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SPACE SHUTTLE HIGH PRESSURE AUXILIARY PROPULSION SUBSYSTEM DEFINITION STUDY

DESIGN HANDBOOK

Contract Number NAS 8-26248

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY - EAST

MCDONNELL DOUGLAS CORPORATION

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SPACE SHUTTLE HIGH PRESSURE AUXILIARY PROPULSION SUBSYSTEM DEFINITION STUDY

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DESIGN HANDBOOK

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PREFACE

This subsystem description handbook defines the high pressure auxiliary propulsion subsystems for the space shuttle, selected as the result of the high pressure auxiliary propulsion subsystem definition study. This effort was performed for the National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, Alabama, under contract NAS 8-26248.

This handbook provides subsystem design and operational description, along with a guide for subsystem design reflecting requirements other than those specifically investigated during the study. This handbook includes schematics and physical descriptions; pressures, temperatures and flow balances; estimated weights; and transient and steady state operating characteristics.

CONTENTS

EFFECTIVE PAGES

1. INTRODUCTION

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

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

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

Within these broad categories there were many APS options available. Typically, storage of propellants, 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 alternative implementation schemes offered different advantages and disadvantages in terms of subsystem performance and required technology developments. Thus, APS selection for the shuttle, and definition of the advanced technology necessary for APS development, required in-depth studies to select the type of APS best suited to shuttle requirements. Preliminary studies also permitted identification of the advanced technology effort required for APS development.

To fulfill these needs, NASA contracted for APS definition studies of both high and low pressure APS. These studies were divided into two phases. The first, Subtask A was a conceptual subsystem definition designed to provide NASA with sufficient data for selection of the best means of APS implementation in both high and low pressure categories. The second phase, Subtask B, involved 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 (MDAC-EAST) under Contract No. NAS 8-26248, and is summarized in Reference (a). NASA technical direction for this effort was provided by the National Aeronautics & Space Administration, Marshall Space Flight Center (MSFC) at Huntsville, Alabama, through the office of Mr. John McCarty, Deputy Chief, Propulsion and Power Branch, Astronautics Laboratory. The Aerojet Liquid Rocket Company, under subcontract to MDAC-East provided the analysis and design support necessary to define the active components for APS evaluation.

The problem addressed in Subtask A of the high pressure APS study was to provide sufficient comparative data on various APS concepts to allow selection of the best high pressure approach for Subtask B preliminary design. This required consideration of a large number of high pressure APS concepts. Here, the predominate concern was the relative merit of the 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, the 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 (b). Mission and control requirements for the vehicles were also defined in Reference (b). The results of the first phase (conceptual subsystem definition) of the high pressure APS study are summarized in Reference (c). An interim subsystem description handbook, Reference (d), was prepared to define the APS configurations resulting from the Subtask A effort.

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

This handbook defines preliminary APS designs, operating performance, and weight sensitivities resulting from Subtask B for high and low cross range orbiters, and for the booster.

2. SUBSYSTEM DESCRIPTION

APS requirements were established to satisfy Reference (e) control requirements. Figure 2-1 summarizes number of thrusters, thrust level, and total impulse

	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*

** USAGE DUE TO ATTITUDE SENSOR ERRORS NOT INCLUDED
* 100 LB-SEC MINIMUM IMPULSE BIT
17TH ORBIT RENDEZVOUS

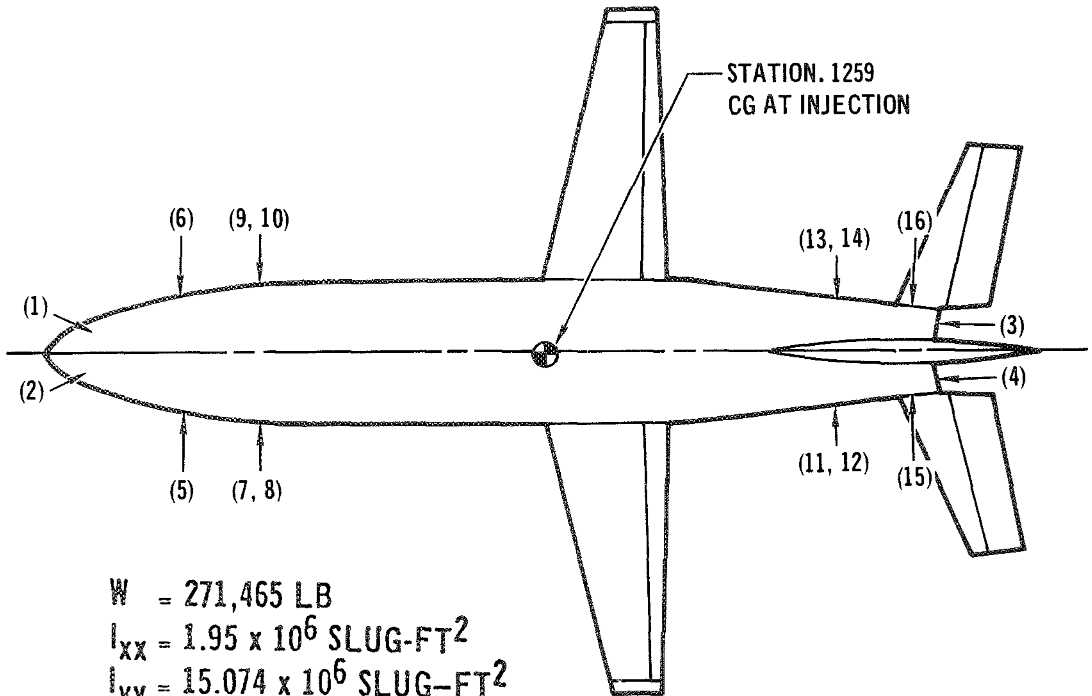
REQUIREMENTS SUMMARY
Subtask B

FIGURE 2-1

required for each vehicle. Thruster locations are illustrated in Figures 2-2, 2-3 and 2-4. These locations were established to satisfy the criteria of minimum weight, avoidance of heat shield penetration whenever possible, and use of common thrust levels between vehicles. Tankage locations within the vehicles, Figure 2-5, were maintained consistent with the locations shown in Reference (e).

2.1 Subsystem Design - In the high pressure APS design, propellant is stored as a liquid in low pressure tankage. A turbopump at the tank outlet raises propellant pressure to that required for operation, while gas generator powers the turbopump and heats the liquid propellants (in a heat exchanger downstream of the pump) to temperatures required for operation of the gaseous bipropellant thruster assemblies.

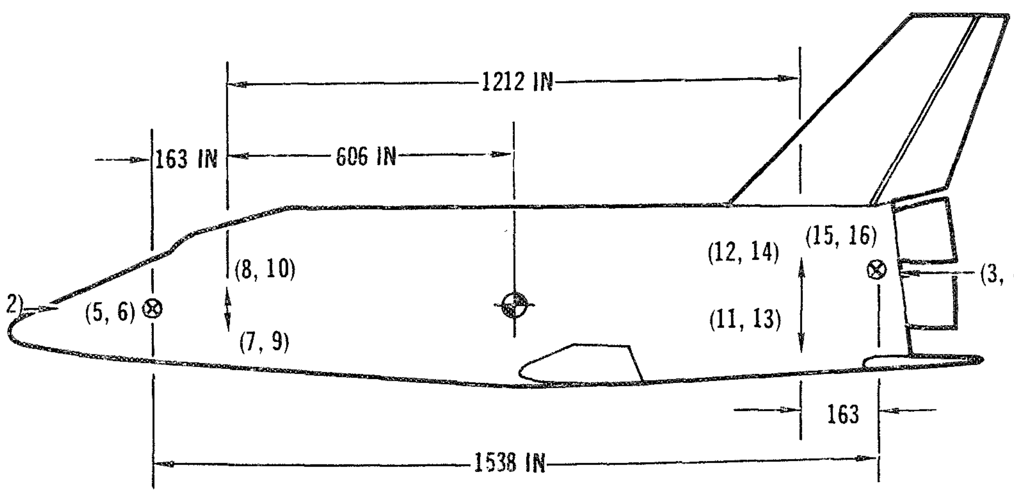
After thermal conditioning in the heat exchanger, high pressure gaseous propellants are stored in accumulators until required by the thrusters. Thus, the operating mode of the accumulators and thrusters is that of a stored gas, bipropellant propulsion subsystem. Turbopumps, heat exchangers, and gas generators combine to make up a conditioning assembly to change the propellant state from that of a low pressure liquid to a high pressure gas. The conditioner assembly operates on demand to maintain a continuous gas supply for thruster operation. A simple schematic of this arrangement is shown in Figure 2-6. Only the hydrogen propel-

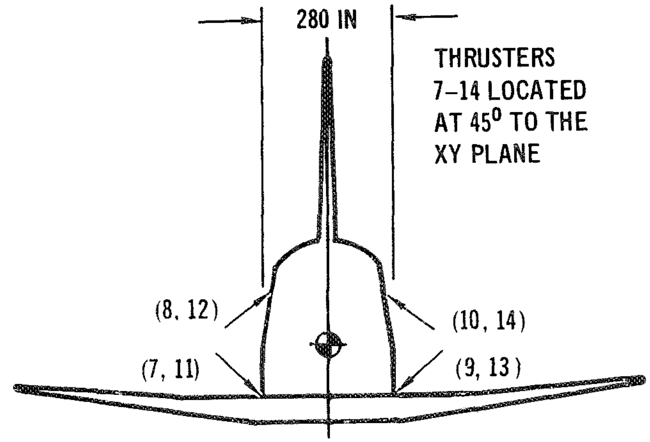


W = 271,465 LB
I_{xx} = 1.95 x 10^6 SLUG-FT^2
I_{yy} = 15.074 x 10^6 SLUG-FT^2
I_{zz} = 15.438 x 10^6 SLUG-FT^2

THRUSTER ASSEMBLY SUMMARY – ORBITER B

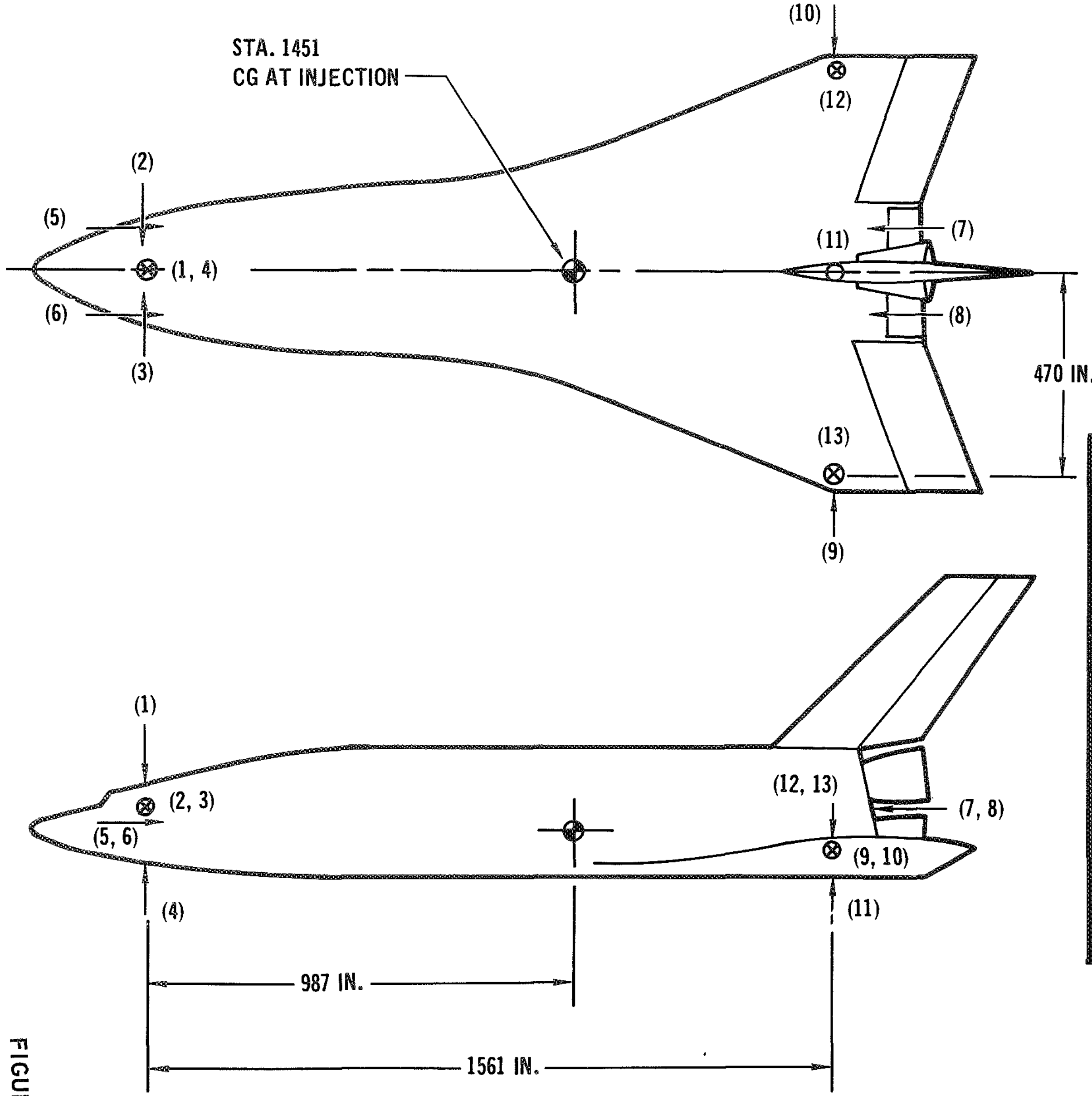
THRUSTER ASSEMBLY NUMBER	NUMBER OF 1850 LB_F THRUSTERS	PURPOSE
1	1	– X
2	1	– X
3	3	+ X
4	3	+ X
5	2	+ Y, + YAW
6	2	– Y, – YAW
7	1	– Z, – PITCH, – ROLL
8	1	+ Z, + PITCH, + ROLL
9	1	– Z, – PITCH, + ROLL
10	1	+ Z, + PITCH, – ROLL
11	1	– Z, + PITCH, – ROLL
12	1	+ Z, – PITCH, + ROLL
13	1	– Z, + PITCH, + ROLL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





