, all secondary oxygen addition can be autoignited by the hot gas products, and



COMPARISON OF TEMPERATURES IN EQUIVALENT MR DESIGNS FIGURE 4-17 separate ignition sources are not required. This concept, however, requires a maximum number of oxygen stages.

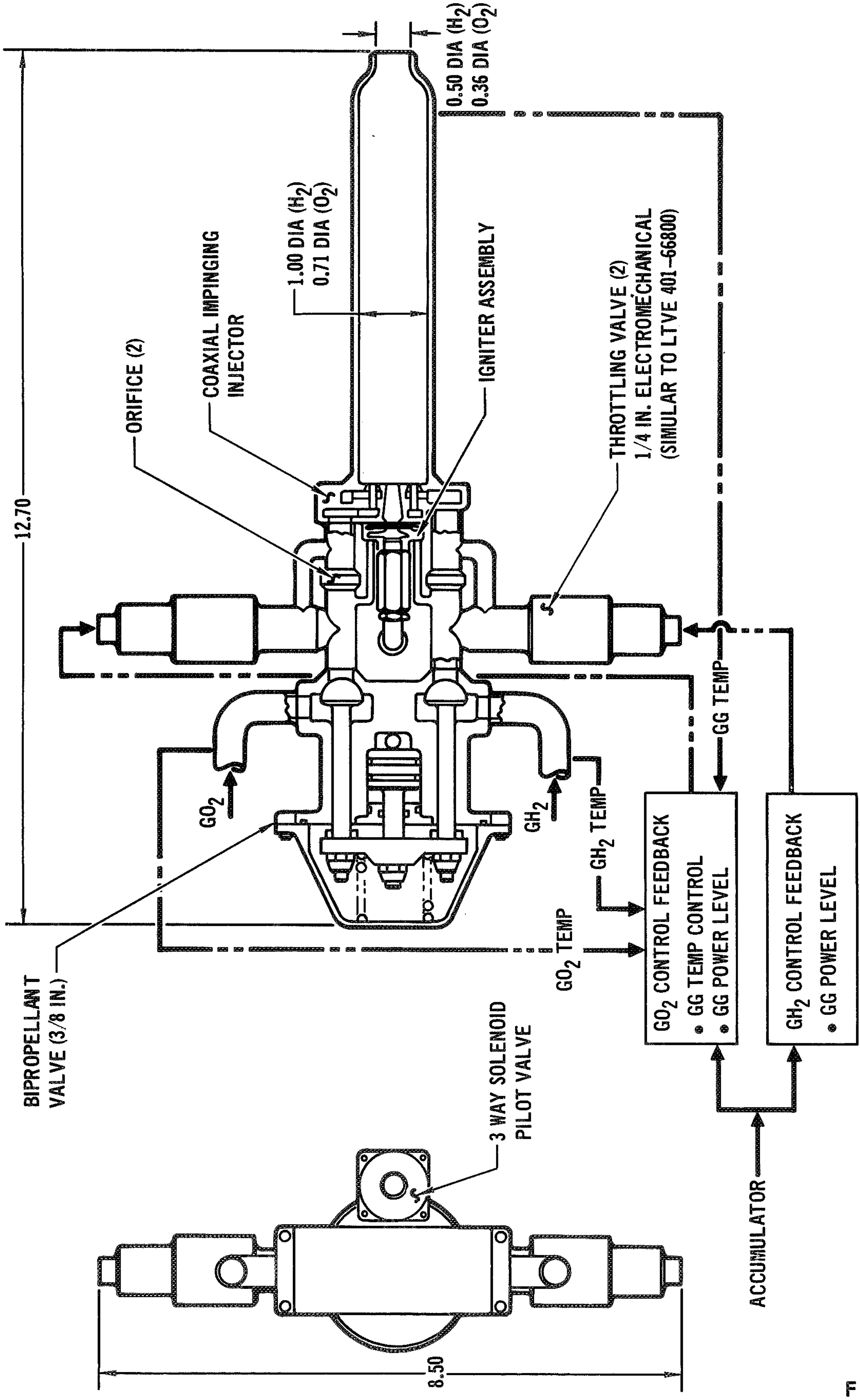
The second concept shown uses a similar approach to reduce the hot side temperature of the heat exchanger. The hot gas can cool significantly more between stages, allowing a reduction in the number of stages. However, here ignition sources are used at each oxygen stage. The third approach shown uses a single point oxygen addition. All oxygen is added at the inlet of the heat exchanger, and an ignition source provided. This concept operates at the maximum hot side temperature, but is simplest from control and design standpoints. These concepts were compared on the basis of technology requirements: the single point injection approach was selected, as it offered minimal complexity. The selected design is based on application of injector plate fabrication technology developed for staged combustion cycles. The design of the heat exchanger is shown in Figure 4-18 which illustrates the platelet construction technique. In this selected design, the hot and cold side heat transfer coefficients are controlled by flow passage tailoring. As shown in the blowup of Figure 4-18, propellants enter the heat exchanger base and are used to regeneratively cool the heat exchanger shell by flowing up the outside wall and down the inside wall parallel to the hot gas flow. The propellants also enter the plates at one side of the lower end, flow upward through the center, split and flow down the outside of the plates and accept heat from the parallel flowing hot gas. The heated propellants are then collected in a manifold on the opposite side from the inlet at the lower extremity of the plate and directed to the accumulators. To uniformly distribute the supplemental oxygen, a distribution manifold is located upstream of the plates. A catalytic igniter in the manifold is used as the ignition source for the turbine exhaust gas and the gaseous oxygen. During accumulator recharge, oxygen addition is controlled to maintain a near constant propellant temperature at the heat exchanger outlet. This provides the high hot side temperatures necessary to preclude condensation of water vapor in the exhaust gas.

Gas Generator Subassembly - Gas generators are required to provide power for turbopump operation and energy to reburn heat exchanger assembly. These units operate with gaseous hydrogen/oxygen propellants in the same manner as the thruster assemblies and they provide a throttling capability to limit operating temperature and to maintain accumulator pressure in the presence of varying APS flow demand. The design selected is shown in Figure 4-19. This concept uses an electrical spark igniter and operates at 2000°R combustion temperature and 500 lbf/in^2a steady-state operating pressure. Of principal significance to this assembly is



HIGH TEMPERATURE HEAT EXCHANGER

FIGURE 4–18



APS GAS GENERATOR

FIGURE 4-19

the control valve. The valve design is effectively two valves in one. The primary flow control is accomplished by a linked, on/off, bipropellant valve with a pilot operated, pneumatic actuator. Vernier control of flow is provided by independent hydrogen and oxygen throttle valves driven by torque motors. The primary flow is admitted to the assembly and split to two flow paths, one allowing approximately 80 percent of the flow and controlled by a fixed orifice assembly. The remainder of the flow is routed to a bypass circuit, which includes the throttle valves. In this manner, up to 20 percent flow reduction can be obtained. Both the hydrogen and oxygen throttle valves are controlled to adjust the power to the turbine to the level required to maintain minimum accumulator pressure during steady-state operation. Additional control of the oxygen valve is provided to adjust the gas generator mixture ratio to maintain the desired turbine operating temperatures.

4.2.4 Propellant Storage Assembly - The propellant storage assembly maintains the cryogenic propellants in their liquid state and positions them for delivery to the turbopumps. The assembly operates similarly to conventional storable propellant tankage. Pressure within the tank is maintained by mechanical regulation of a helium pressure supply. Propellants are kept 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, passed over the outer shell, and the heat leak taken up by propellant 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-g operation in any vehicle direction.

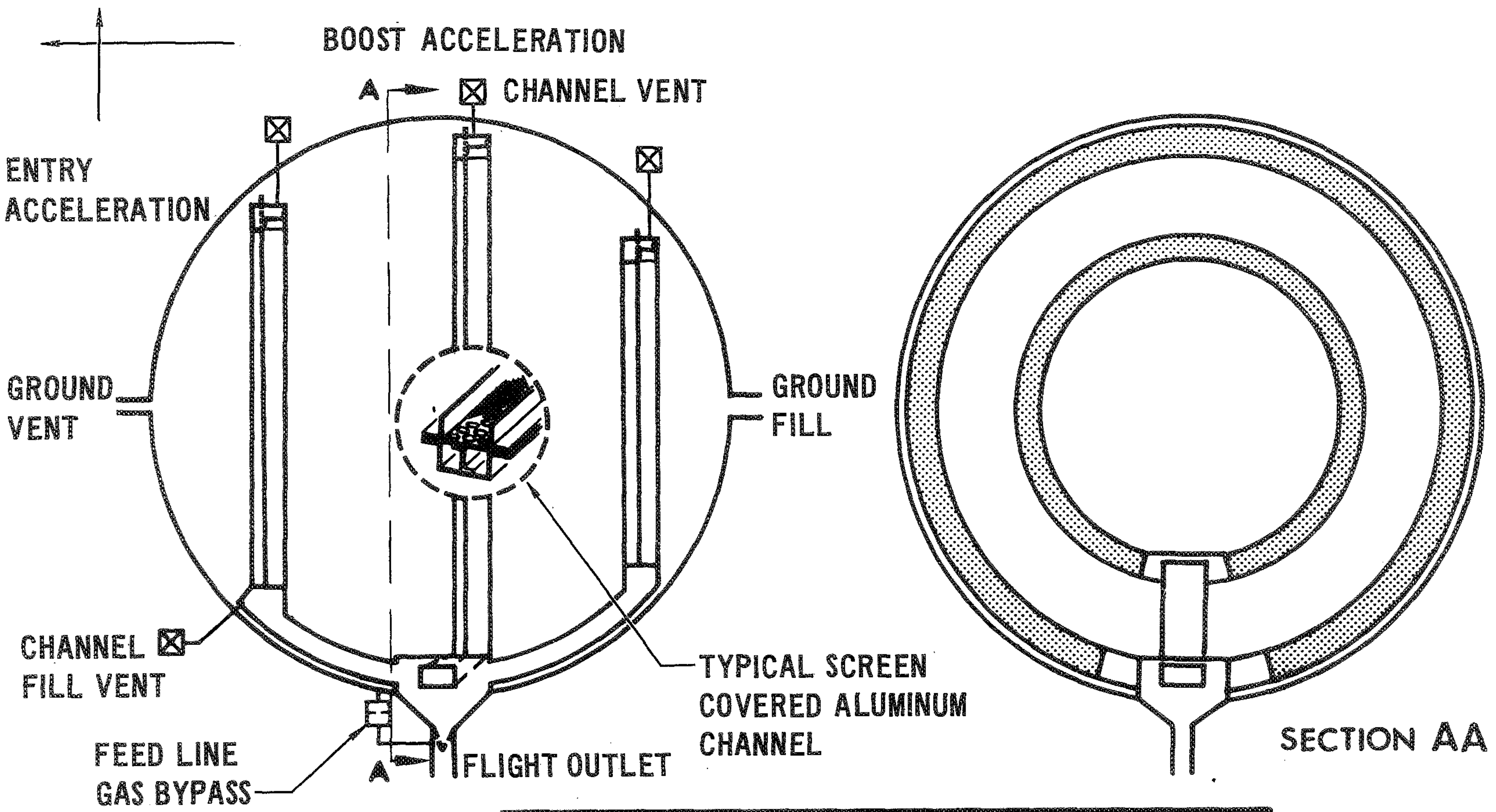
Three primary subassemblies are required:

(1) propellant acquisition subassembly
(2) thermal protection subassembly
(3) pressurization subassembly.

