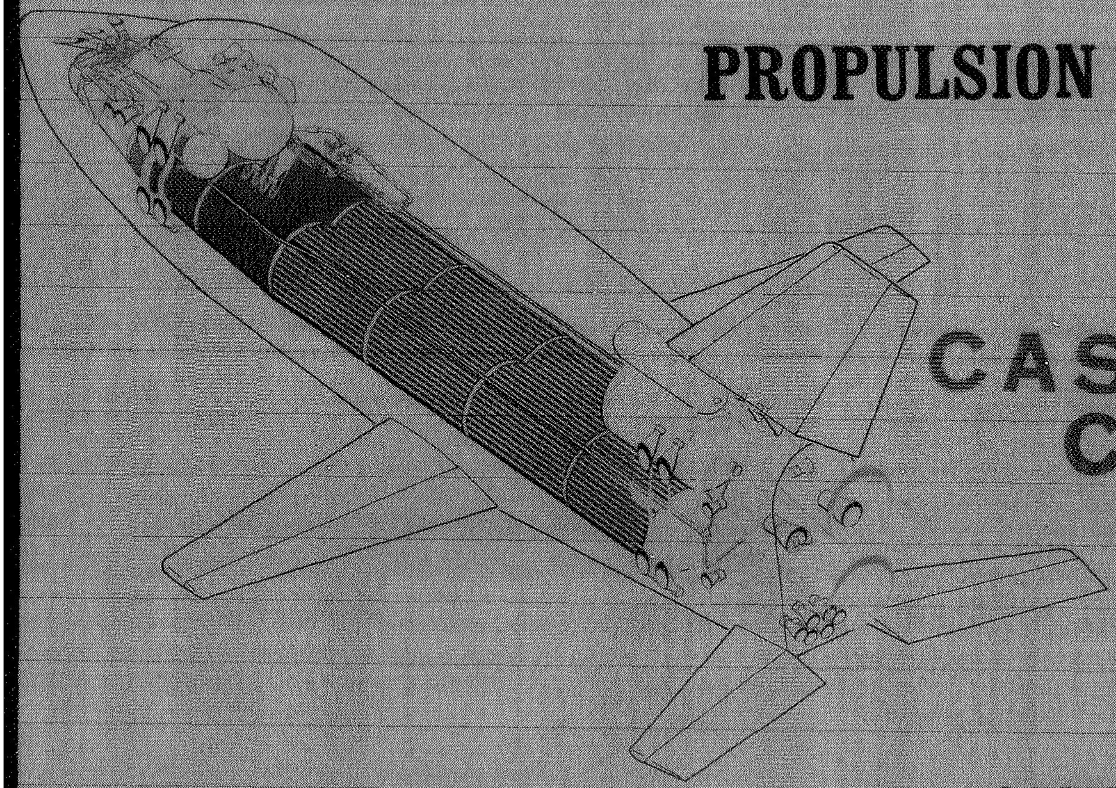
N71-22010
NASA CR-114945

REPORT MDC E0293

SPACE SHUTTLE LOW PRESSURE AUXILIARY PROPULSION SUBSYSTEM DEFINITION



SUMMARY REPORT

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY - EAST

MCDONNELL DOUGLAS CORPORATION

COPY NO. 108

SPACE SHUTTLE LOW PRESSURE AUXILIARY PROPULSION SUBSYSTEM DEFINITION

CONTRACT NO. NAS 9–11012

29 JANUARY 1971 REPORT MDC E0293

SUMMARY REPORT

Prepared by:

P.J. Kelly, Study Manager

T.F. Schweickert, Study Technical Director

Approved by:

L.F. Kohrs, Manager, Propulsion

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY • EAST

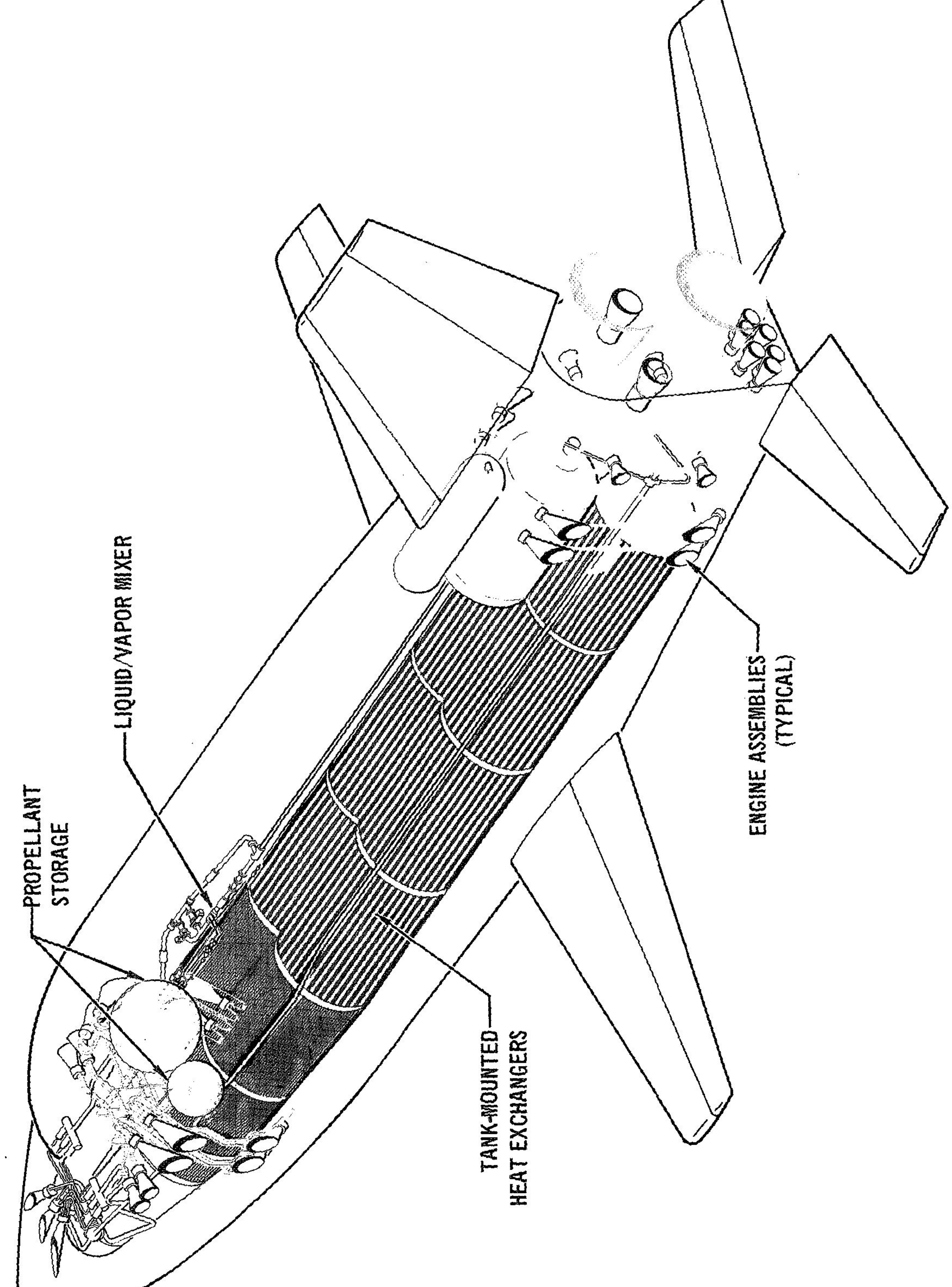
Saint Louis, Missouri 63166 (314) 232-0232

MCDONNELL DOUGLAS CORPORATION

ABSTRACT

This summary report provides an overview of a study to define the most attractive low pressure, oxygen/hydrogen auxiliary propulsion subsystem (APS) for NASA space shuttle boosters and orbiters. The study was performed for the National Aeronautics and Space Administration, Manned Spacecraft Center (MSC), Houston, Texas, under Contract No. NAS 9-11012.

The study program was divided into two phases. The first, Subtask A, was a conceptual subsystem definition phase designed to identify APS concepts best suited to each of two baseline shuttle boosters and orbiters. The second phase, Subtask B, comprised a preliminary design of selected subsystems to establish indepth understanding of subsystem design and operation. Detailed results of these two study phases are contained in McDonnell-Douglas Astronautics Company (MDAC) Reports E0302 and E0303. As discussed in this report, conceptual subsystem definition studies have shown that a low pressure APS can potentially fulfill shuttle requirements, and that such an APS is simple in design and operational approach. The most attractive low pressure concepts use the main engine propellant tanks as low pressure gas accumulators. Propellant residuals trapped in the main engine tanks following boost are sufficient to meet booster APS propellant demands. The booster APS operates as a simple blowdown subsystem and no additional control is required. The orbiter requires separate liquid propellant storage tanks to supplement boost residuals. Propellant from the storage tanks is circulated through passive, tank-mounted heat exchangers where it is superheated and injected into the main engine tanks. Warm propellant vapors from the main engine tanks are mixed with additional liquid propellants in a downstream liquid/vapor mixer, and supplied to the engines at constant temperature and pressure (constant density). A Design Handbook (MDAC Report E0301) provides design, operation, and performance data on the selected booster and orbiter APS.



LOW PRESSURE ORBITER APS INSTALLATION

CONTENTS

EFFECTIVE PAGES

Title

ii through iv

1-1 through 1-2

2-1

3-1 through 3-25

4-1 through 4-28

5-1

6-1

1. INTRODUCTION

Auxiliary propulsion will be required for space shuttle attitude and translational control. Operating on the same types of propellant (i.e., oxygen and hydrogen) as the shuttle main propulsion, these subsystems will have a minimum service life of 100 mission cycles without major overhaul or refurbishment. Two basic design approaches have been conceived for the auxiliary propulsion subsystem (APS): a high pressure concept, using turbopumps or turbocompressors to achieve high operating pressure levels, and a low pressure concept using the main engine propellant tanks as an integral part of the subsystem and operating at main engine tank ullage pressures. This report deals only with low pressure APS concepts. It summarizes the scope and results of a study conducted under MSC Contract No. NAS 9-11012, titled "Space Shuttle Low Pressure Auxiliary Propulsion Subsystem Definition." The study was performed for the National Aeronautics and Space Administration, Manned Spacecraft Center (MSC), Houston, Texas, under the technical direction of Mr. Norman Chaffee. The study objective was "to conduct preliminary auxiliary propulsion subsystem studies, which (would) generate information and data, for use in the overall shuttle vehicle effort," and which would, "identify attractive APS concepts, define their range of applicability and limitations and identify critical technology areas and development priorities." McDonnell Douglas Astronautics Company-East (MDAC-East) was the prime study agency with Aerojet Liquid Rocket Company (ALRC), as major subcontractor, providing basic component data.

The study program was divided into two phases. The first, Subtask A, was a conceptual subsystem definition phase designed to identify APS concepts best suited to each of two baseline shuttle boosters and orbiters. The second phase, Subtask B, comprised a preliminary design of selected subsystems to establish indepth understanding of subsystem design and operation. Detailed results of these two study phases are contained in MDAC Report Nos. E0302 and E0303.

The selected orbiter APS concept requires separate liquid propellant storage tanks to supplement boost residuals. Propellant from the storage tanks is circulated through tubular, passive heat exchangers where it is superheated and injected into the main engine tanks. Warm propellant vapors from the main engine tanks are mixed with additional liquid propellants in a downstream liquid/vapor mixer and supplied to the engines at constant temperature and pressure (constant density).

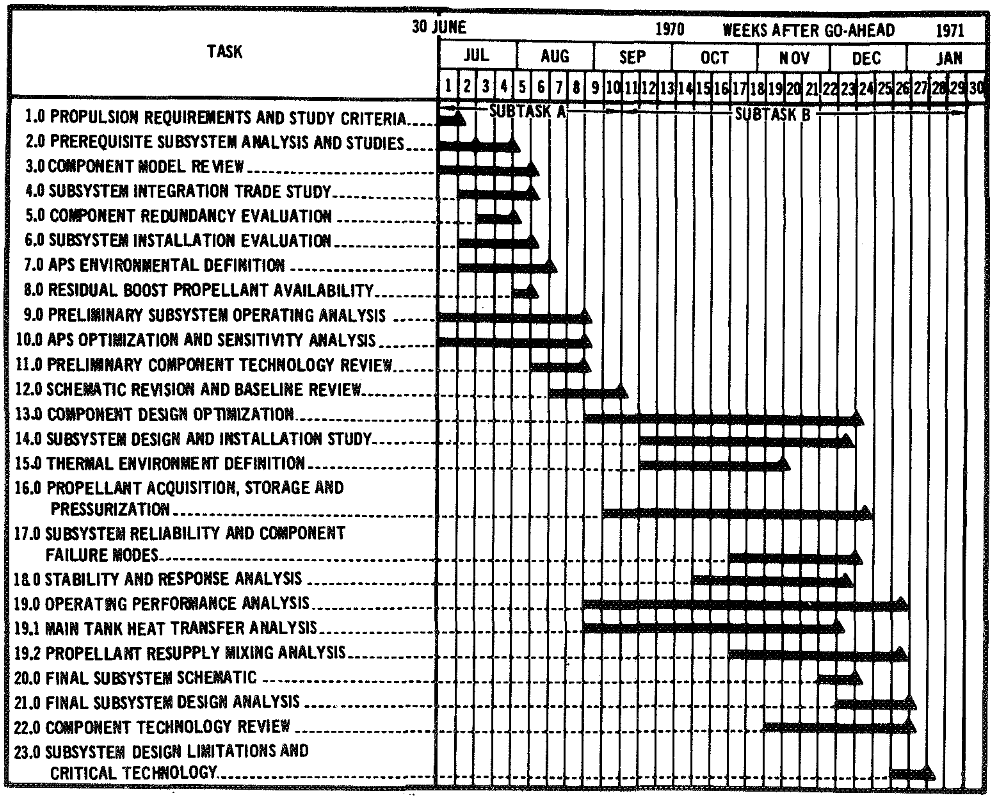
Design requirements presented herein differ from those applied to the high pressure APS study (Reference C). Weight estimates are presented in Paragraph 4.6 for alternate propellant tankage and engine arrangements to facilitate comparison, on the same basis, of low and high pressure APS designs.

The selected booster APS consists of propellant distribution and engine assemblies. It operates entirely from main engine tank residual propellants, requiring no additional propellant tankage, pumps, conditioning equipment, or mixing assemblies. The Design Handbook (MDAC Report E0301) provides design and operating data on the selected subsystems.

2. STUDY APPROACH

This study was divided into two levels of design detail. The first, Subtask A, was broad in scope, considering many concepts. During this phase, attractive concepts were synthesized, their range of applicability defined, and critical technology areas identified. The concept(s) which best satisfied space shuttle requirements and goals were selected for more detailed analysis and subsystem definition. To ensure that data generated during this first study phase be sufficiently general for overall shuttle study efforts, APS concepts were evaluated for two specific shuttle configurations (high and low crossrange) with varying requirements and interface characteristics.

The second study phase, Subtask B, involved preliminary design of selected APS concepts. Design concepts were updated to reflect revisions in shuttle requirements, the component and assembly requirements for updated designs were defined, and component types best suited to the APS were evaluated in detail to establish their performance, and transient characteristics. The resulting subsystem was analyzed to determine performance, operating characteristics, and advanced technology requirements necessary for subsystem development. The study schedule defining individual tasks is shown in Figure 2-1.



STUDY SCHEDULE

3. SUBTASK A - CONCEPT DEFINITION AND TRADE STUDIES

The primary objectives of Subtask A were analysis and critique of candidate concepts, and selection of a preferred approach. Concept screening studies, performed at study inception, identified 68 candidate low pressure APS for Subtask A study. Design analyses and intrasubsystem trades were necessary to ensure that each concept was shown to best advantage, and that all concepts were compatible with specific shuttle vehicles. When these studies were complete, concepts were compared on the basis of subsystem simplicity, weight and volume, mission flexibility, and required development and technology. From this study effort, subsystem concepts were selected by NASA for preliminary design. The selected orbiter APS approach used a passive heat exchanger for conditioning APS propellant, and a liquid/vapor mixer to control engine inlet conditions. The booster APS, as a result of its low total impulse requirement, demanded no propellant storage or conditioning equipment. Rather, it operated in a blowdown mode on main engine tank ullage vapors.

Major results of this study phase are discussed in the following paragraphs.

3.1 Requirements - APS guidelines and requirements for Subtask A are shown in Figure 3-1. The mission timeline was developed for a space station logistic

GUIDELINES AND CONSTRAINTS
- SUBSYSTEMS MUST PROVIDE OPERATIONAL PERFORMANCE AFTER FIRST FAILURE, AND SAFE OPERATION AFTER SECOND FAILURE
- MINIMUM CROSS-COUPLING WITH ENGINE OUT

MISSION VARIABLES
- SPACE STATION/BASE LOGISTIC RESUPPLY REFERENCE MISSION
- CIRCULAR ORBIT, 270 NM X 55^0 INCLINATION
- MISSION DURATION – 7 DAYS SUSTAINING LIFETIME

AUXILIARY PROPULSION SUBSYSTEM/ORBIT MANEUVERING SUBSYSTEM
- TOTAL VELOCITY INCREMENT = 32 FT/SEC – BOOSTER
  2180 FT/SEC – ORBITER
- ACCELERATION

	(NOMINAL)	(MINIMUM)
– ATTITUDE CONTROL, DEG/SEC^2	0.5–P; 1.0–Y, R	0.3
– TRANSLATION, FT/SEC^2 (*)	0.1	0.07

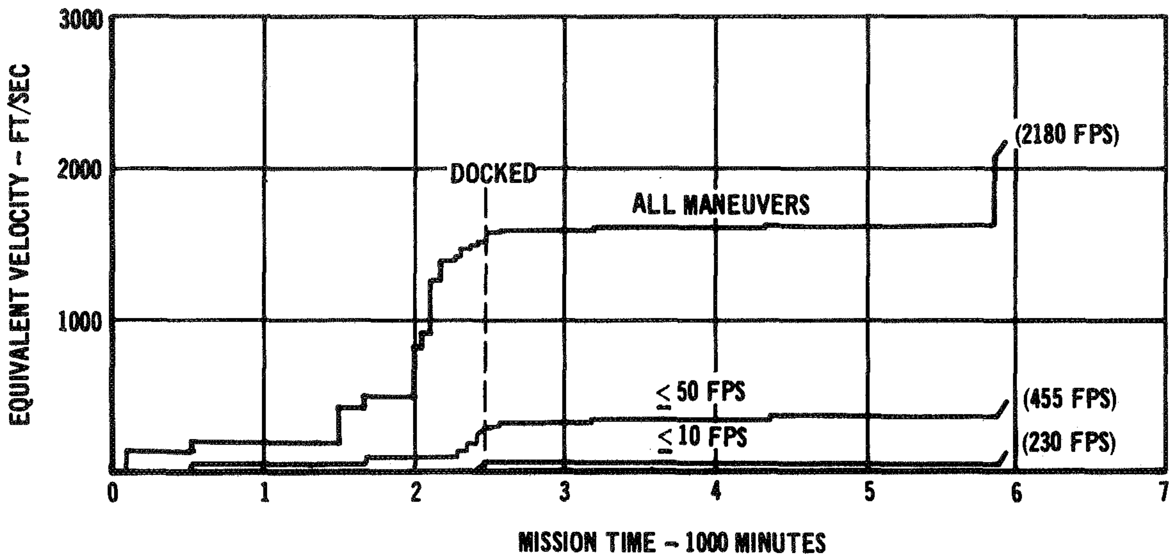
- IMPULSE ALLOCATION (*)
  (1) APS SATISFIES ALL REQUIREMENTS EXCEPT +X TRANSLATIONAL MANEUVERS GREATER THAN 10 FT/SEC
  (2) APS SATISFIES ALL REQUIREMENTS EXCEPT +X TRANSLATIONAL MANEUVERS GREATER THAN 50 FT/SEC
  (3) APS SATISFIES ALL REQUIREMENTS

* ORBITER ONLY

APS REQUIREMENTS – SUBTASK A

FIGURE 3–1

support mission. The equivalent velocity increment for this mission is 32 ft/sec for booster attitude control, and 2180 ft/sec for orbiter control and translational maneuvers. Various APS/orbit maneuvering subsystem (OMS) velocity allocations were prescribed for Subtask A study. The effect of these allocations on APS velocity requirements is shown in Figure 3-2.



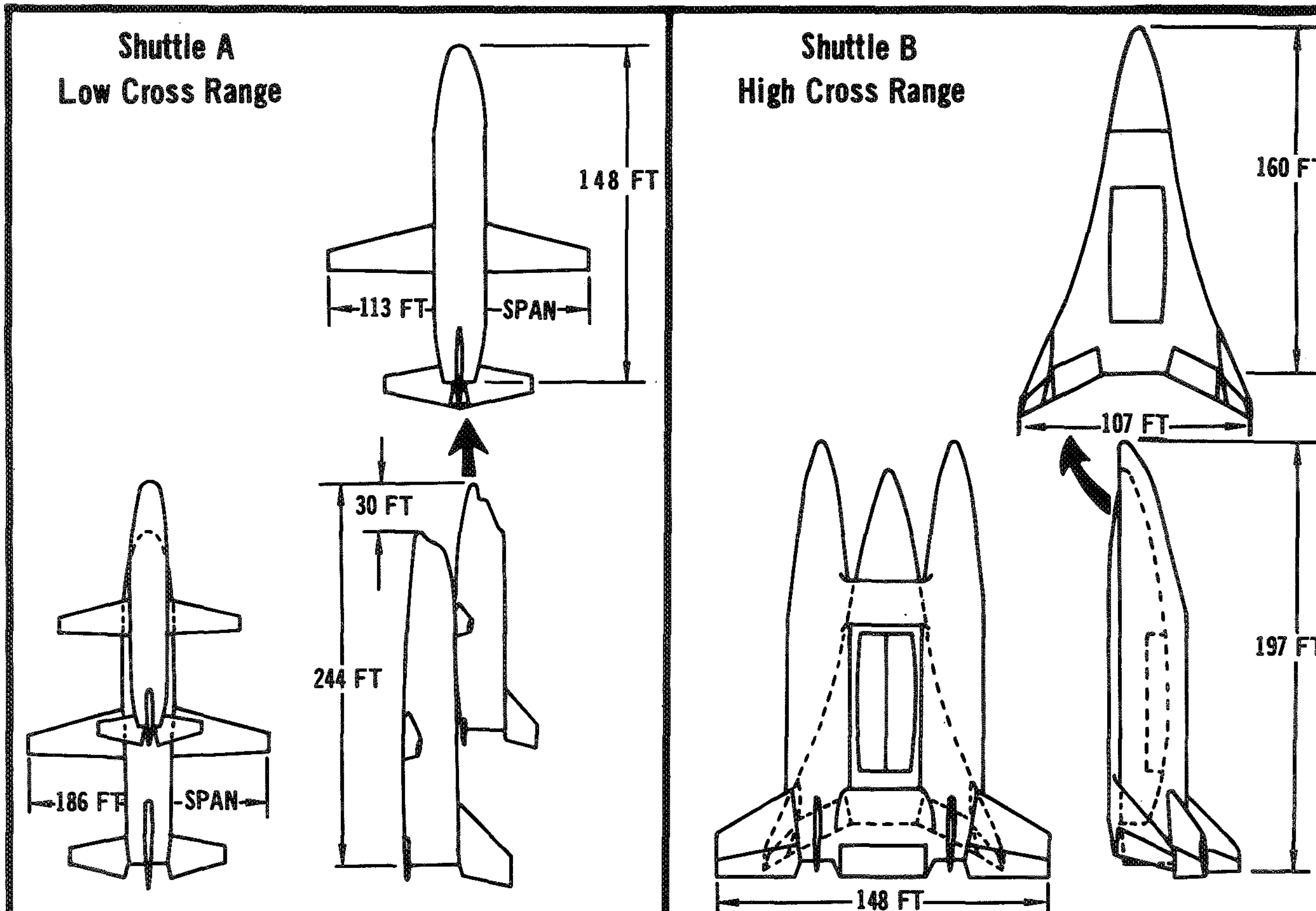
APS VELOCITY – TIME HISTORY

FIGURE 3-2

A representative range of vehicle design approaches was achieved by considering two different, 2-stage, shuttles for APS comparison studies. Both stages of shuttle A have fixed, low-sweep wings and similar aerodynamic shapes. Shuttle B embodies a twin bodied canard first stage and a highly swept delta wing upper stage. Both baseline shuttles are depicted in Figure 3-3.

3.2 Concept Matrix - By definition, the low pressure APS use the main engine propellant tanks as an integral part of the subsystem and operate at main engine tank ullage pressures. Operating pressure levels are maintained by resupplying the main engine tanks from separate propellant tankage. The basic low pressure concept is shown in Figure 3-4. The primary features in concept definition are:

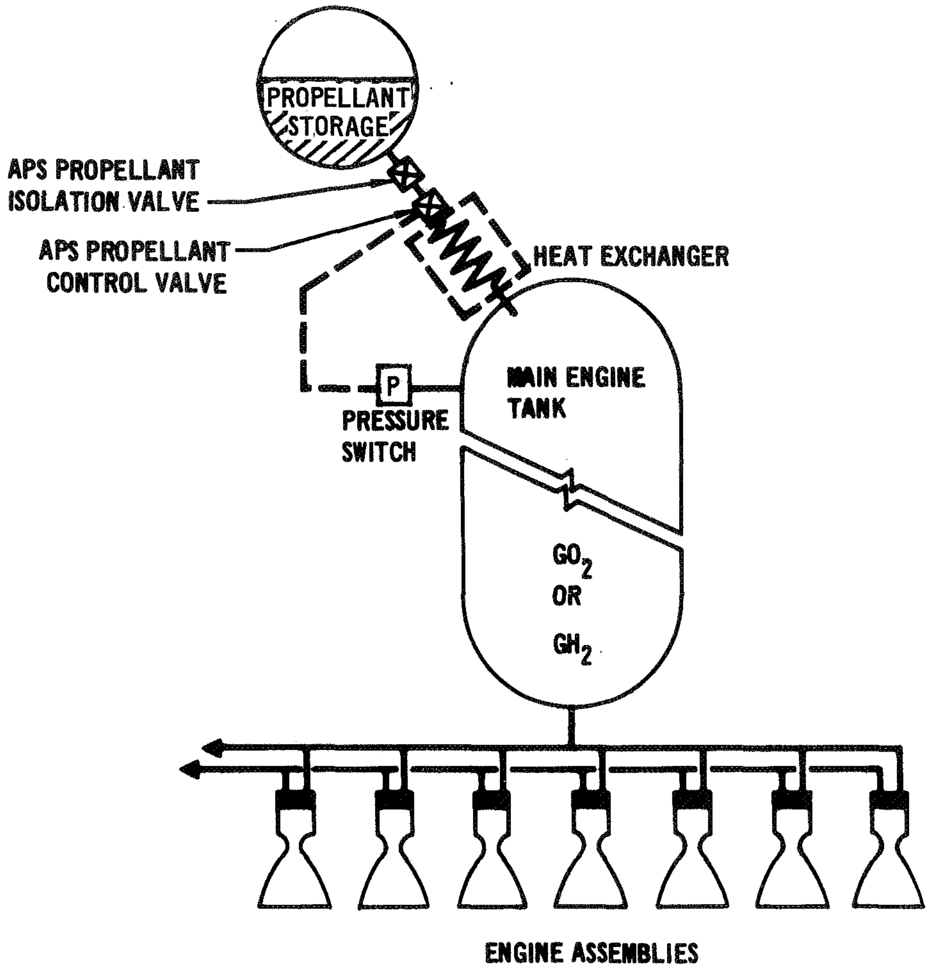
(1) APS propellant storage state
(2) method of propellant conditioning
(3) engine inlet propellant temperature/pressure controls
(4) mission requirements (viz., thrust, total impulse, and maximum single impulse burn).