ORBITER B THRUSTER LOCATIONS

FIGURE 2–2



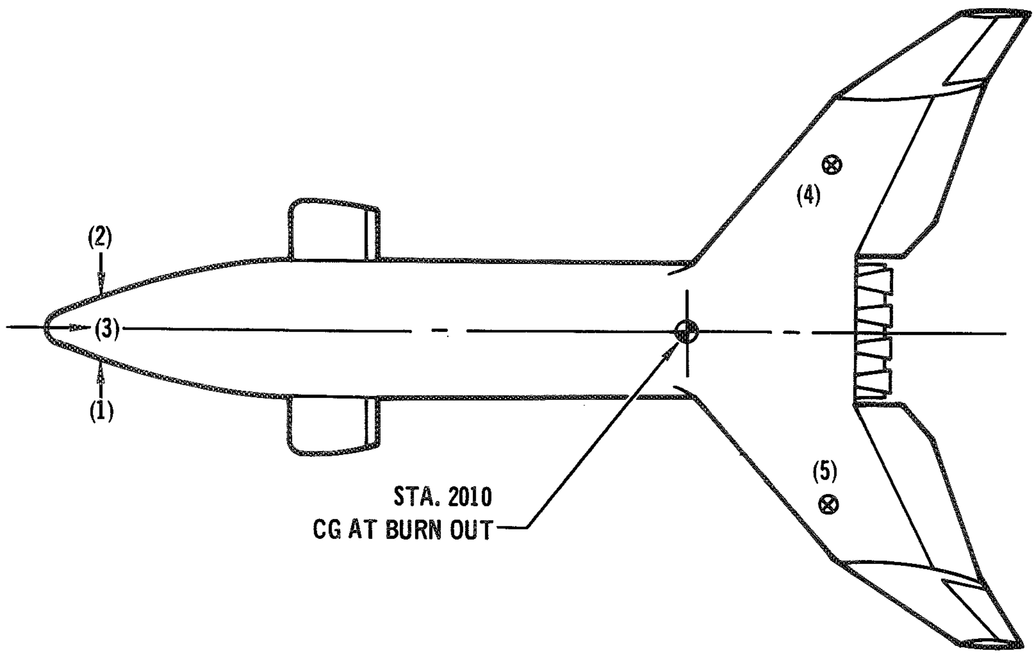
$W = 273{,}644$ LB
$I_{xx} = 2.059 \times 10^6$ SLUG-FT^2
$I_{yy} = 13.607 \times 10^6$ SLUG-FT^2
$I_{zz} = 14.433 \times 10^6$ SLUG-FT^2

THRUSTER ASSEMBLY SUMMARY – ORBITER C

THRUSTER ASSEMBLY NUMBER	NUMBER OF 1850 LBF THRUSTERS	
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

ORBITER C THRUSTER LOCATIONS

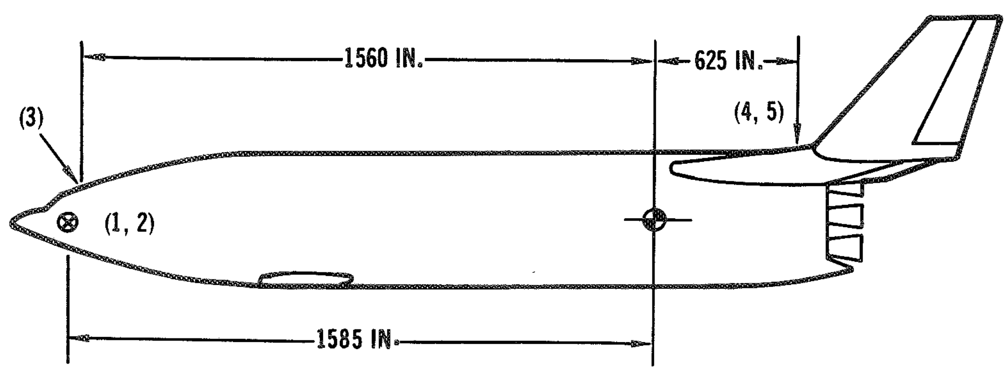
FIGURE 2–3

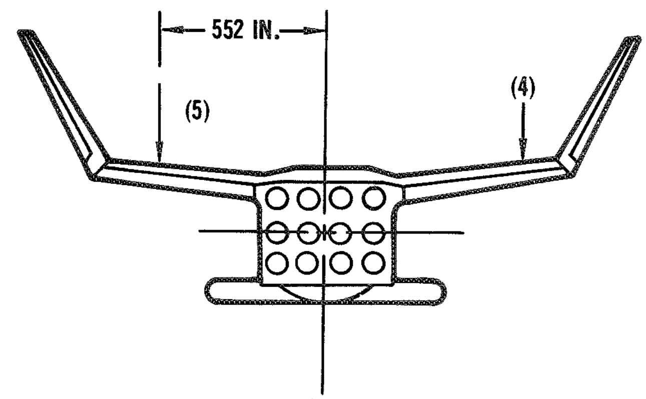


THRUSTER ASSEMBLY SUMMARY – BOOSTER

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

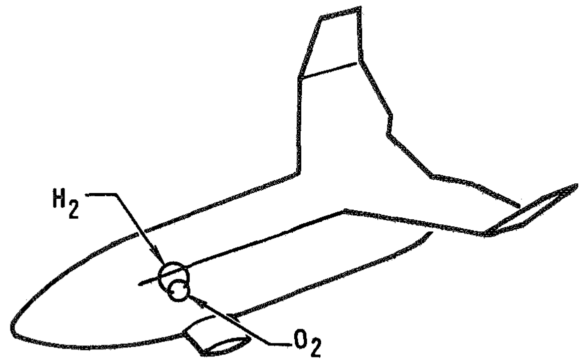
W = 474,876 LB
$I_{xx} = 7.017 \times 10^6$ SLUG–FT^2
$I_{yy} = 53.918 \times 10^6$ SLUG–FT^2
$I_{zz} = 57.013 \times 10^6$ SLUG–FT^2



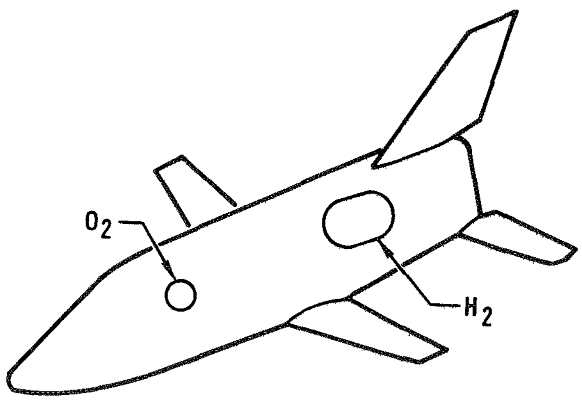


BOOSTER THRUSTER LOCATIONS

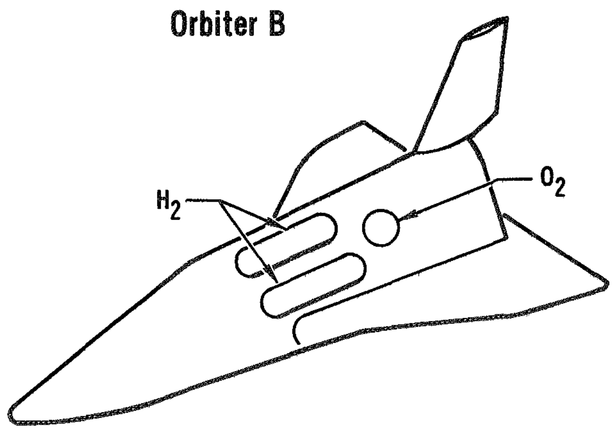
FIGURE 2–4



Booster



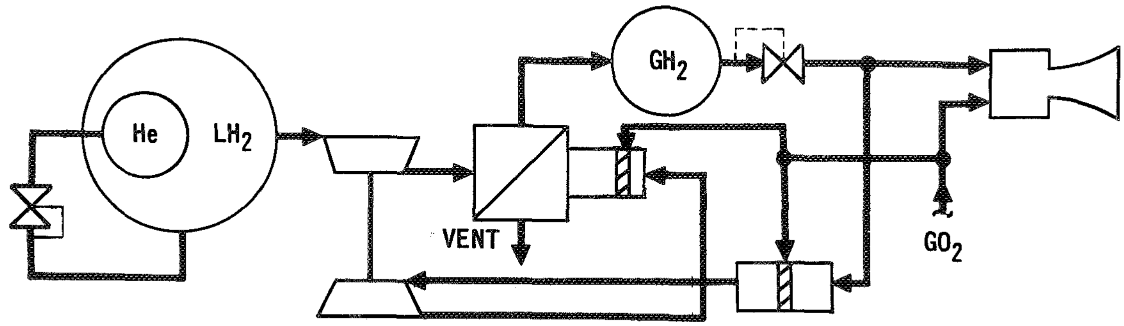
Orbiter B



Orbiter C

APS TANKAGE REQUIREMENTS

FIGURE 2-5



TURBOPUMP APS SCHEMATIC

FIGURE 2-6

lant side is shown, however the schematic is also representative of the oxygen configuration. The schematic symbols are defined in Figure 2-7.

The turbopump APS defined for orbiter B, orbiter C and the booster are basically similar. Conditioning assemblies are identical in configuration and operation for the three vehicles. Differences are associated entirely with vehicle configuration, which dictate different tank size and locations, line and thruster locations, and vent arrangements. The following subsystem description will address orbiter B, but will note orbiter C and booster configurations wherever they are different.

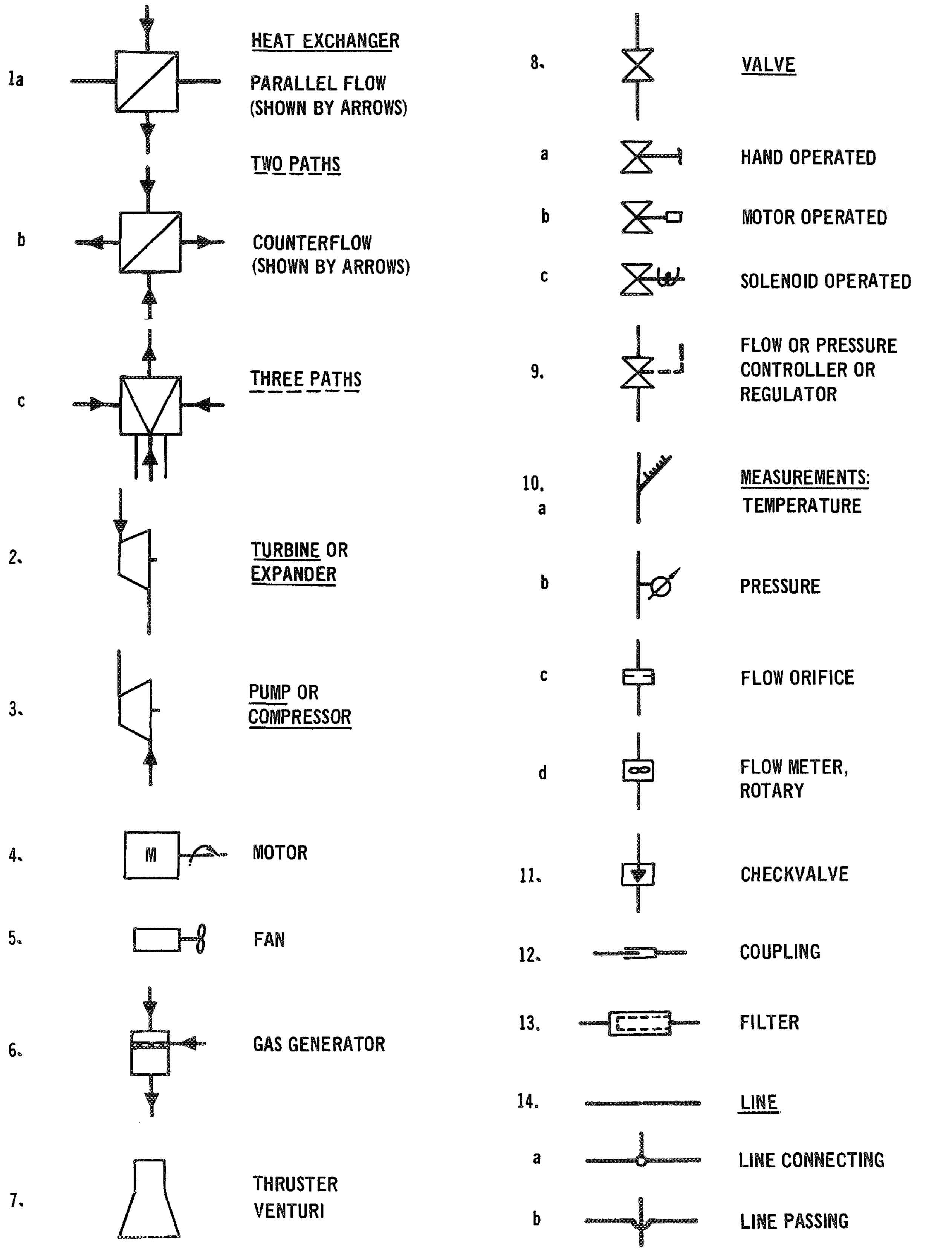
APS design characteristics are defined by subsystem schematics, i.e., installation drawings and subsystem weight breakdowns. Subsystem schematics are divided into two parts:

(1) the basic subsystem, and

(2) the line/thruster schematic.