For each, several alternate approaches were available that could potentially satisfy APS requirements; these were compared to establish approaches best suited to APS design. The following paragraphs summarize the studies for each individual subassembly associated with propellant storage.

Propellant Acquisition Subassembly - A propellant acquisition device is required to ensure liquid outflow during low-g orbital phases of the mission. During these phases, vehicle acceleration will tend to randomly orient the propellant within the tank, thereby potentially uncovering the tank outlet. Some device is, therefore, necessary to ensure that liquid will be retained at the outlet, or to provide a flow path for communication between the liquid mass (in any random orientation) and the tank outlet. Of the several concepts that could be considered for this function, surface tension screen devices appeared the only practical approach, considering APS tank sizes and reuse requirements. Devices of this type are passive, thus providing high reliability and multicycle reuse capability. Three basic concepts using surface tension screens were evaluated. The first was a wall-oriented device placing the screen in close proximity to the tank wall throughout the tank. This approach provides communication between liquid mass and tank outlet, as long as the liquid is in contact with the wall. The remaining two approaches provide containment of a prescribed amount of liquid within the surface tension screen. Both are refillable during +X maneuvers, when the propellant mass will be oriented by acceleration forces. In the first of these, the screen cavity is sized to contain the maximum amount of propellant that could be used between +X maneuvers of sufficient duration to allow refill. The second is a combination approach, providing a contained propellant cavity, and also a flow path between contained propellant and propellant mass. This condition endures as long as the tank contains enough propellant for the deorbit burn (i.e., approximately one-third of the propellant). Based on confidence in operation and performance, the first approach was selected. The propellant acquisition device design selected, using this general approach, is shown in Figure 4-20. It consists of screen channels located around the tank circumference, plus a single enclosed collector manifold which connects each channel to an outlet sump. The acquisition device will selectively pass liquid to the feed system as long as there is contact with the liquid mass. The wall oriented nature of the device ensures that this contact will be made. Screen mesh and flow passage dimensions were selected so that the pressure drop across the screen vapor/liquid interface never exceeds the screen bubble point prior to reentry. During reentry, deceleration forces will result in channels draining however, these same forces will orient the propellant at the outlet of the tank for continued propellant use.

Thermal Protection Subassembly - Satisfactory turbopump operation requires that the propellants be maintained as gas free, subcooled liquids to avoid vapor ingestion and assure a net positive suction pressure at the pump inlet. To avoid excessive propellant boiloff and to prevent vaporization within the surface tension screen, an efficient thermal protection subassembly must be provided. Primary thermal protection is based on the use of high performance, multilayer, aluminized mylar insulation to reduce vaporization and boiloff losses. This



	ORBITER B	ORBITER C	BOOSTER
SCREEN SIZE	2 @ 250 x 1370 (17 μ) 1 @ 200 x 600 (40 μ)	2 @ 250 x 1370 (17 μ) 1 @ 200 x 600 (40 μ)	200 x 600 (40 μ)
CHANNEL SIZE (IN.)			
H_2	5 x 8	4 x 6	5 x 8
O_2	3 x 6	3 x 4	3 x 6

APS PROPELLANT ACQUISITION CONCEPT

FIGURE 4-20

insulation approach offered a well-documented background of demonstrated design data and was considered to be the only practical approach for long term cryogenic propellant storage. However, since the insulation cannot completely eliminate heat leak into the tank, a heat exchanger assembly must be provided to preclude bulk liquid heating, and the mylar insulation must be protected while within the atmosphere. This is necessary in order to prevent condensation, which results in degradation of thermal properties and reuse capability.

Several insulation protection alternates were investigated. These were:

(1) vacuum jacketed dewars, using a rigid structural outer shell

(2) nonvacuum jacketed tanks, with flexible or semirigid covers to protect the mylar insulation.

The nonvacuum jacketed approaches required noncondensible gas purges while in the atmosphere to preclude condensation. The dewar approach was simplest, but its weight penalties were not considered justifiable, and a lighter weight approach, requiring purge gas, was selected. This approach uses a fiberglass outer shell to cover the mylar insulation. Both hydrogen and oxygen tanks use a nitrogen gas purge to prevent cryopumping during ground holds, but, since nitrogen would condense at liquid hydrogen temperatures, the hydrogen tank also incorporates a layer of foam insulation to provide a temperature gradient between liquid propellants and internal layers of mylar insulation. During reentry, the fiberglass jackets are pressurized with helium to prevent collapse pressure loads, and to preclude admission of atmospheric air during entry.

For the heat exchanger/cooling assembly three alternates were considered.

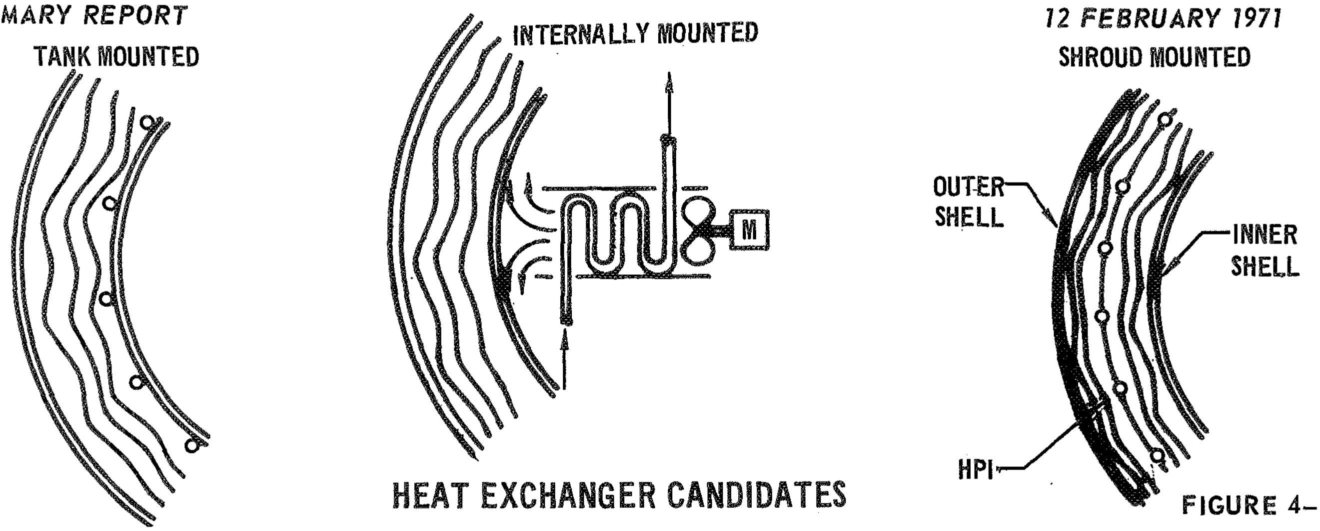
(1) tubular heat exchanger mounted directly to the tank wall

(2) tubular heat exchanger attached to a thin metal radiation shroud displaced from the tank wall

(3) compact heat exchanger mounted inside the propellant tank.

These three alternates are illustrated in Figure 4-21. The third alternate shown, that using the radiation shroud, was selected. A heat exchanger mounted directly to the tank was considered inadequate, since it would allow development of temperature gradients between cooling tubes unless internal circulation fans were provided. The second approach, using a compact heat exchanger, offered little weight advantage, and also required propellant circulation within the tank.

Using the selected heat exchanger approach and the insulation system defined above, analyses were conducted to determine the amount of flow required to maintain the propellants in their liquid state, and to define a flow schematic for



HEAT EXCHANGER CANDIDATES

FIGURE 4-21

the coolant. Figure 4-22 is a schematic of the tankage coolant loop. Hydrogen is continuously circulated through the cooling tubes to intercept residual heat leak through the insulation and the heat short paths. Liquid hydrogen is extracted from the hydrogen tank, throttled to reduce its temperature, and then directed to the tank cooling shroud, where it absorbs heat through vaporization. The hydrogen is then used to cool the hydrogen turbopump assemblies, the oxygen tank and the oxygen turbopump assemblies in series.