	Shuttle A BOOSTER	Shuttle A ORBITER	Shuttle B BOOSTER	Shuttle B ORBITER
GROSS WEIGHT	2,759,100	624,900	2,888,200	611,800
REENTRY WEIGHT	458,600	164,000	496,200	241,902
MAIN PROPELLANT TANK				
– VOLUME, FT^3 (O_2)	29,925	5,204	30,350	4,620
(H_2)	80,652	13,964	95,300	11,650
– PRESSURE, LBF/IN^2A (O_2)	35	35	31	46
(H_2)	45	45	46	46
MINIMUM APS ACCELERATION				
– ANGULAR, DEG/SEC^2	0.3 (P,Y,R)	0.3 (P,Y,R)	0.3 (P,Y,R)	0.3 (P,Y.R.)
– TRANSLATION, FT/SEC^2	0	0.07 (X,Y,Z)	0	0.07 (X,Y,Z.)

VEHICLE DESCRIPTIONS – SUBTASK A

FIGURE 3–3



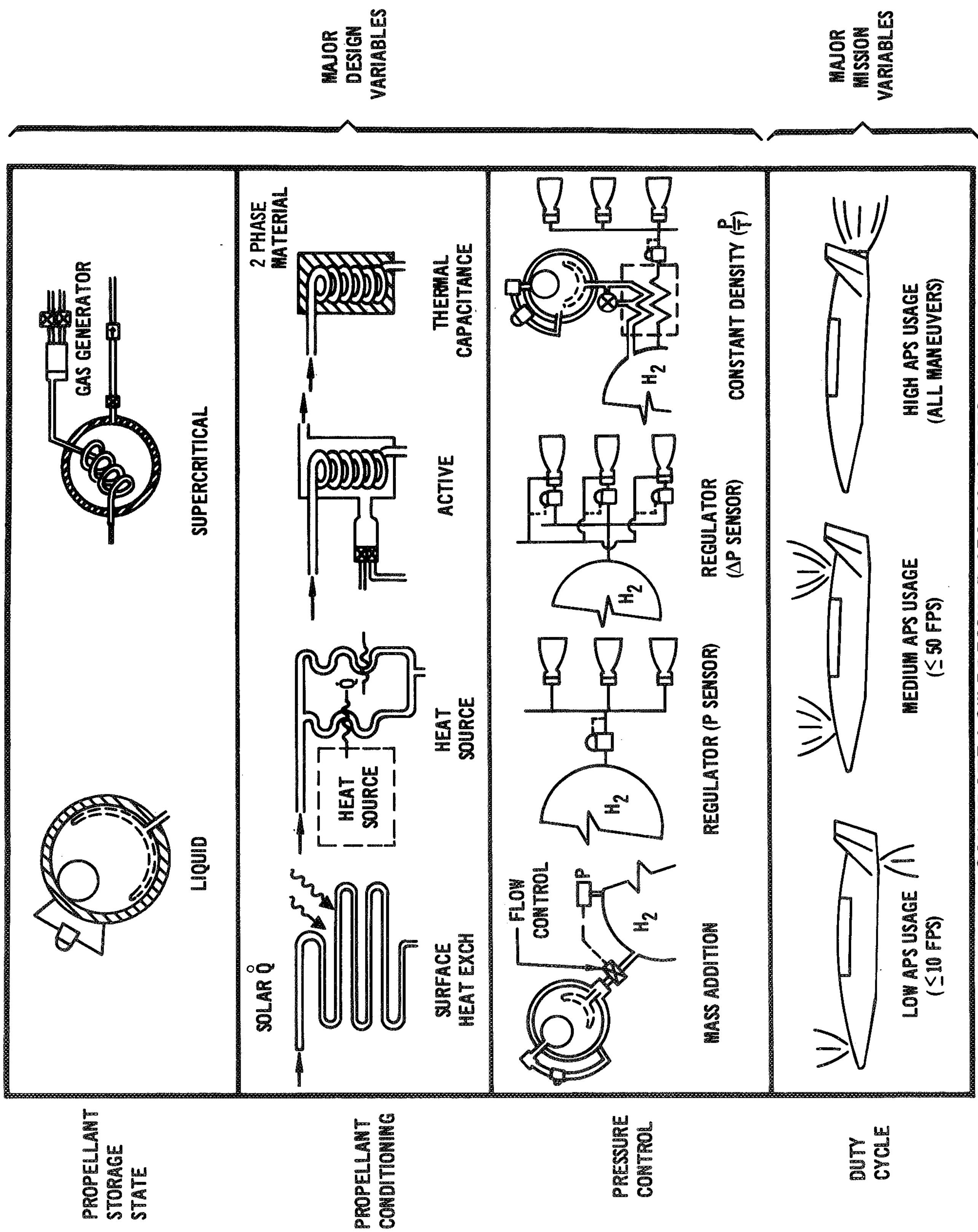
BASIC LOW PRESSURE APS CONCEPT

FIGURE 3-4

Figure 3-5 illustrates the alternate approaches considered for each of these features. Preliminary subsystem analysis reduced these alternates to the number of attractive and/or viable approaches shown in Figures 3-6 and 3-7 for booster and orbiter vehicles, respectively. All were carried through Subtask A evaluation and comparison studies.

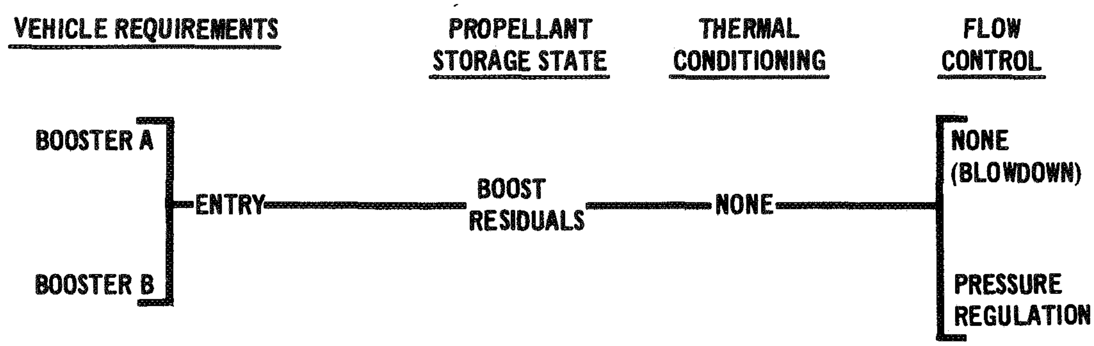
3.3 Intrasubsystem Trades - A number of intrasubsystem studies were performed to define competitive APS design parameters, and to determine the feasibility of propulsion subsystem integration. These included evaluation of engine arrangement, orbiter APS/OMS propellant storage integration, and usable main engine tank propellant residuals.

Engine Arrangement - Effort under this trade study included evaluation of thrust requirements for each vehicle element, and definition of APS total impulse



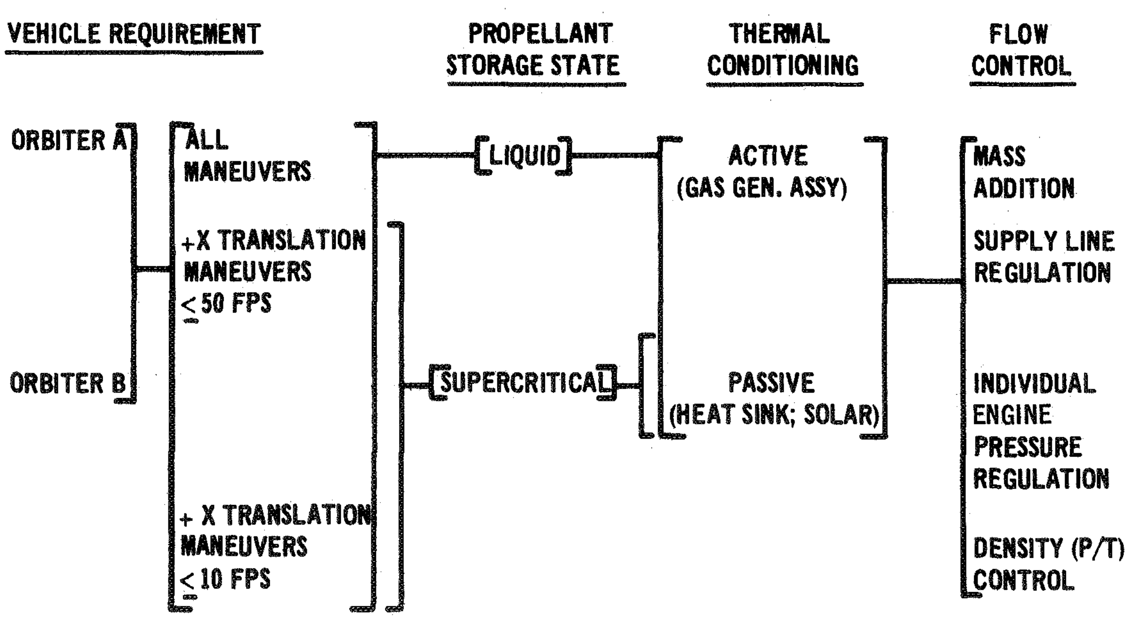
CANDIDATE LOW PRESSURE APS CONCEPTS
(CONCEPT SCREENING)

FIGURE 3–5



BOOSTER CONCEPT MATRIX

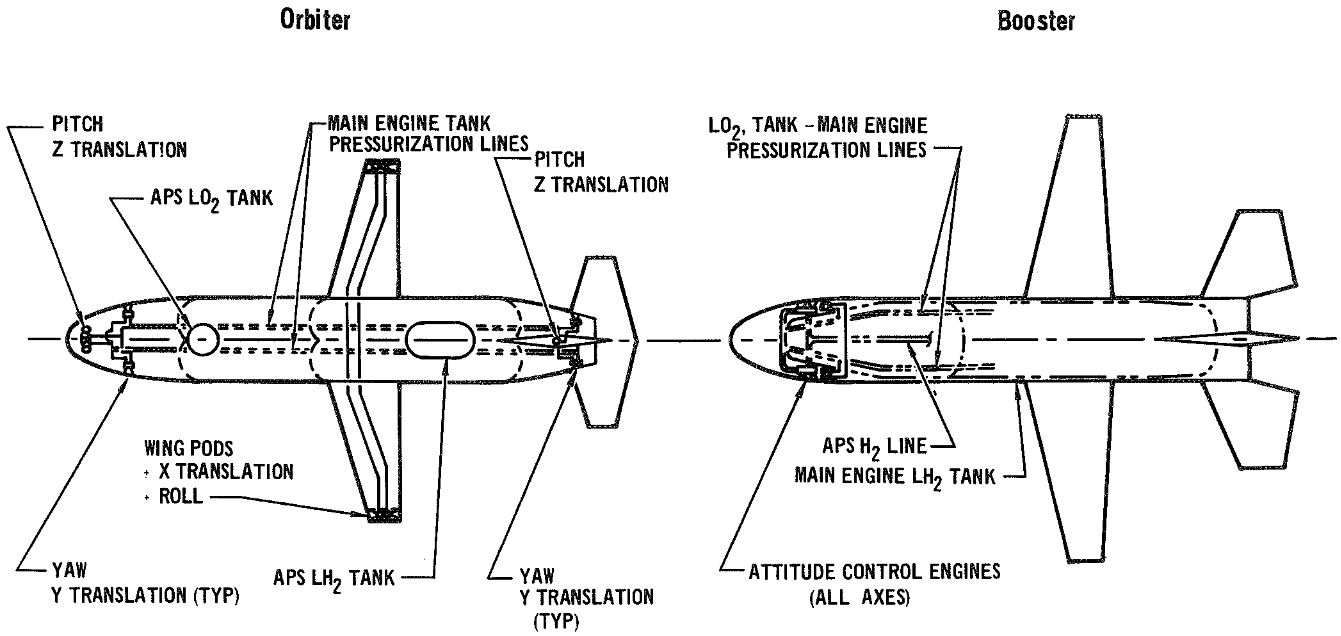
FIGURE 3-6



ORBITER CONCEPT MATRIX

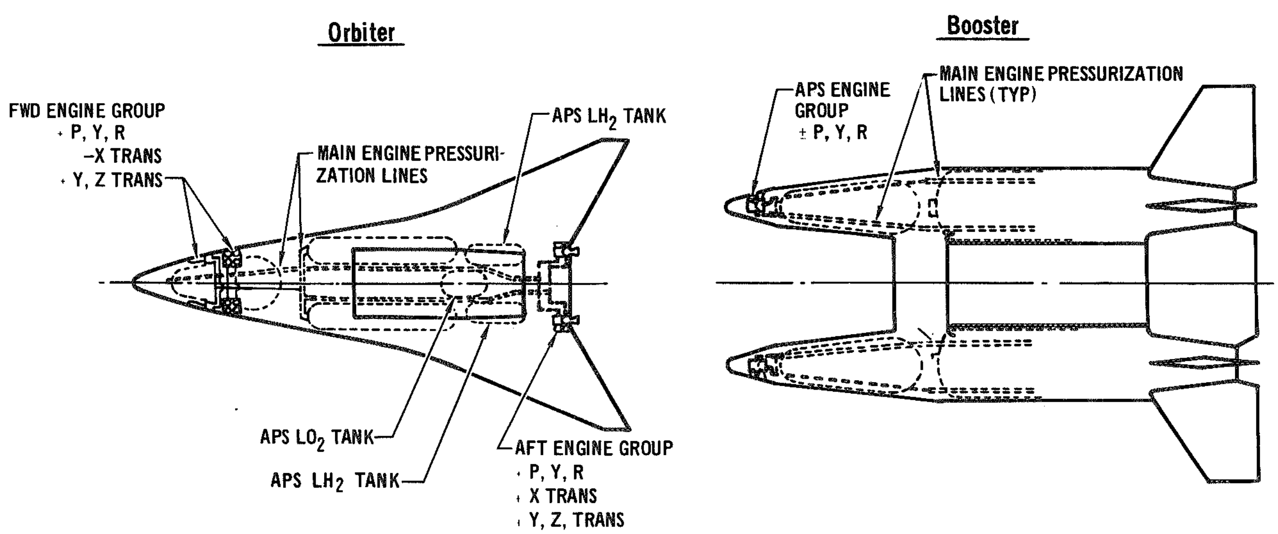
FIGURE 3-7

requirements. Engine thrust levels and number of engines were designed to provide, at minimum weight, specified control and/or translation acceleration with two engine failures. Figures 3-8 and 3-9 show the selected engine arrangement and



SHUTTLE A – APS INSTALLATION

FIGURE 3–8



SHUTTLE B – APS INSTALLATION

FIGURE 3–9

distribution network for each vehicle. Engine thrust levels and number of engines are summarized in Figure 3-10. APS total impulse requirements were generated for the selected engine arrangements at each APS/OMS velocity allocation. The total impulse values shown in Figure 3-10 include allowance for propellant settling prior to an OMS burn.

VEHICLE	THRUST LEVEL (LB)	NUMBER OF ENGINES	TOTAL IMPULSE (10^6 LB SEC)			
			BOOSTER	ORBITER		
				$\leq$ 10 FPS	$\leq$ 50 FPS	ALL
BOOSTER A	2600	18	0.475	–	–	–
ORBITER A	500	32	–	1.500	2.985	13.938
BOOSTER B	2000	16	0.475	–	–	–
ORBITER B	1000	28	–	1.778	3.521	16.079

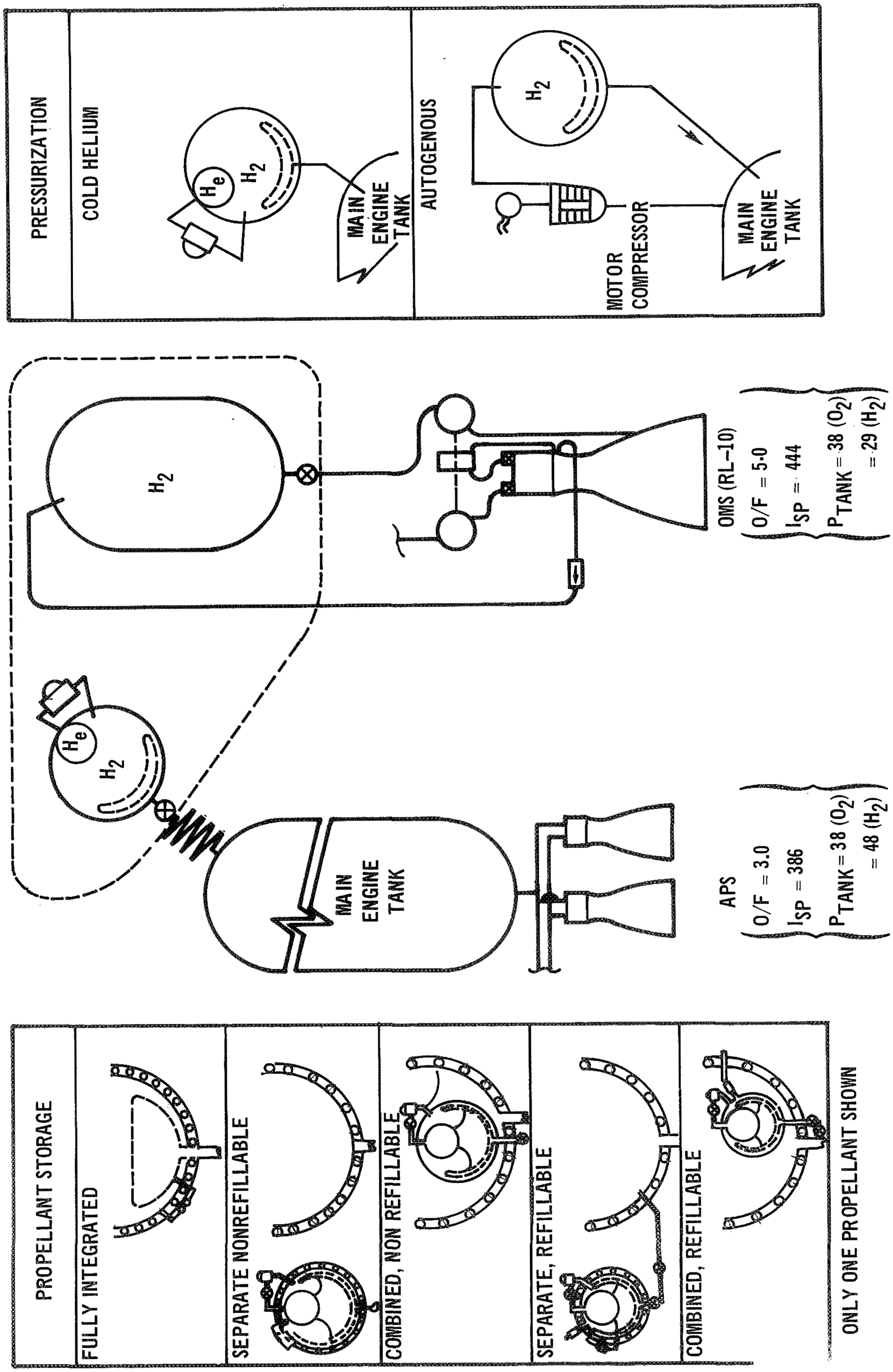
REQUIREMENTS SUMMARY

FIGURE 3-10

APS/OMS Propellant Integration - For those orbiter missions which presuppose both an APS and OMS for control and translation, many possibilities (both type and extent) exist for propellant integration. In terms of APS weight and performance, propellant storage concepts were evaluated to define propellant state (liquid or supercritical), liquid storage pressurization type (cold helium or autogenous), and extent of APS/OMS tankage integration (separate or combined, refillable or nonrefillable). Orbiter A propellant requirements for the three APS velocity profiles of Figure 3-2 were 3890 lb ($\leq$ 10 ft/sec), 7724 lb ($\leq$ 50 ft/sec) and 36,100 lb (all maneuvers). Corresponding total OMS/APS propellant requirements are 35,680 lb, 33,834 lb and 36,100 lb. Differences in total propellant arose from an approximate 60 second specific impulse increment between liquid OMS (assumes RL-10A3-3 engine) and gaseous APS engines.

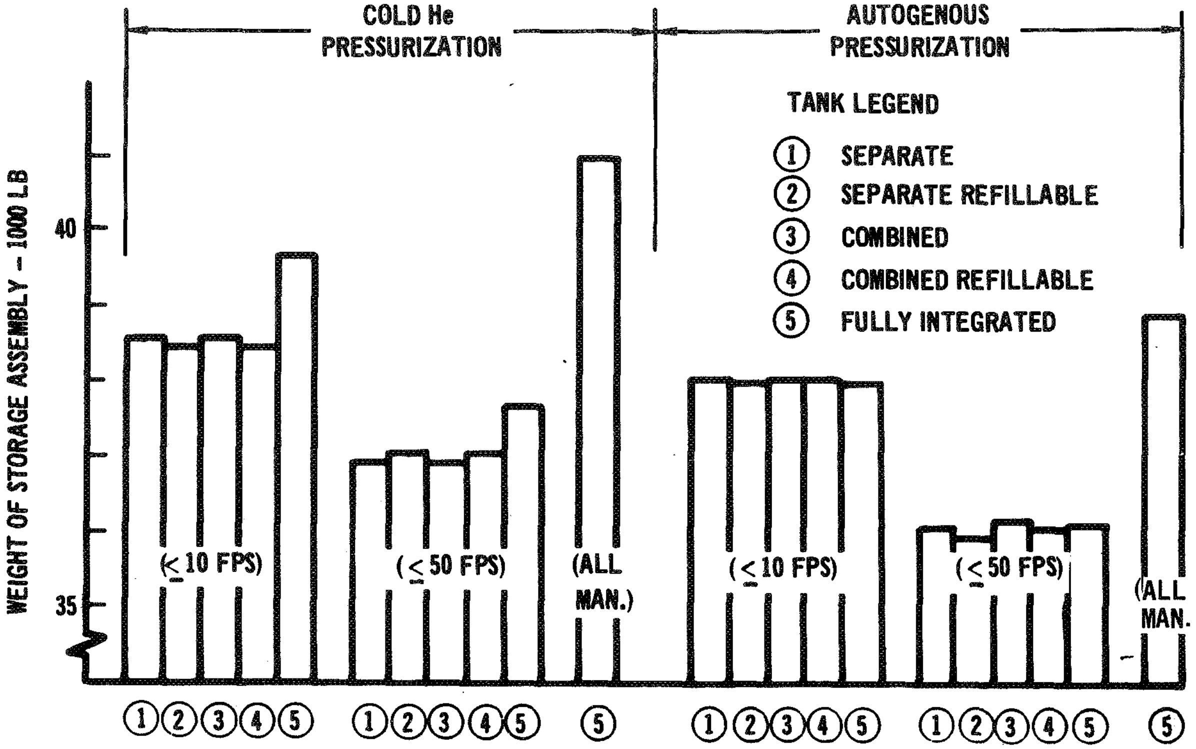
Trade study concepts for liquid propellant storage are shown in Figure 3-11. Weight estimates for combined APS/OMS liquid propellant storage assemblies are shown by the bar chart in Figure 3-12. The chart illustrates that, when pressurized with cold helium, concepts employing pressure isolation (i.e., separate tanks for APS and OMS propellants) were lighter than fully integrated tankage. This results primarily from the fact that the APS tanks must operate above main engine tank pressures to allow resupply propellant transfer and thus there is a pressurant weight penalty for the OMS tank when propellant is integrated. The weight increment between separate and integrated tankage disappears for the lighter, autogenously pressurized tankage.

Separate tankage was selected for both propellant supplies because it reduced



APS/OMS INTEGRATION CONCEPTS

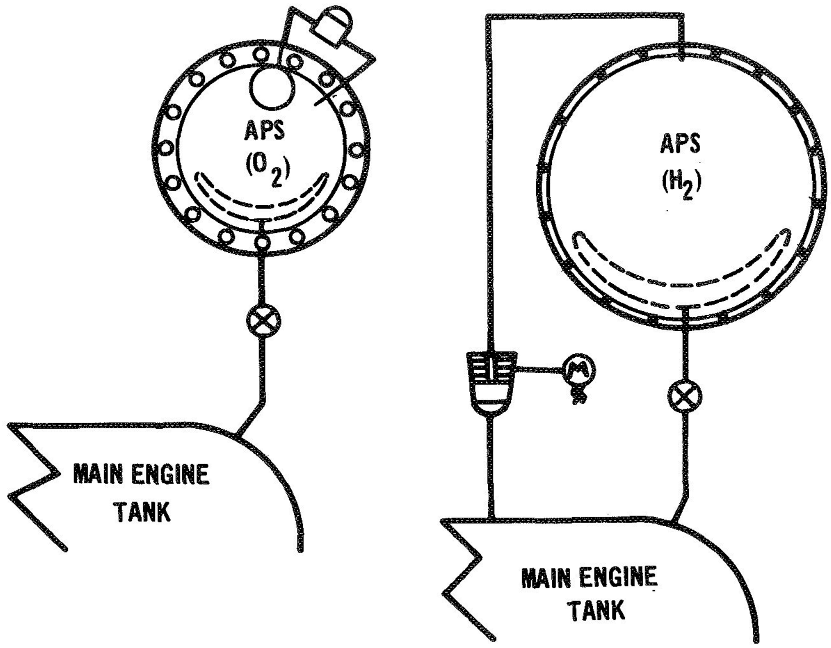
FIGURE 3-11



APS/OMS TANKAGE WEIGHT SUMMARY FIGURE 3-12

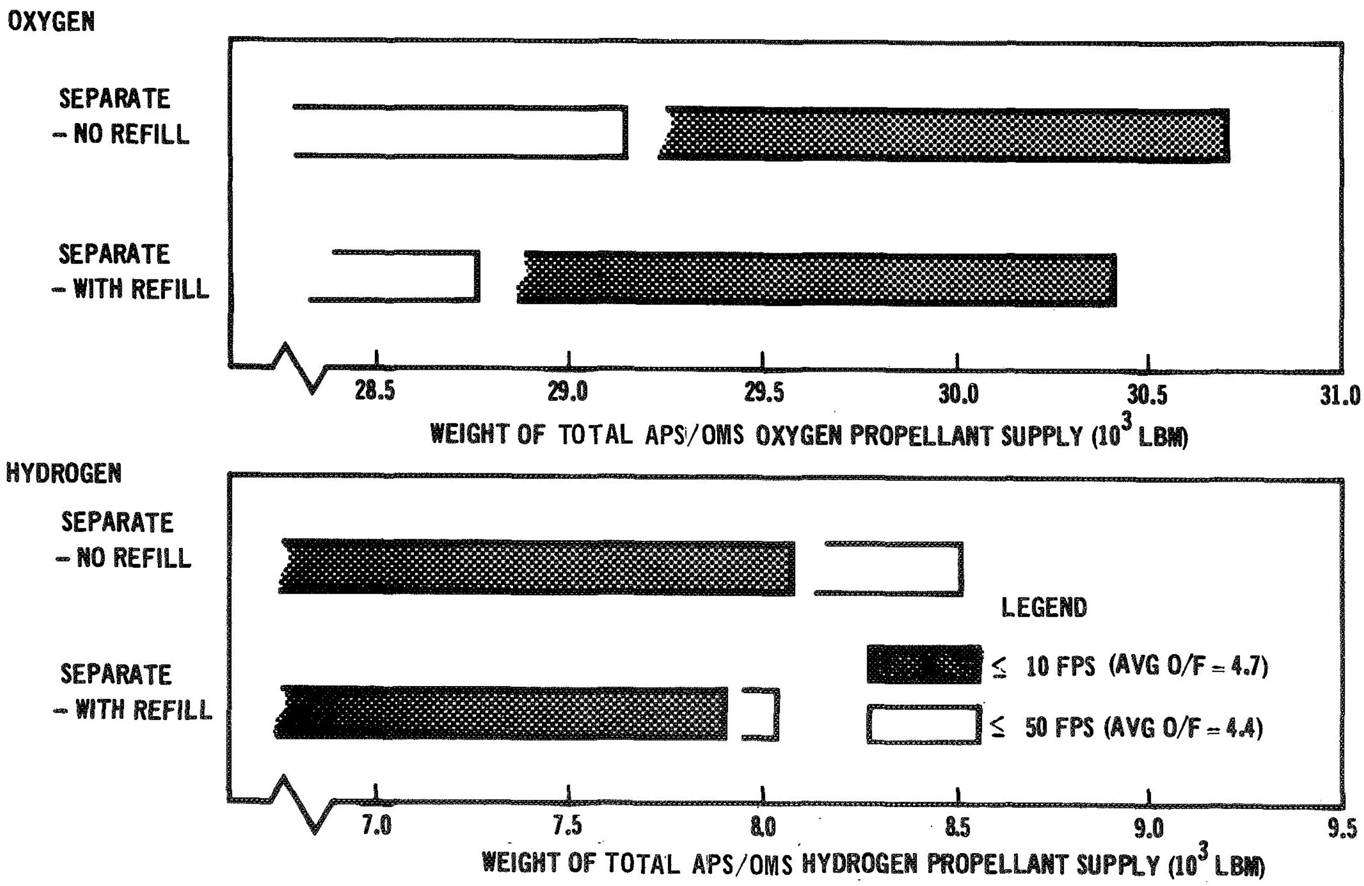
the technology and development problems associated with propellant acquisition. Autogenous pressurization was selected for the hydrogen tankage because it provided a significant weight advantage over cold helium. Pressurization weights for LO_2 tanks, however, showed that this weight advantage was lost for autogenous pressurization of liquid oxygen because of the higher molecular weight of the pressurizing gas and the high tank wall heat loss for the smaller diameter tanks. Cold helium was selected. The selected tankage concepts are shown in Figure 3-13.