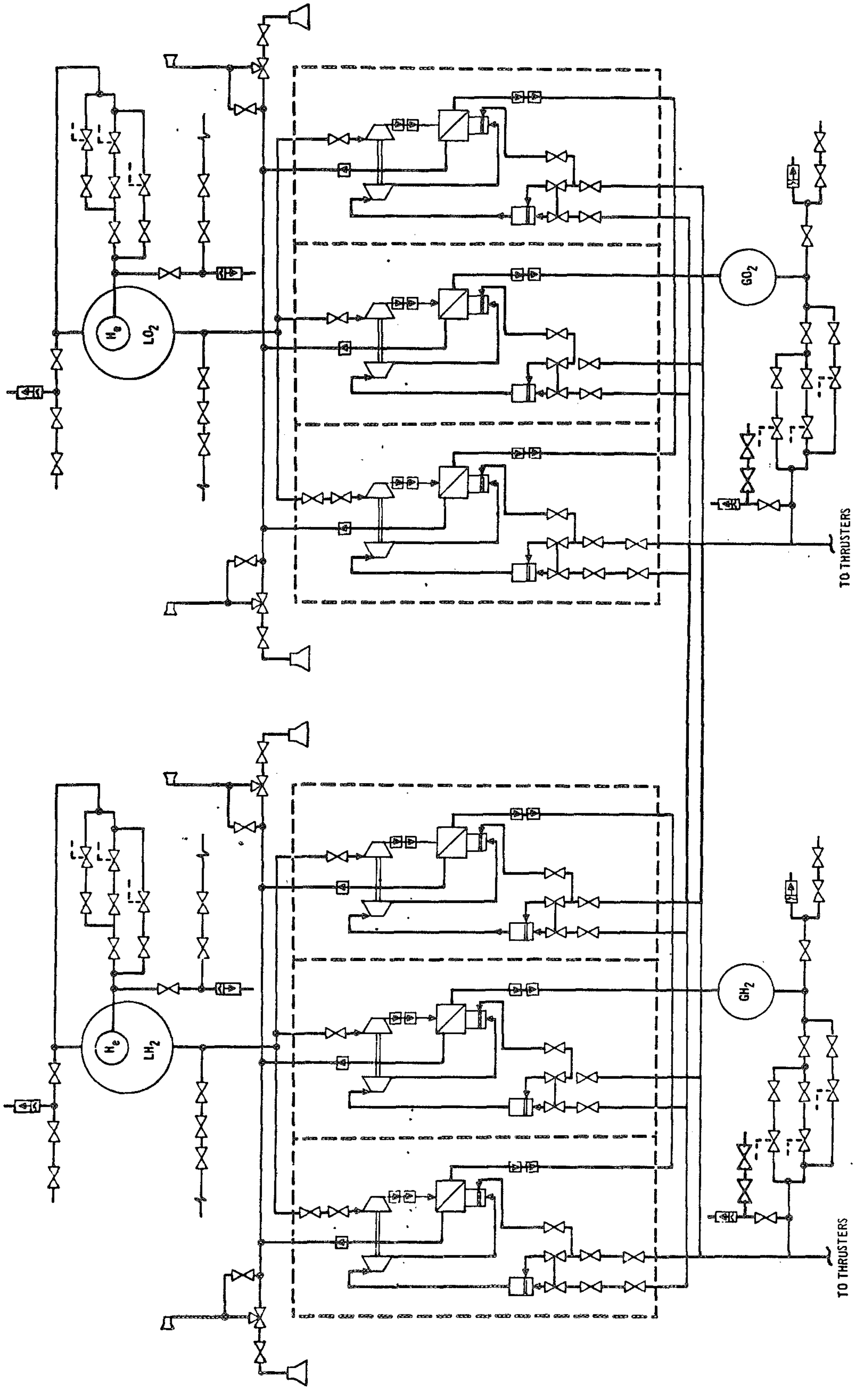
Subsystem schematics, including redundancy required to provide first-failure-operational, second-failure-fail-safe, reliability requirements are shown in Figures 2-8 and 2-9. These redundancy requirements were defined by failure mode effects analyses, documented in Reference (f). The gaseous propellant distribution schematics, along with the manifolds and manifold isolation valve definition, are shown in Figures 2-10, 2-11, and 2-12. Installation of the subsystems within the vehicles is shown in Figures 2-13, 2-14, and 2-15. Serviceability and maintainability were considered in locating subsystem components; wherever possible, components were located in proximity to the payload bay, since this location is accessible with the payload removed. Access to other components, such as thrusters and valves, is achieved by means of vehicle skin panel removal.

Subsystem design point summaries and weights are shown in Figure 2-16. Component weight breakdowns for these design points, and significant APS volume