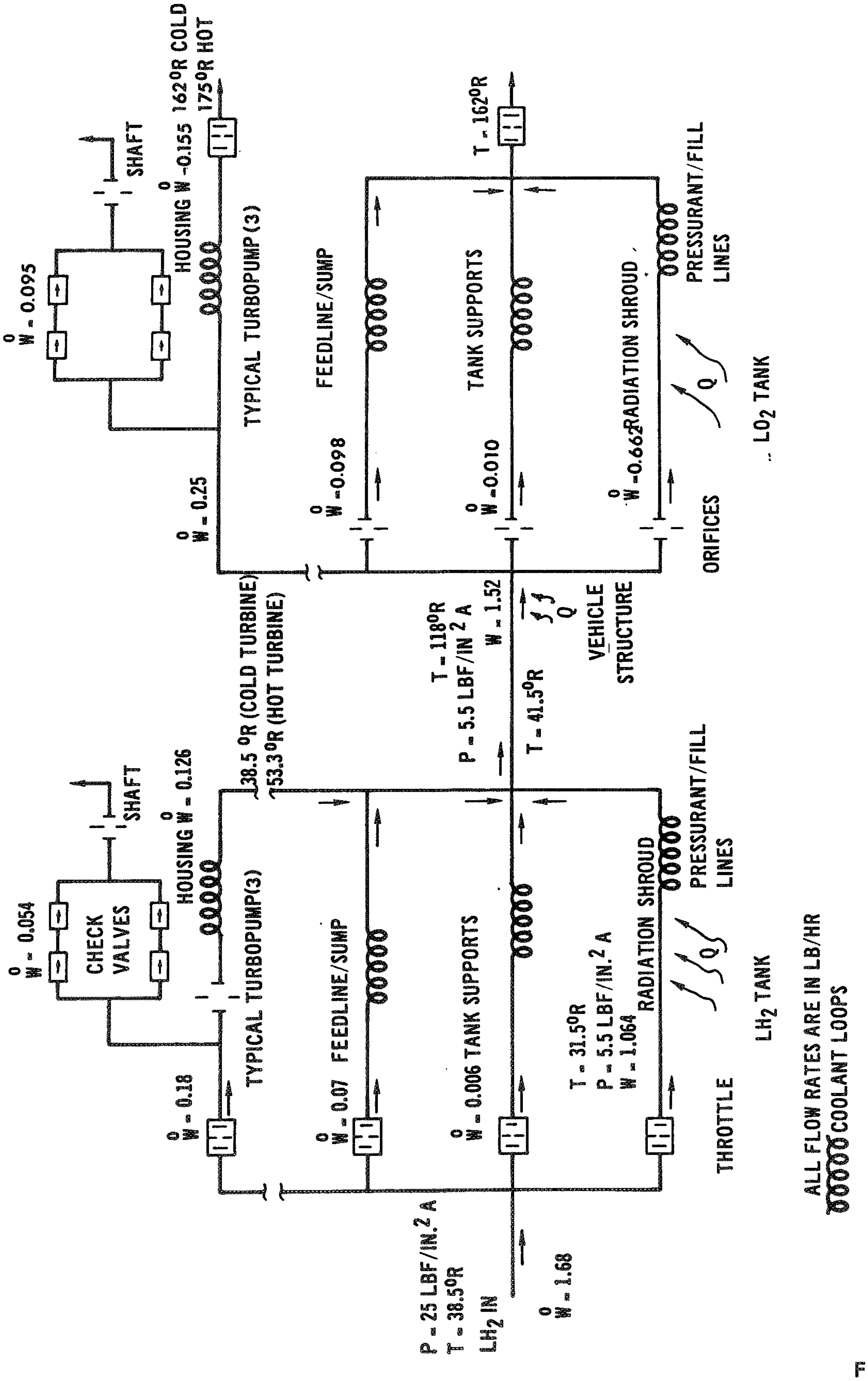
Pressurization Subassembly - Two candidate pressurization types were evaluated:

(1) autogenous pressurization, using gaseous propellants from the accumulators

(2) cold helium pressurization, with submerged injection.

Weight comparisons between the two approaches were made and, at the design pressures of interest, cold helium was the lightest weight for the oxygen tank, while autogenous pressurization was slightly the lighter for hydrogen tankage. These weight comparisons, however, were somewhat conservative, as they did not include changes to the conditioner design and accumulators necessary to accommodate increased pressurization flow requirements. Thus, the small weight advantage afforded by autogeneous pressurization was not considered realistic, and the simpler, more conventional, cold helium pressurization approach was selected for both propellants. The small weight penalty for helium was outweighed by its inherent simplicity and sound technology base.

4.3 APS Design and Performance - Subtask B effort resulted in definition of preliminary design, performance, and operational characteristics of the turbopump APS, identified by this study to be the most attractive high pressure APS concept. Component designs and performance were investigated and established to define the most realistic APS component configuration. With these components established, APS

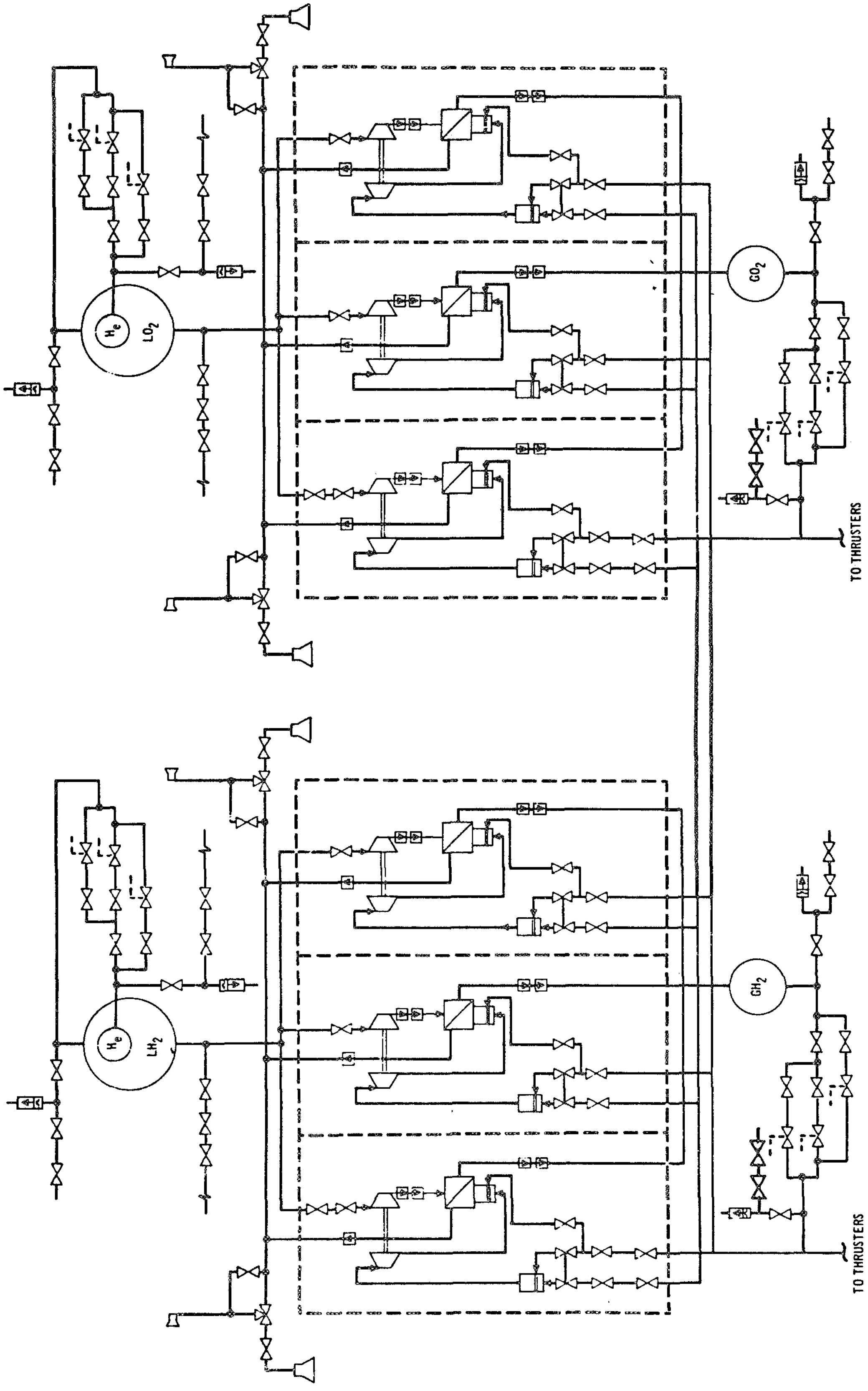


VENT SUBASSEMBLY SCHEMATIC

FIGURE 4-22

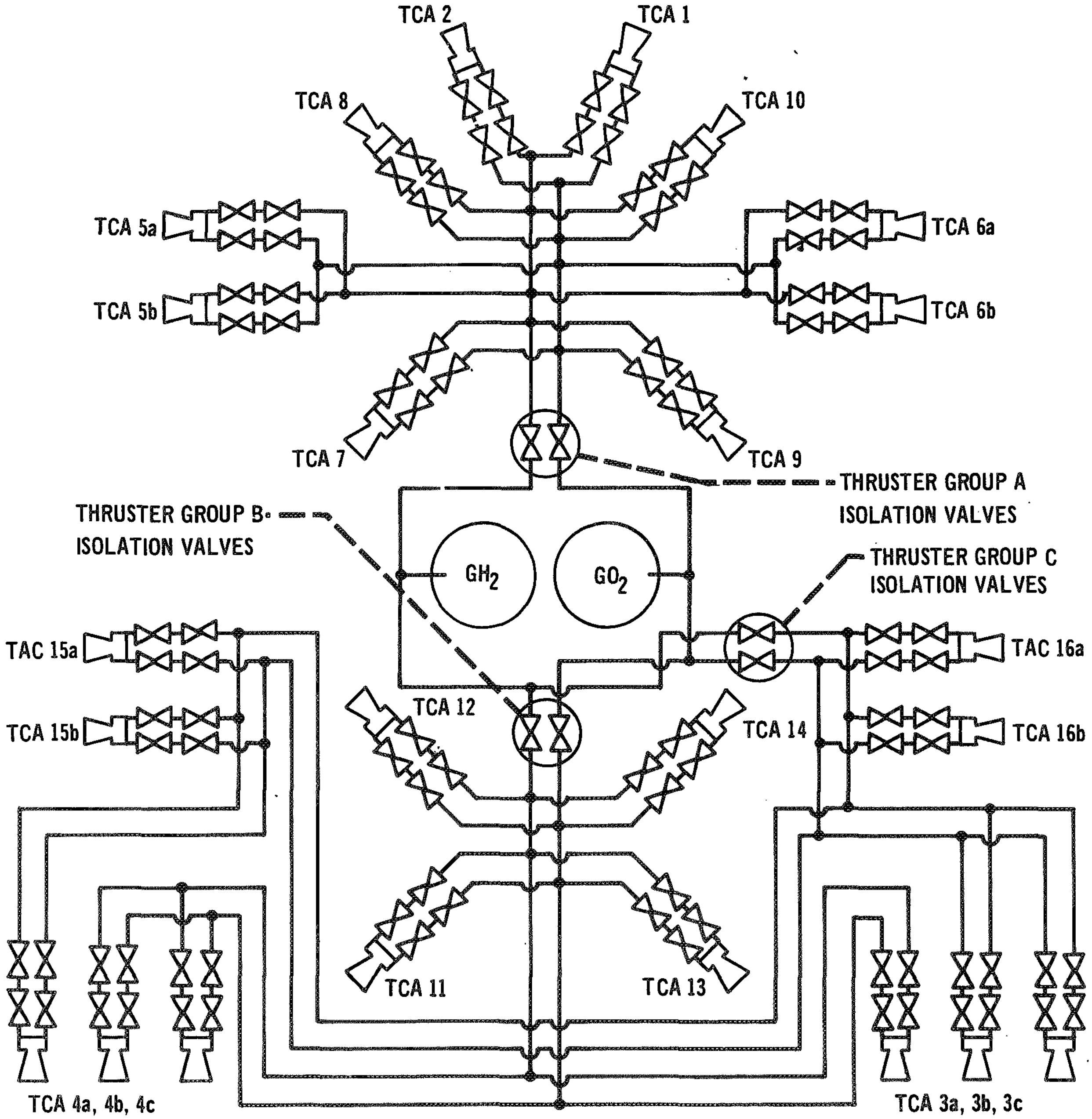
designs and installation characteristics were baselined to satisfy vehicle control requirements of Reference (d). Figure 4-4 summarizes number of thrusters, thrust level, and total impulse required for each vehicle addressed in Subtask B. Designs were developed to satisfy these requirements for each vehicle. The resulting APS are basically the same for Orbiter B, Orbiter C and the Booster. Conditioning assemblies are identical in configuration and operation for the three vehicles. Differences in design result from different tank sizes and locations, line and thruster locations, and vent arrangements. However, these differences are, in general, minor. The schematic of the storage and conditioning assemblies for Orbiter B is shown in Figure 4-23. The schematic for Orbiter C is identical, except that two hydrogen tanks are used. It is identical also to that of the booster, except that a propulsive vent is not used. Figures 4-24, 4-25 and 4-26 provide schematics of the thrusters and distribution lines for all three vehicles. APS schematics provide the component redundancy necessary to satisfy shuttle failure criteria of first failure-fail operational, second failure-fail safe (i.e., provide reentry capability). These criteria necessitated triple redundancy of active components. Three parallel redundant regulators are provided for each pressure regulating function, as are three completely independent conditioning assemblies for each propellant loop. When the primary conditioning assembly fails, it is isolated and a new conditioning assembly is activated. Each thruster has isolation valves in series with the thruster propellant valves to allow individual isolation of a failed-open thruster. A second set of valves isolates each propellant manifold to provide isolation of a thruster valve double failure and the valve's individual isolation valve. Tanks, accumulators, lines, and fittings were considered structure, and redundancy was not provided. For these schematics, complete functional flow diagrams were established and failure mode and effects analyses were performed to verify that the APS would in fact satisfy shuttle failure criteria.