Supercritical propellant storage concepts were also of interest since, unlike liquids, propellant orientation and acquisition are not required. Since propellant quality from supercritical storage was not compatible with the liquid OMS engine, only separate tankage was considered. However, since the supercritical APS tanks could be refilled from liquid OMS tanks, a comparison of refillable and nonrefillable tanks was required. Weight estimates for these concepts are shown in Figure 3-14. The refillable concepts are lighter but this is offset (at the low APS maneuver level) by increased technology requirements and subsystem complexity. Thus, nonrefillable storage assemblies were selected for the low APS maneuver levels ($\leq$ 10 ft/sec) and refillable storage was chosen for intermediate maneuver



SELECTED LIQUID STORAGE CONCEPT

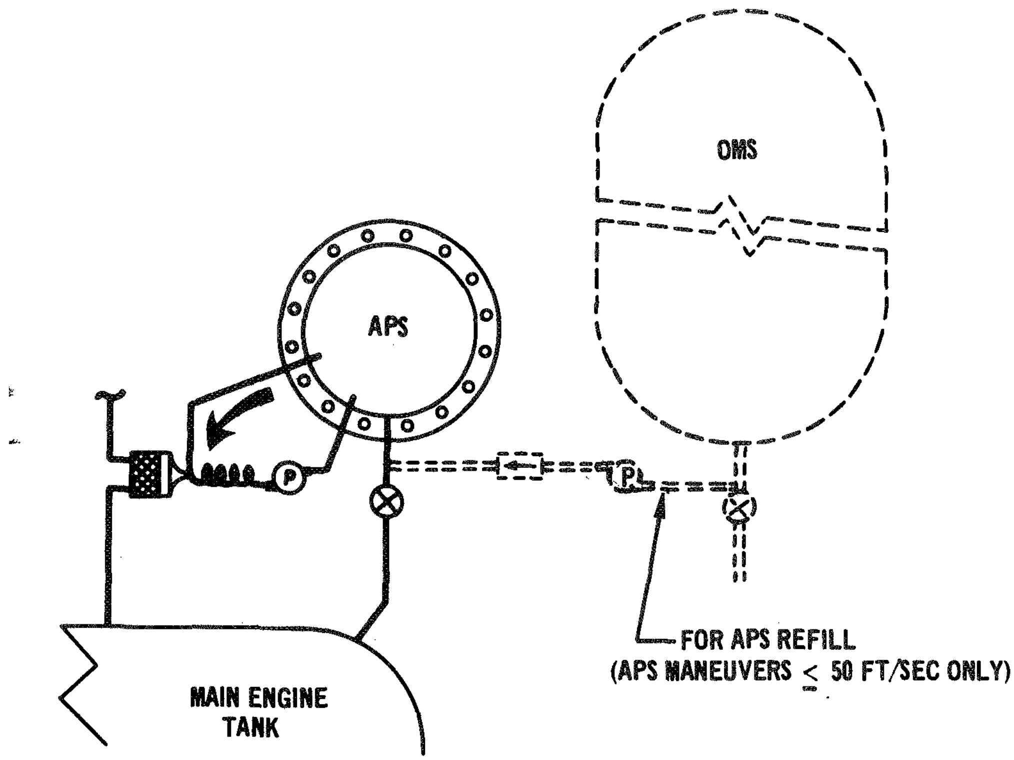
FIGURE 3-13



SUPERCRITICAL TANKAGE WEIGHT COMPARISON

FIGURE 3-14

levels ($\leq$ 50 ft/sec). Selected concepts are shown in Figure 3-15.



SELECTED SUPERCRITICAL STORAGE CONCEPT FIGURE 3-15

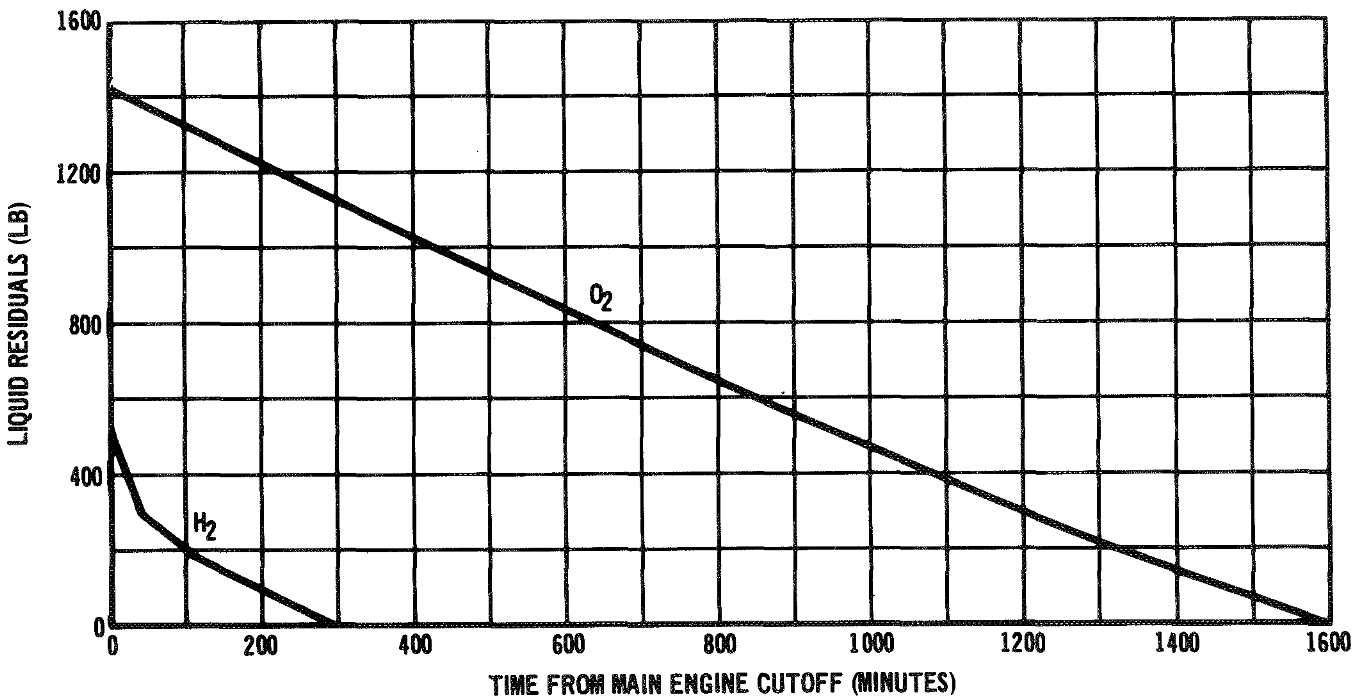
Usable Main Engine Residuals - Main engine tank liquid propellant residuals represent a potential savings in APS propellant requirements. This savings can be realized if APS propellant utilization coincides with residual boiloff rates. An estimate of usable residuals was important to the Subtask A study effort, since it effected APS weights and determination of an optimal APS/OMS impulse allocation. Figure 3-16 provides the total residual propellant inventory for each vehicle

	VEHICLE A				VEHICLE B			
	BOOSTER		ORBITER		BOOSTER		ORBITER	
	O_2	H_2	O_2	H_2	O_2	H_2	O_2	H_2
LIQUID								
TANK	1,502	0	276	0	0	0	0	0
ENGINES	2,184	176	397	32	2,184	175	397	31
LINES	11,116	455	1,154	116	10,816	425	273	0
PROPELLANT UTILIZATION ERROR	0	3,191	0	362	0	0	0	0
TOTAL LIQUID RESIDUALS, LBM	14,802	3,822	1,827	510	13,000	600	670	31
VAPOR RESIDUALS, LBM	12,400	3,440	2,160	595	7,000	2,500	2,100	279
TOTAL RESIDUAL, LBM	27,202	7,262	3,987	1,105	20,000	3,100	2,770	310
PERCENT LIQUID BY MASS	54.5	52.6	46	46.2	65	19	24	10

BOOST PROPELLANT RESIDUALS FIGURE 3-16

stage, based on Reference A data.

An approximate model for residual boiloff rate was established after analysis of flight test data from eleven S-IV and S-IVB flights. Major conclusions drawn from this analysis were: (1) that the best model for oxygen was that residuals remained in a settled orientation during on-orbit maneuvers and (2) the best model for hydrogen was that residuals would not be settled and would contact up to 65 percent of the tank wall during on-orbit operations. Applying these equivalent models to calculated orbiter tank heating rates yielded the residual liquid propellant histories shown in Figure 3-17. The amount of liquid usable by the APS



LIQUID RESIDUAL MASS-TIME HISTORY
(ORBITER A MAIN ENGINE TANK)

FIGURE 3-17

increases as the subsystem was used for more maneuvers in the early phases of the mission. For the Reference mission, liquid residual utilization by the APS increased by a factor of two or more between low and high APS maneuver levels. These results, summarized in Figure 3-18, were applied to subsystem weight and sizing analyses.

3.4 Design Analysis - Two factors were determined to be most essential to the viability of a low pressure APS concept. First, the subsystem must be capable of maintaining high operating pressure levels in order to provide reasonable weights and engine size. Second, engine propellant inlet conditions must be controlled to preclude severe thrust and mixture ratio excursions.

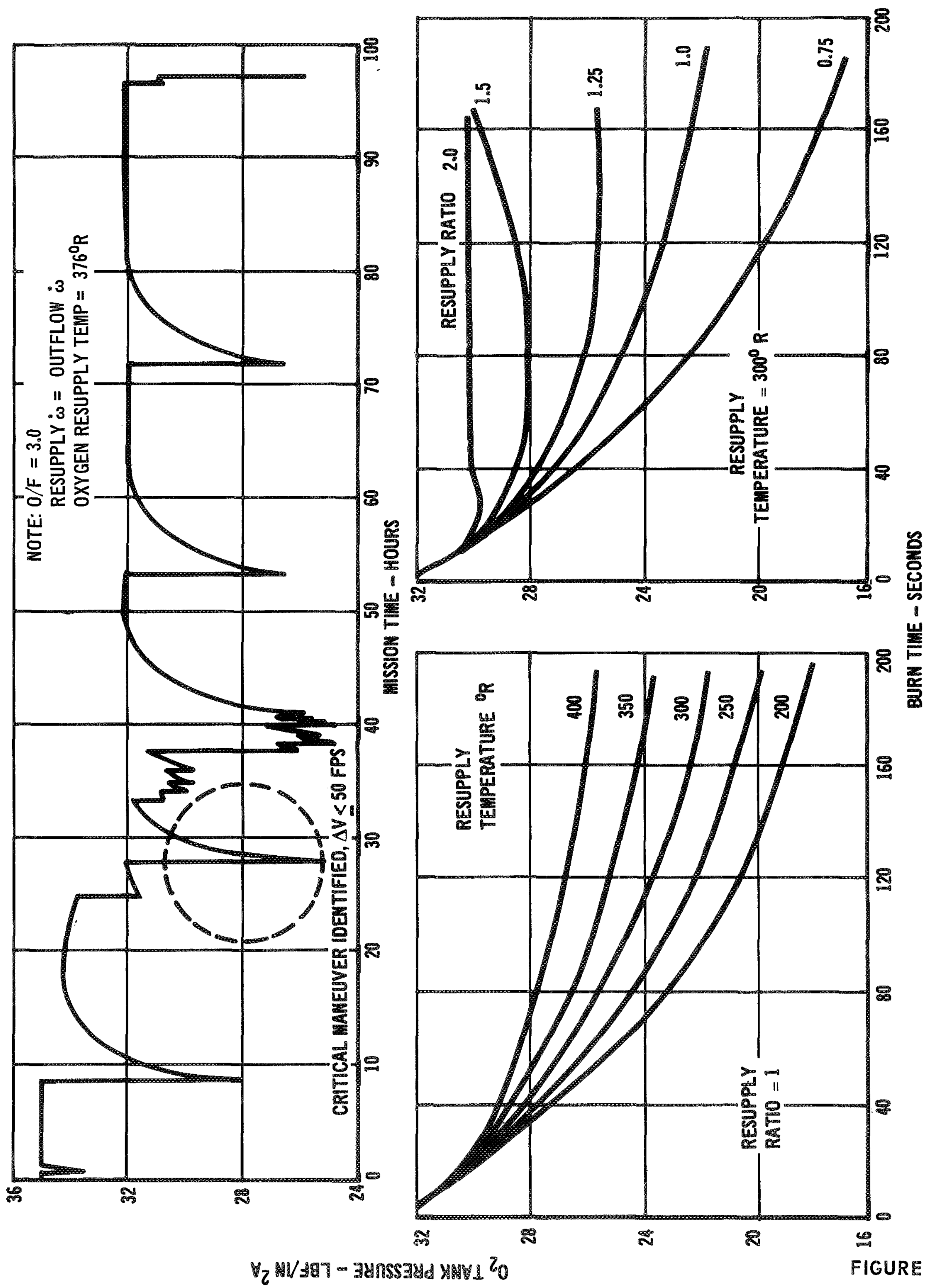
VEHICLE	PROP.	LIQUID RESIDUAL (LB)	APS USABLE (LBM)			
			BOOSTERS	ORBITERS		
				≤ 10 FPS	≤ 50 FPS	ALL MAN.
ORBITER A	O_2	1,827	-	262	365	643
	H_2	510	-	125	163	362
BOOSTER A	O_2	14,802	*	-	-	-
	H_2	3,822	*	-	-	-
ORBITER B	O_2	670	-	75	118	139
	H_2	31	-	0	27	31
BOOSTER B	O_2	13,000	*	-	-	-
	H_2	600	*	-	-	-

*NEGLIGIBLE DURING 6 MINUTE REENTRY

SUMMARY OF APS UTILIZATION OF BOOST LIQUID RESIDUALS FIGURE 3-18

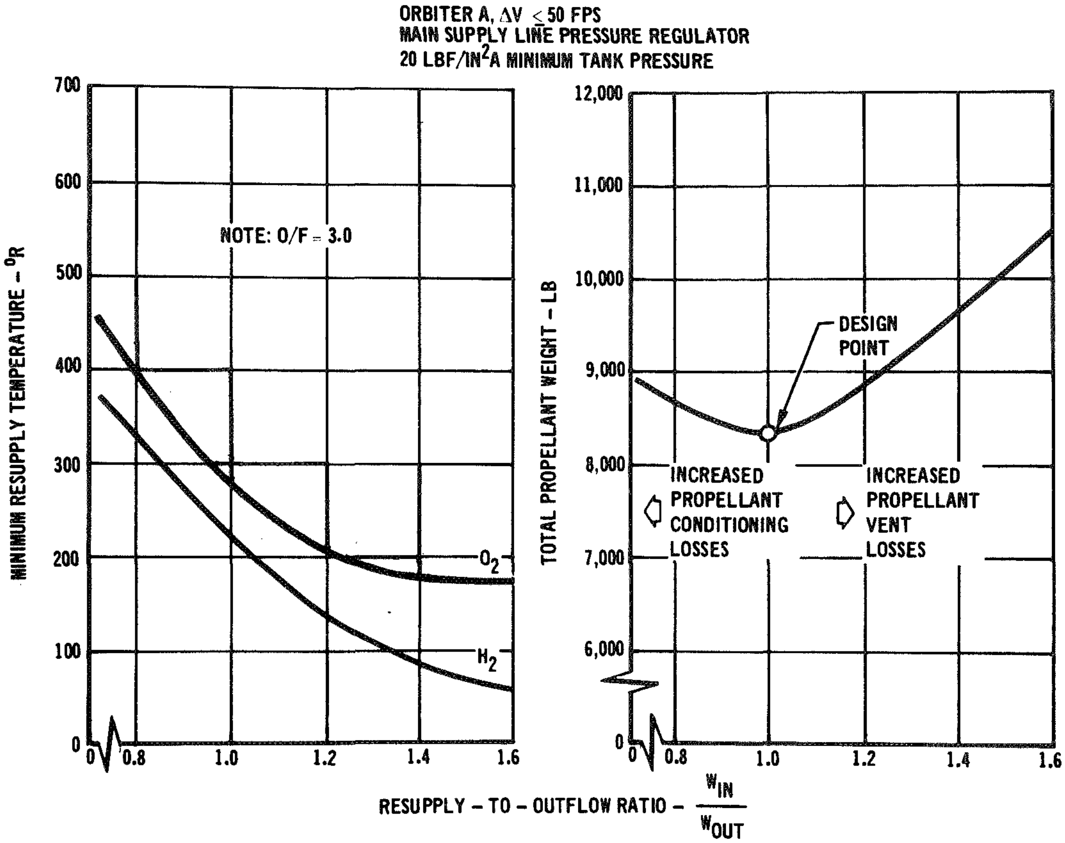
Main Engine Tank Resupply - Main engine tank pressure histories were generated for each APS duty cycle in order to identify critical maneuvers, i.e., the maneuver which produces the lowest main engine tank pressure. The pressure at the conclusion of this maneuver controls APS pressure budget; hence, it controls line and engine sizes. A typical orbiter tank pressure history is presented in Figure 3-19. Shown in this figure are the effects of resupply flowrate, and resupply temperature on tank pressures during the burn. As shown, for a fixed resupply flowrate, there is a corresponding resupply temperature required to maintain tank pressure. Conversely, for a fixed temperature, a corresponding flowrate is required. Higher tank pressures can be maintained by increasing either flowrate or temperature. Combined requirements for resupply temperatures and flowrates to maintain a main engine tank pressure of 20 lbf/in^2a are shown in Figure 3-20 for a 50 ft/sec burn. As shown, optimum resupply-to-outflow flowrate ratio ($\mathring{\omega}$) for minimum propellant weight is 1:1. Overcharging the main boost tanks with cold propellant vapors ($\mathring{\omega}$> 1:1) increases vent losses when propellants warm up during periods of low APS activity. Undercharging them with warm vapors ($\mathring{\omega}$< 1:1) results in increased requirements for resupply propellant conditioning. This latter case also necessitates eventual mass makeup later in the mission.

These same conclusions applied to all of the APS/OMS velocity allocations. A mass resupply flowrate ratio of unity was therefore selected and, at this flowrate, the conditioning temperature required to hold a specified minimum main engine tank pressure was determined for each mission duty cycle (Figure 3-21). The curves show that resupply temperature requirements must increase to maintain higher minimum pressures and also that conditioning temperature must increase when the APS performs larger maneuvers. Figure 3-22 shows the effect of minimum

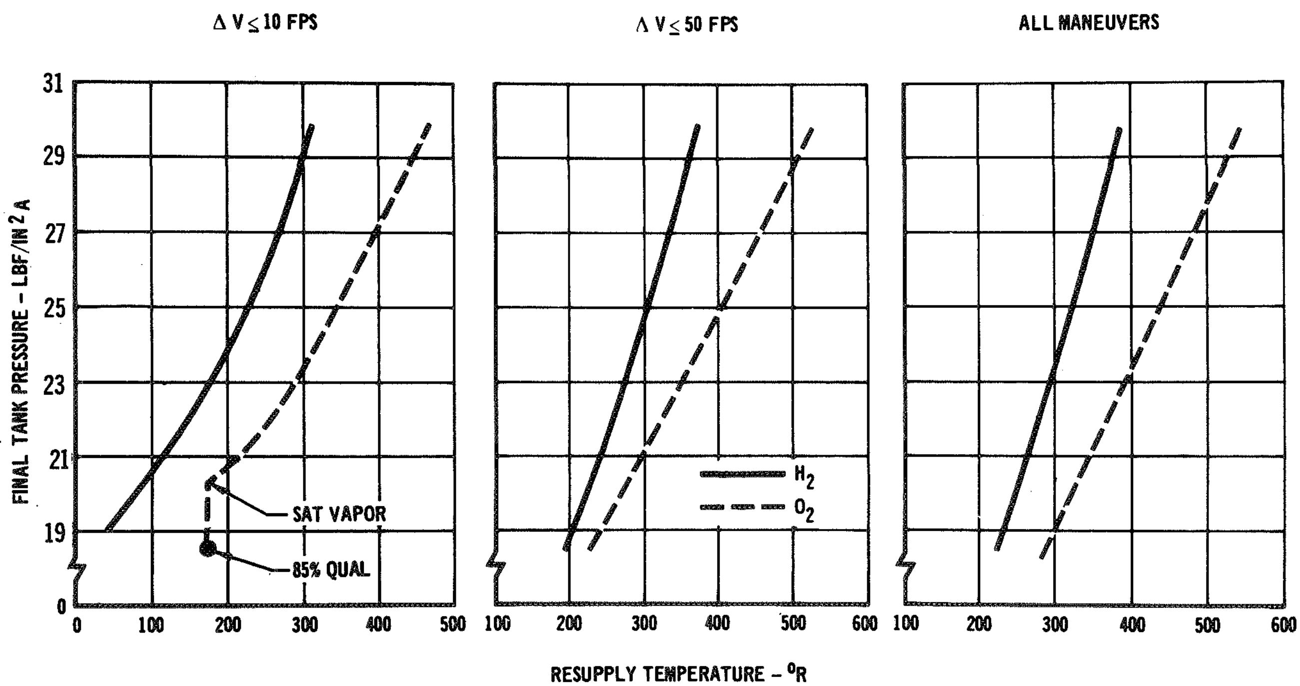


PROPELLANT RESUPPLY REQUIREMENTS DEFINED BY SINGLE BURN TOTAL IMPULSE

FIGURE 3–19

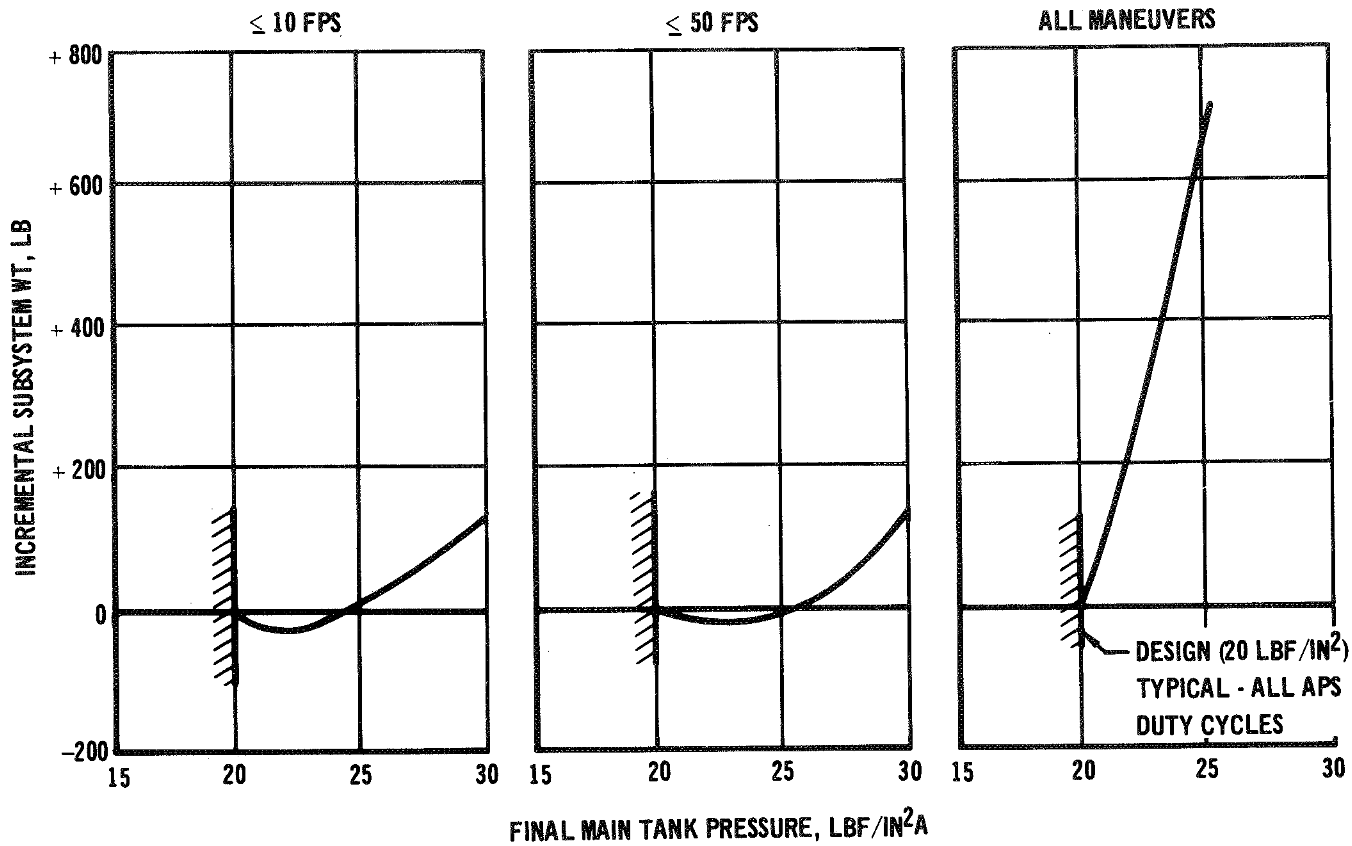


SELECTION OF RESUPPLY FLOW RATE FIGURE 3-20



MAIN TANK PRESSURE DEPENDENCY ON RESUPPLY TEMPERATURE
(Orbiter A)

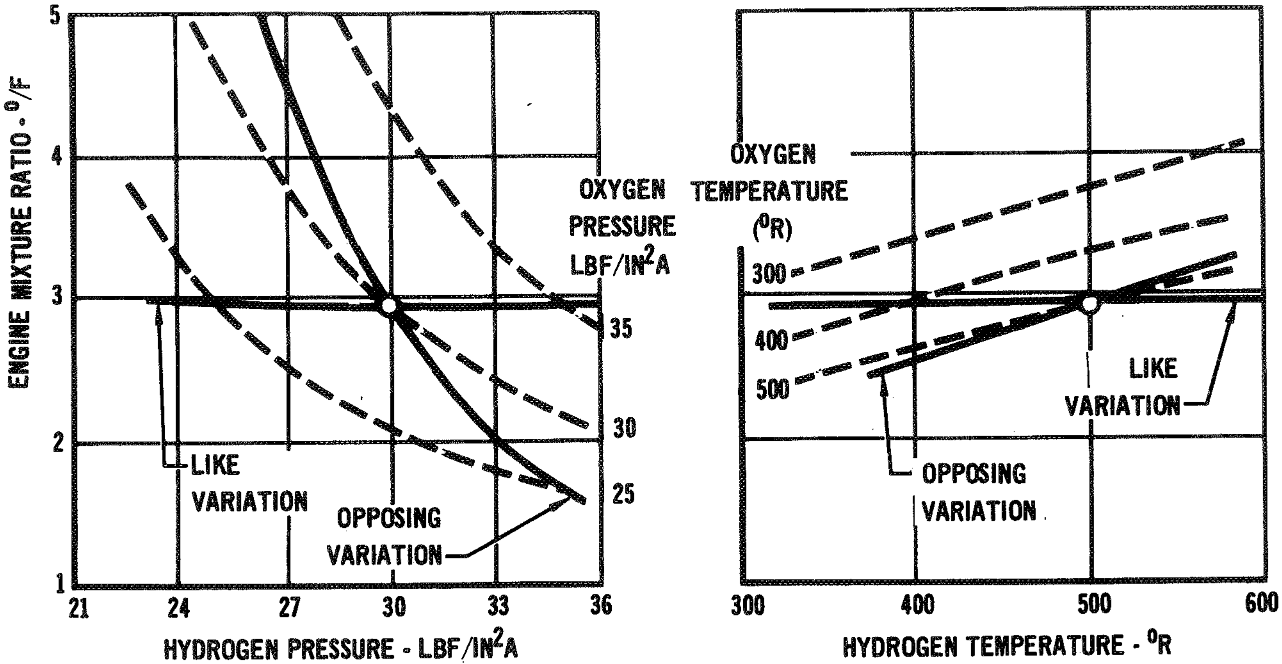
FIGURE 3-21



SELECTION OF MINIMUM MAIN TANK PRESSURE FIGURE 3-22

pressure on APS weight. A weight optimum is realized at minimum tank pressures of 22-23 lbf/in^{2}a for APS duty cycles of $\leq$ 10 ft/sec and $\leq$ 50 ft/sec, and at a much lower pressure when the APS is used for all maneuvers. Weight optimas occur because line and engine weights decrease with increasing tank pressure, but the propellant conditioning penalty required to maintain these pressures increases rapidly. A 20 lbf/in^2 minimum pressure limit was selected because it was near-optimum (from the standpoint of minimal subsystem weight), and provided a reasonable margin against collapse pressure loads during reentry.