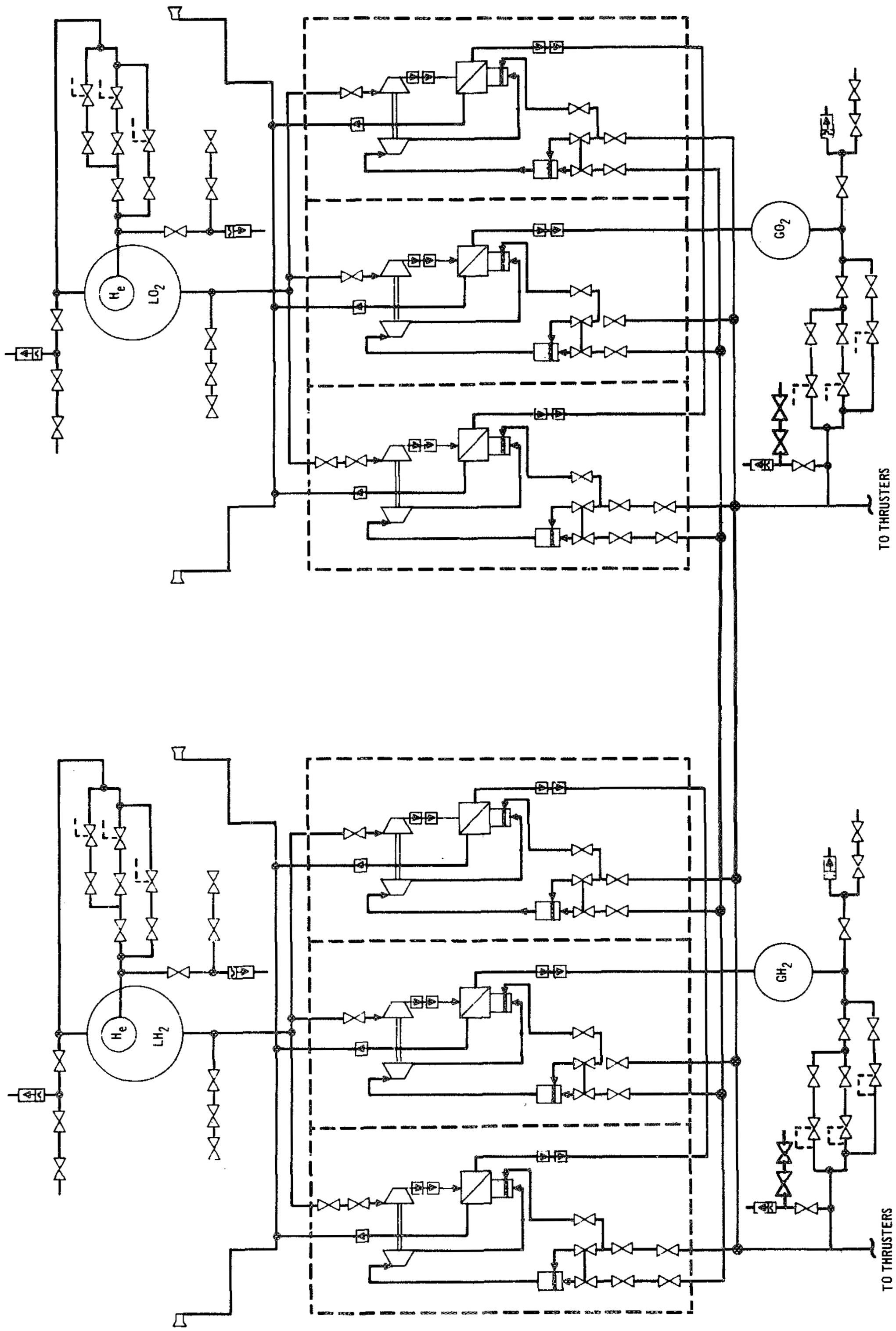
SCHEMATIC SYMBOLS

FIGURE 2-7



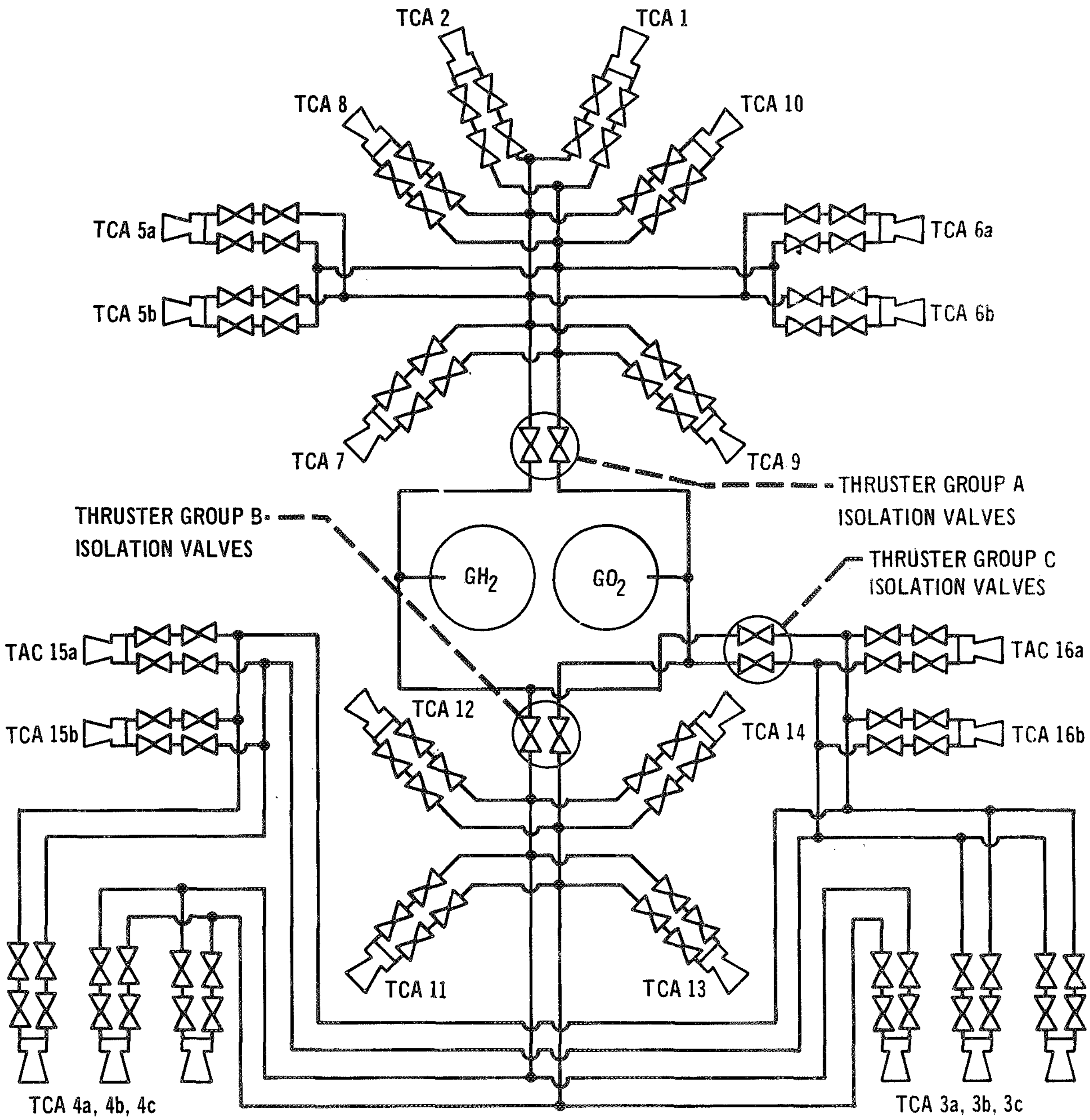
APS ORBITER SCHEMATIC

FIGURE 2-8



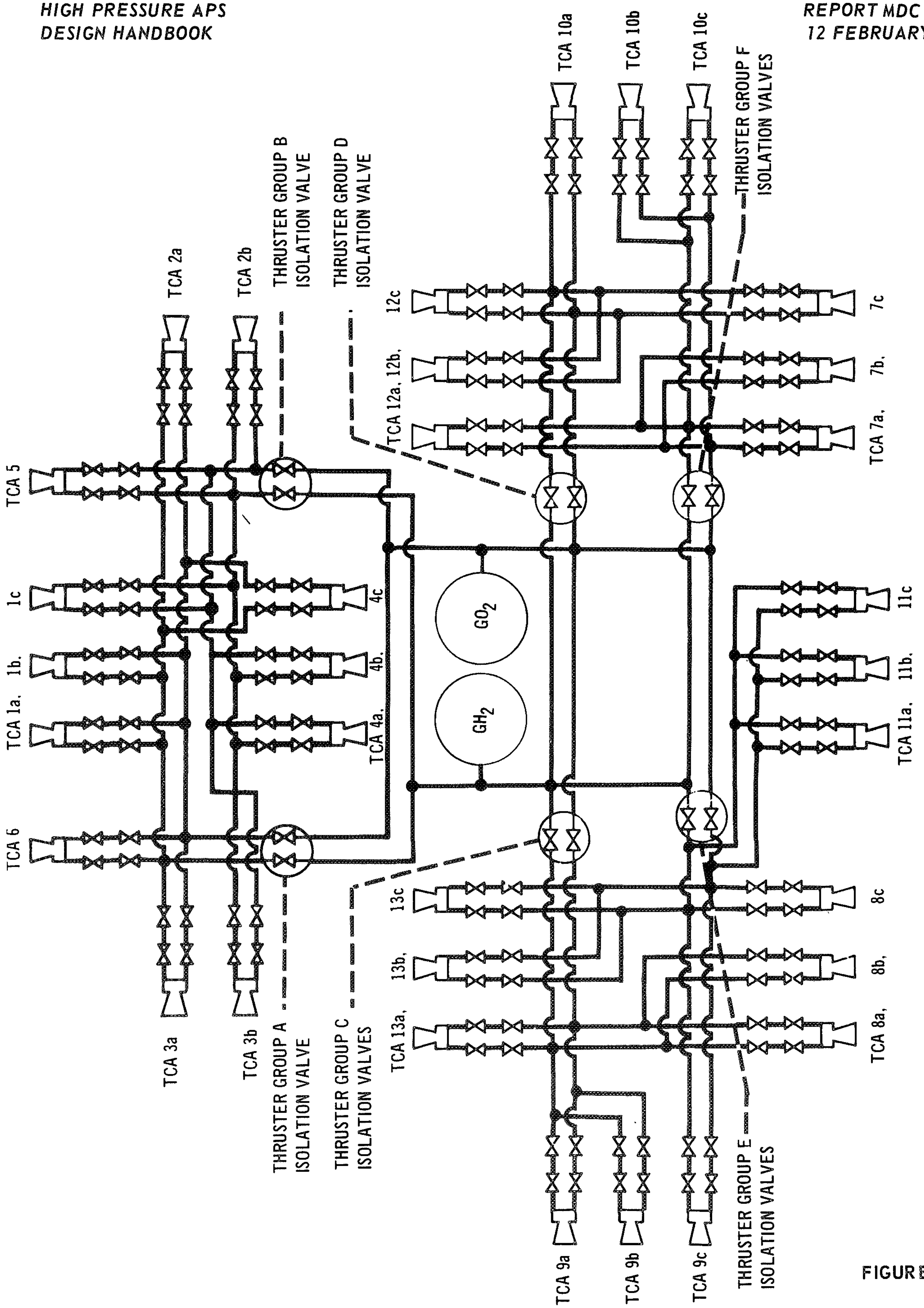
APS BOOSTER SCHEMATIC

FIGURE 2–9



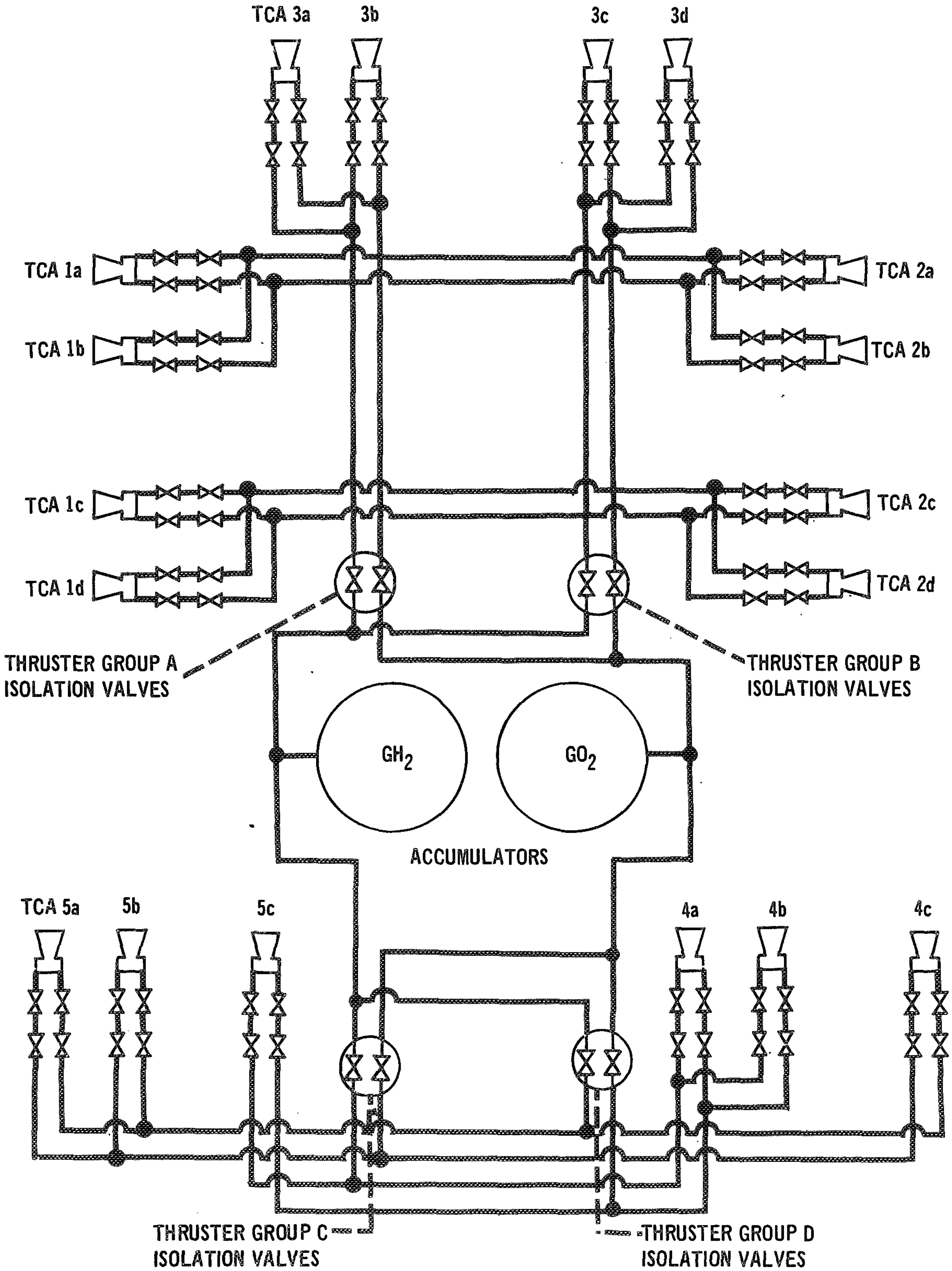
ORBITER B PROPELLANT DISTRIBUTION

FIGURE 2-10



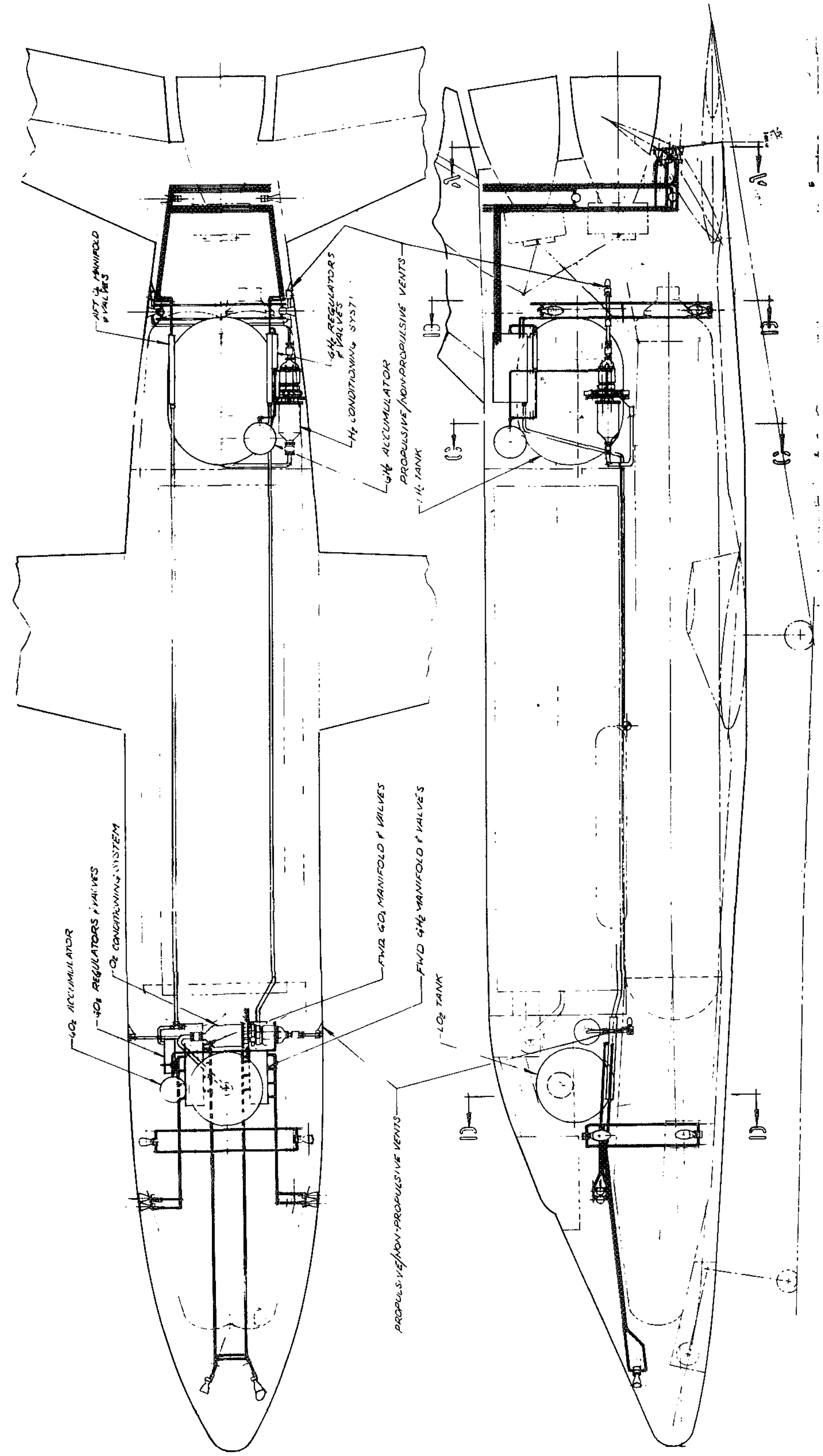
ORBITER C PROPELLANT DISTRIBUTION

FIGURE 2-11



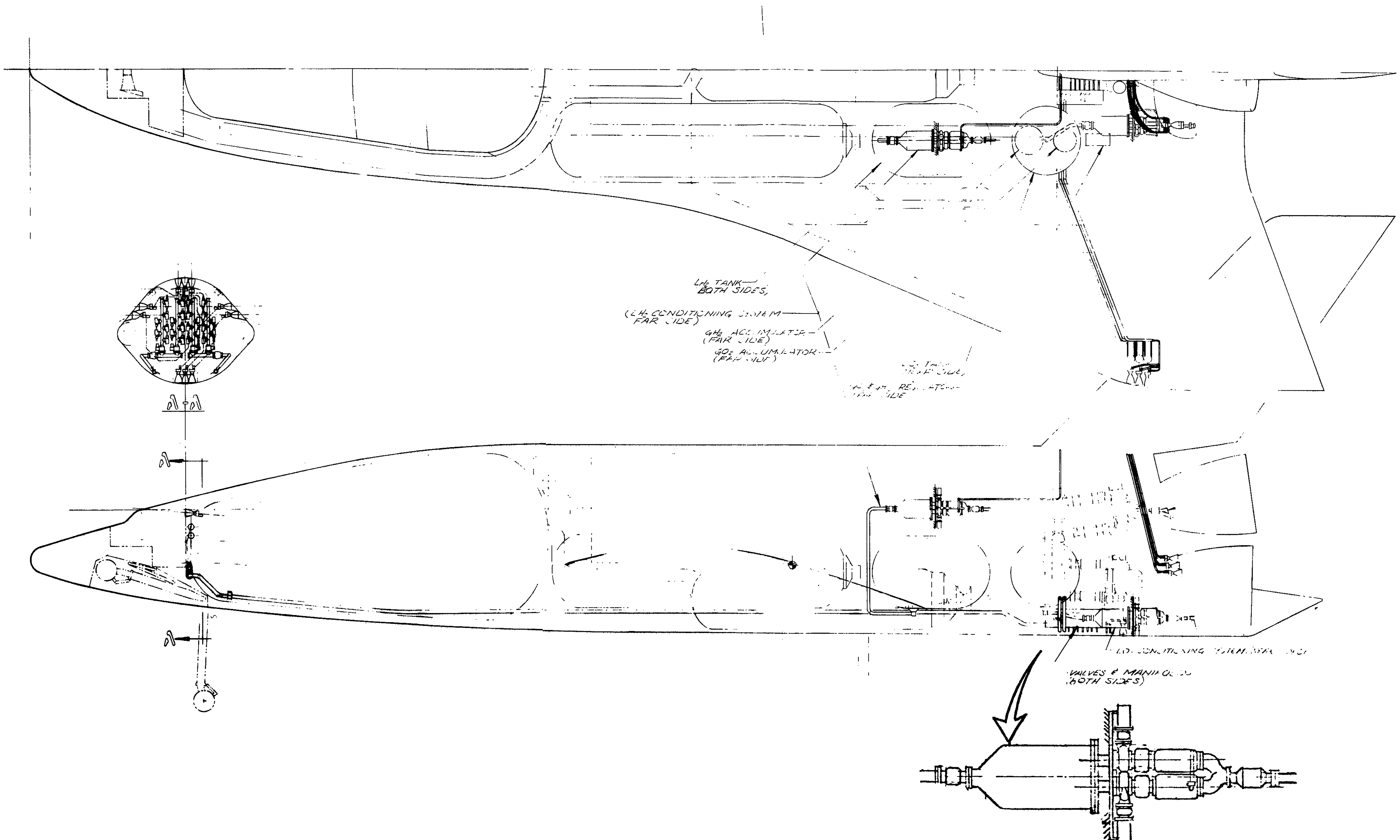
BOOSTER PROPELLANT DISTRIBUTION

FIGURE 2-12



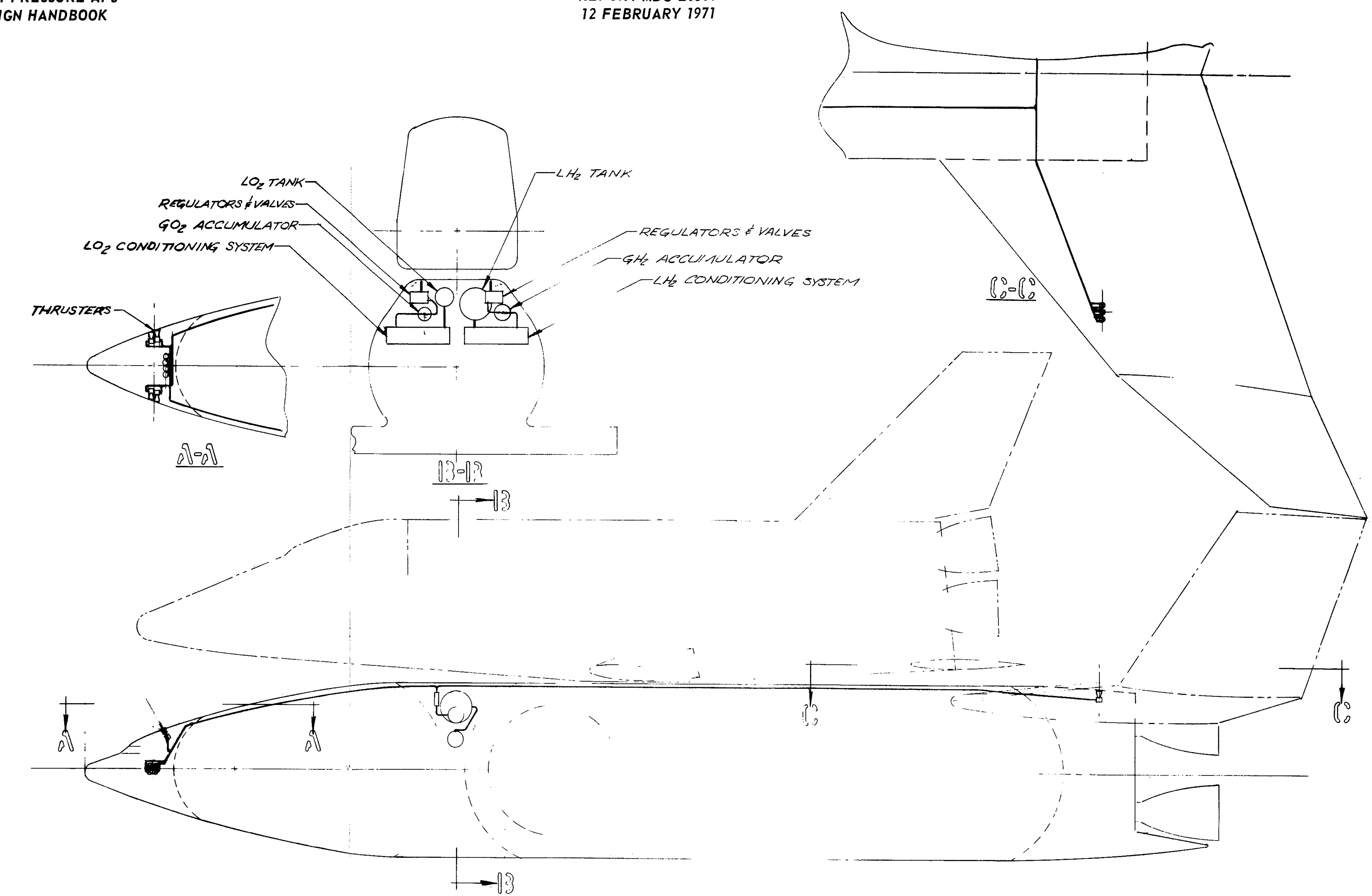
ORBITER B APS INSTALLATION

FIGURE 2-13



ORBITER C APS INSTALLATION

FIGURE 2–14



BOOSTER APS INSTALLATION

FIGURE 2-15

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 (^oR) – H_2	37	37	37
O_2	162	162	162
THRUSTER INLET MINIMUM PROPELLANT TEMPERATURE (^oR) – 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 $LBF/IN.^2A$ – H_2	25	25	25
O_2	30	30	35
THRUSTER SPECIFIC IMPULSE – SEC	446.9/455.2*	446.9/455.2*	444.9
SUBSYSTEM SPECIFIC IMPULSE – SEC	416.0/423.7*	416.0/423.7*	410.8
SUBSYSTEM 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 2–16

items, are shown in Figures 2-17, 2-18, and 2-19. Design points shown are for weight-optimized subsystems. Subsystem pressure and temperature balances for optimized subsystems and flow rates for turbine power equal 105% power required at P_{min} are defined (along with turbopump component requirements) in Figures 2-20, 2-21, and 2-22. These data are presented in schematic form in Figures 2-23 through 2-25.

2.2 Weight Sensitivities - Turbopump APS were investigated to determine subsystem weight sensitivity to changes in design variables. These sensitivities were determined by holding all but one design parameter constant at their design points, and varying that one parameter over a limited range. These sensitivities do not, therefore, represent the change in optimum subsystem weight corresponding to a variation in each parameter, since a change in any one parameter generally produces new optimum values for the other design variables. Resulting APS weight sensitivities are shown in Figures 2-26 through 2-28 for both orbiters and the booster.

Also investigated in Subtask B was subsystem weight sensitivity to various design requirements, including:

(1) thrust level per thruster
(2) subsystem total thrust
(3) total impulse
(4) number of thrusters.

Resulting variations in subsystem weight are shown in Figures 2-29 through 2-31 and were obtained, as above, by varying one parameter while holding the others constant at their design points. A more detailed weight sensitivity breakdown is shown in Figures 2-32 through 2-66 for orbiters B and C and for the booster. In these figures, component weight changes for a limited range of design variables and requirements are tabulated. Figures 2-66a, 2-66b, and 2-66c present the variations in design conditions for the weight sensitivities.

2.3 Subsystem Operation - APS propellants are stored as liquids at low pressure, then raised to subsystem operating pressure by turbine driven pumps. Heat exchangers, using hot combustion gas, change the liquid propellant to the gaseous phase and also provide propellant superheat. To avoid excessive conditioning assembly cycling, accumulators are provided to decouple thrusters from conditioners. Conditioner operation is controlled by commanding propellant conditioning assemblies to resupply accumulators when accumulator pressure drops below a switching pressure level. Assembly operation is illustrated in Figures 2-67 and 2-67a. Gas generator valves and pump suction valves are commanded to open by accumulator pressure switches, and