One of the major considerations involved in design evaluation of the APS is total subsystem weight. APS design optimization required a rapid and accurate means of generating APS weights for different design conditions so that design points providing minimum subsystem weight could be determined. In order to generate accurate, representative, and consistent subsystem weights for many different design points, an APS design and sizing computer program was developed. This program allowed definition of subsystem weight and performance for any set



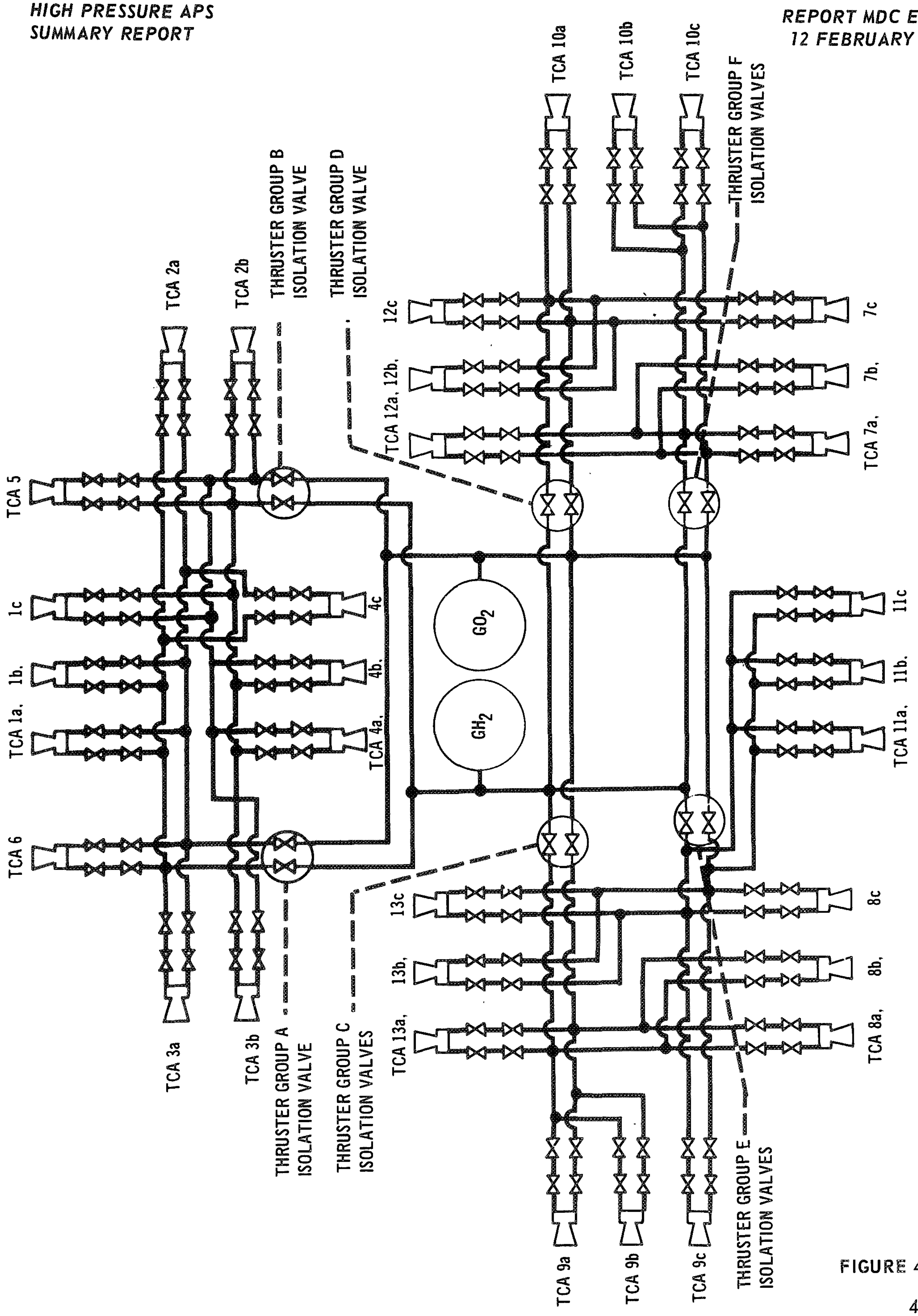
APS ORBITER B SCHEMATIC

FIGURE 4-23



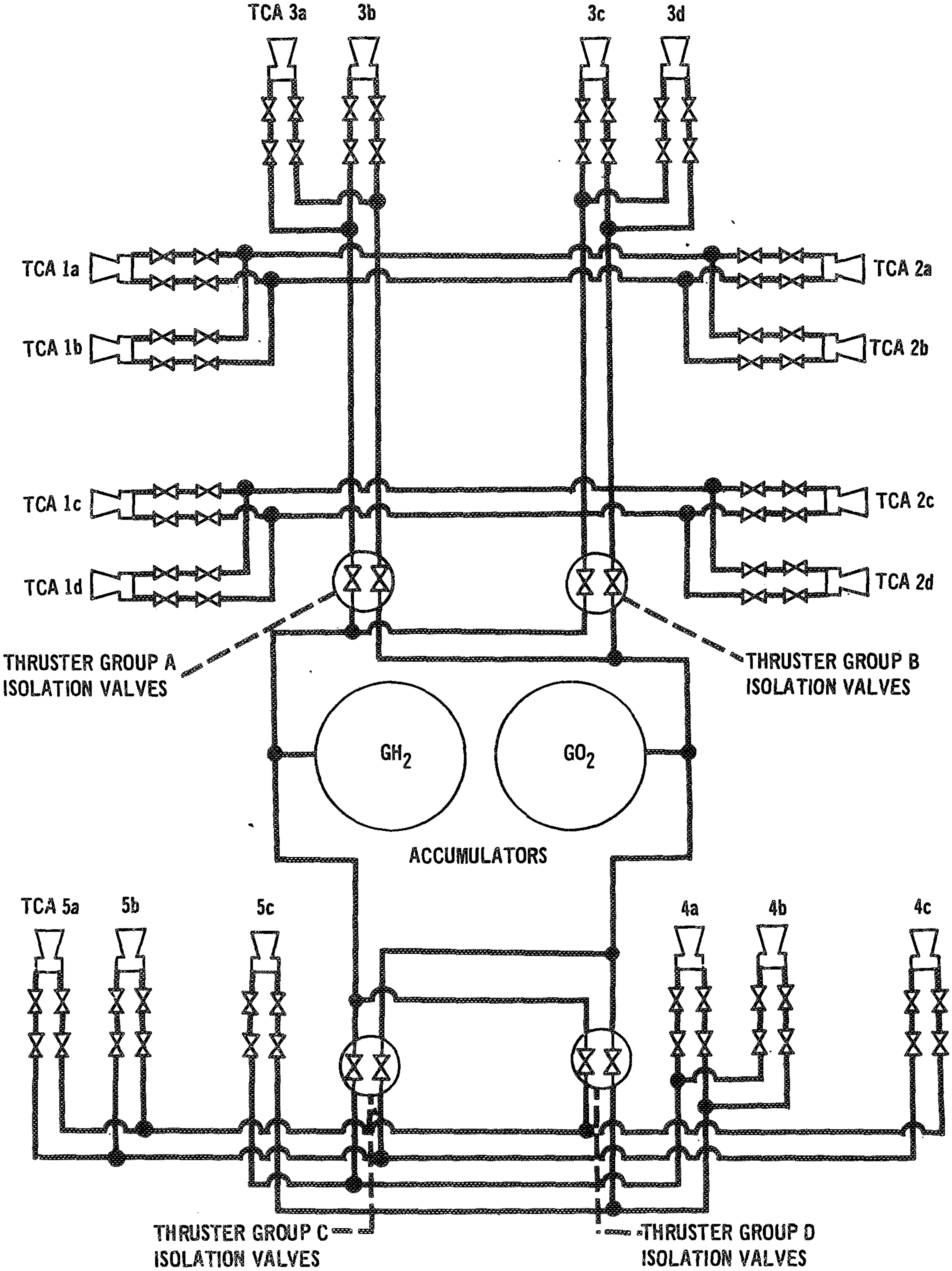
ORBITER B PROPELLANT DISTRIBUTION

FIGURE 4-24



ORBITER C PROPELLANT DISTRIBUTION

FIGURE 4-25



BOOSTER PROPELLANT DISTRIBUTION

FIGURE 4-26

of specified design conditions. It also served as a compact library of representative component weights, volumes, and performance for a high-chamber-pressure turbopump APS.