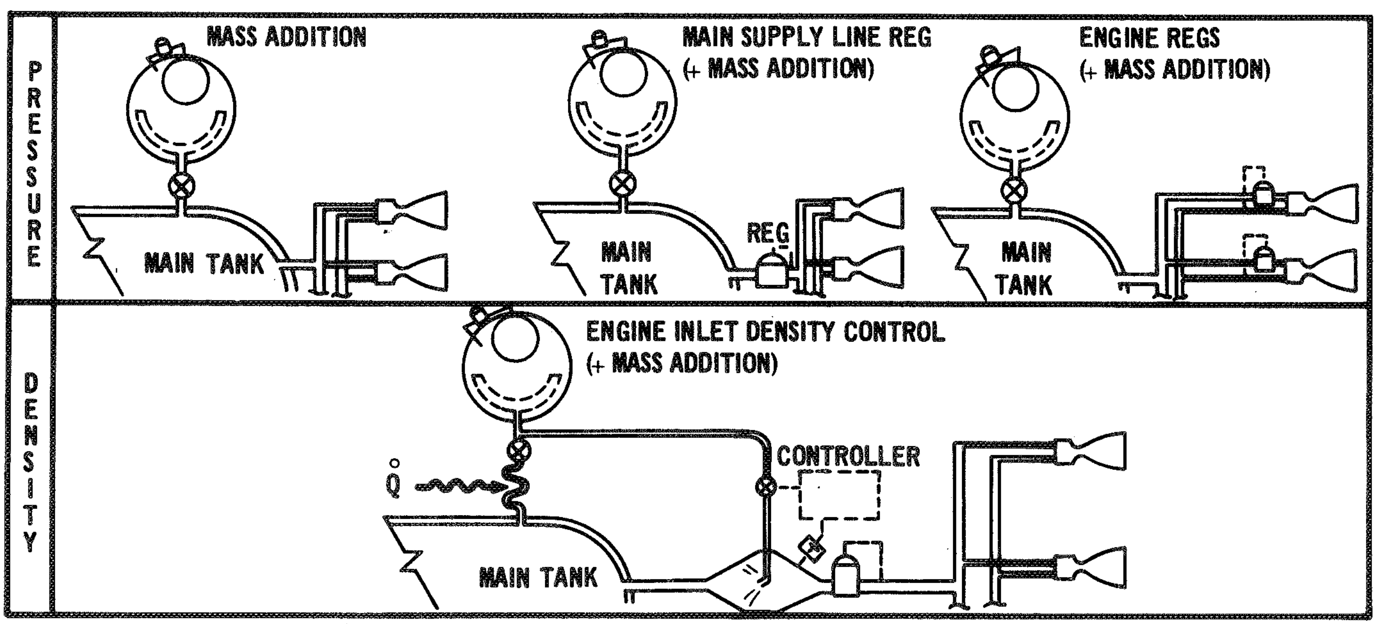
Control of Engine Inlet Conditions - The low total pressure budget available, and the desire to minimize subsystem weight necessitated a minimum allocation for engine injector pressure drop. It was estimated that the minimum practical pressure drop to ensure good mixing and stable operation was 2.0 lbf/in^{2}d. This value was used for weight and performance estimates throughout the study. The difficulty with such a low ΔP injector is that small pressure or temperature variations produce significant shifts in engine operating parameters, notably thrust and mixture ratio. As the sensitivities of Figure 3-23 show, an opposing variation in oxidizer and fuel inlet pressure of only a few lbf/in^2 from nominal produces major



ENGINE MIXTURE RATIO SENSITIVITY
CHAMBER PRESSURE - 20 LBF/IN^{2}A

FIGURE 3-23

changes in engine mixture ratio. The APS supply must be capable of controlling engine operating conditions to reasonable limits. Alternate methods of control are shown in Figure 3-24. Solutions vary from simple mass addition (controlling



APS FLOW CONTROL CONCEPTS

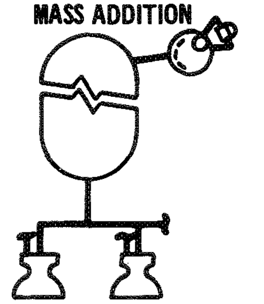
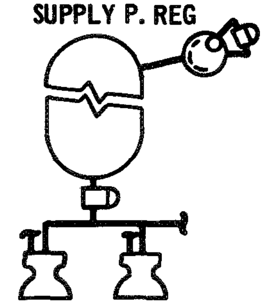
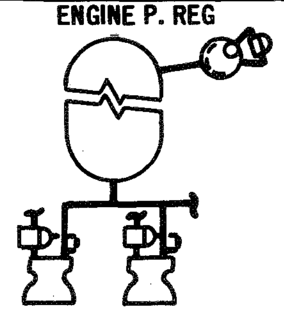
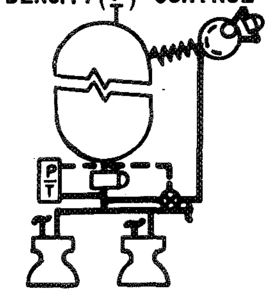
FIGURE 3-24

pressures within the main engine tanks to a tight deadband) to the more sophisticated constant density control (controlling propellant pressures and temperatures to specified values). Figure 3-25 shows the effect of each concept on subsystem design variables. The constant density control required less propellant conditioning since only a portion of the propellants were conditioned and supplied to the main engine tanks.

3.5 Concept Comparison/Selection - Each low pressure APS concept considered in Subtask A was evaluated on the basis of technology, simplicity, weight and volume, flexibility and development. The concept(s) meriting the highest ranking were selected for more indepth analyses during the Subtask B preliminary design phase. Selection criteria weighting and the rationale applied in making the selections are presented in Figure 3-26.

In order to facilitate concept selection, alternate flow control schemes were considered first. Then, with the preferred flow control concept identified, candidate approaches to propellant storage and propellant conditioning were evaluated and selections made. Since neither propellant storage nor propellant conditioning assemblies are required for the booster elements, concept comparisons were limited to flow control variations.

Propellant Flow Control - Operating characteristics for the four orbiter flow control concepts are shown in Figure 3-27. An arbitrary velocity increment of 50 ft/sec was assumed for this example, and main engine tank resupply temperatures were selected to maintain tank pressure above 20 lbf/in^2. As illustrated, significant engine performance variations occur in the case of mass addition. Main supply line pressure regulators control engine thrust, but mixture ratio variations are large because of temperature changes. Differential pressure regulators, located immediately upstream of the engines, offer better mixture ratio control, but provide poor control of engine thrust. The constant density (P/T) concept controls both. This concept also minimizes conditioning requirements, since only a portion of total engine flow is extracted from the main engine tank; the remainder is supplied to the mixing chamber in the liquid phase. These concepts are compared in Figure 3-28 against the rating factors discussed earlier. The point tally shows that the constant density control concept was selected for the orbiter despite a very conservative rating for technology extension. Liquid/vapor mixers have found past usage on engine test stands for low temperature propellant conditioning, but additional effort is required to demonstrate stable flow and homogeneous mixing for a twofold variation in liquid-to-vapor mass ratios.

FLOW CONTROL CONCEPT	MASS ADDITION 			SUPPLY P. REG 			ENGINE P. REG 			DENSITY ($\frac{P}{T}$) CONTROL 		
MISSION	≤ 10	≤ 50	ALL	≤ 10	≤ 50	ALL	≤ 10	≤ 50	ALL	≤ 10	≤ 50	ALL
REQUIRED CONDITIONING TEMP ^oR (O_2)	200(1)	276	326	200(1)	276	326	200(1)	276	326	SAT VAPOR	265	328
(H_2)	150(1)	226	252	150(1)	226	252	150(1)	226	252	SAT LIQUID	100(1)	236
GAS GENERATOR COND. REQUIREMENT (% TOTAL PROPELLANT)	9.89	14.58	16.25	9.89	14.58	16.25	9.89	14.58	16.25	3.2	5.82	10.42
ENGINE SPECIFIC IMPULSE	377.2	375.5	377.4	377.2	375.6	377.4	377.2	375.6	377.4	372.4	376.3	376.3

FLOW CONTROL CONCEPT COMPARISON

(1) RESUPPLY CONDITIONING TEMPERATURE SELECTED TO ENSURE H_2 AND O_2 ENGINE INLET TEMPERATURES ARE MAINTAINED ABOVE 200^oR AND 300^oR, RESPECTIVELY.

FIGURE 3–25

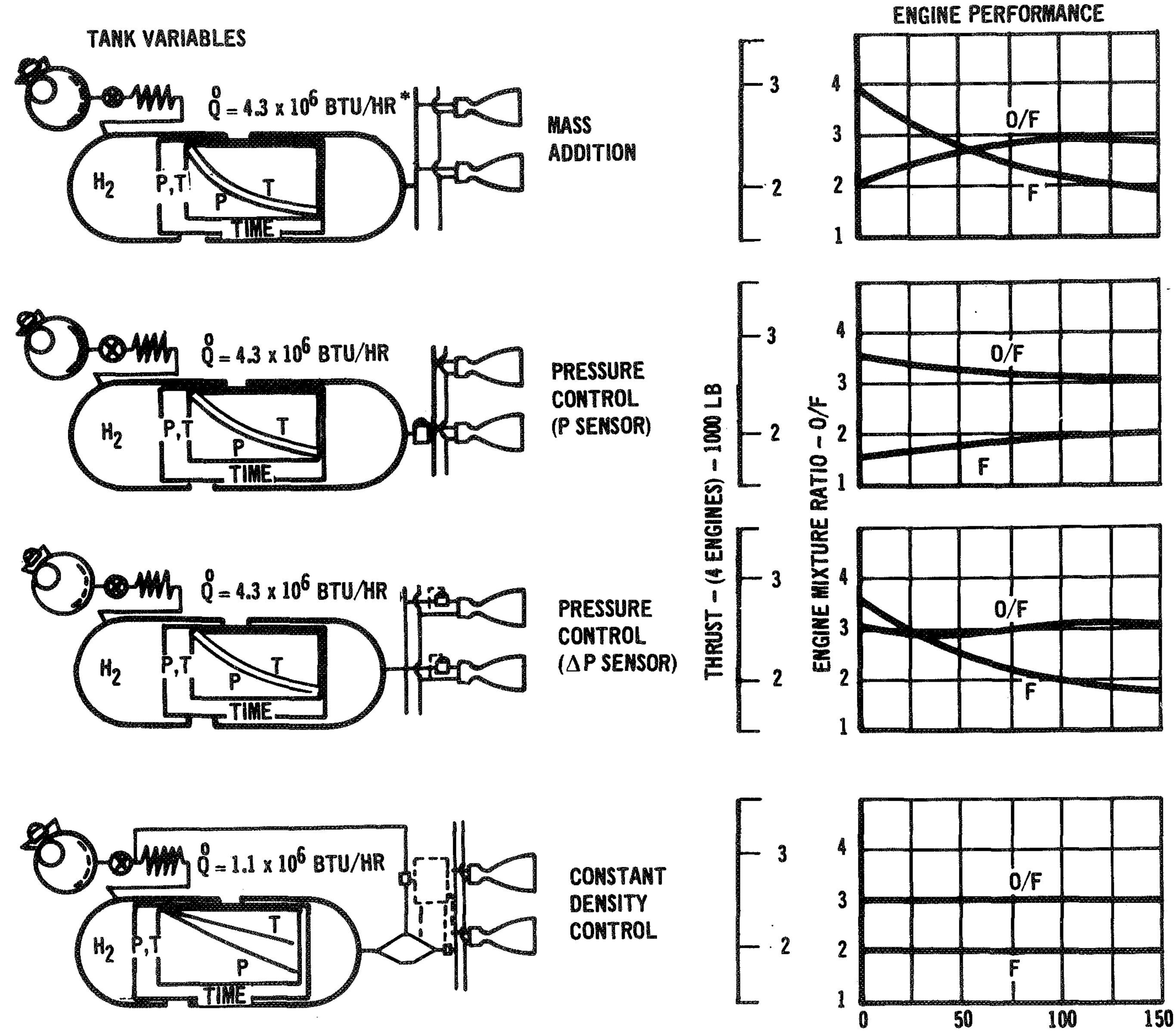
SELECTION CRITERIA	WEIGHTING (PERCENT OF TOTAL)	RATIONALE TO BE USED FOR WEIGHTING
TECHNOLOGY REQUIRED	0 – 20	WEIGHTING BASED ON ENGINEERING JUDGEMENT OF DEVELOPMENT RISK, SCALING FROM STATE-OF-THE-ART THROUGH EXTENSION OF AN EXISTING TECHNOLOGY BASE, TO COMPLETELY NEW CONCEPTS OR APPROACHES.
SUBSYSTEM SIMPLICITY	0 – 15	WEIGHTING BASED ON CONSIDERATION OF: 1) NUMBER OF COMPONENTS AND INTEGRATION COMPLEXITY, 2) ASSEMBLY AND SUBSYSTEM CONTROL REQUIREMENTS, AND 3) COMPLEXITY OF SUBSYSTEM INTERFACES AND OPERATION.
SUBSYSTEM WEIGHT AND VOLUME	0 – 25	WEIGHTING BASED ON ABSOLUTE WEIGHT AND VOLUME, CONSIDERING LOWEST WEIGHT SYSTEM AS REFERENCE AND A 10 PERCENT ORBITER PAYLOAD LOSS AS UNACCEPTABLE.
FLEXIBILITY FOR MISSION CHANGES	0 – 25	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.
DEVELOPMENT PROGRAM	0 – 15	WEIGHTING BASED ON ESTIMATES OF DEVELOPMENT TEST REQUIREMENTS CONSIDERING SUCH FACTORS AS NEED FOR ENVIRONMENT SIMULATION (ZERO g, VACUUM, ETC.) AND FACILITY AVAILABILITY FOR TEST.

FIGURE 3-26

APS STUDY CONCEPT SELECTION – SELECTION CRITERIA AND WEIGHTING FACTORS

Booster flow control concepts were limited to simple pressure blowdown (no control) and pressure regulation using differential pressure regulators for individual engine assemblies. Performance trends were similar to those shown for the orbiter (mass addition and differential regulators) but main engine tank pressure decay is much less significant, since the quantity of booster main engine tank ullage vapors greatly exceeds mission requirements. Thrust and mixture ratio excursions for the blowdown concept (Figure 3-29) are satisfactory for high performance and reliable operation. Consequently, a blowdown concept was selected for the boosters because of its inherent design/operational simplicity and lower subsystem weight.

Propellant Storage and Conditioning – (Orbiter Only) – Comparisons of propellant storage and conditioning concepts are given in Figure 3-30. Of the storage concepts, liquid storage offers advantages in all categories of comparison, except technology, for APS maneuvers $\leq$ 10 ft/sec. Here, separate, nonrefillable tankage is employed for both storage concepts. Supercritical storage possesses an advantage because a propellant acquisition device is not required. Supercritical



*DENOTES HEAT EXCHANGER REQUIREMENT FOR LH_2 CONDITIONING

FIGURE 3-27

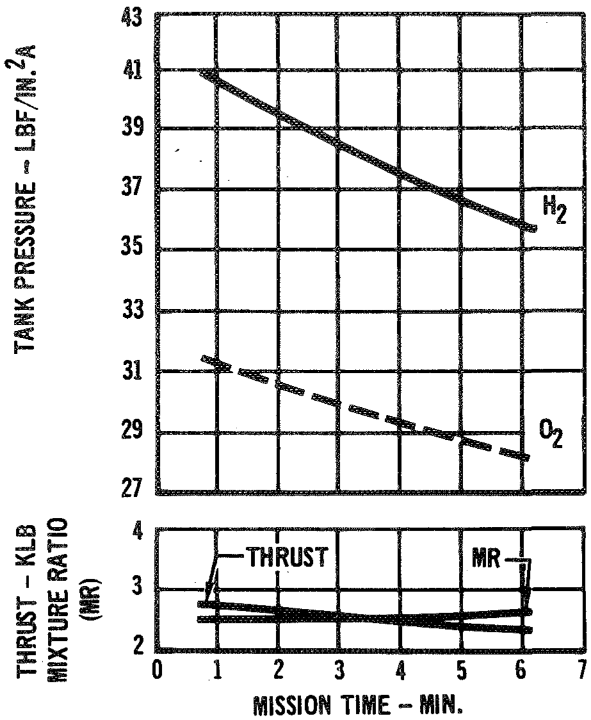
WHY CONSTANT DENSITY CONTROL?

SELECTION FACTORS	MASS ADDITION	SUPPLY LINE REGULATOR	ENGINE REGULATOR	CONST DENSITY
TECHNOLOGY (20%)	20	15	17	10
SIMPLICITY (15%)	15	9	9	6
WEIGHT AND VOLUME (25%)	20	17	18	25
MISSION FLEXIBILITY (25%)	8	13	17	24
DEVELOPMENT (15%)	15	10	14	12
TOTAL	68	64	75	77*

* SELECTED

FLOW CONTROL CONCEPT SELECTION

FIGURE 3-28



VEHICLE A BOOSTER APS OPERATIONAL CHARACTERISTICS FIGURE 3-29

tanks for the intermediate maneuver levels, however, require refill from separate OMS tanks, and are penalized for added complexity and technology. Tankage is also heavier because of high requisite storage pressures. Based on these considerations, it was concluded that liquid propellant storage is superior to supercritical storage. This applies equally to orbiters A and B.

The choice between passive and active propellant conditioning is less obvious. Passive conditioning offers advantages for APS usage $\leq$ 10 ft/sec in terms of technology, simplicity, and weight, but these factors are compromised by integration requirements for missions $\leq$ 50 ft/sec since passive heat exchanger surface areas increase for larger velocity increments and longer times are required for temperature recovery between burns. For $\leq$ 50 ft/sec missions the passive and active heat exchangers were effectively equal with the active showing a slight advantage.

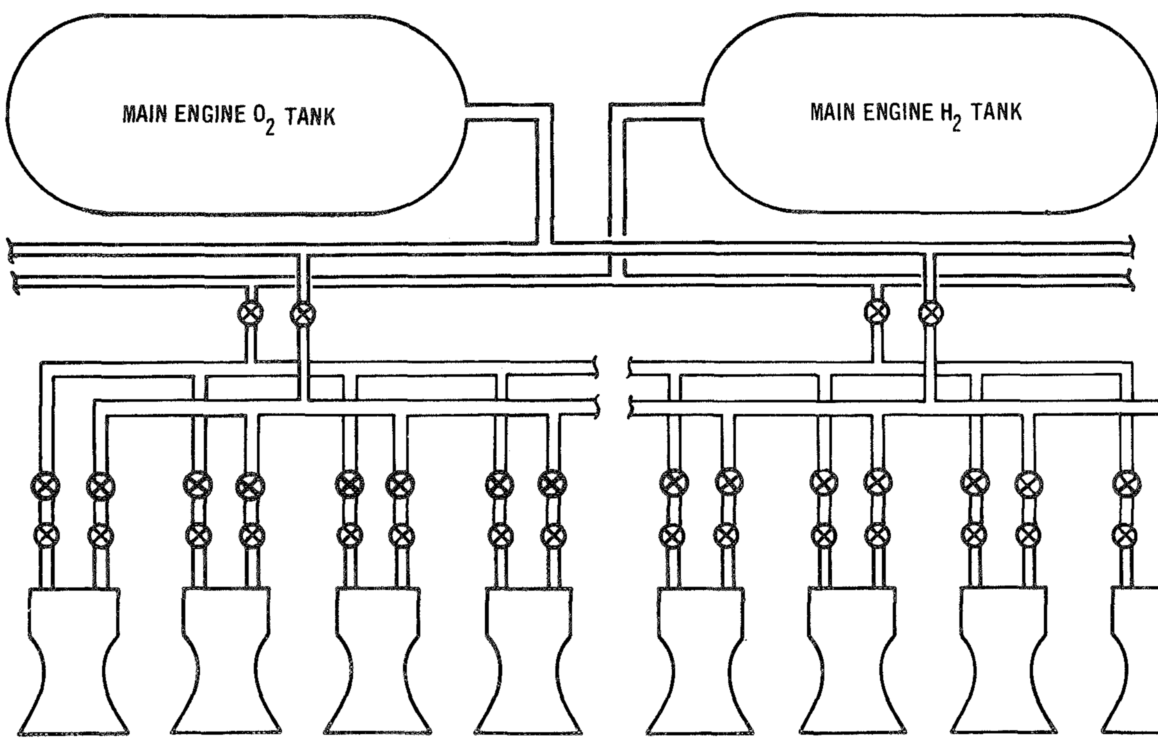
Baseline Concepts - Based on the above study results, NASA selected the baseline subsystems shown in Figures 3-31 and 3-32 for the Subtask B preliminary design phase. The subsystem schematics shown satisfy the mission failure criteria that the APS be fully operational after the first failure, and that it provide a safe reentry after two component failures.

SELECTION CRITERIA	≤10 FT/SEC				≤50 FT/SEC			
	PASSIVE		ACTIVE		PASSIVE		ACTIVE	
	SUPER CRITICAL	LIQUID	SUPER CRITICAL	LIQUID	SUPER CRITICAL	LIQUID	SUPER CRITICAL	LIQUID
TECHNOLOGY (20 POINTS)								
HARDWARE TECHNOLOGY EXTENSION (10)	7	8	4	5	7	8	4	5
PROPELLANT ACQUISITION (10)	7	6	7	5	4	6	4	5
	(14)	(14)	(11)	(10)	(11)	(14)	(8)	(10)
SIMPLICITY (15 POINTS)								
NUMBER OF COMPONENTS (5)	4	5	2	3	4	5	2	3
OPERATIONAL COMPLEXITY (5)	4	5	1	2	4	5	1	2
INTEGRATION COMPLEXITY (3)	2	3	3	3	2	1	3	3
CONTROL REQUIREMENTS (2)	1	2	1	2	1	1	1	2
	(11)	(15)	(7)	(10)	(11)	(12)	(7)	(10)
FLEXIBILITY (25 POINTS)								
OPERATING CONSTRAINTS (10)	8	8	9	9	6	8	7	9
SENSITIVITY TO MAX ΔV BURN (5)	3	3	4	4	3	2	4	4
SENSITIVITY TO THRUST LEVEL (5)	2	5	2	5	2	5	2	5
SENSITIVITY TO TIME BETWEEN BURNS (3)	1	2	3	3	1	1	3	3
SENSITIVITY TO TOTAL IMPULSE (2)	1	2	1	1	1	2	1	1
	(15)	(20)	(19)	(22)	(13)	(18)	(17)	(22)
WEIGHT AND VOLUME (25 POINTS)								
80 LB (1 PT)	17	25	12	24	23	25	18	24
60 CU FT (1 PT)	0	0	0	0	0	0	0	0
	(17)	(25)	(12)	(24)	(23)	(25)	(18)	(24)
DEVELOPMENT (15 POINTS)								
ENVIRONMENTAL SIMULATION (6)	3	4	4	5	2	4	3	5
INTEGRATED TEST REQUIREMENTS (6)	3	3	5	5	2	3	4	5
FACILITY REQUIREMENTS (3)	2	2	1	3	2	2	1	3
	(8)	(9)	(10)	(13)	(6)	(9)	(8)	(13)
TOTAL POINTS	65	83 √	59	79	64	78	58	79 √

√SELECTED

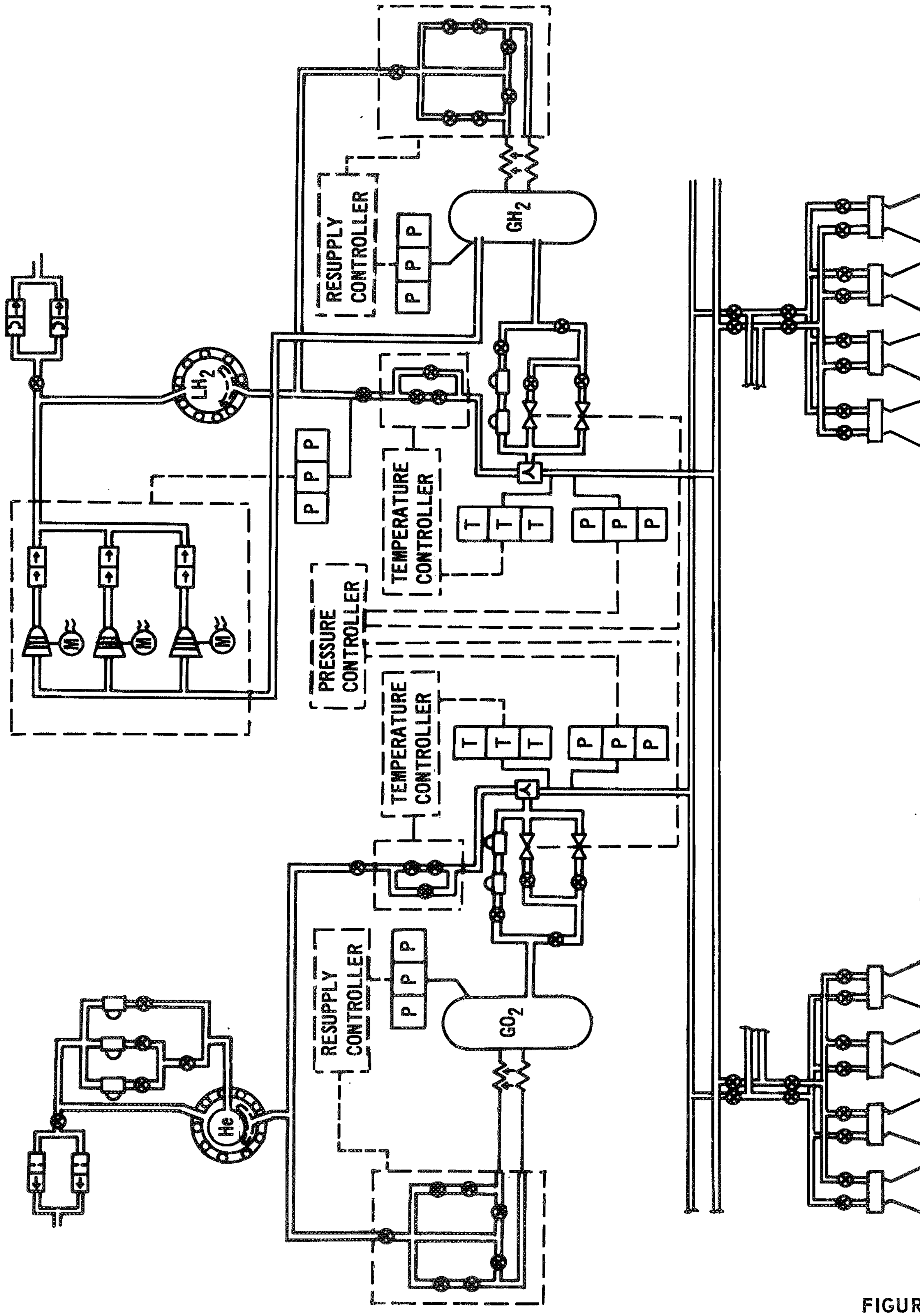
PROPELLANT STORAGE AND CONDITIONING COMPARISON

FIGURE 3-30



SELECTED BOOSTER APS CONCEPT

FIGURE 3-31



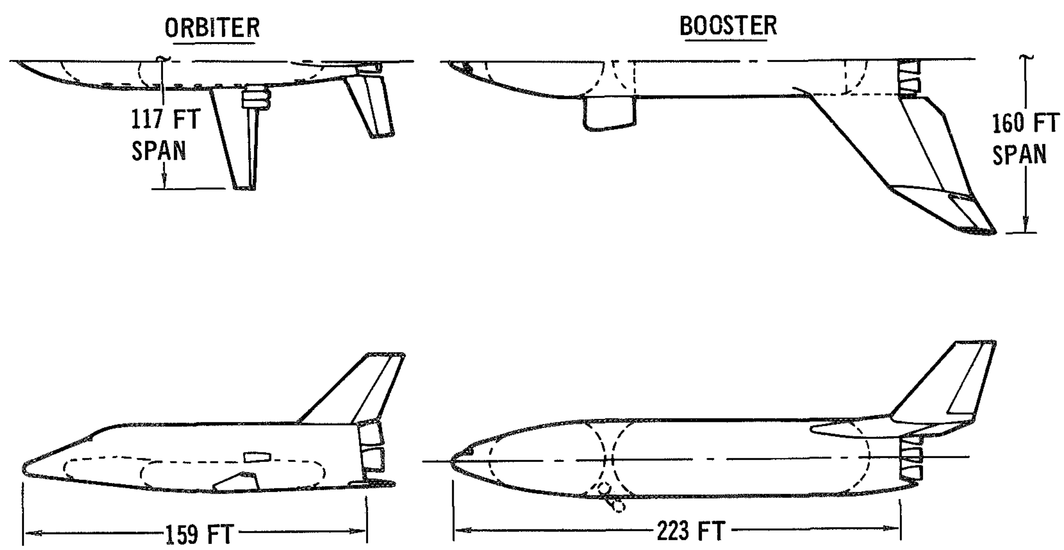
SELECTED ORBITER APS CONCEPT

FIGURE 3–32

4. SUBTASK B - PRELIMINARY DESIGN

Subtask B established preliminary designs based on the conceptual subsystems selected in Subtask A. Specifically, this included definition of subsystem performance and operating characteristics, component designs and installation features, and weight and reliability estimates. Vehicle descriptions and mission requirements were updated for this phase of the study as space shuttle program plans solidified and more descriptive design detail became available from concurrent Phase B space shuttle studies (Reference B). Certain areas of APS conceptual design were recommended by the NASA technical director for detailed Subtask B effort. The most significant of these was an alternate approach to the passive heat exchanger. Surface mounted heat exchangers were assumed for Subtask A. However, a heat exchanger mounted directly to the main engine tank was potentially much less sensitive to vehicle structural configuration and since main engine tanks represent a large fraction of total vehicle structure, they provide a large heat sink capability.