SUBSYSTEM ELEMENTS	WEIGHT – LB		VOLUME – FT^3	
	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS				
TOTAL PROPELLANT	6334	23,552		
PROPELLANT TANKAGE	1036	417	1449	332
PRESSURANT AND TANKAGE	450	79		
INSULATION	248	50		
CONDITIONING ASSEMBLY				
HEAT EXCHANGERS (3)	255	297		
TURBOPUMPS (3)	76	124		
GAS GENERATORS (3)	37			
FEED ASSEMBLY				
ACCUMULATORS (1)	679	321	29	12
LINES	146	152		
REGULATORS (6)	26	29		
VALVES (THRUSTER ISOLATION (2) AND MANIFOLD)	105	90		
THRUSTER (18/6) *	917			
PROPULSIVE VENT AND LINES	275	184		
TOTAL SUBSYSTEM	35,879		1822	

* ATTITUDE/TRANSLATION

APS COMPONENT WEIGHT BREAKDOWN
Orbiter B

FIGURE 2–17

SUBSYSTEM ELEMENTS	WEIGHT – LB		VOLUME – FT^3	
	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS				
TOTAL PROPELLANT	6486	23,748	1485	335
PROPELLANT TANKAGE	1338	477		
PRESSURANT AND TANKAGE	454	80		
INSULATION	318	63		
CONDITIONING ASSEMBLY				
HEAT EXCHANGERS (3)	255	297		
TURBOPUMPS (3)	75	124		
GAS GENERATORS (3)	37			
FEED ASSEMBLY				
ACCUMULATORS (1)	700	332	30	12
LINES	162	169		
REGULATORS (6)	26	29		
VALVES (THRUSTER ISOLATION (2) AND MANIFOLD)	111	96		
THRUSTER (27/6) *	1,244			
PROPULSIVE VENT AND LINES	269	180		
TOTAL SUBSYSTEM	37,070		1862	

* ATTITUDE/TRANSLATION

APS COMPONENT WEIGHT BREAKDOWN
Orbiter C

FIGURE 2–18

SUBSYSTEM ELEMENTS	WEIGHT – LB		VOLUME – FT^3	
	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS				
TOTAL PROPELLANT	469	1737		
PROPELLANT TANKAGE	225	138	108	25
PRESSURANT AND TANKAGE	34	8		
INSULATION	30	4		
CONDITIONING ASSEMBLY				
HEAT EXCHANGERS (3)	259	297		
TURBOPUMPS (3)	86	98		
GAS GENERATORS (3)	37			
FEED ASSEMBLY				
ACCUMULATORS (1)	437	200	17	7
LINES	141	146		
REGULATORS (6)	26	29		
VALVES (THRUSTER ISOLATION (2) AND MANIFOLD	134	122		
THRUSTER (18)	609			
VENT AND LINES	11	7		
TOTAL SUBSYSTEM	5310		157	

APS COMPONENT WEIGHT BREAKDOWN
Booster

FIGURE 2–19

THRUSTER	ATTITUDE CONTROL	TRANSLATION (+ X)
CHAMBER PRESSURE, $LBF/IN.^2A$	500	500
EXPANSION RATIO	60	120
THRUST LEVEL, LB	1850	1850
NUMBER OF CYCLES	600	–
BURN TIME, SEC	–	<1560
INLET TEMP, H_2, MAX/MIN/NOM, ^oR	600/200/252	600/200/252
INLET TEMP, O_2, MAX/MIN/NOM, ^oR	600/350/406	600/350/406
INLET PRESSURE, $LBF/IN.^2A$	675 H_2 – 600 O_2	675 H_2 – 600 O_2
MIXTURE RATIO MAX/MIN/NOM	4.7:1/3.5:1/ 4:1	4.7:1/3.5:1/4:1

GAS GENERATORS/HEAT EXCHANGERS	H_2 (GG)	O_2 (GG)	H_2 (HX)	O_2 (HX)
COMBUSTION PRESSURE, $LBF/IN.^2A$	500	500	30	107
COMBUSTION TEMP, ^oR	2000	2000	3750	4151
MIXTURE RATIO	1	1	0.78	0.85
NUMBER OF CYCLES	50	50	50	50
BURN TIME, SEC	<1560	<1560	<1560	<1560
INLET TEMP, H_2, MAX/MIN/NOM, ^oR	600/200/252	600/200/252	1410	1830
INLET TEMP, O_2, MAX/MIN/NOM. ^oR	600/350/406	600/350/406	600/350/406	600/350/406
INLET PRESSURE	675 H_2/600 O_2	675 H_2/600 O_2	30	107
FLOW RATE	0.443	0.274	0.785	0.506

REGULATORS	H_2	O_2
INLET PRESSURE, MAX, $LBF/IN.^2A$	2318	2066
INLET PRESSURE, MIN. $LBF/IN.^2A$	1021	914
INLET TEMP, MAX/MIN/NOM, ^oR	600/253/253	600/420/440
REGULATED PRESSURE, $LBF/IN.^2A$	715	640
FLOW RATE, LB/SEC	3.66	14.18
NUMBER OF CYCLES	15,600	15,600