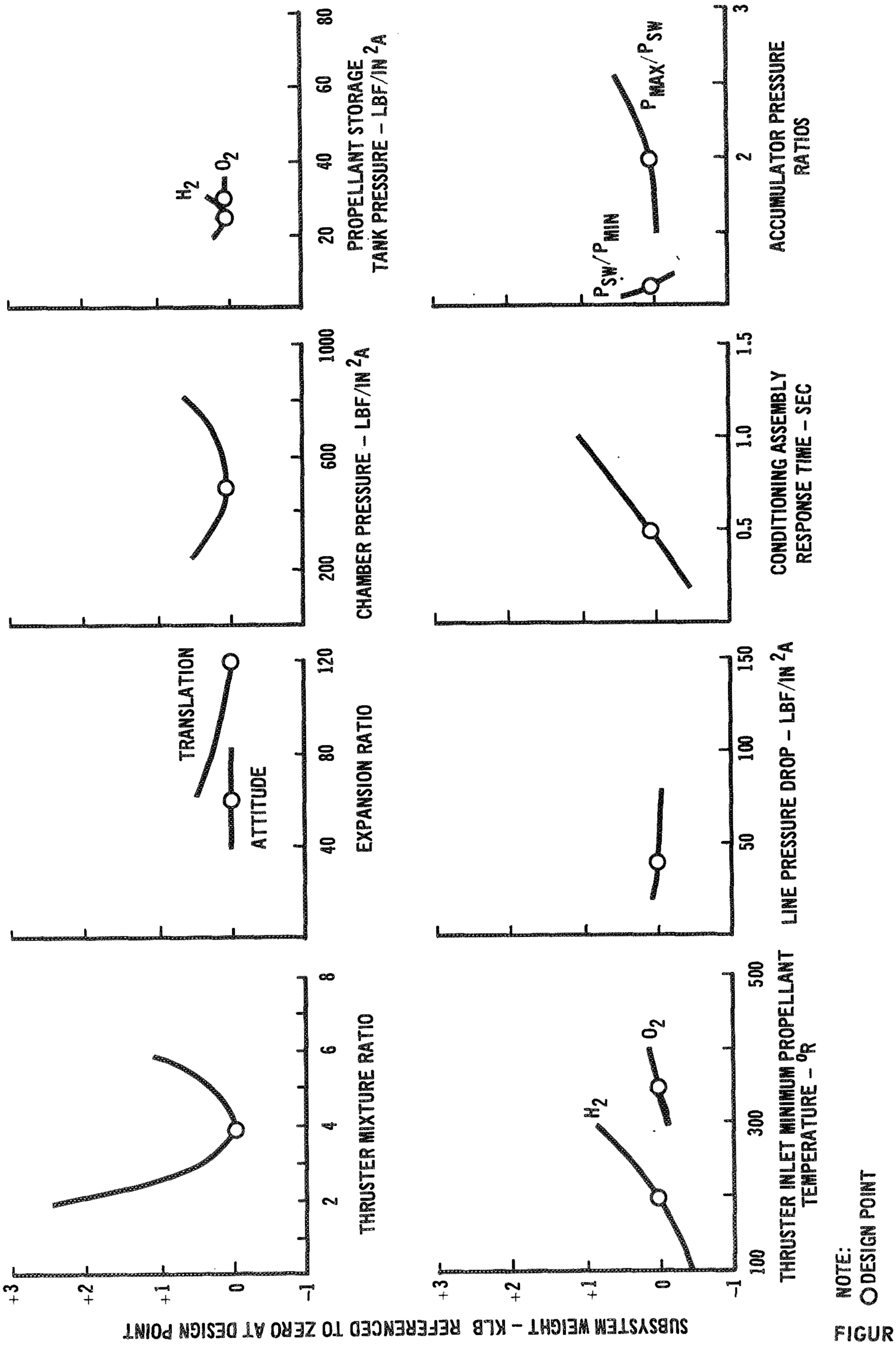
Using this computer program, total subsystem weights were generated, and the subsystem design point was optimized by means of subsystem linear weight sensitivities.

APS weight sensitivities to single design variables for the final Subtask B baseline APS are shown in Figures 4-27 to 4-29 for Orbiter B, Orbiter C, and the Booster, respectively. Figures 4-30 through 4-32 provide corresponding sensitivity to requirements. Figure 4-33 summarizes APS design characteristics and shows resulting overall APS weight.

The APS was sized and designed on the basis of nominal, steady-state, component performance. In actual operation, heat transfer into the accumulators and supply lines will alter operating pressures and temperatures, with resultant performance variations. Similarly, off-nominal performance of components and/or assemblies will result in performance changes; therefore, in order to establish APS design adequacy, it was necessary to simulate APS operation during a mission.

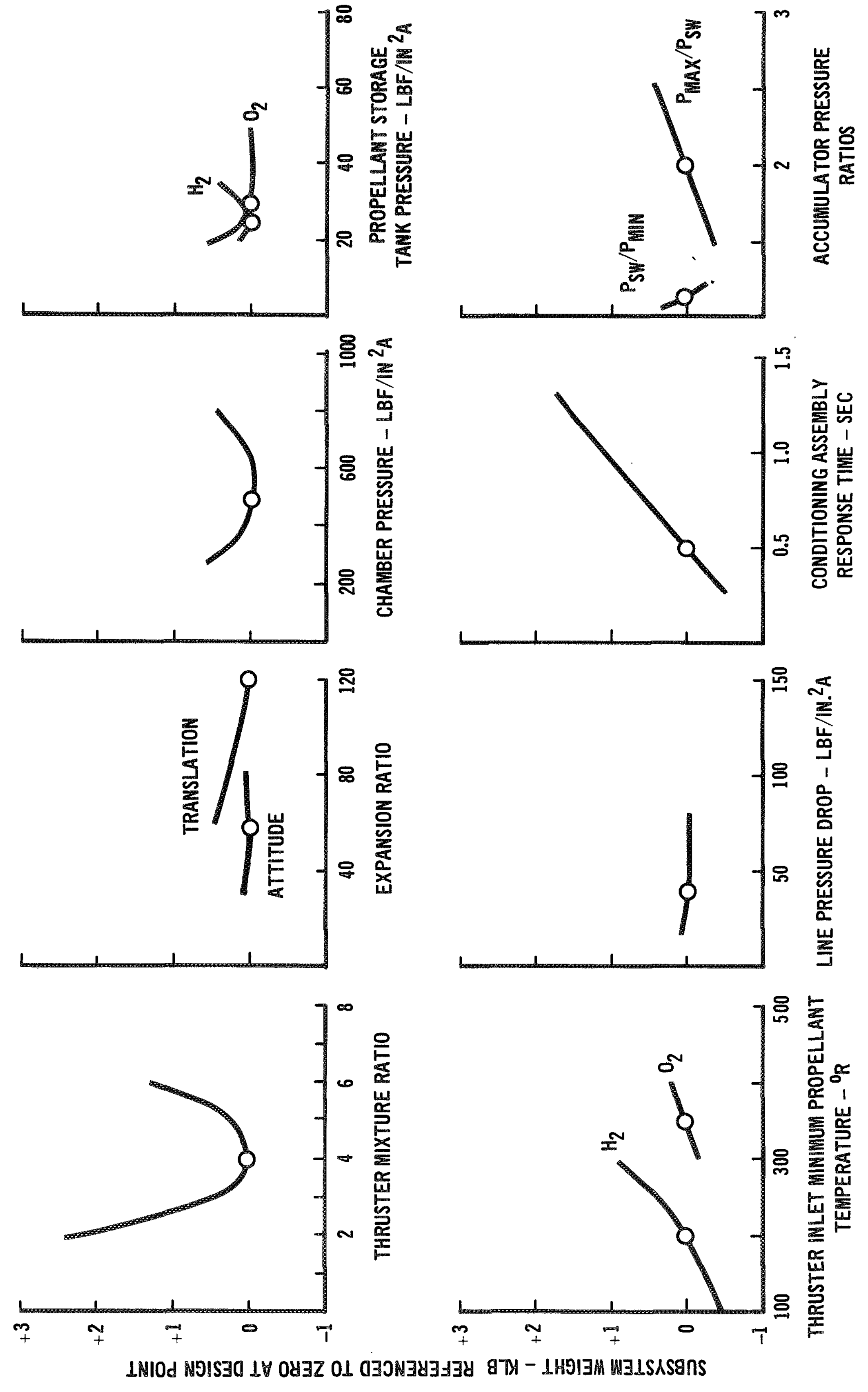
To accomplish these analyses, another computer program was developed, which models thrusters, supply lines, accumulators, and conditioner assembly while simulating APS flow rate demands during the mission. Actual mission time is compressed for these analyses by approximating limit cycle control phases of the mission as an equivalent average flow rate. The program calculates thrust, total impulse, pressures, temperatures, and flow rates relating to operation of the accumulators, lines, and thrusters.

For the selected designs, parametric analyses defined the performance characteristics of the APS under simulated mission operating conditions. These analyses included investigation of the impact of variances in propellant conditioning temperatures and pressure regulator performance. Figures 4-34 and 4-35 illustrate the nominal operation of the subsystem during the missions (i.e., with all components and assemblies operating at their design values). Results (Figures 4-34 and 4-35) show that variations in mixture ratio and chamber pressure resulting from temperature changes within the subsystem are not excessive. Additionally, analyses were conducted during the study to investigate the operation of the subsystem in the presence of off-nominal component operation. Specifically, variances in regulator pressure and conditioner flow and temperature were considered.