4.1 Subtask B Requirements - A new vehicle description was provided at the start of Subtask B studies. This configuration, shown in Figure 4-1, consists



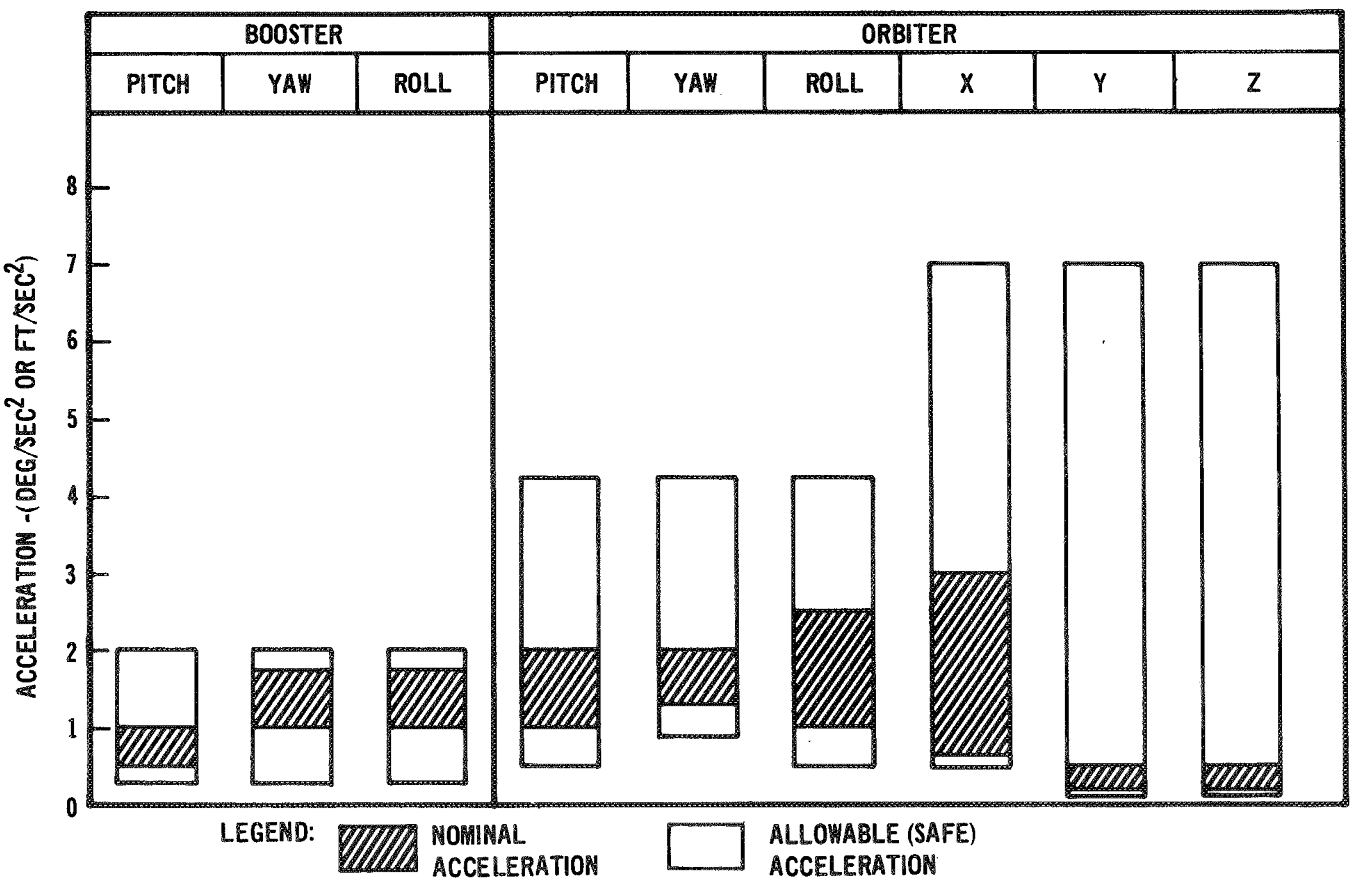
	WEIGHTS (LB)	
	ORBITER	BOOSTER
MAIN ENGINE SHUTDOWN	271,465	474,876
SUBSONIC CRUISE	234,400	451,219

SUBTASK B VEHICLE CONFIGURATION

FIGURE 4-1

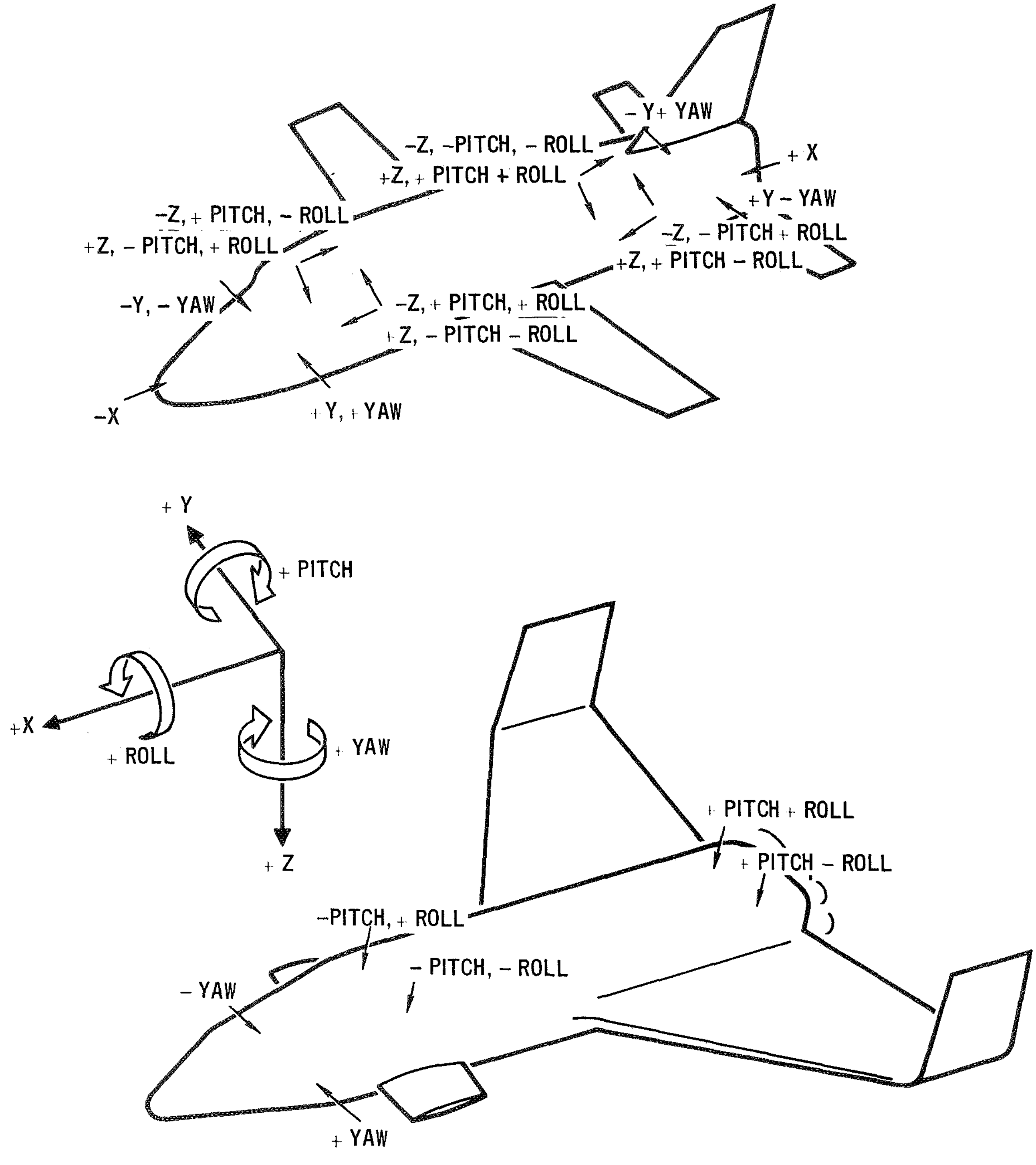
of a delta wing, canard booster, and a low-sweep, fixed straight wing orbiter. Both stages are designed to reenter the earth's atmosphere at a high (60°) angle-of- attack in order to limit vehicle heating rates and temperatures upon reentry.

Vehicle acceleration requirements were revised to those shown in Figure 4-2. Booster acceleration levels were unchanged from Subtask A, but orbiter accelerations were increased significantly. Nominal minimum accelerations in the +X direction, for example, were increased from 0.1 to 0.65 ft/sec^2. Similar increases were specified for other axes. An orbiter reentry bank angle (coordinated yaw-roll) acceleration requirement of 1.5 deg/sec^2 was also introduced. Except for this added requirement, which was based on all engines operating, engine arrangements were predicated on APS capability of providing nominal acceleration levels with one engine out, and minimum acceleration levels with two engines out. Figure 4-3 shows the resultant engine arrangement for each vehicle element. Twenty 2500 lb thrust engines, and thirty-three 1080 lb thrust engines are used on booster and orbiter, respectively. (An alternate engine arrangement is discussed in Section 4.5. That arrangement was designed to the same criteria



DESIGN ACCELERATION LEVELS

FIGURE 4-2



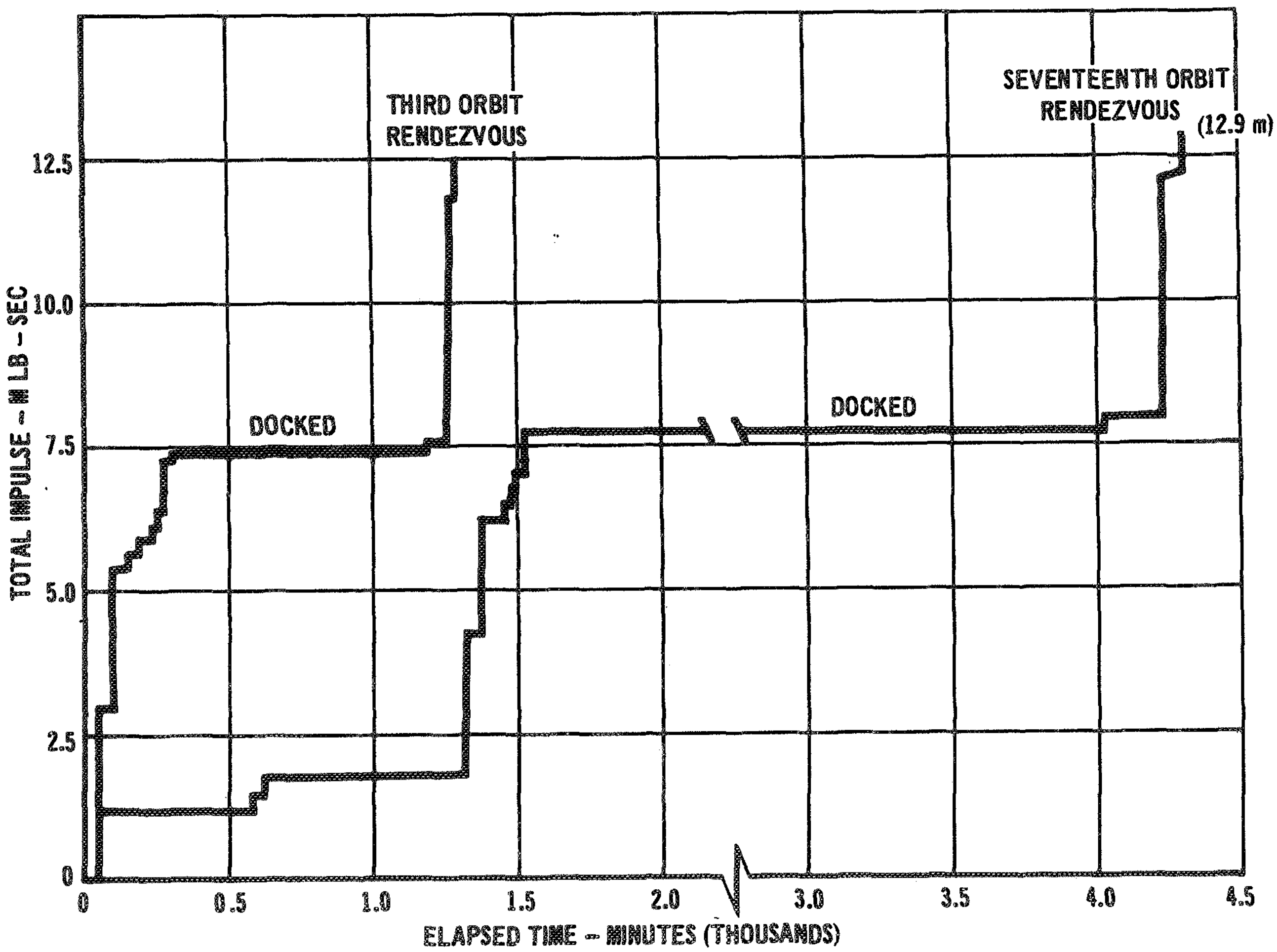
ENGINE ARRANGEMENT FIGURE 4-3

as the high pressure APS, Reference C, for which bank angle and one engine-out acceleration requirements were not imposed, thus providing a better basis for comparing the two design approaches. The low pressure APS for that comparison employs twenty-four, 1220 lb thrust engines.)

Total impulse requirement for booster APS is nearly double that of Subtask A, increasing from an equivalent velocity increment of 32 ft/sec to 59 ft/sec. Booster main tank operating pressures were also reduced and vapor temperatures increased, resulting in less available propellant vapors for APS usage. These changes have a significant impact on booster subsystem sizing and performance in terms of reduced APS pressure budget and reduced total impulse capability.

Orbiter mission timelines were modified somewhat by Reference B, but did not significantly affect total impulse requirements. The most favorable distribution of +X maneuvers between APS and OMS was to be defined for two orbiter missions, representing third and seventeenth orbit rendezvous with a space station. The revised orbiter impulse-time histories are illustrated in Figure 4-4.

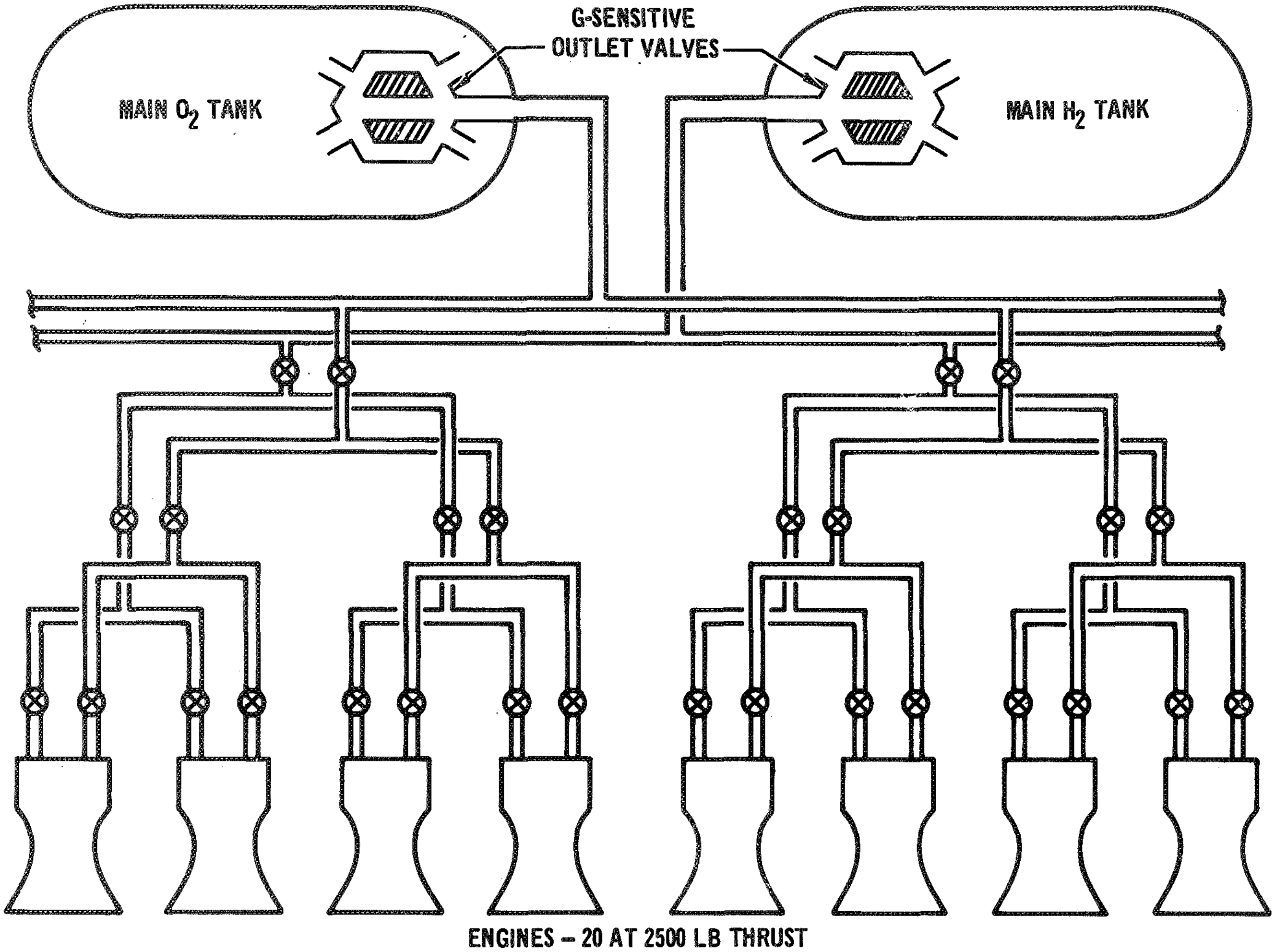
4.2 Baseline Design Concepts - Subtask A concept designs were modified, because of revised requirements and design criteria, as well as additional component and subsystem analyses performed during Subtask B, preliminary design effort. The revised designs follow.



ORBITER IMPULSE TIME HISTORY
(SPACE STATION/BASE LOGISTICS MISSION)

FIGURE 4-4

4.2.1 Booster APS - The booster APS consists of propellant distribution and engine assemblies (shown schematically in Figure 4-5). The subsystem operates



BOOSTER BASELINE AUXILIARY PROPULSION SUBSYSTEM FIGURE 4-5

entirely from available main engine tank propellant vapors in a blowdown mode, over a pressure range of 26 to 17 lbf/in^2. Liquid residuals remaining in the tank at main engine shutdown are prevented from entering the feed system by g-sensitive valves located at tank outlets. Distribution and engine assemblies are sized to provide 2500 lb thrust at the end of blowdown, when tank pressures and temperatures are lowest. A mixture ratio of 2.0 and a nozzle expansion ratio of 2:1 provide minimum subsystem weight. Figure 4-6 summarizes baseline design features, while Figure 4-7 shows subsystem installation.

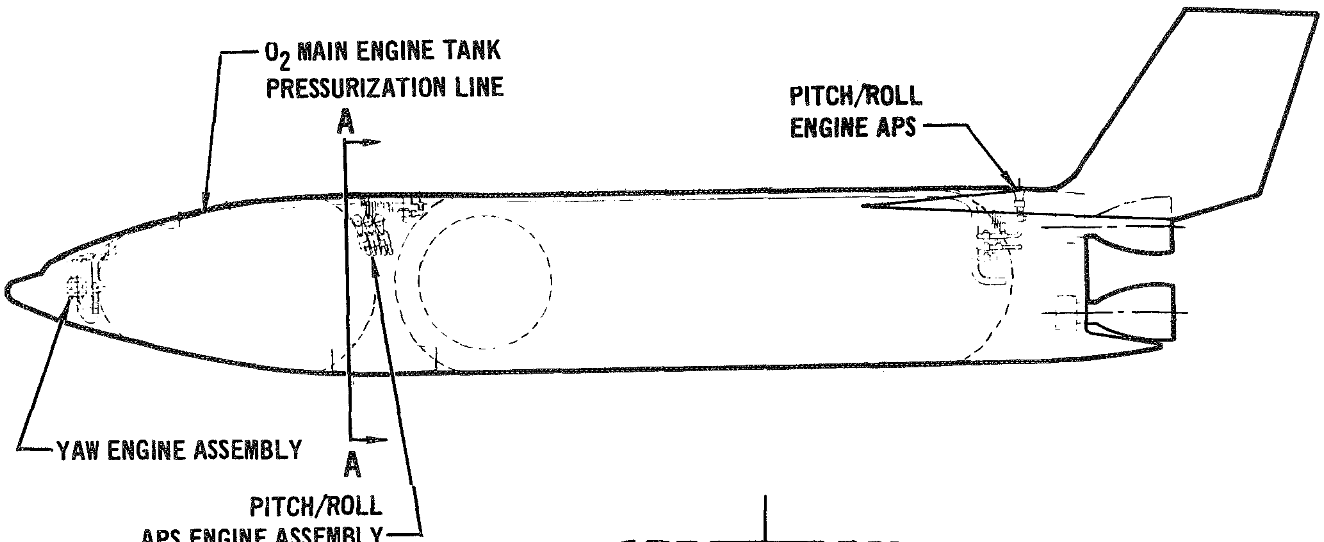
4.2.2 Orbiter APS - The orbiter APS, shown schematically in Figure 4-8, consists of five major assemblies:

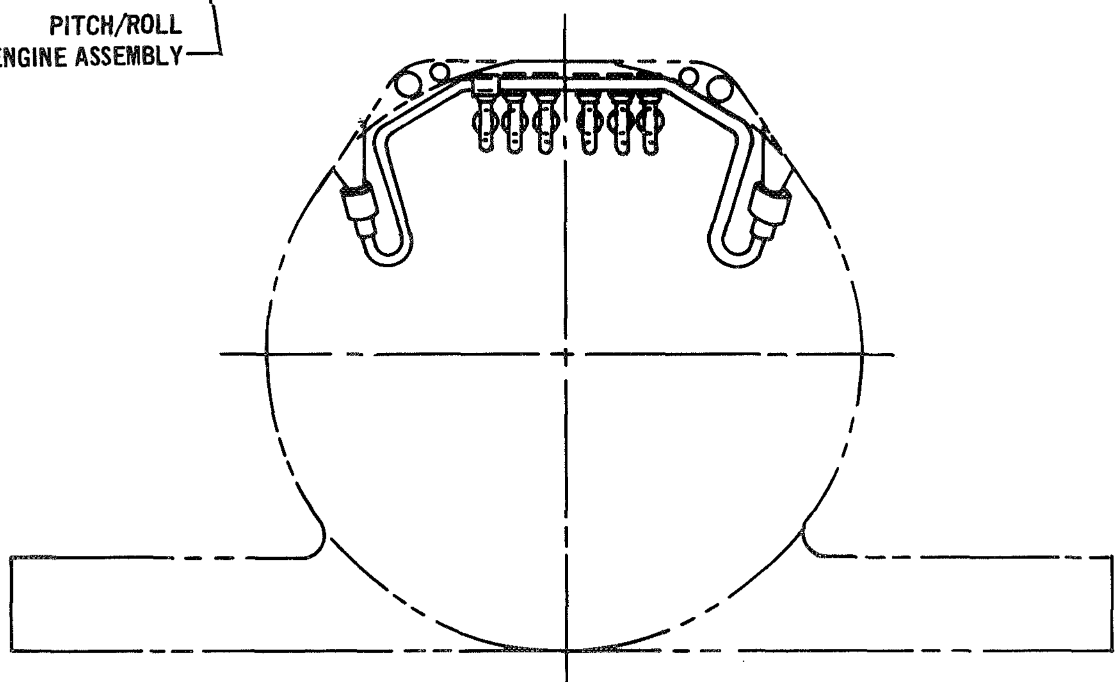
(1) propellant storage assembly

	O_2	H_2
MAIN TANK		
INITIAL VAPOR TEMPERATURE, °R	520	260
INITIAL PRESSURE, LBF/IN²A	26	26
MINIMUM PRESSURE, LBF/IN²A	17	17
ENGINE AND DISTRIBUTION SYSTEM		
DESIGN ENGINE INLET PRESSURE, LBF/IN²A	14	14
DESIGN ENGINE INLET TEMPERATURE, °R	400	150
ENGINE THRUST, LB	2500	
MIXTURE RATIO	2.0	
CHAMBER PRESSURE, LBF/IN²A	11	
EXPANSION RATIO	2:1	

BOOSTER BASELINE DESIGN SUMMARY

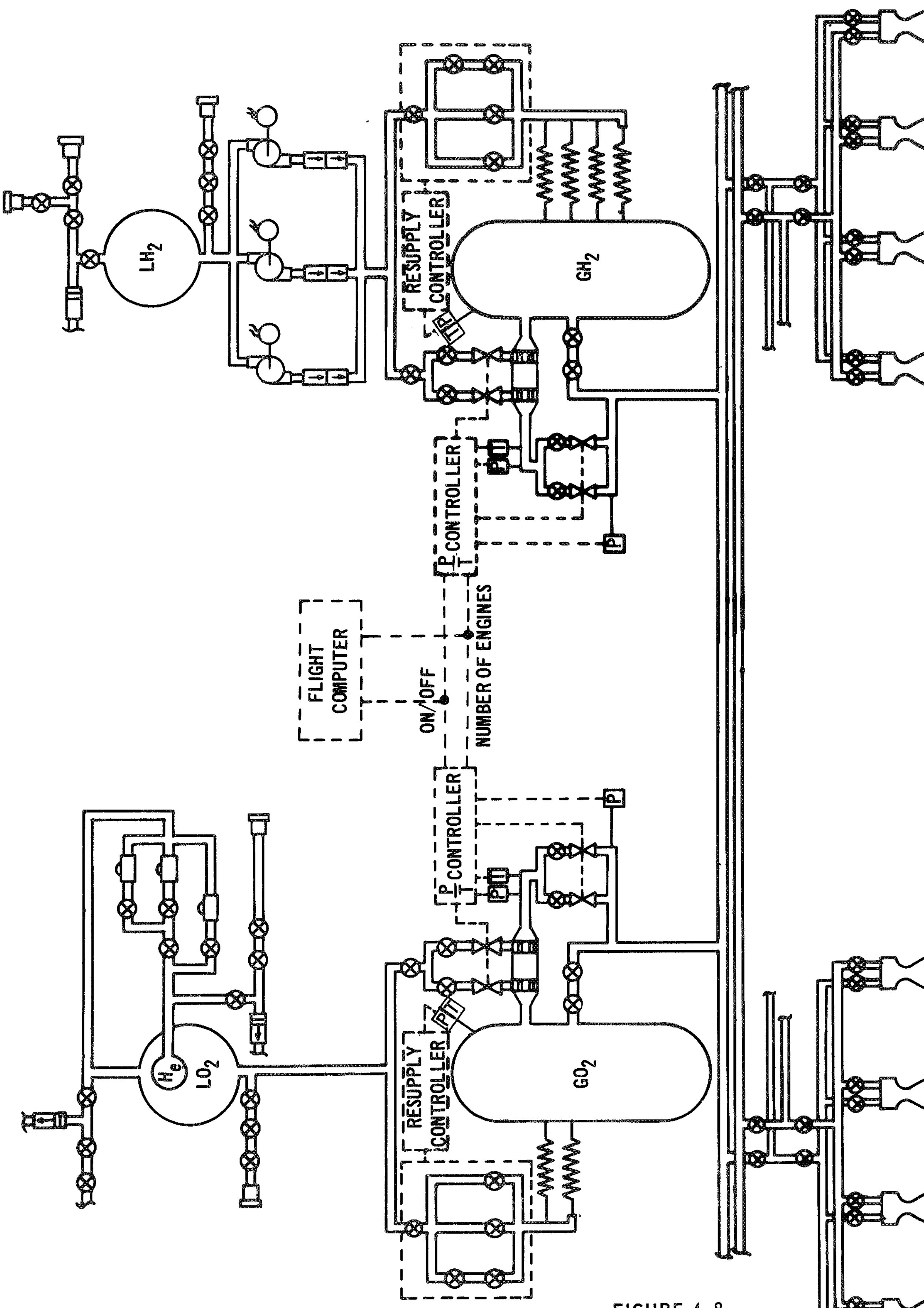
FIGURE 4-6





A-A

FIGURE 4-7



ORBITER
BASELINE AUXILIARY PROPULSION SUBSYSTEM

FIGURE 4-8

(2) tubular, passive heat exchanger assembly

(3) liquid/vapor mixing assembly

(4) propellant distribution assembly, and

(5) engine assemblies.