HEAT EXCHANGER	H_2	O_2
PRESSURE, COLD SIDE–IN, $LBF/IN.^2A$	1043	921
PRESSURE, COLD SIDE–OUT, $LBF/IN.^2A$	1021	914
PRESSURE, HOT SIDE–IN, $LBF/IN.^2A$	30	107
PRESSURE, HOT SIDE–OUT, $LBF/IN.^2A$	26	80
TEMP, COLD SIDE–IN, ^oR	37	162
TEMP, COLD SIDE–OUT, ^oR	253	425
TEMP, HOT SIDE–IN, ^oR	1410	1830
TEMP, HOT SIDE–OUT, ^oR	800	800
FLOW RATE LB/SEC	0.785	0.506
NUMBER OF CYCLES	50	50
TURBOPUMP		
PUMP		
PUMP FLOW RATE, LB/SEC	3.84	14.84
INLET PRESSURE, $LBF/IN.^2A$	25	30
INLET TEMP, ^oR	37	162
OUTLET PRESSURE, MAX/MIN, $LBF/IN.^2$ A	2340/1043	2073/921
NUMBER OF CYCLES	50	50
TURBINE		
FLOW RATE, LB/SEC	0.443	0.274
INLET PRESSURE, $LBF/IN.^2A$	500	500
INLET TEMP, ^oR	2000	2000
PRESSURE RATIO	16.7:1	4.65:1
NUMBER OF CYCLES	50	50

(1) NUMBER OF CYCLES IS CYCLES/MISSION

FIGURE 2–20

TURBOPUMP COMPONENT REQUIREMENTS
Orbiter B

THRUSTER	ATTITUDE CONTROL		TRANSLATION (+ X)	
CHAMBER PRESSURE, LBF/IN.^{2}A	500		500	
EXPANSION RATIO	60		120	
THRUST LEVEL, LB	1850		1850	
NUMBER OF CYCLES	600		–	
BURN TIME, SEC	–		<1560	
INLET TEMP, H_2, MAX/MIN/NOM, ^oR	600/200/252		600/200/252	
INLET TEMP, O_2, MAX/MIN/NOM, ^oR	600/350/406		600/350/406	
INLET PRESSURE, LBF/IN.^{2}A	675 H_2 – 600 O_2		675 H_2 – 600 O_2	
MIXTURE RATIO MAX/MIN/NOM	4.7:1/3.5:1/ 4:1		4.7:1/3.5:1/4:1	
GAS GENERATORS/HEAT EXCHANGERS	H_2 (GG)	O_2 (GG)	H_2 (HX)	O_2 (HX)
COMBUSTION PRESSURE, LBF/IN.^{2}A	500	500	30	107
COMBUSTION TEMP, ^oR	2000	2000	3750	4151
MIXTURE RATIO	1	1	0.77	0.85
NUMBER OF CYCLES	50	50	50	50
BURN TIME, SEC	<1560	<1560	<1560	<1560
INLET TEMP, H_2, MAX/MIN/NOM, ^oR	600/200/252	600/200/252	1410	1830
INLET TEMP, O_2, MAX/MIN/NOM. ^oR	600/350/406	600/350/406	600/350/406	600/350/406
INLET PRESSURE	675 H_2/600 O_2	675 H_2/600 O_2	30	107
FLOW RATE	0.443	0.274	0.784	0.506
REGULATORS	H_2	O_2		
INLET PRESSURE, MAX, LBF/IN.^{2}A	2307	2056		
INLET PRESSURE, MIN. LBF/IN.^{2}A	1021	914		
INLET TEMP, MAX/MIN/NOM, ^oR	600/253/253	600/421/441		
REGULATED PRESSURE, LBF/IN.^{2}A	715	640		
FLOW RATE, LB/SEC	3.66	14.18		
NUMBER OF CYCLES	19,800	19,800		

HEAT EXCHANGER	H_2	O_2
PRESSURE, COLD SIDE–IN, LBF/IN.^{2}A	1043	921
PRESSURE, COLD SIDE–OUT, LBF/IN.^{2}A	1021	914
PRESSURE, HOT SIDE–IN, LBF/IN.^{2}A	30	107
PRESSURE, HOT SIDE–OUT, LBF/IN.^{2}A	26	80
TEMP, COLD SIDE–IN, ^oR	37	162
TEMP, COLD SIDE–OUT, ^oR	253	425
TEMP, HOT SIDE–IN, ^oR	1410	1830
TEMP, HOT SIDE–OUT, ^oR	800	800
FLOW RATE LB/SEC	0.784	0.506
NUMBER OF CYCLES	50	50
TURBOPUMP		
PUMP		
PUMP FLOW RATE, LB/SEC	3.83	14.84
INLET PRESSURE, LBF/IN.^{2}A	25	30
INLET TEMP, ^oR	37	162
OUTLET PRESSURE, MAX/MIN, LBF/IN.^{2} A	1043/2329	921/2063
NUMBER OF CYCLES	50	50
TURBINE		
FLOW RATE, LB/SEC	0.443	0.274
INLET PRESSURE, LBF/IN.^{2}A	500	500
INLET TEMP, ^oR	2000	2000
PRESSURE RATIO	16.7:1	4.67:1
NUMBER OF CYCLES	50	50

(1) NUMBER OF CYCLES IS CYCLES/MISSION

FIGURE 2–21

TURBOPUMP COMPONENT REQUIREMENTS
Orbiter C

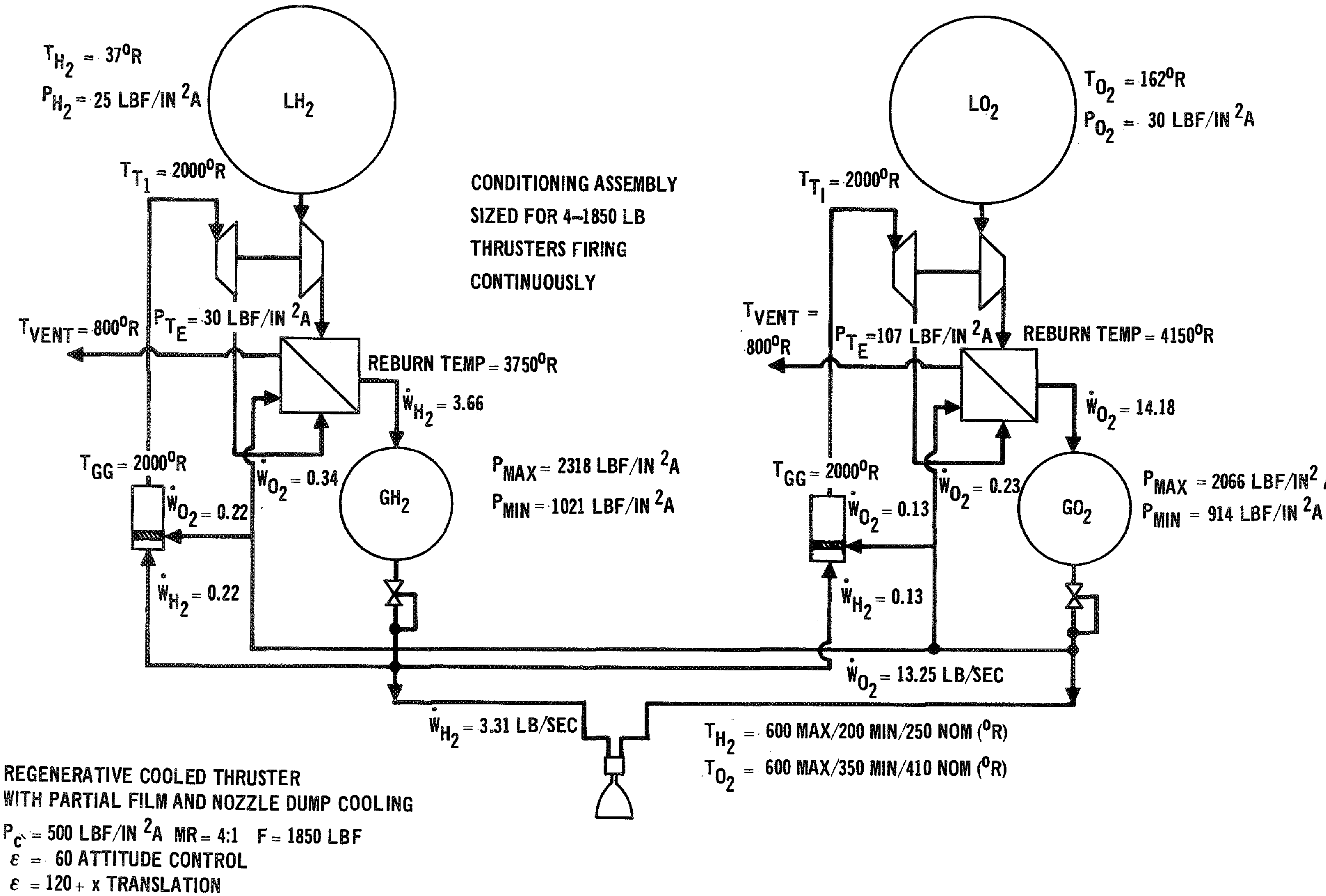
THRUSTER	ATTITUDE CONTROL			
CHAMBER PRESSURE, LBF/IN.^{2}A	500			
EXPANSION RATIO	40			
THRUST LEVEL, LB	1850			
NUMBER OF CYCLES	100			
BURN TIME, SEC	< 360			
INLET TEMP, H_2, MAX/MIN/NOM, ^{0}R	600/200/259			
INLET TEMP, O_2, MAX/MIN/NOM, ^{0}R	600/350/414			
INLET PRESSURE, LBF/IN.^{2}A	675 H_2 – 600 O_2			
MIXTURE RATIO NOM	4:1			
GAS GENERATOR/HEAT EXCHANGER	H_2(GG)	O_2 (GG)	H_2(HX)	O_2(HX)
COMBUSTION PRESSURE, LBF/IN.^{2}A	500	500	30	119
COMBUSTION TEMP, ^{0}R	2000	2000	3843	4160
MIXTURE RATIO	1	1	0.81	0.85
NUMBER OF CYCLES	16	16	16	16
BURN TIME, SEC	<360	<360	<360	<360
INLET TEMP, H_2, MAX/MIN/NOM, ^{0}R	600/200/259	600/200/259	600/200/259	600/200/259
INLET TEMP, O_2, MAX/MIN/NOM, ^{0}R	600/350/414	600/350/414	600/350/414	600/350/414
INLET PRESSURE, LBF/IN.^{2}A	675 H_2/600 O_2	675 H_2/600 O_2	30	119
FLOW RATE, LB/SEC	0.448	0.282	0.809	0.520
REGULATORS				
INLET PRESSURE, MAX, LBF/IN.^{2}A	2532		2258	
INLET PRESSURE, MIN, LBF/IN.^{2}A	1021		914	
INLET TEMP, MAX/MIN/NOM, ^{0}R	600/260/260		600/429/450	
REGULATED PRESSURE, LBF/IN.^{2}A	715		640	
FLOW RATE, LB/SEC	3.71		14.36	
NUMBER OF CYCLES	1800		1800	

HEAT EXCHANGERS	H_2	O_2
PRESSURE, COLD SIDE–IN, LBF/IN.^{2}A	1043	921
PRESSURE, COLD SIDE–OUT, LBF/IN.^{2}A	1021	914
PRESSURE, HOT SIDE–IN, LBF/IN.^{2}A	30	119
PRESSURE, HOT SIDE–OUT, LBF/IN.^{2}A	26	80
TEMP, COLD SIDE–IN, ^{0}R	37	162
TEMP, COLD SIDE–OUT, ^{0}R	260	433
TEMP, HOT SIDE–IN, ^{0}R	1410	1820
TEMP, HOT SIDE–OUT, ^{0}R	800	800
FLOW RATE, LB/SEC	0.809	0.520
NUMBER OF CYCLES	16	16
TURBOPUMP		
PUMP		
PUMP FLOW RATE, LB/SEC	3.83	15.03
INLET PRESSURE, LBF/IN.^{2}A	25	35
INLET TEMPERATURE, ^{0}R	37	162
OUTLET PRESSURE, MAX/MIN, LBF/IN.^{2} A	2554/1043	2280/921
NUMBER OF CYCLES	16	16
TURBINE		
FLOW RATE, LB/SEC	0.448	0.282
INLET PRESSURE, LBF/IN.^{2} A	500	500
INLET TEMPERATURE, ^{0}R	2000	2000
PRESSURE RATIO	16.7:1	4.21:1
NUMBER OF CYCLES	16	16