WEIGHT SENSITIVITY TO DESIGN VARIABLES
ORBITER B

FIGURE 4–27

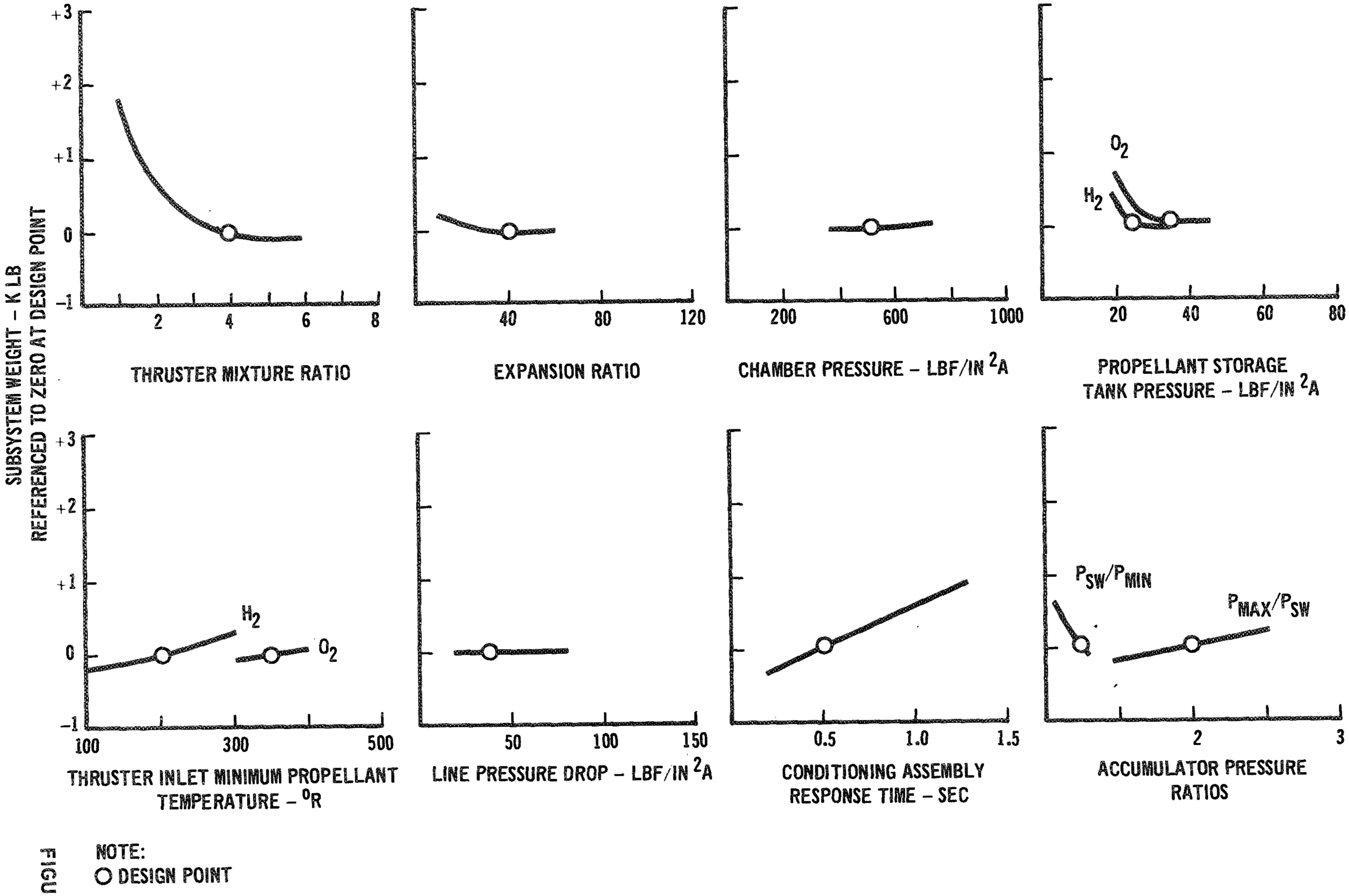


NOTE:
○ DESIGN POINT

WEIGHT SENSITIVITY TO DESIGN VARIABLES

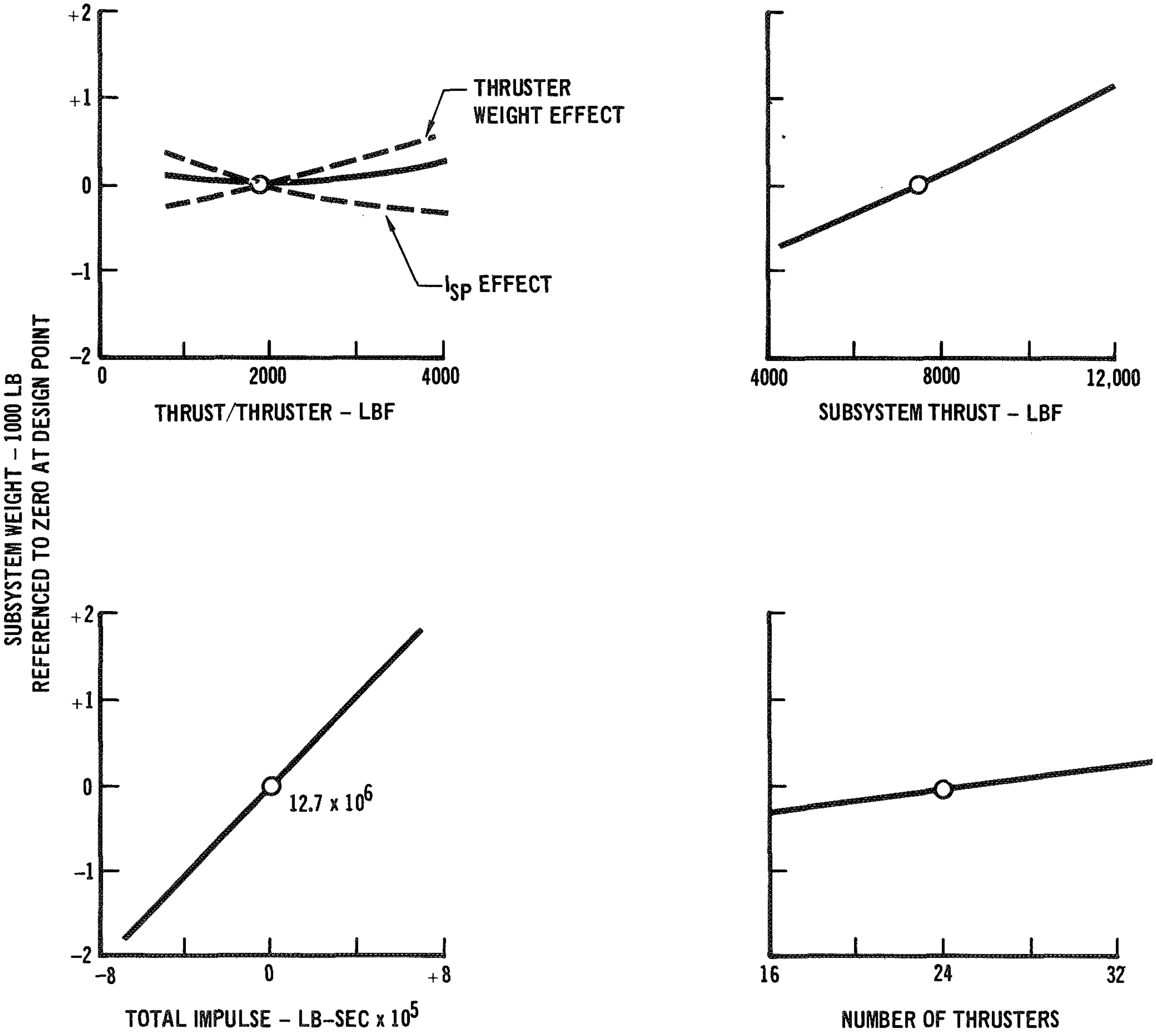
ORBITER C

FIGURE 4-28



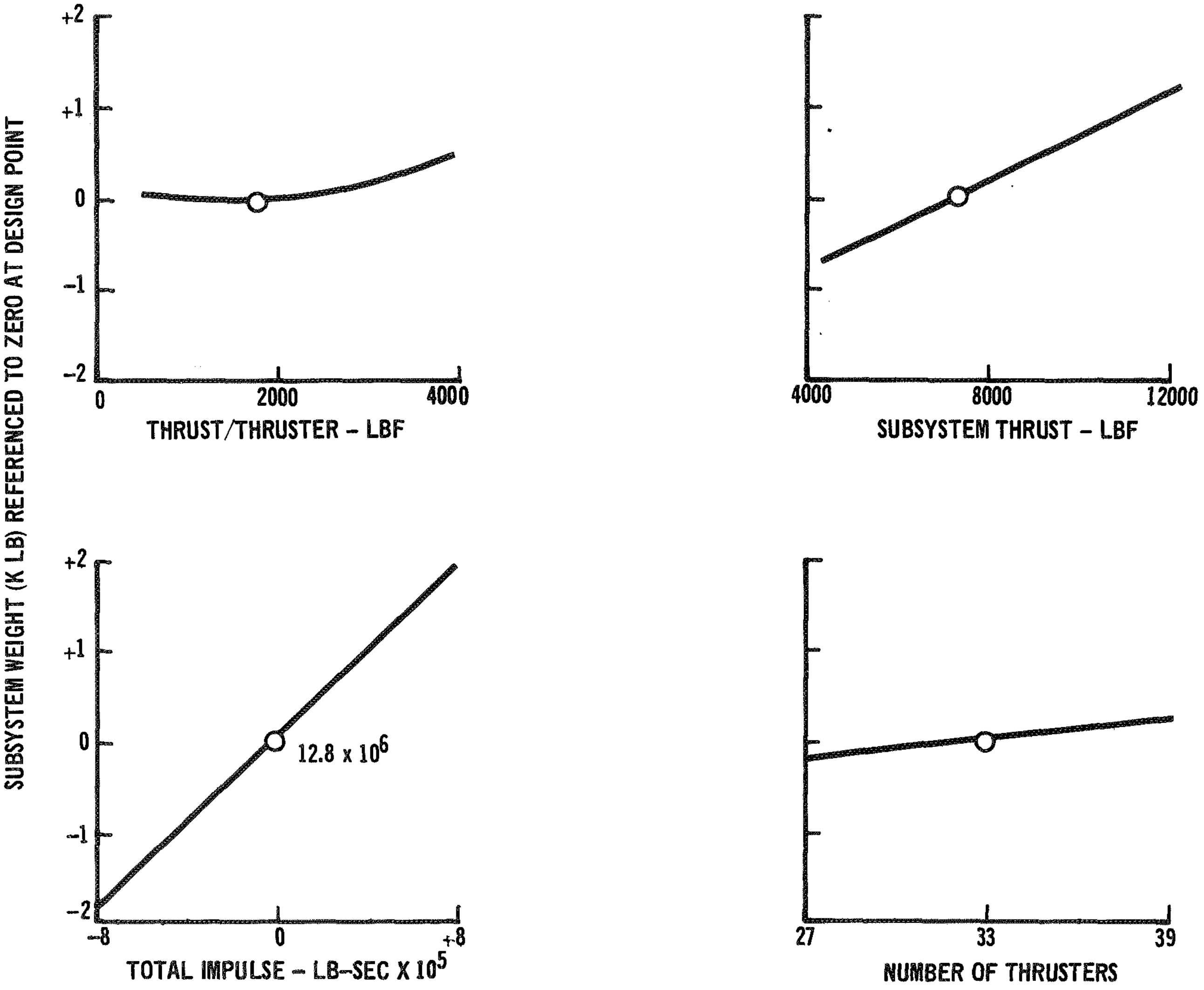
WEIGHT SENSITIVITY TO DESIGN VARIABLES
BOOSTER