The APS is used in conjunction with an Orbit Maneuvering Subsystem (OMS). The OMS provides all high total impulse maneuvers, such as orbit circularization, plane changes, and deorbit functions, while the APS provides all attitude control and vernier maneuvers ($\leq$ 40 ft/sec). The APS design uses thirty-three 1080 lb thrust engines with an 8:1 nozzle expansion ratio operating at a mixture ratio of 3.0.

Main engine tanks are used as gas accumulators with an operating pressure range of 16 to 30 lbf/in^{2}a. Main tank resupply occurs when propellant vapor pressure-to-temperature drops below .057 (30 lbf/in^2/530°R). Resupply propellant is first vaporized and superheated by passive heat exchangers before injection into main engine tanks. During major APS maneuvers, warm main tank propellant vapors are mixed with cold propellants in a downstream mixing chamber, for supply to the engines at constant temperature and pressure. Subsystem design characteristics are summarized in Figure 4-9, while Figure 4-10 shows subsystem installation.

	O_2	H_2
LIQUID STORAGE AND PRESSURIZATION SYSTEM		
PROPELLANT WEIGHT, LB	4496	2499
PROPELLANT TANK PRESSURE, LBF/IN^{2}A	35	40
PROPELLANT TANK VOLUME, FT$_3$	67	633
PRESSURIZATION TYPE	COLD H_e	PUMP
PROPELLANT SUPPLY PRESSURE, LBF/IN^{2}A	35	35
HEAT EXCHANGER		
AREA, FT^2	1,790	3,100
TUBE LENGTH, FT	17.5	15.0
TUBE SPACING	4.0	10.0
TUBE DIAMETER, IN.	0.394	0.298
NUMBER OF TUBES	308	248
LIQUID-VAPOR MIXER		
OUTLET TEMPERATURE, °R	200	150
INJECTOR (LIQUID) INLET PRESSURE, LBF/IN^{2}A	30	30
LIQUID THROTTLE RATIO	10:1	10:1
GAS-SIDE PRESSURE DROP, LBF/IN^{2}D	1.0	1.5
ENGINE AND DISTRIBUTION SYSTEM		
DESIGN REGULATED PRESSURE, LBF/IN^{2}A	20	20
MAXIMUM LINE DIAMETER, IN.	8.3	8.3
ENGINE INLET PRESSURE, LBF/IN^{2}A	15.7	15.7
ENGINE THRUST, LB	1,080	
CHAMBER PRESSURE, LBF/IN^{2}A	13.7	
MIXTURE RATIO	3.0	
EXPANSION RATIO	8:1	

ORBITER BASELINE DESIGN SUMMARY

FIGURE 4-9

4.3 APS Design and Operation - Design and operational characteristics of primary subsystem assemblies are described below:

(a) Engine Assembly - Engine assemblies include propellant control valves, injector, combustion chamber, and nozzle. The engine design, which is shown in Figure 4-11, features a multiple element, coaxial injector and hydrogen film-cooled chamber and nozzle walls. The engine head end assembly is made of aluminum to minimize weight, and is attached to the Haynes alloy combustion chamber by a bimetallic ring. Pneumatically actuated coaxial poppet valves provide fast response, high cycle life, and positive sealing. The orbiter engine delivers 1080 lb thrust at a specific impulse of 377 sec. The booster APS engine, which is similar to the orbiter engine, delivers a vacuum thrust of 2500 lb at a specific impulse of 342 sec.

(b) Propellant Distribution Assembly - All APS supply lines are constructed of minimum gage aluminum ducting, using linear and angular compensator bellows to absorb thermal and manufacturing tolerances. Line weights are minimized by using existing main engine tank pressurization lines as primary APS

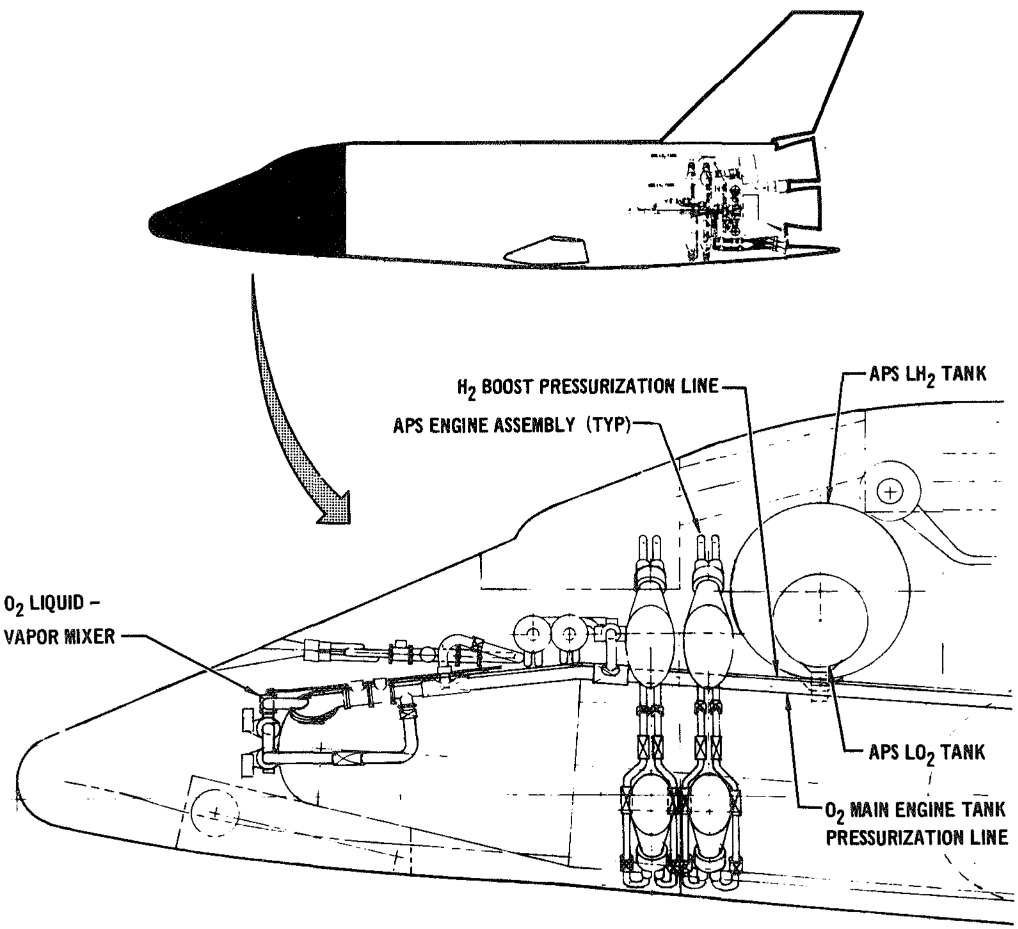
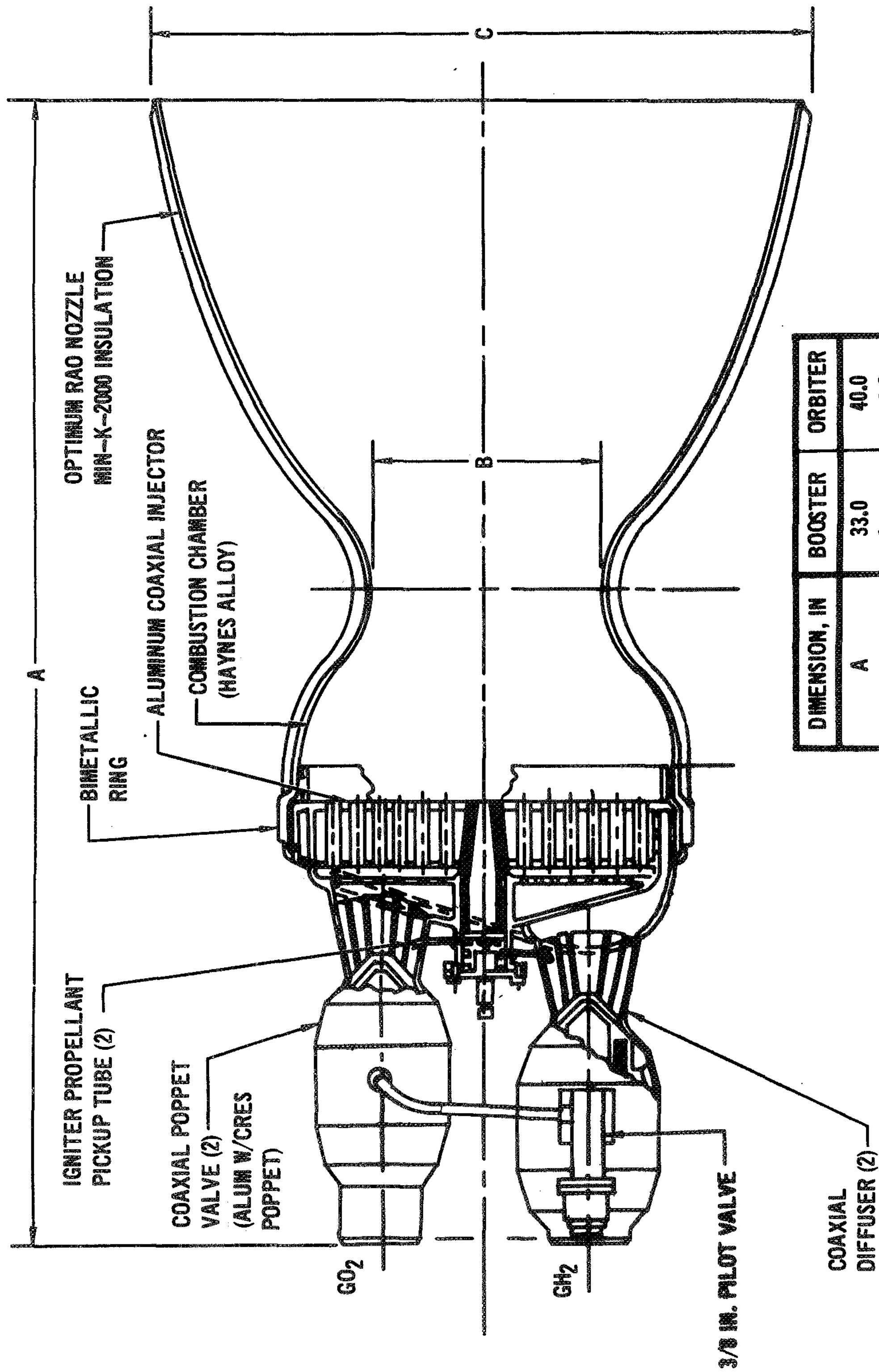


FIGURE 4-10

ORBITER APS INSTALLATION



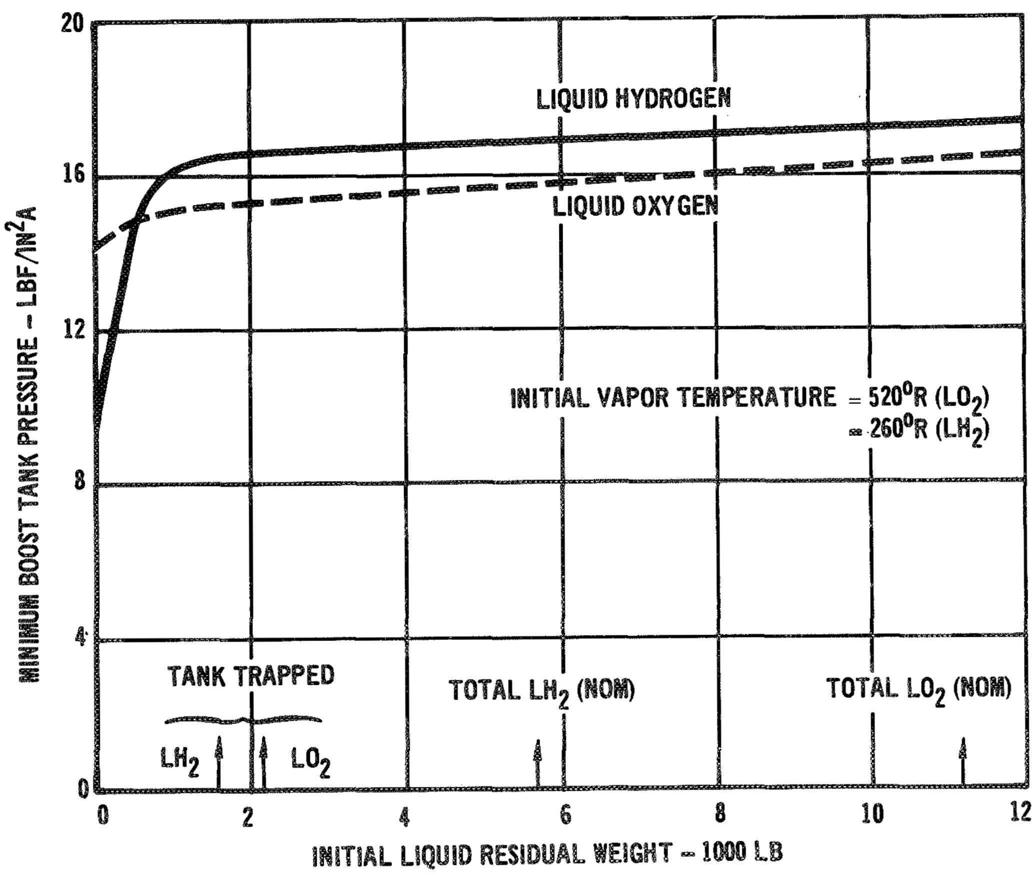
DIMENSION, IN	BOOSTER	ORBITER
A	33.0	40.0
B	14.2	8.0
C	21.0	24.0

ENGINE ASSEMBLY

FIGURE 4-11

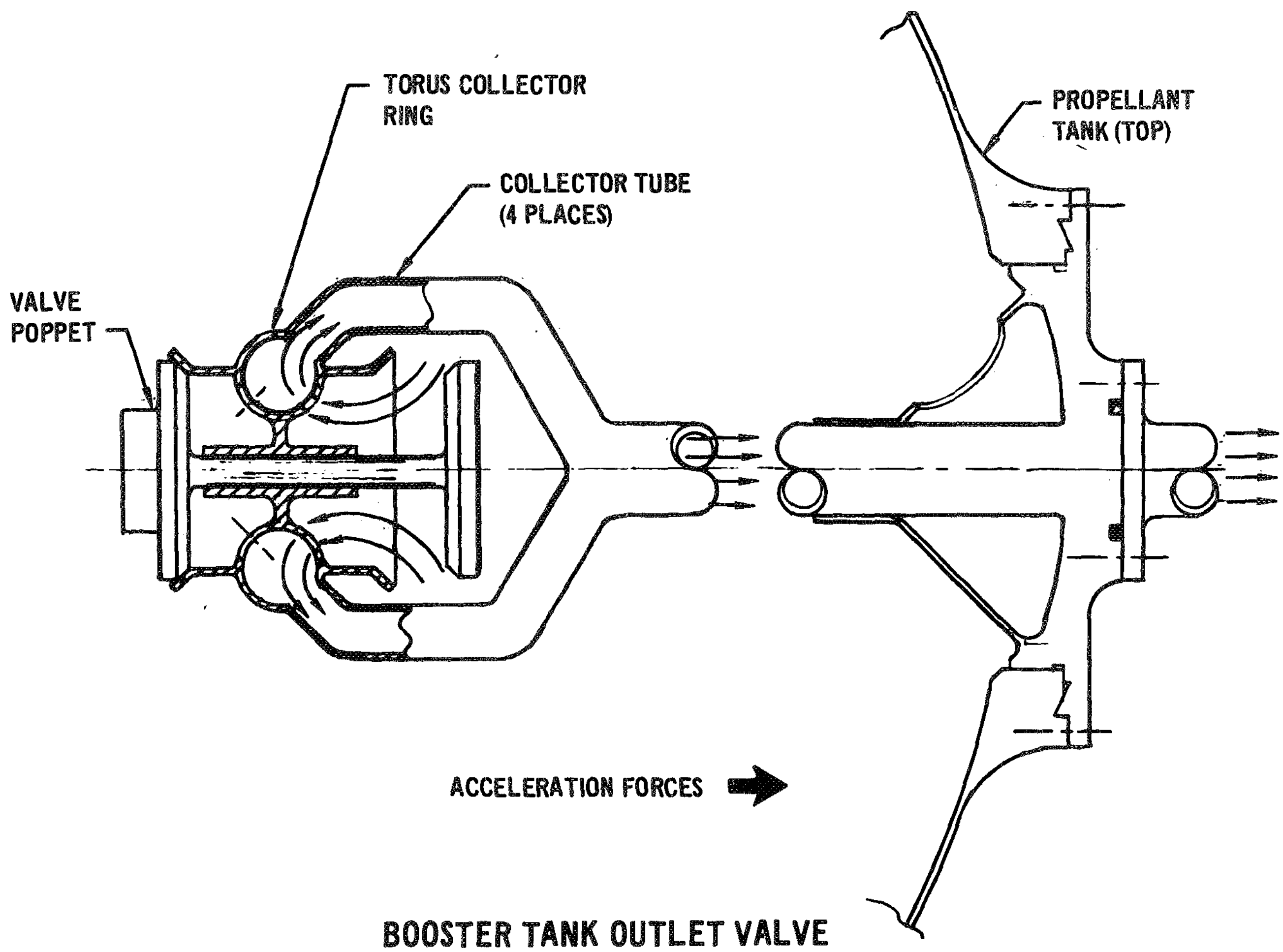
trunklines. These lines extend nearly the full length of the vehicle and are of sufficient diameter (18 in. on the booster and 8.2 in. on the orbiter) to accommodate APS flow requirements. The remainder of the distribution network is sized to provide minimum subsystem weight by balancing line weight penalty as a function of frictional losses and engine weight penalty as a function of resultant chamber pressure. Propellant flow to engines is supplied at minimum pressures of 14 lbf/in^2a and 16 lbf/in^2a for booster and orbiter, respectively. Visor-type isolation valves are used to safeguard the subsystem against failed-open engine valves.

(c) Main Tank Liquid/Vapor Separators - The booster requires a minimum of 1000 lb of liquid residuals in each propellant tank to maintain tank pressures above 15-16 lbf/in^2a upon completion of the mission profile. This is well below the amount of liquids that will be trapped in the booster main engine tanks (Figure 4-12). To ensure that only gases are extracted for APS operation, liquid/vapor separator valves, shown in Figure 4-13, are installed at the



SENSITIVITY OF BOOSTER MAIN TANK PRESSURE TO LIQUID RESIDUAL WEIGHT

FIGURE 4-12



BOOSTER TANK OUTLET VALVE
(G SENSITIVE VALVE POPPET)

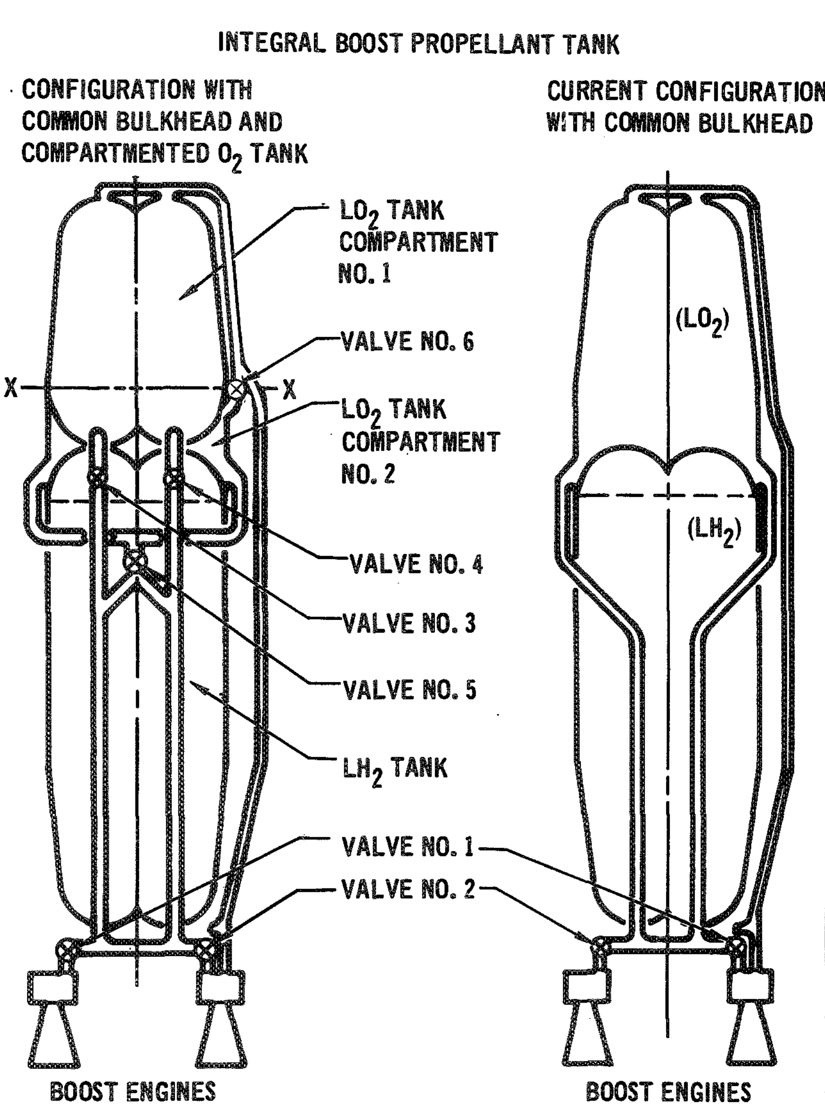
FIGURE 4-13

entrances to APS supply lines. The booster mission is too short for a zero g-propellant configuration to develop; the liquids will either be in contact with the walls or reacting to imposed g-loads. The APS separator valve prevents liquid ingestion under either condition. A tank stand-off prevents the outlet from being submerged by liquids when they are in contact with the wall, while a low friction, g-sensitive valve poppet closes the outlet valve when acceleration forces cause bulk liquid to move toward it.

For the orbiter, analyses show that nominally only 610 lb (or 19 percent) of available liquid residuals can be used by the APS without alteration of tank operation and design. Most of this (80 percent) is LO_2. Due to rapid LH_2 boil-off, utilization of liquid hydrogen residuals is poor and LH_2 will be dumped through the main propulsion subsystem immediately after orbit insertion. Liquid oxygen, on the other hand, is useful and will be retained in a compartmented tank, as shown in Figure 4-14. In this approach, a tension bulkhead is installed above the common LO_2/LH_2 compression bulkhead to absorb liquid head loads during high launch g. The volume between the two bulkheads is loaded with LO_2; thus, there is no loss in LO_2 tank volume. Inasmuch as the inner tank compartment is isolated from high launch head pressures, compression bulkhead weight is reduced to a level at which the two bulkheads weigh no more than the one compression bulkhead in the original tank design. During main engine operation, the primary LO_2 tank drains first, leaving it dry and ready for use as the GO_2 accumulator. LO_2 residuals are trapped in the smaller LO_2 compartment. Insulation of this compartment reduces LO_2 boiloff rate and increases APS propellant utilization by approximately 1064 lb. Valve sequencing for this operation is shown in Figure 4-14.

(d) Propellant Storage -(Orbiter Only) - APS propellant tanks contain approximately 4500 lb of LO_2 and 2500 lb of LH_2. Oxygen and hydrogen propellant tanks are similar in design. A cutaway of the LH_2 tank is shown in Figure 4-15 and design features of both tanks are summarized in Figure 4-16. Each is insulated with multilayer, aluminized Mylar insulation protected by a fiber glass outer covering. The outer shell is pressurized during boost and entry to prevent structural failure under collapse pressure loads, and is vented on-orbit to achieve the insulative qualities of evacuated, multilayer insulation. Propellant positioning is achieved with surface tension screen devices, made up of several annular trays. Trays are separated from tank walls to prevent propellant vaporization within the acquisition device, but are close enough to the wall to allow contact with liquid for any propellant orientation. Cold helium, and submerged, low-suction-pressure pumps are used for transfer of LO_2 and LH_2 propellants, respectively.