(1) NUMBER OF CYCLES IS CYCLES/MISSION

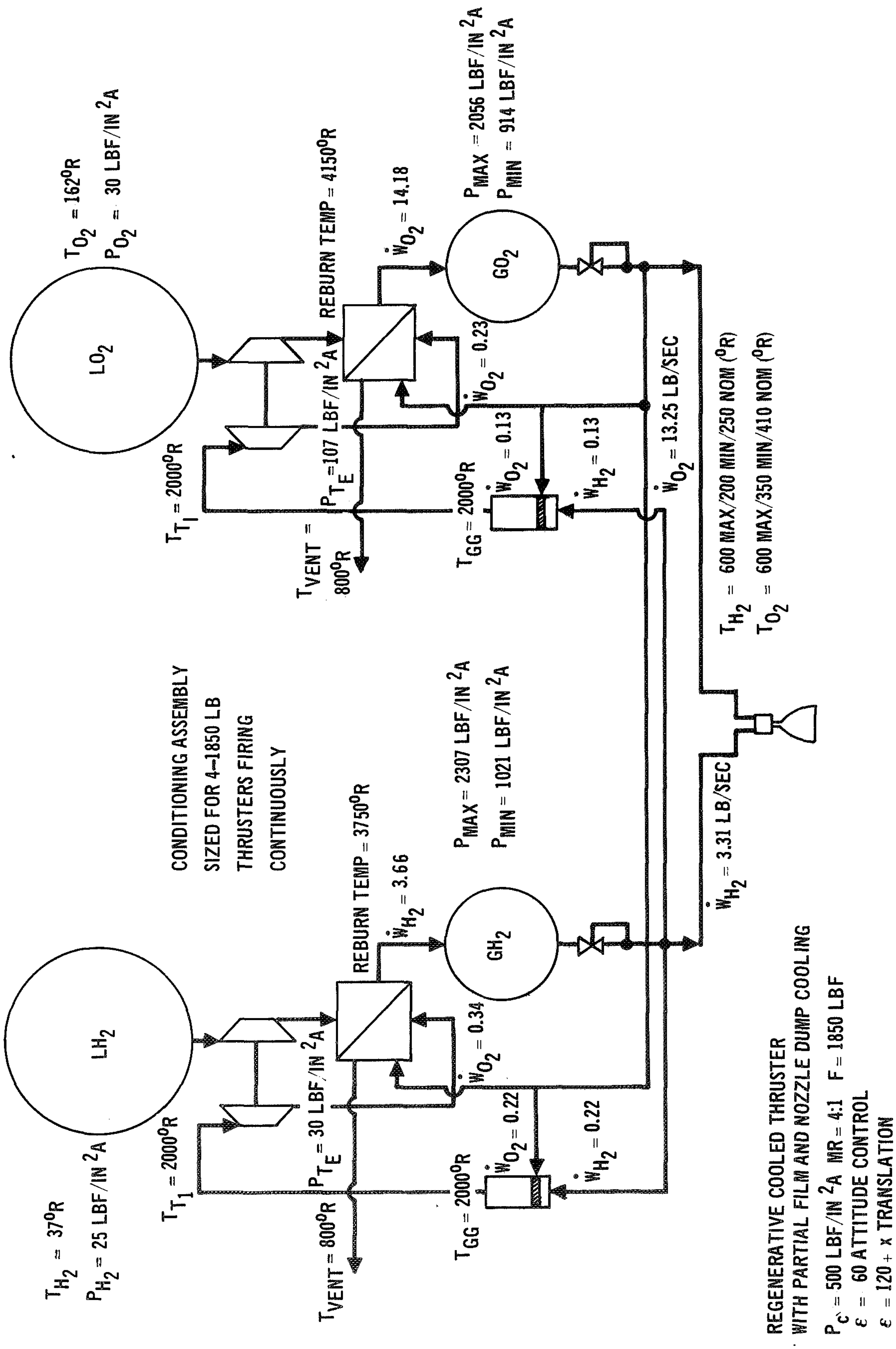
TURBOPUMP COMPONENT REQUIREMENTS
Booster

FIGURE 2–22



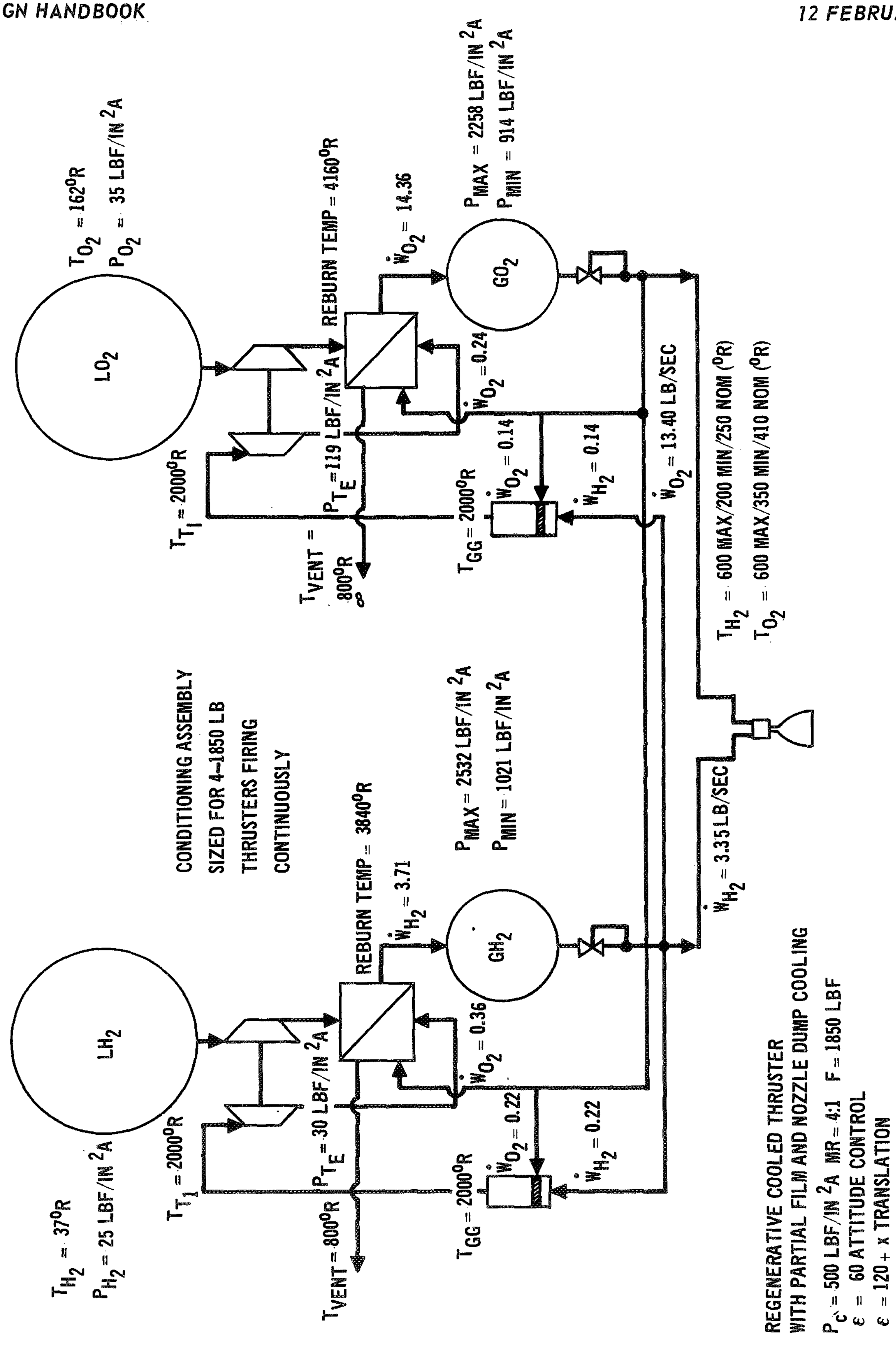
APS PRESSURES, TEMPERATURES AND FLOWS
Orbiter B

FIGURE 2–23

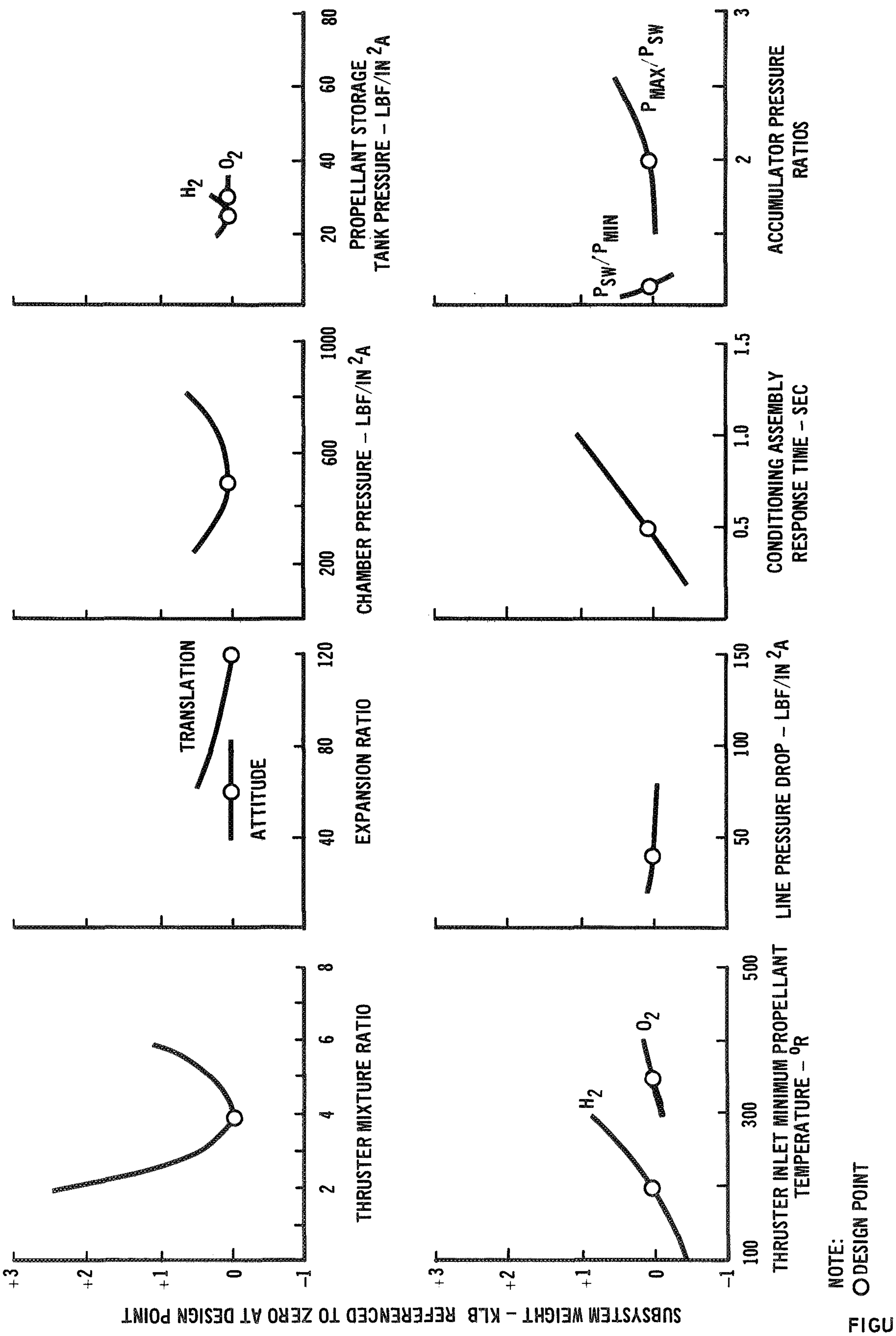


APS PRESSURES, TEMPERATURES AND FLOWS
Orbiter C

FIGURE 2–24



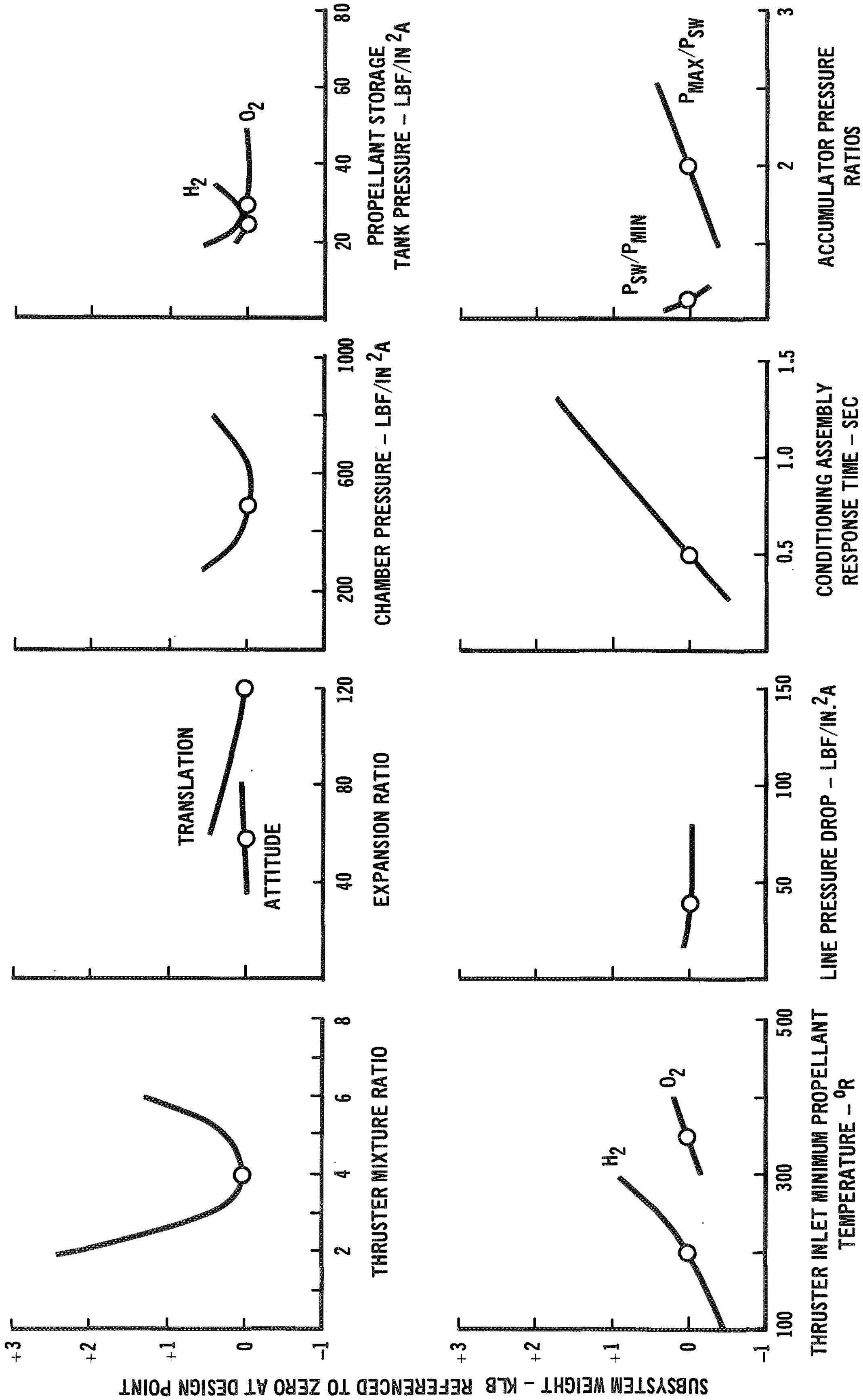
APS PRESSURES, TEMPERATURES AND FLOWS
BOOSTER