FIGURE 4–29



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS
Orbiter B

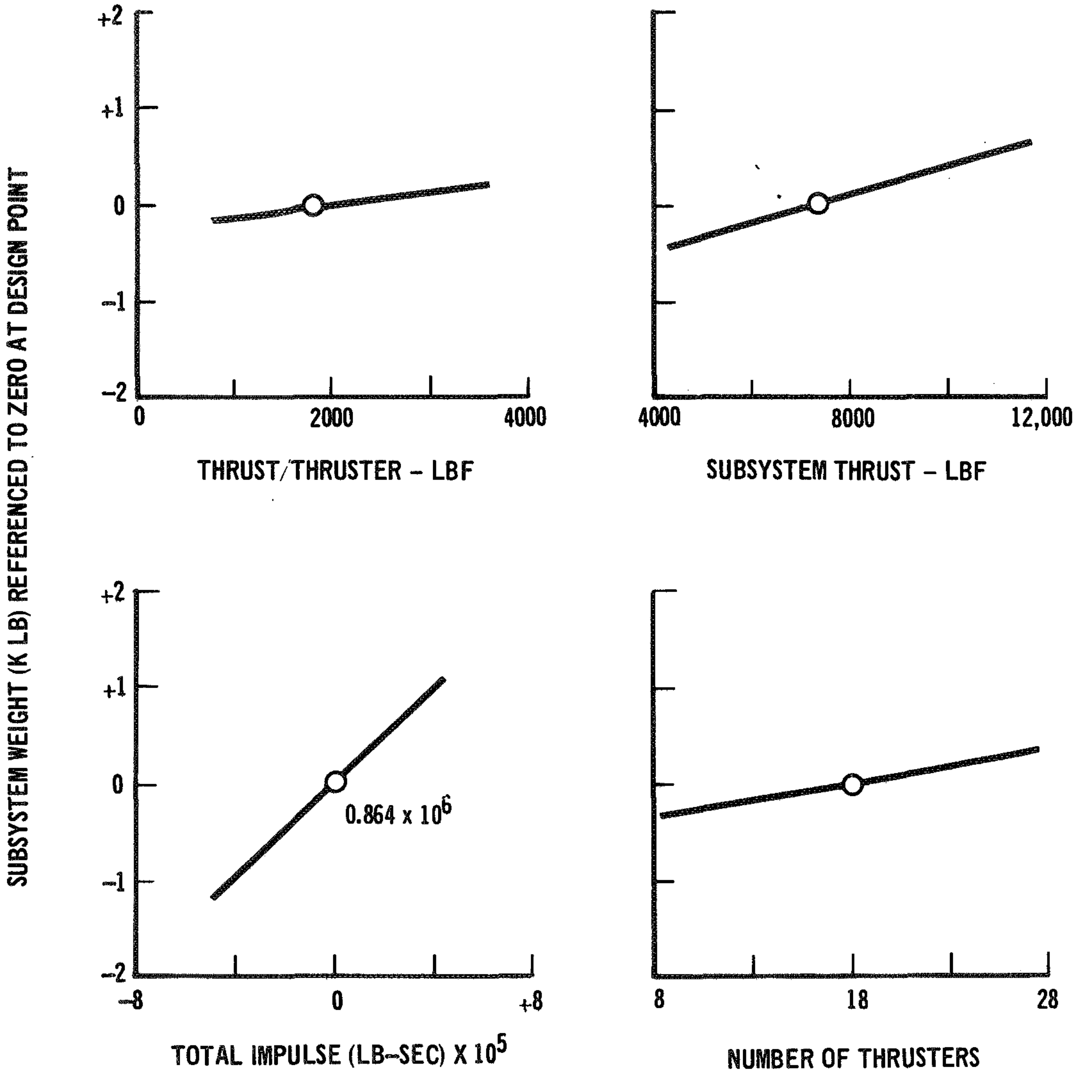
FIGURE 4-30



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

Orbiter C

FIGURE 4-31



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS
BOOSTER

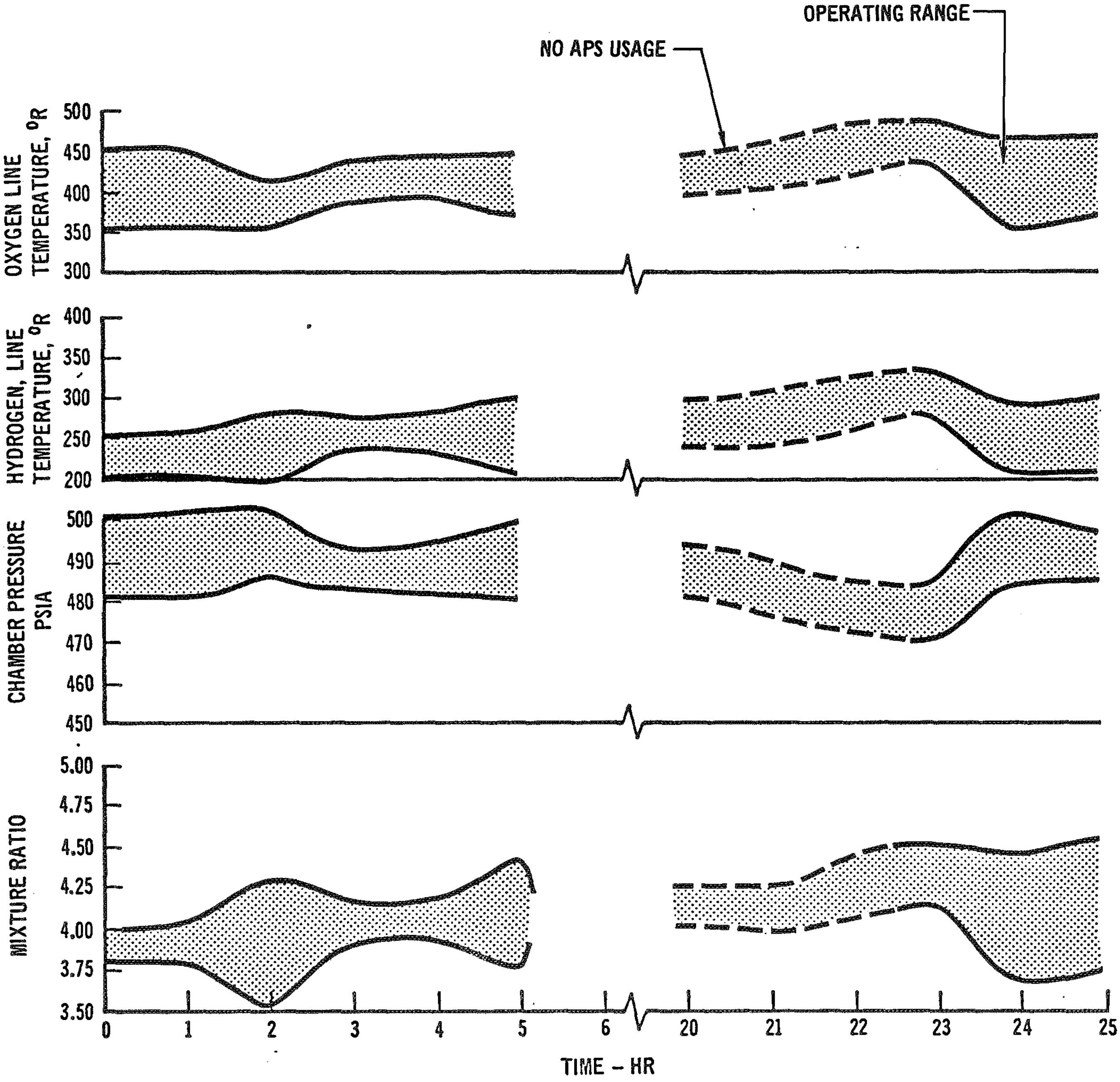
FIGURE 4–32

DESIGN VARIABLES	ORBITER B	ORBITER C	BOOSTER
THRUSTER MIXTURE RATIO	4	4	4
EXPANSION RATIO	60/120*	60/120*	40
CHAMBER PRESSURE (LBF/IN.^{2})	500	500	500
LINE PRESSURE DROP LBF/IN.^{2}	40	40	40
PROPELLANT TEMPERATURE (^{0}R) – H_2	37	37	37
O_2	162	162	162
THRUSTER INLET PROPELLANT MINIMUM TEMPERATURE (^{0}R) – H_2	200	200	200
O_2	350	350	350
ACCUMULATOR PRESSURE RATIO – MAX/SWITCH – H_2/O_2	2	2	2
SWITCH/MIN – H_2/O_2	1.135/1.13	1.13/1.125	1.24
PROPELLANT TANK PRESSURE LBF/IN.^{2}A – H_2	25	25	25
O_2	30	30	35
THRUSTER SPECIFIC IMPULSE – SEC	446.9/455.2*	446.9/455.2*	444.9
SYSTEM SPECIFIC IMPULSE – SEC	416.0/423.7*	416.0/423.7*	410.8
SYSTEM MIXTURE RATIO	3.87	3.87	3.87
WEIGHT	35,879	37,070	5,310