(e) Passive Heat Exchanger (Orbiter Only) - During APS operation, when main engine tank vapor pressure-to-temperature ratio drops below .057 lbf/in^2 - °R, additional propellant is resupplied from liquid storage tanks. This propellant is first circulated through a passive heat exchanger, where it is vaporized and superheated to relatively high resupply temperatures. Comparison of heat exchanger installations, mounted either to the vehicle skin or to the main engine tanks, showed tank-mounted installations to be superior in terms of integration and performance. The heat exchanger consists of thin wall, aluminum tubing mounted



SEQUENCE OF OPERATION FOR CONFIGURATION WITH COMPARTMENTED O_2 TANK

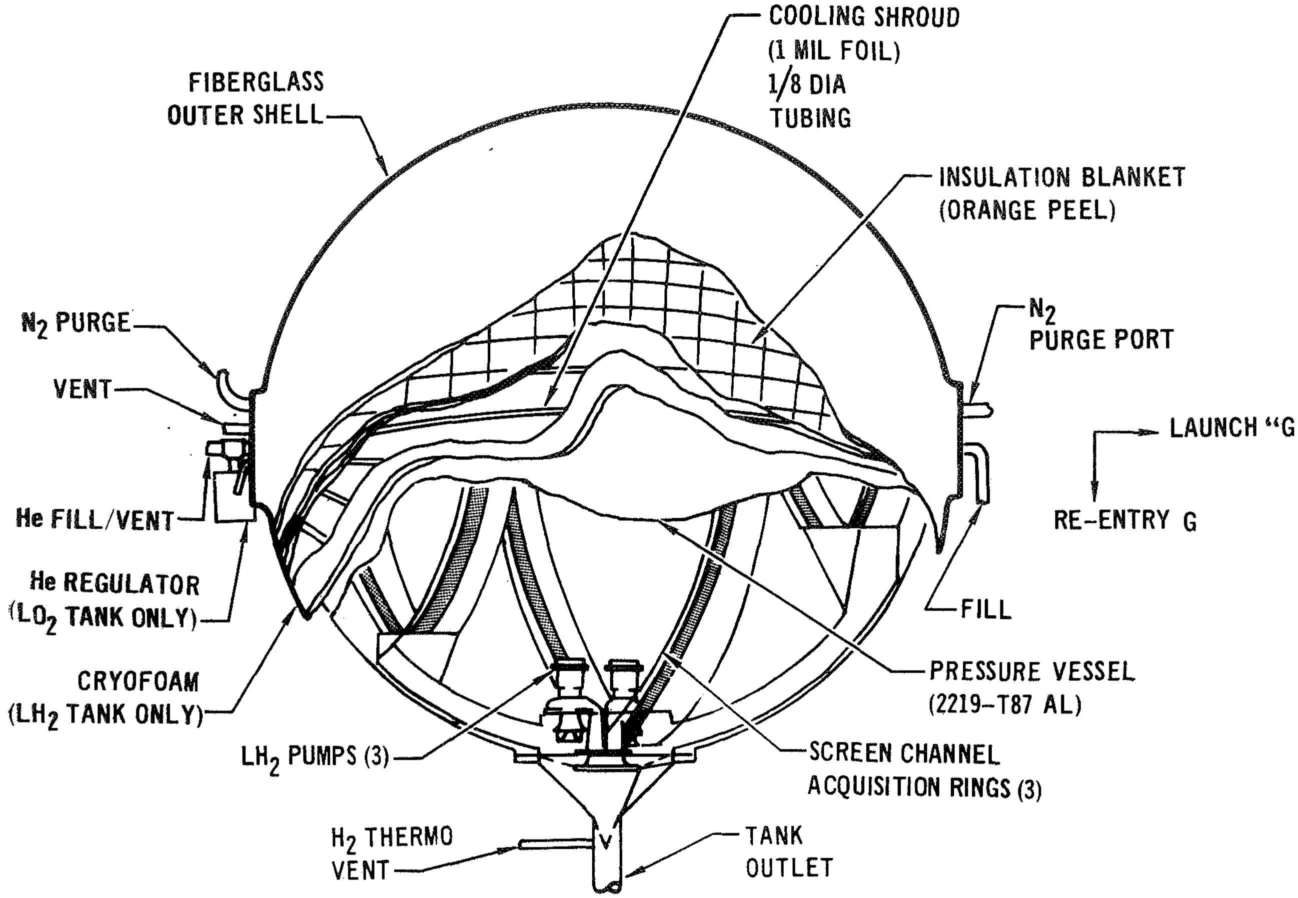
EVENT	VALVE OPERATION	REMARKS
PRELAUNCH	NOS. 1 & 2 CLOSED NOS. 3, 4, 5, 6 OPEN	LOAD COMPARTMENTS NOS. 1 & 2
LIFTOFF	ALL VALVES OPEN EXCEPT NO. 5	ALL LO_2 FLOW FROM COMPARTMENT NO. 1
LO_2 SUPPLY DEPLETED TO LEVEL X–X	OPEN NO. 5	LO_2 FLOW FROM COMPARTMENTS NO. 1 & 2
END OF BOOST	CLOSE ALL VALVES EXCEPT NO. 5	ALL O_2 RESIDUALS ARE CONTAINED IN COMPARTMENT NO. 2.

ORBITER TANK WEIGHT COMPARISON

ITEM	BOOST TANK CONFIGURATION: COMMON BULKHEAD	BOOST TANK CONFIGURATION: COMPARTMENTED O_2 TANK
COMMON BULKHEAD	950 LB	540 LB
COMPARTMENT BULKHEAD	–	210 LB
VALVES	–	175 LB
LINES AND MOTION COMPENSATORS	–	75 LB
	950 LB	1000 LB

COMPARTMENTED OXYGEN PROPELLANT TANK

FIGURE 4–14



PROPELLANT TANK INSULATION COOLING CONCEPT FIGURE 4-15

directly to the tank wall longitudinal stiffeners. Figure 4-17 shows the tube attachment. The oxygen heat exchanger is divided into two, 17.5 ft long panels, each with 154 tubes, approximately 0.4 in. in diameter. The hydrogen heat exchanger is divided into four 15 ft panels, each consisting of sixty-two 0.3 in diameter tubes. The section modulus of the tubes adds to tank longitudinal rib stiffness, thus permitting a reduction in tank rib height and weight.

Figure 4-18 shows heat exchanger performance during the most critical mission phase, immediately prior to docking.

(f) Liquid/Vapor Mixer Assembly (Orbiter Only) - This assembly consists of a pressure regulator and a liquid vapor mixing chamber, each independently controlled. The assembly provides constant propellant pressure and temperature at the engine inlets during all major APS operations. The pressure regulator (Figure 4-19) is an IRIS throttle valve with torque motor drive. Downstream

	OXYGEN	HYDROGEN
PRESSURIZATION		
TYPE	COLD HELIUM	PUMP
STORAGE PRESSURE, LBF/IN^2A	3000	(40 HE PREPRESS)
STORAGE TEMPERATURE, ^{o}R	165	-
SUPPLY PRESSURE, $LBF/IN.^2A$	35	35 MIN
PUMP HORSEPOWER, BHP	-	6.1
ELECTRICAL POWER	-	208V (23 AMPS)
PROPELLANT TANK		
VOLUME, FT^3	67	633
DESIGN PRESSURE, $LBF/IN.^2A$	35	40
MATERIAL	2219-T87 AL	2219-T87 AL
INSULATION	HPI	HPI/CRYOFOAM
THICKNESS, IN.	0.97	0.68 (HPI)/0.42 (FOAM)
COOLING	H_2VENT	H_2VENT
VENT RATE, LB/HR	-	0.45
SHROUD	1 MIL AL FOIL	1 MIL AL FOIL
TUBING	1/8 DIA;0.010 WALL	1/8 DIA; 0.010 WALL
PROPELLANT ACQUISITION	SCREEN TRAP	SCREEN TRAP
EXTRACTION RATE, GPM	103	550
HYDROSTATIC HEAD, LBF/FT^2	41	6.4
EXPULSION EFFICIENCY	0.987	0.991

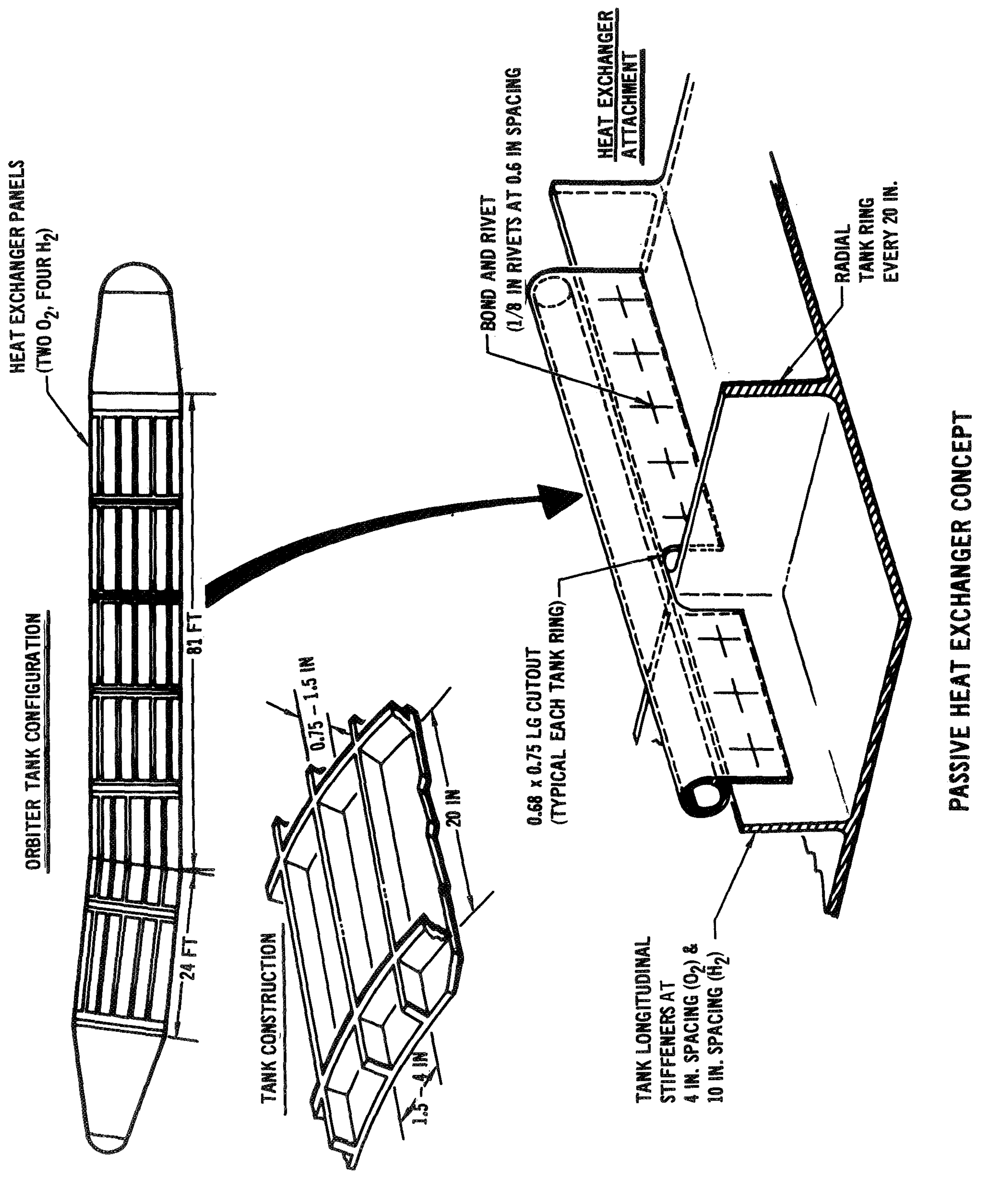
APS PROPELLANT STORAGE DESIGN SUMMARY

FIGURE 4-16

pressure sensing is used to modulate valve flow area, controlling downstream pressure to a constant 19 lbf/in^2a. The liquid/vapor mixer consists of a liquid injection element in the gas stream and a cavitating venturi throttle valve for liquid flow control.

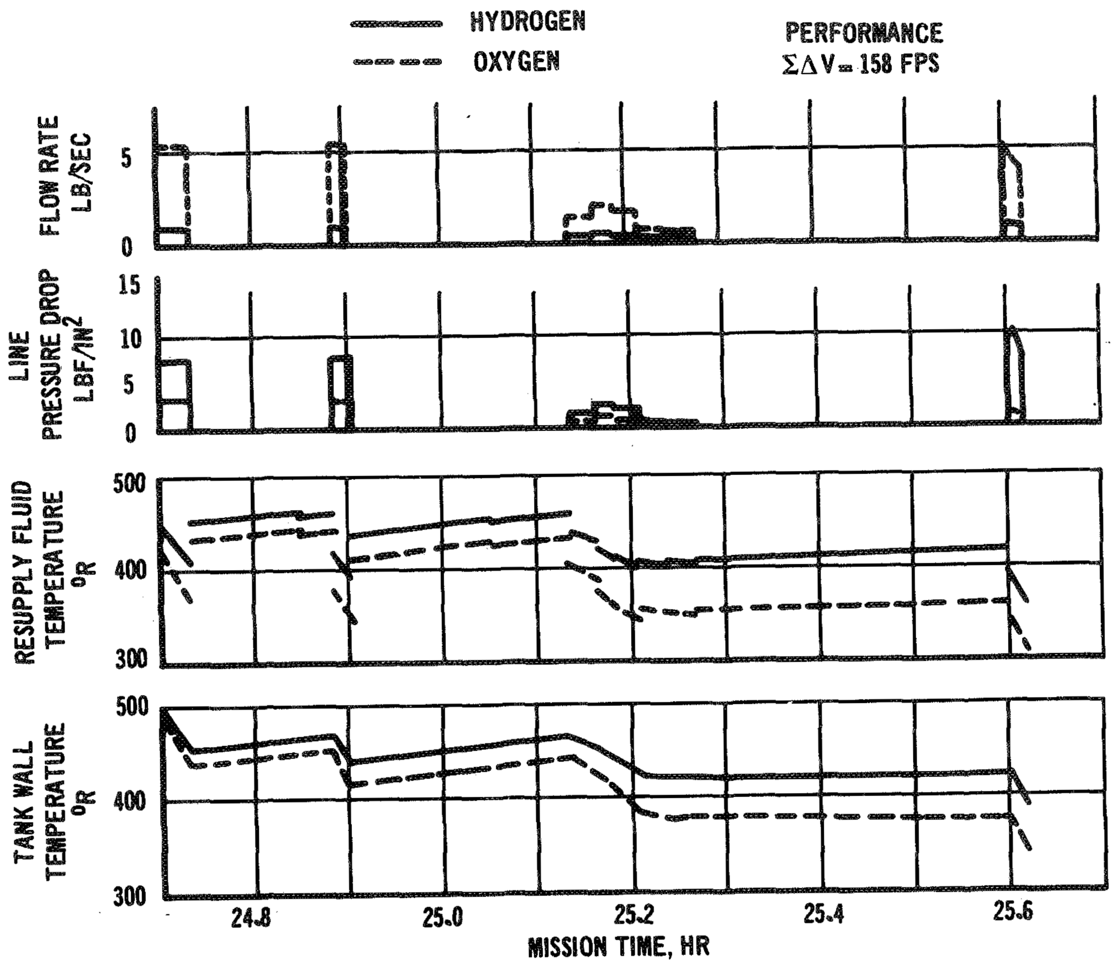
Figure 4-20 illustrates operation of the entire assembly. Warm propellant vapors, extracted from the main engine tank, pass through the mixing chamber, where they are mixed with cold liquids. Liquid flowrate is controlled, by a cavitating venturi throttle valve, to achieve a constant outlet temperature. Design outlet temperatures are 200°F (O_2) and 150°R (H_2). Initially, when the temperature of the vapors being removed from the main engine tank is high, a large percentage of total flowrate is liquid. As tank temperature and pressure decay with time, liquid flowrate must be decreased to maintain desired mixer outlet conditions. Since both temperatures and pressures are controlled, constant propellant densities are provided at engine inlets.

The liquid vapor mixer is used only for major APS burns. During periods



PASSIVE HEAT EXCHANGER CONCEPT

FIGURE 4-17



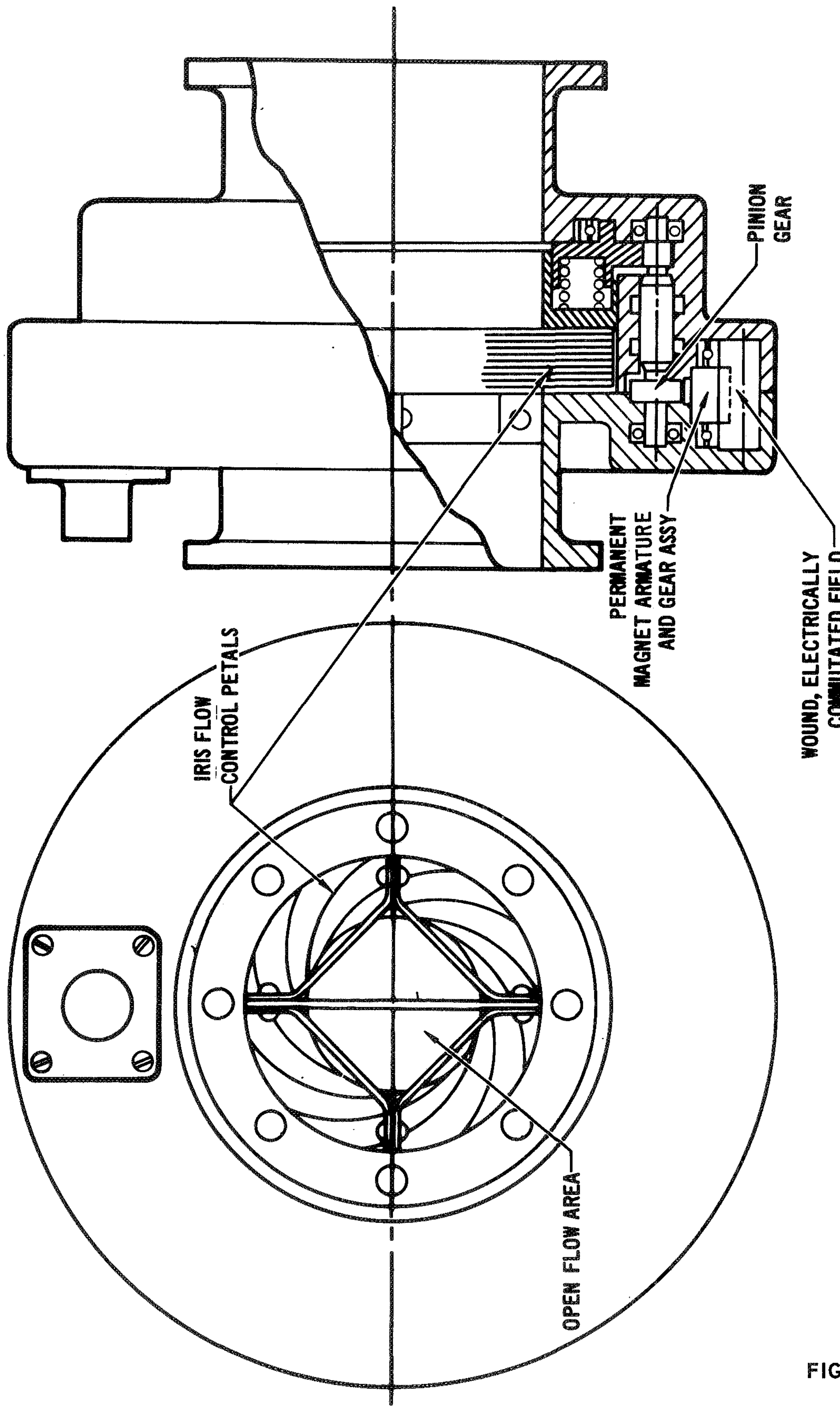
HEAT EXCHANGER OPERATION (SEVENTEENTH ORBIT RENDEZVOUS)
Braking and Docking Maneuvers

FIGURE 4-18

of low APS usage, all propellants are extracted from main engine tanks, and the regulator retains the flow area setting from the last major maneuver. This mixed-mode operation provides acceptable engine performance, while greatly reducing required controller operating range and response requirements.

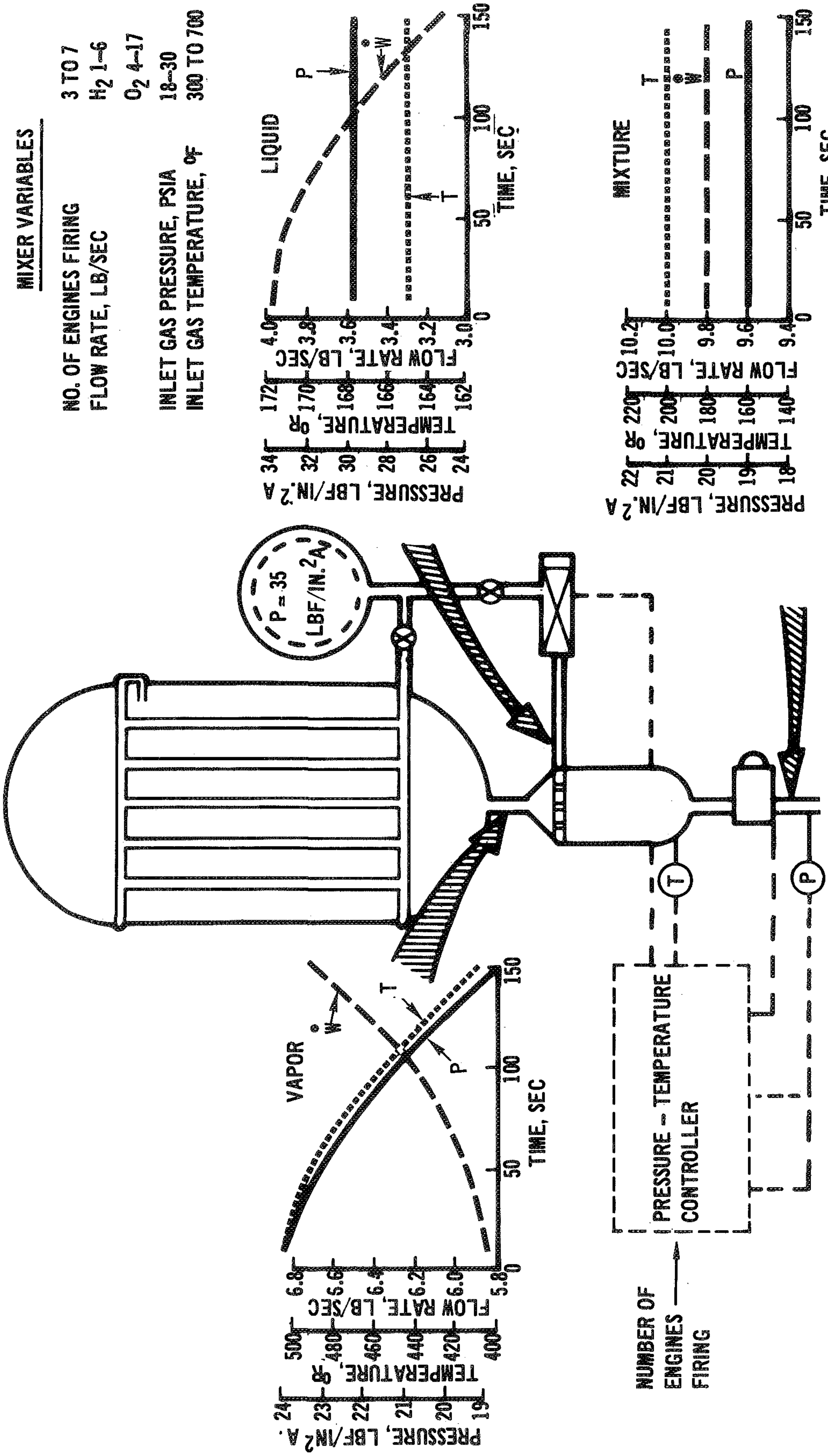
(g) Pneumatic Actuation Assembly - Rapid response, high seat load requirements of the engine valves necessitate a separate pneumatic control loop for valve actuation. The pneumatic assembly uses a 3500 lbf/in^2a ambient helium supply, regulated to 250 lbf/in^2a, to provide a valve opening response of 50 ms. A single, solenoid, pilot valve on each engine provides simultaneous actuation of both propellant valves. Total helium requirements are 3.5 lb for the booster and 11.0 lb for the orbiter.

4.4 Mission Performance - The following paragraphs describe mission performance and the effect of operating environments on subystem operation.



IRIS REGULATOR DESIGN

FIGURE 4–19

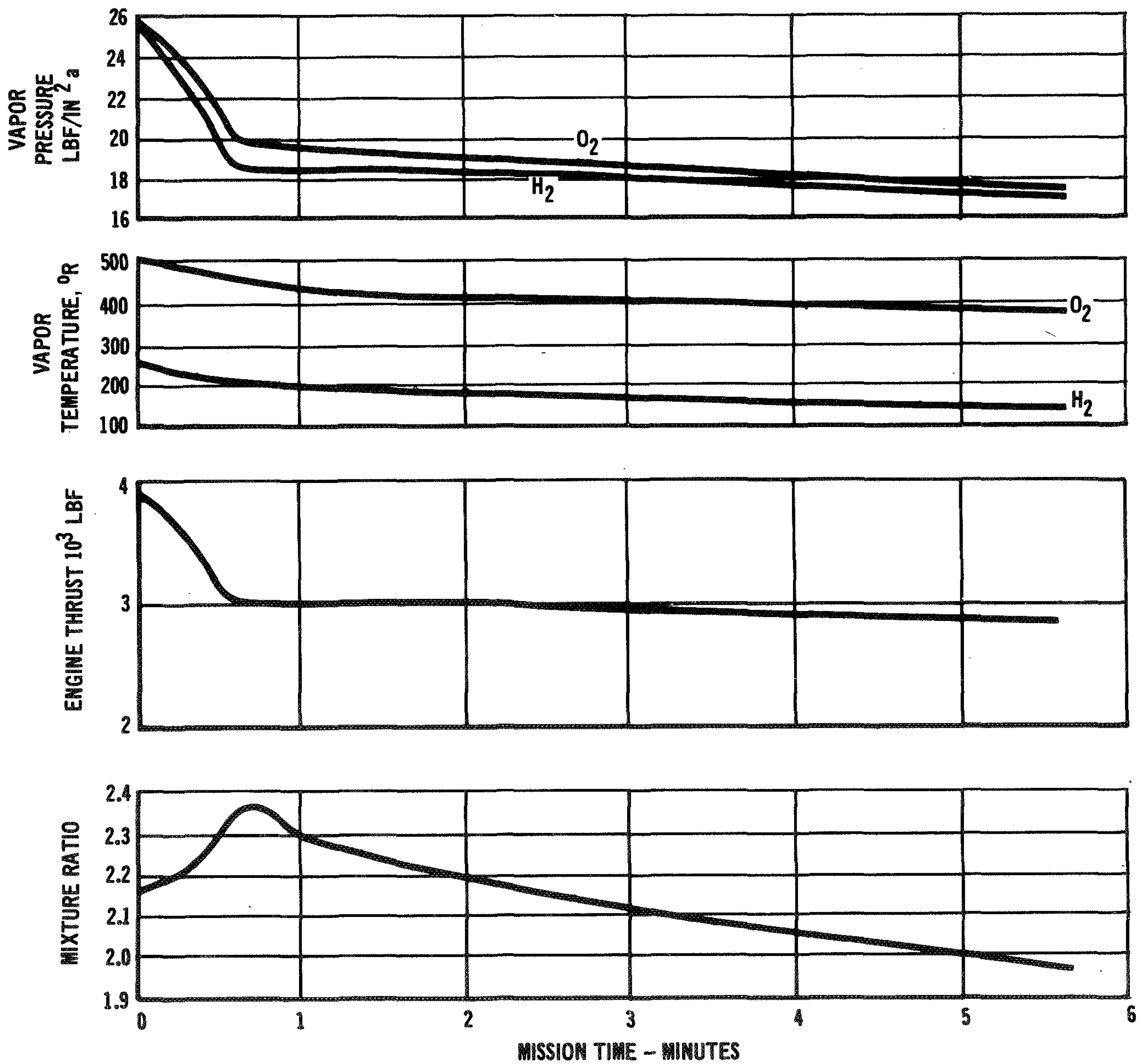


LIQUID – VAPOR MIXER

Steady State Operating Characteristics – Oxygen

FIGURE 4–20

(a) Booster Mission Duty Cycle - The booster APS is used to damp both main engine shutdown and vehicle separation transients, and to orient and control vehicle attitudes during reentry. Total mission duty cycle is approximately 6 minutes long and results in a total impulse expenditure of 864,000 lb-sec. Figure 4-21 shows main engine tank temperature and pressure histories during APS operation. Also shown is the resultant effect of these variables on engine performance (thrust and mixture ratio). Tank pressures do not decay below



BOOSTER APS MISSION OPERATING CHARACTERISTICS

FIGURE 4-21

17 lbf/in^{2}a and temperatures do not exceed the minimum required for good engine ignition and performance.