*ATTITUDE CONTROL/TRANSLATION

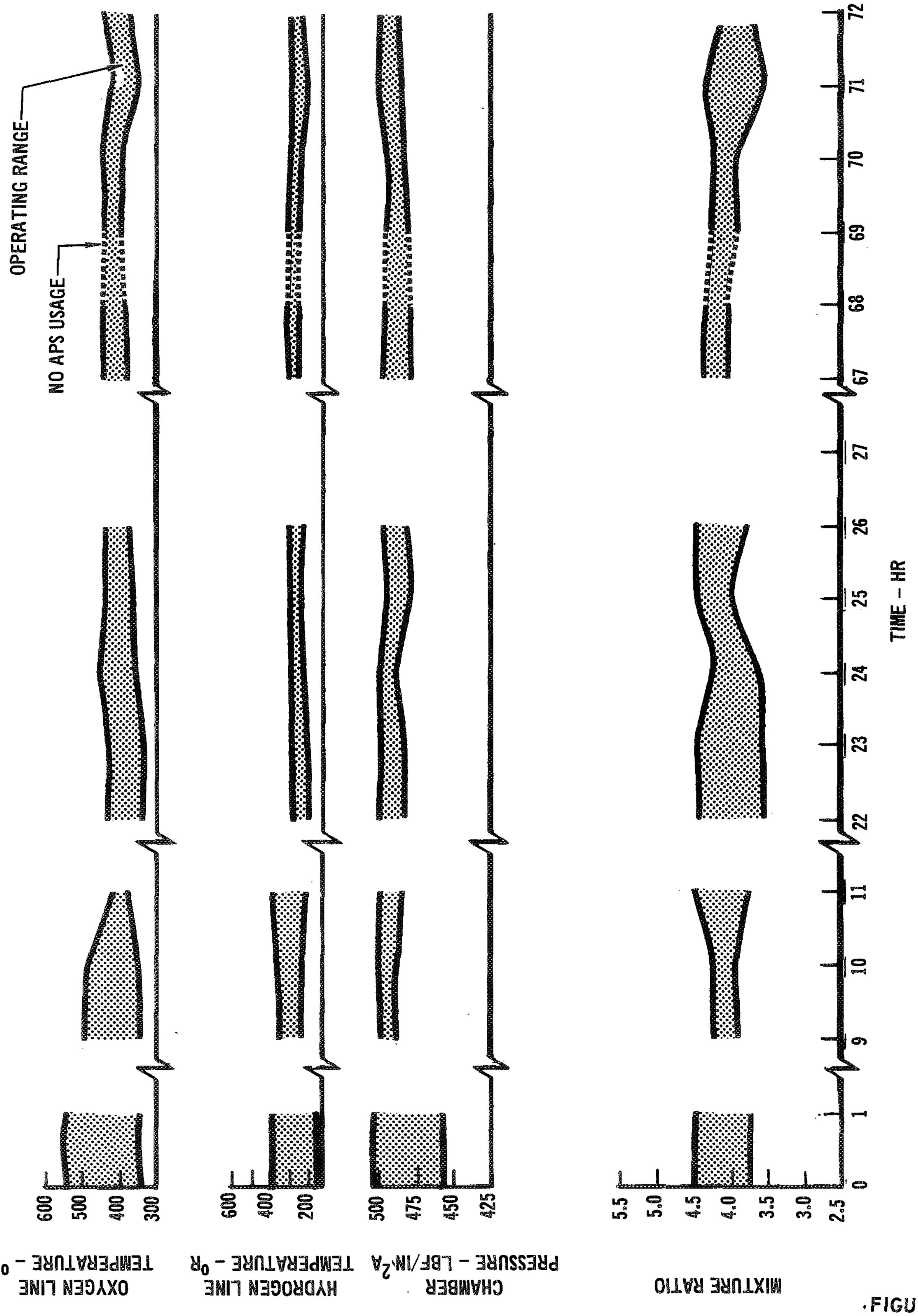
TURBOPUMP APS DESIGN POINTS AND WEIGHTS

FIGURE 4-33



SUBSYSTEM OPERATING CHARACTERISTICS
3RD ORBIT NOMINAL VENTED

FIGURE 4-34



SUBSYSTEM OPERATING CHARACTERISTICS
NOMINAL DESIGN CONDITIONS
17TH ORBIT RENDEZVOUS

FIGURE 4-35

Results of these analyses show that, while off-nominal operation increases performance variations during the mission, variations are not extreme, and are in fact, within the capability of the thruster assembly. Figure 4-36 provides a summary of mean APS total impulse and mixture ratio, integrated over the complete mission for the nominal design and taking into consideration the presence of off-nominal influences.

DESIGN CONDITIONS	3RD ORBIT RENDEZVOUS		17TH ORBIT RENDEZVOUS	
	INTEGRATED MIXTURE RATIO	TOTAL IMPULSE LBF-SEC	INTEGRATED MIXTURE RATIO	TOTAL IMPULSE LBF-SEC
NOMINAL DESIGN CONDITIONS	4.048	12,078,498	4.027	13,336,867
NOMINAL DESIGN CONDITIONS (NO VENT)*	4.048	12,077,977	4.020	13,335,566
OXYGEN CONDITIONING TEMPERATURE INCREASED 5%	3.938	11,973,966	3.931	13,204,708
HYDROGEN CONDITIONING TEMPERATURE INCREASED 5%	4.132	12,061,734	4.134	13,299,448
OXYGEN REGULATION PRESSURE INCREASED 5%	4.004	12,063,065	4.004	13,301,044
HYDROGEN REGULATION PRESSURE INCREASED 5%	4.009	12,091,579	4.039	13,334,203

* NO VENTING OF LINES AFTER DOCKED PHASE OF MISSION

APS OFF NOMINAL DESIGN SUMMARY
Orbiter B

FIGURE 4-36

5. STUDY CONCLUSIONS

During Subtask A of this study, all viable candidates for gaseous H_2/O_2 high pressure auxiliary propulsion subsystems were compared on the basis of weight, technology, simplicity, and flexibility to requirements. From this comparison, the turbopump APS concept was clearly the best selection for both boosters and orbiters. Subtask A, additionally, provided a comparison of APS designed for a range of +X maneuver velocity levels. Specifically, APS were designed to perform all maneuvers, and also to provide only small maneuver velocity changes. In the latter cases, an orbit maneuvering subsystem (OMS) is required for major velocity changes. Evaluation of the OMS was not a part of this study, so a comparison of combined APS/OMS requirements was not possible. However, on the basis of the APS designs only, the all-maneuver case showed an advantage because of increased flexibility. On the basis of these results, NASA selected the turbopump APS for Subtask B preliminary design, and specified that preliminary design effort be directed to an APS capable of performing all maneuvers.

In Subtask B (preliminary design) the specified concept was studied to develop an optimized design capable of satisfying shuttle requirements. This was accomplished through a series of interrelated studies associated with APS components, assemblies, and subsystems which provided an integrated APS design and established its performance characteristics in an installed configuration. The resulting preliminary design evidences no requirements which are considered to be unreasonable extensions of state-of-the-art technology. However, in terms of thrust level, total impulse, and reuse capability, shuttle requirements are far beyond those for any previous control propulsion susbystem. Consequently, no APS components capable of satisfying these requirements exist today. The preliminary APS design resulting from this study is based on analytical techniques and/or component performance which have been demonstrated either for smaller scale hardware, or in technology programs.

Funded technology development programs are currently underway for some of the more critical components, such as valves, ignition, and thrust chamber cooling, and for certain aspects of the propellant storage assembly. Those areas of technology which appear to require additional effort in support of APS development are summarized in Figure 5-1.

This APS study program has not fully explored potential tolerances within the subsystems, the accuracy of sensors and controls, nor has it defined the three sigma performance boundaries. For these reasons, further, more detailed analysis of the integrated subassembly, in parallel with the exploratory programs outlined in Figure 5-1, is required.

TECHNOLOGY CONCERN	ALTERNATIVE APPROACH	IMPACT OF CHANGE
• TURBOPUMP COOLING/RESPONSE	• INCREASED COOLANT FLOW • REDUCED RESPONSE REQUIREMENT	• 40 LB INCREASE FOR TWICE DESIGN COOLANT FLOW • 300 LB INCREASE FOR FACTOR OF FOUR IN EQUIVALENT START TIME
• THRUSTER ASSEMBLY PERFORMANCE	• REDUCTION IN PERFORMANCE REQUIREMENTS	• INCREASED APS WEIGHT, APPROXIMATELY 100 LB PER SECOND I_{SP} REDUCTION
• THRUSTER ASSEMBLY LIFE CAPABILITY	• INCREASED COOLANT FLOW • PERIODIC REPLACEMENT	• INCREASED APS WEIGHT, APPROXIMATELY 300 LB FOR FACTOR OF 2 ERROR IN CYCLE CAPABILITY PREDICTION • INCREASED MAINTENANCE/TURN AROUND TIME
• PRESSURE VESSEL CYCLE LIFE CAPABILITY	• INCREASED DESIGN MARGIN	• INCREASED APS WEIGHT, APPROXIMATELY 500 LB FOR 50% INCREASE IN SAFETY FACTORS
• CONTROL COMPONENT LIFE CAPABILITY VALVES, IGNITERS, REGULATORS	• PERIODIC REPLACEMENT	• INCREASED MAINTENANCE/TURN AROUND TIME
• PROPELLANT ACQUISITION ASSEMBLY DESIGN AND VERIFICATION	• USE OF MULTIPLE SMALL REFILLABLE TANKS	• INCREASED WEIGHT (APPROXIMATELY 400 LB), INCREASED DESIGN AND CONTROL COMPLEXITY AND REDUCED APS FLEXIBILITY
• HIGH TEMPERATURE REBURN HEAT EXCHANGER DESIGN	• SERIES-STAGED COMBUSTION HEAT EXCHANGERS TO LIMIT MATERIAL TEMPERATURE • CONVENTIONAL–MODERATE TEMPERATURE HEAT EXCHANGERS (2000°R) • NO REBURN HEAT EXCHANGER	• INCREASED OPERATIONAL AND CONTROL COMPLEXITY WITH MULTIPLE OXYGEN INJECTION (IGNITION) • INCREASED APS WEIGHT, APPROXIMATELY 1800 LB • INCREASED APS WEIGHT, APPROXIMATELY 2200 LB
• HIGH PERFORMANCE INSULATION REUSABILITY – PROPELLANT TANKS – DISTRIBUTION LINES	 • VACUUM JACKETED DEWARS • VACUUM JACKETED LINES	 • INCREASED APS WEIGHT, APPROXIMATELY 650 LB • MAJOR INCREASES IN INSTALLATION/DESIGN COMPLEXITY, INCREASED APS WEIGHT, APPROXIMATELY 400 LB
• TURBOPUMP LIFE CAPABILITY	• REDUCE OPERATING REQUIREMENTS • PERIODIC REPLACEMENT	• INCREASED APS WEIGHT, APPROXIMATELY 700 LB FOR FACTOR OF 2 REDUCTION IN CYCLE CAPABILITY PREDICTION • INCREASED MAINTENANCE/TURN AROUND TIME

CRITIQUE OF HIGH PRESSURE APS TECHNOLOGY

FIGURE 5-1

6. REFERENCES

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FIGURE 6-1

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