The above data were generated for initial tank ullage pressures of 26 lbf/in^{2}a and temperatures of 520°R (O_2) and 260°R (H_2). The initial hydrogen tank ullage temperature was reduced from the 450°R specified in Reference B in order to hold tank pressure safely above ambient pressure environs. To do this without affecting booster/orbiter main engine commonality, main propulsion pressurant-propellant line heat exchangers were added to the booster design and the weight increases were assessed against the booster APS (Para. 4.5).

Mixing of main tank liquid and vapor residuals at main engine shutdown could have a significant effect on initial propellant properties. In analyzing this effect, it was assumed that complete equilibration (mixing) of tank-trapped liquid and vapor residuals could occur, causing a collapse in tank pressures and temperatures at the start of APS operation. APS performance for these conditions is shown in Figure 4-22. As illustrated, engine performance for this worst-case operating point is totally satisfactory.

(b) Orbiter Mission Duty Cycle - Initial Subtask B analyses concentrated on determination of optimal orbiter APS/OMS impulse split. The specified mission timeline includes large on-orbit maneuvering requirements, occurring primarily in the +X direction, and ranging in incremental velocities from 20 to 500 ft/sec. Optimum distribution of the +X maneuvers between OMS and APS depends on size of burn, OMS start and shutdown losses, and relative APS/OMS specific impulse. To establish an optimum, OMS characteristics were based on use of the RL 10A3-3 engine. The results, presented in Figure 4-23, show that the optimal impulse split occurs when the OMS is used to perform the four largest burns, comprising a total velocity increment of approximately 1150 ft/sec. Variation in OMS start and shutdown losses between 50 and 200 lb/start were investigated, but these changes had little effect on optimal OMS velocity. Selection of this velocity allocation results in a maximum APS burn of only 40 ft/sec.

The orbiter APS uses a mixed-mode type of operation. Basically, the subsystem employs a liquid/vapor mixer to control APS engine inlet conditions during all major APS operations, and operates in a blowdown mode during periods of low APS activity. In the latter case all propellant is extracted from the main tanks, while mixers and main supply line regulators are inactive. Main tank pressures

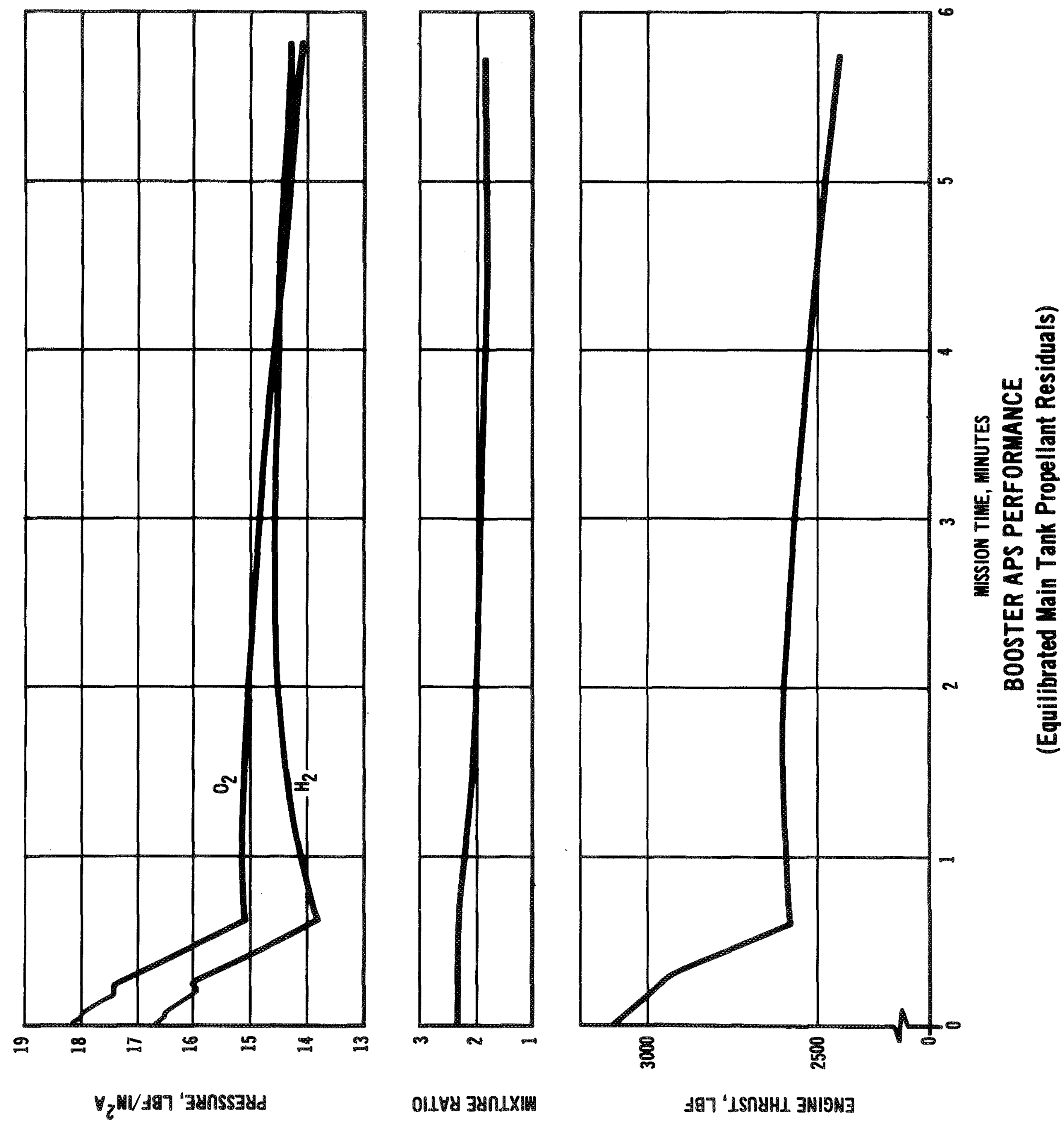
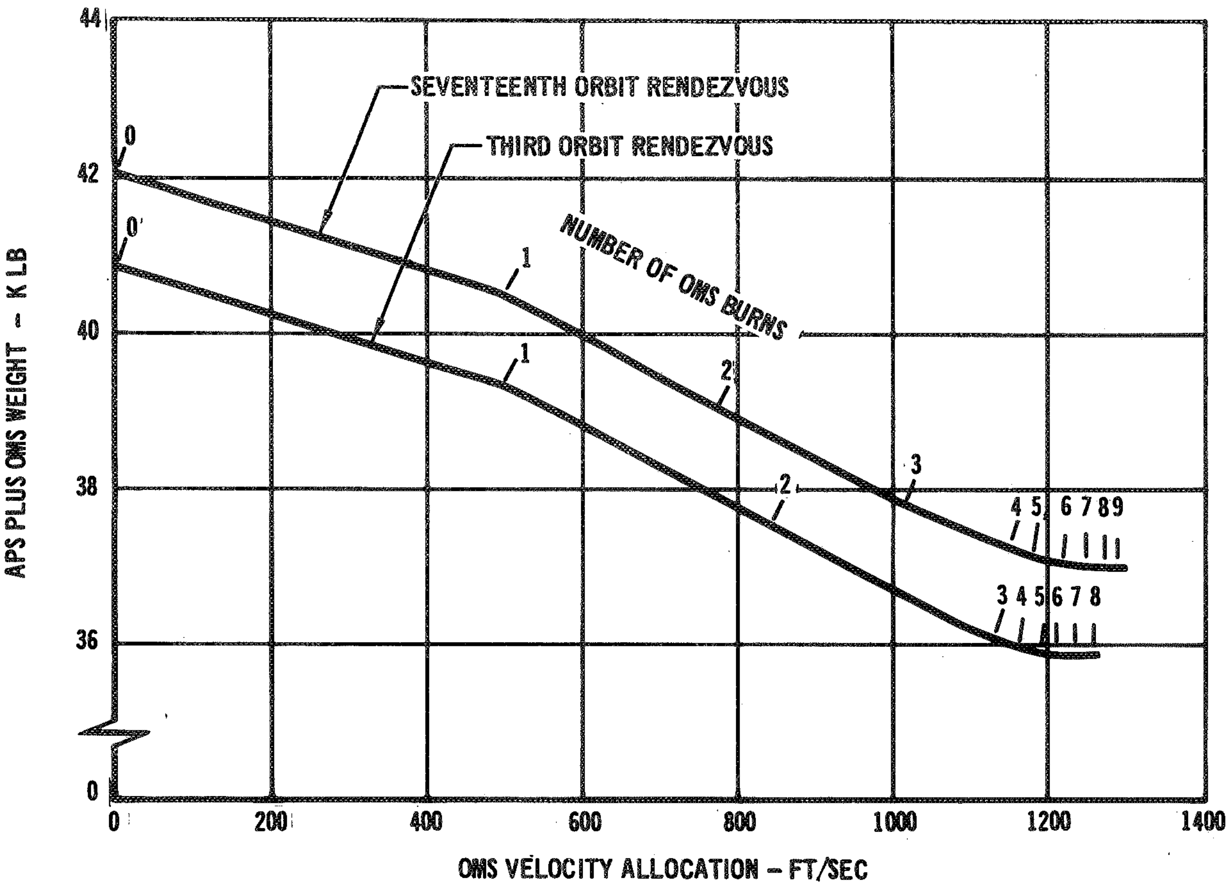

PRESSURE, LBF/IN^{2}A
19
18
17
16
15
14
13
O_2
H_2
MIXTURE RATIO
3
2
1
ENGINE THRUST, LBF
3000
2500
0
0
1
2
3
4
5
6
MISSION TIME, MINUTES
BOOSTER APS PERFORMANCE
(Equilibrated Main Tank Propellant Residuals)

FIGURE 4-22



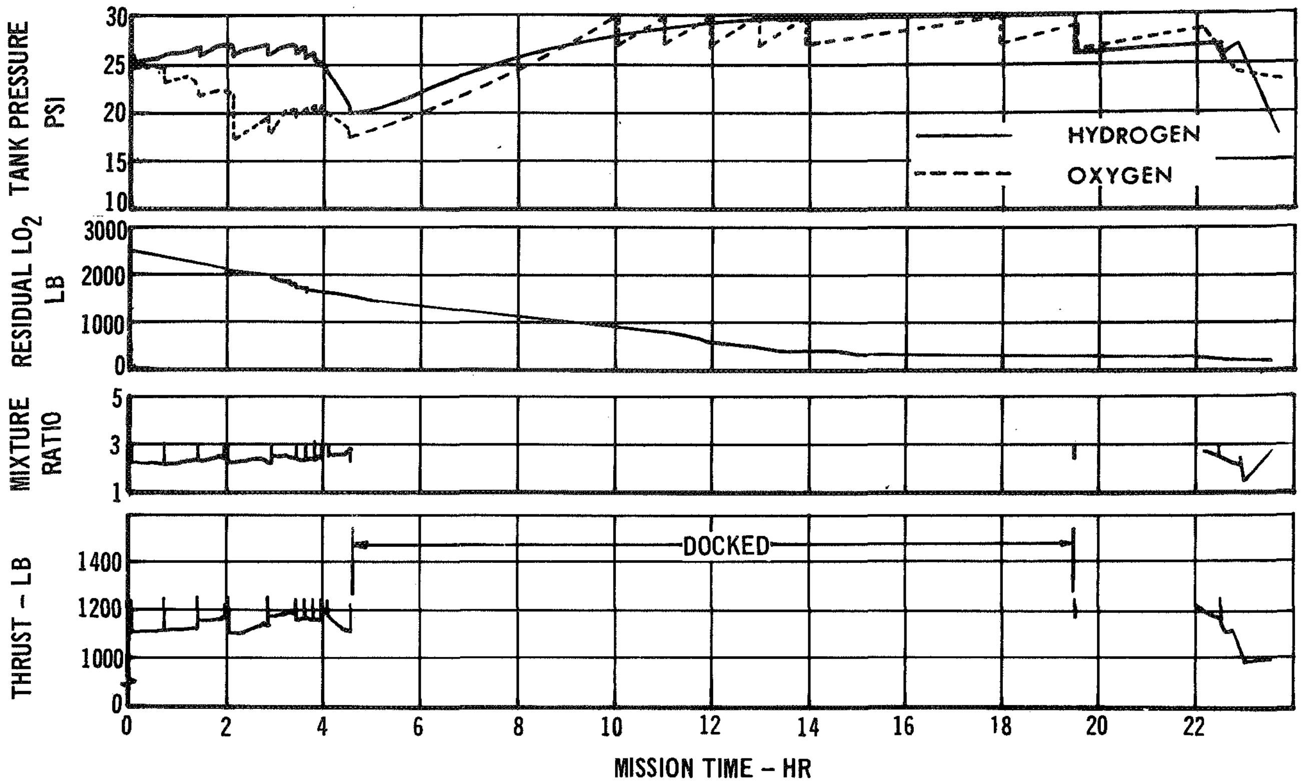
APS/OMS IMPULSE ALLOCATION — FIGURE 4-23

and temperatures, and engine performance parameters during APS operation, are given in Figures 4-24 and 4-25 for the third and seventeenth orbit rendezvous missions. Engine performance is satisfactory throughout. The seventeenth orbit rendezvous is the more stringent of the two missions from the standpoint of propellant requirements and minimum boost tank pressures.

4.5 Weight and Reliability Estimates - Subsystem weights for the baselines discussed in the preceding paragraphs are 5647 lb and 12868 lb for booster and orbiter, respectively. Detailed weight breakdowns are presented in Figures 4-26 and 4-27. Booster APS weight includes 660 lb H_2 pressurant and 57 lb H_2 heat exchanger, both of which are associated with a reduction in residual H_2 vapor temperature (at main engine shutdown) from 450°R (Reference B) to 260°R. For the orbiter, APS weights are provided for three configurations:

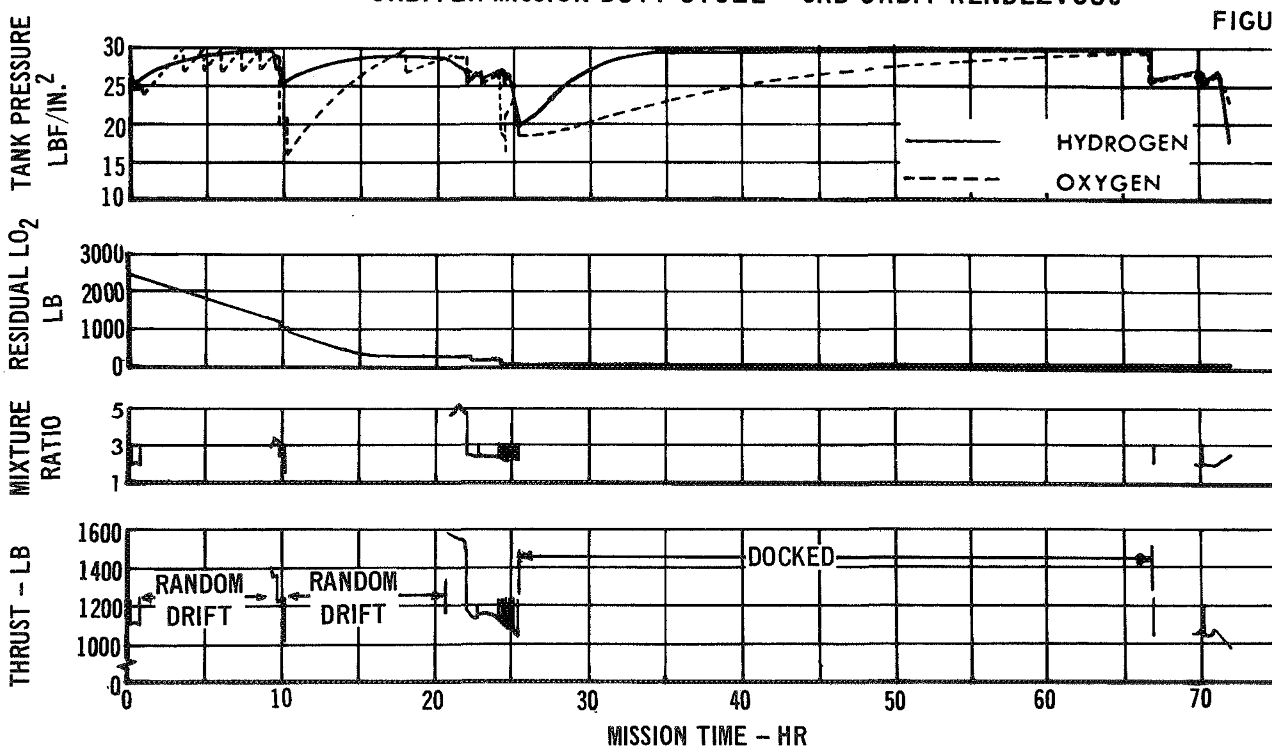
(1) a reference APS configuration which uses thirty-three 1080 lb thrust engines and separate APS/OMS propellant tankage

(2) a configuration which differs from the reference only in the number and thrust level of APS engines (twenty-four at 1220 lb thrust)



ORBITER MISSION DUTY CYCLE – 3RD ORBIT RENDEZVOUS

FIGURE 4–24



ORBITER MISSION DUTY CYCLE – 17TH ORBIT RENDEZVOUS

FIGURE 4–25

COMPONENT (NO.)	WEIGHT, LB O_2	H_2
PROPELLANT	NONE REQUIRED, MAIN ENGINE TANK RESIDUALS ARE UTILIZED	
MAIN ENGINE PROPULSION MODS	(63)	(795)
PRESSURANT PENALTY	0	660
LIQUID/VAPOR SEPARATION VALVES (1)	63	78
HEAT EXCHANGER	0	57
PROPELLANT DISTRIBUTION ASSEMBLY	(657)	(1051)
LINES	227	350
COMPENSATORS, LINEAR (23)	104	251
COMPENSATORS, ANGULAR (46)	64	105
ISOLATION VALVES (21)	262	345
ENGINE ASSEMBLIES	(3081)	
ENGINES (20)	2980	
PNEUMATIC SUBASSEMBLY		
HELIUM	3.5	
TANKS (3)	34.0	
VALVES (28)	12.5	
REGULATORS (3)	9.0	
LINES	42	
TOTAL	(5647)	

BOOSTER APS WEIGHT

FIGURE 4-26

(3) a configuration which differs from the reference only in propellant tankage integration (integral versus separate APS/OMS tanks).

The last two cases are provided to facilitate weight comparisons between low pressure and high pressure APS (Reference C) on a common basis, i.e., integral propellant tankage and no requirement for nominal acceleration capability with one engine out.

APS baselines were designed to satisfy fail operational/fail safe requirements. Reliability estimates generated as part of this study are presented, by functional component group, in Figure 4-28. As shown, the orbiter APS has an operational reliability of 0.997 with a fail-safe reliability exceeding 0.9999. The booster APS has an operational reliability of approximately 0.9999 and a fail-safe reliability in excess of 0.9999999. These results show that the basic simplicity of the low pressure APS offers a high level of operational reliability and safety.

COMPONENT/ASSEMBLY	CONFIGURATION A (REF) ENGINES: 33 @ 1080 LBS TANKAGE: SEPARATE APS/OMS		CONFIGURATION B ENGINES: 24 @ 1220 LBS TANKAGE: SEPARATE APS/OMS		CONFIGURATION C ENGINES: 33 @ 1080 LBS TANKAGE: INTEGRAL APS/OMS	
	(O_2)	(H_2)	(O_2)	(H_2)	(O_2)	(H_2)
PROPELLANT	(4496)	(2499)	(4935)	(2645)	(4496)	(2499)
MAIN PROPULSION MODIFICATIONS	(92)	(42)	(92)	(42)	(92)	(42)
COMPARTMENTED TANK	50	–	50	–	50	–
PRESSURANT LINE BYPASS VALVES	42	42	42	42	42	42
PROPELLANT STORAGE ASSEMBLY	(233)	(820)	(246)	(853)	(129)	(674)
TANK, INSULATION AND VENT	164	556	173	581	82	489
PRESSURIZATION	32	159	35	164	32	114
PROPELLANT SCREENS	37	105	38	108	15	71
PROPELLANT CONDITIONING ASSEMBLY	(149)	(327)	(149)	(327)	(149)	(327)
HEAT EXCHANGER	103	252	103	252	103	252
LINES AND MANIFOLDS	37	64	37	64	37	64
VALVES	9	11	9	11	9	11
LIQUID/VAPOR MIXING ASSEMBLY	(96)	(108)	(96)	(108)	(96)	(108)
MIXER	17	11	17	11	17	11
THROTTLE VALVES	22	22	22	22	22	22
CONTROL VALVES	44	55	44	55	44	55
REGULATORS	13	20	13	20	13	20
DISTRIBUTION ASSEMBLY	(565)	(707)	(477)	(598)	(565)	(707)
LINES	174	258	150	219	174	258
COMPENSATORS	165	203	138	173	165	203
ISOLATION VALVES	226	246	189	206	226	246
ENGINE ASSEMBLIES	(2734)		(2231)		(2734)	
ENGINES	2541		2052		2541	
PNEUMATIC CONTROLS	193		179		193	
TOTAL, LBM	12,868		12,799		12,618	

ORBITER APS WEIGHTS

FIGURE 4–27

FUNCTIONAL GROUP	ORBITER OPERATIONAL	ORBITER FAIL SAFE	BOOSTER OPERATIONAL	BOOSTER FAIL SAFE
LO_2 STORAGE AND PRESSURIZATION	0.999990	0.99999997	–	–
LH_2 STORAGE AND PRESSURIZATION	0.999997	0.99999999	–	–
PROPELLANT CONDITIONING – O_2	0.999994	0.99999999	–	–
PROPELLANT CONDITIONING – H_2	0.999993	0.99999999	–	–
PROPELLANT DISTRIBUTION AND ENGINES	0.999743	0.99997069	0.999923	0.99999998
ENGINE PNEUMATIC CONTROL	0.999749	0.99999996	0.999991	0.99999999
SUBSYSTEM	0.997196	0.99997059	0.999914	0.99999997

ASSUMPTIONS:
(1) COMPONENT EXTERNAL LEAKAGE CAN BE CONTROLLED BY PROPER SEAL DESIGN
(2) SENSING AND SWITCHING RELIABILITY IS EQUAL TO 1.0.
(3) STRUCTURAL RELIABILITY IS EQUAL TO 1.0.
(4) MAIN PROPULSION SUBSYSTEM COMPONENTS USED BY THE AUXILIARY PROPULSION SYSTEM WILL NOT DEGRADE APS OPERATION OR SAFETY.
(5) THE NON-OPERATING FAILURE RATE FOR APS COMPONENTS WILL NOT BE SIGNIFICANT

APS RELIABILITY

FIGURE 4–28

4.6 Component Technology - As stated in the introduction, an assessment of component technology requirements was a primary part of this study. In terms of thrust levels and reuse capability, APS requirements are far beyond those for any previous control propulsion subsystem. Therefore, no APS components capable of satisfying these requirements exist today. Conceptual subsystem definition studies discussed in this report have shown that a low pressure APS can potentially fulfill shuttle requirements, and that such an APS is simple in design and operational approach. None of the components required in the subsystem are currently available, but exploratory programs are underway on engines, valves, and certain aspects of storage tank design. In most cases, technological issues center on component size and dynamic response. These can be resolved through normal subsystem development evolution; i.e., progression from analysis to component and assembly tests, to (finally) breadboard tests with full scale hardware. A critique of the major technology issues and/or concerns are presented in Figure 4-29.

COMPONENT/ ASSEMBLY	DESIGN VARIABLE	ISSUE
PROPELLANT STORAGE	INSULATION/ PURGE	POTENTIAL INSULATION (HPI) DEGRADATION WITH REPEATED VENT AND PRESSURIZATION CYCLES AND LONG TERM CORROSION
	PROPELLANT ACQUISITION (SCREEN DEVICE)	TESTS REQUIRED ON LARGE (10 FT DIA) TANKS TO ASSESS HEAT LEAKS; INTEGRITY UNDER LAUNCH VIBRATION; AND EFFECTS OF NORMAL FABRICATION TOLERANCES
HEAT EXCHANGER	INSTALLATION	TANK FABRICATION COST AND ABILITY TO TEST
	CONTROL AND STABILITY	PASSIVE HEAT SOURCE PROVIDES POOR CONTROL OF HEAT INPUT AND LOCATION OF PROPELLANT PHASE CHANGE, POTENTIAL CHUGGING INSTABILITY
MAIN ENGINE TANK	THERMODYNAMICS	REQUIRES BETTER DEFINITION OF LIQUID RESIDUAL MOTION AND VAPORIZATION RATES; THERMAL STRATIFICATION OF VAPORS; AND MIXING OF RESUPPLY PROPELLANTS
LIQUID/VAPOR MIXER	MIXING EFFECTIVENESS	TESTS REQUIRED TO ASSURE HOMOGENEOUS TEMPERATURES AND PRESSURES IN SHORT FLOW LENGTHS
	CONTROL	ADDITIONAL EFFORT REQUIRED IN AREA OF TEMPERATURE TRANSDUCING RESPONSE, ACCURACY AND RELIABILITY
ENGINE	WEIGHT	LIGHTWEIGHT MATERIALS AND FABRICATION TECHNIQUES REQUIRED
	LOW TEMPERATURE PROPELLANTS	MINIMUM PROPELLANT INLET TEMPERATURE FOR RELIABLE IGNITION AND PERFORMANCE SHOULD BE DETERMINED

KEY TECHNOLOGY ISSUES

FIGURE 4-29

5. CONCLUSIONS

The low pressure auxiliary propulsion subsystem (APS) concept, as demonstrated by results of this study, is a practical approach to space shuttle control and maneuver requirements. Technology issues relate primarily to component size and dynamic response, factors which generally can be resolved through normal development. NASA initiated tests on some of the more critical components (i.e., engine and propellant valves) have shown that performance goals, cooling, and ignition are practical and can be achieved without great difficulty. More effort is required, however, in the areas of propellant acquisition, main engine tank thermodynamics, and main engine tank/heat exchanger integration.

The preferred orbiter APS approach has been identified as one in which the APS is used in conjunction with an Orbit Maneuvering Subsystem (OMS). The OMS, with RL10A3-3 engines, is used for four high total impulse maneuvers, while APS provides all attitude control and vernier maneuvers. The baseline APS uses separate propellant tankage, but alternate configurations using integral tankage and different engine arrangements were also investigated in order to provide direct weight comparison with an all-maneuver, high pressure APS (Reference C). Combined low pressure APS/OMS weight for this comparison is 37,252 lb, of which 12,549 lb is attributable to the APS. The baseline APS, designed to more stringent operational failure criteria, weighs 12,868 lb.

Orbiter APS uses a passive heat exchanger for propellant conditioning and a liquid/vapor mixer to control engine inlet conditions during major APS operations. Booster APS requires no auxiliary propellant storage, being capable of satisfying total impulse requirements by operating on main engine tank propellant vapors in a simple blowdown mode.

6. REFERENCES

A. Space Shuttle Vehicle Description and Requirements Document (NASA), dated 15 July 1970. (Attachment to Statement of Work, Space Shuttle Auxiliary Propulsion Subsystem Definition)

B. Space Shuttle Vehicle Description and Requirements Document (NASA), dated 1 October 1970.

C. Space Shuttle High Pressure Auxiliary Propulsion Subsystem Definition, Summary, McDonnell Douglas Astronautics Company (East) Report MDCE 0299, dated March 1971.

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY • EAST

Saint Louis, Missouri 63166 314 · 232 · 0232