WEIGHT SENSITIVITY TO DESIGN VARIABLES

ORBITER B

FIGURE 2–26

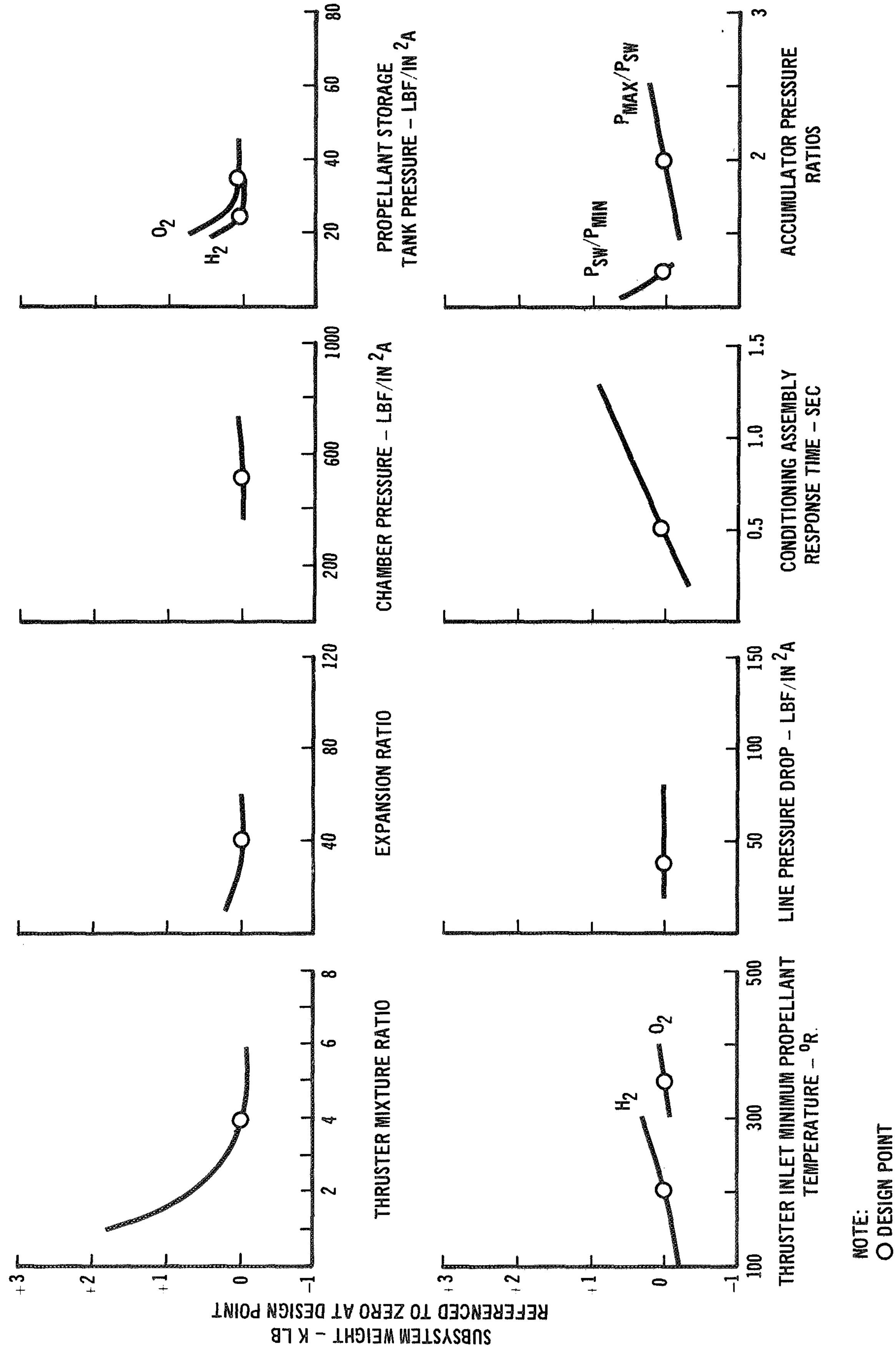


NOTE:
O DESIGN POINT

WEIGHT SENSITIVITY TO DESIGN VARIABLES

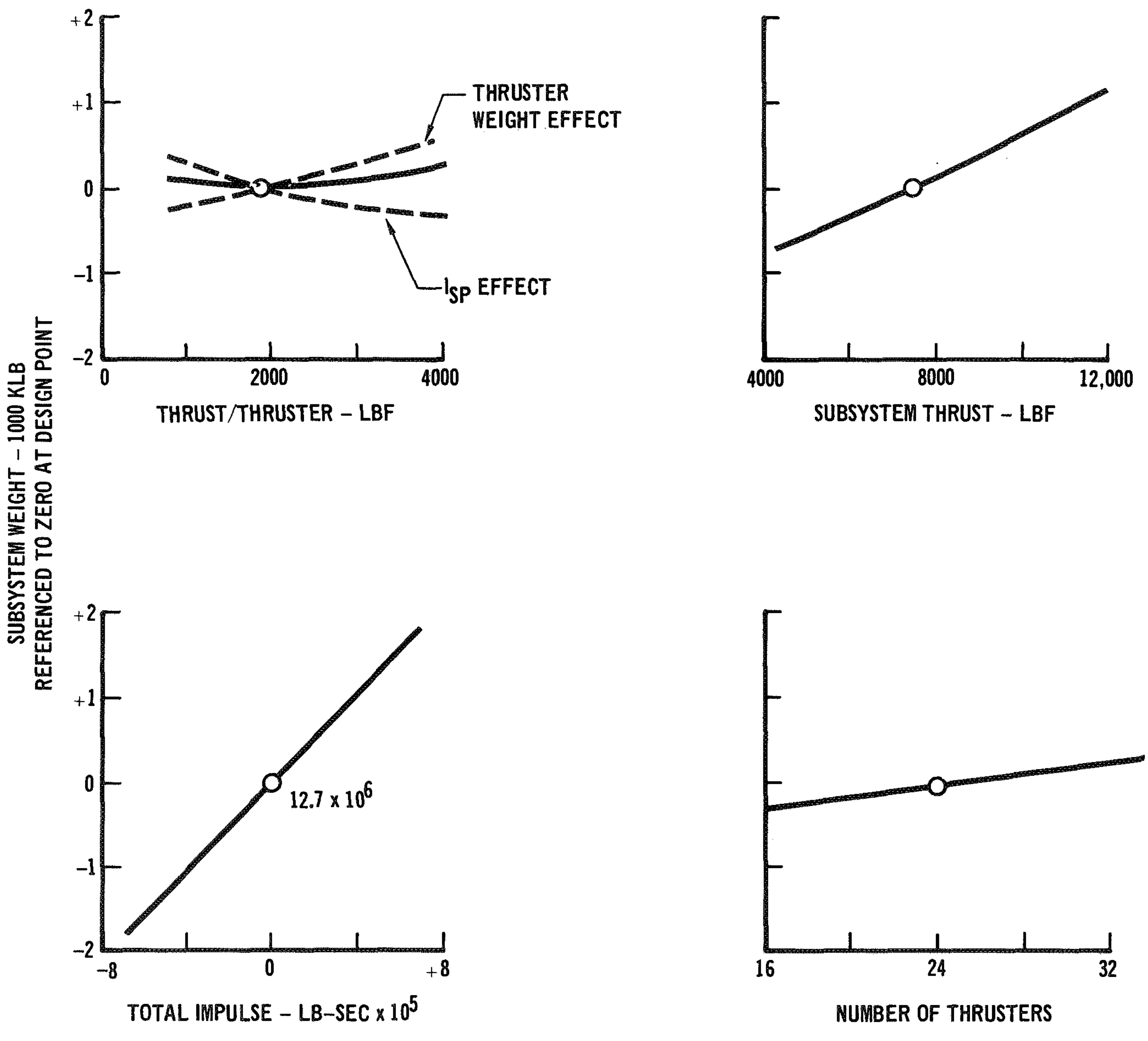
ORBITER C

FIGURE 2–27



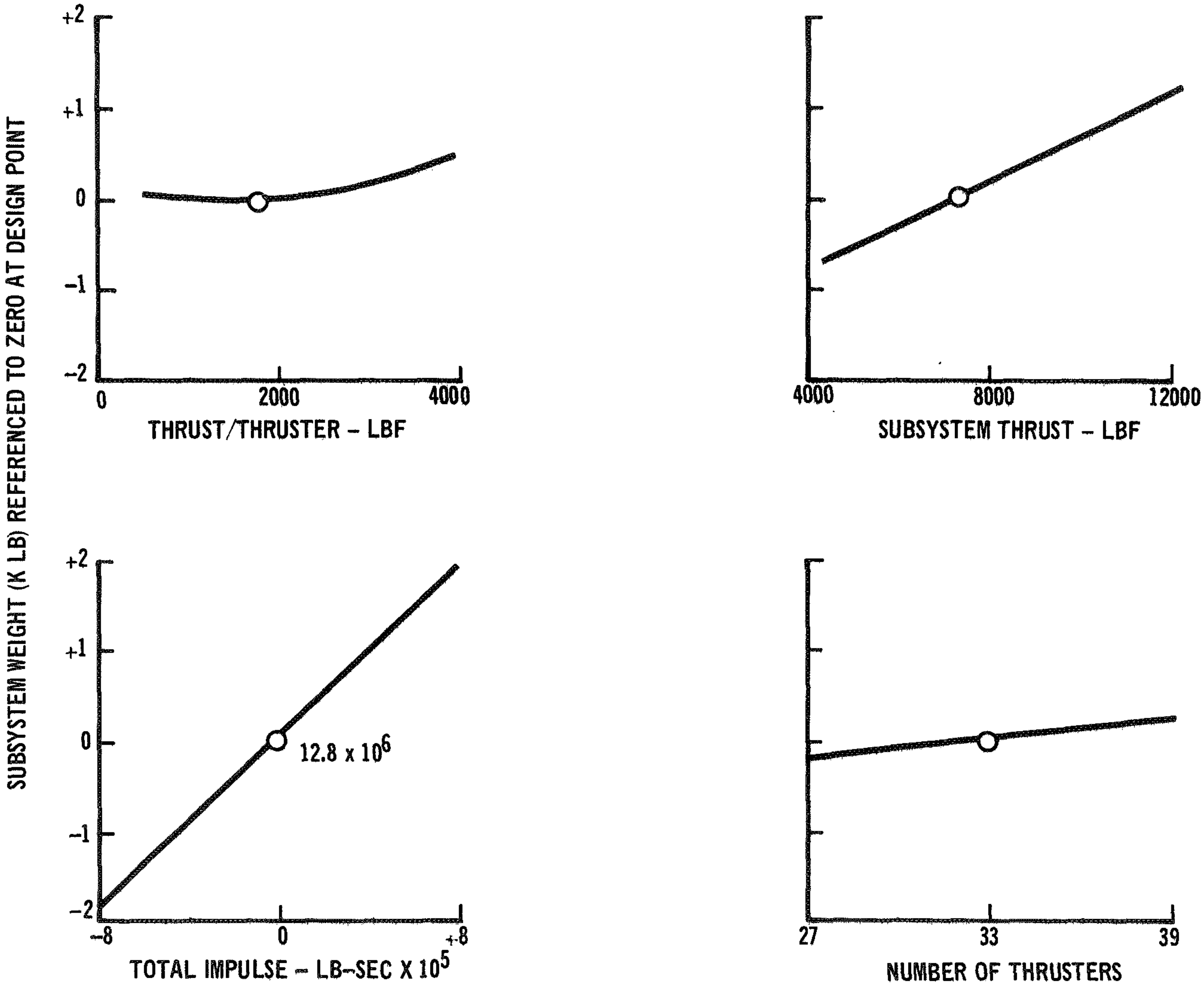
WEIGHT SENSITIVITY TO DESIGN VARIABLES
BOOSTER

FIGURE 2-28



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS
Orbiter B

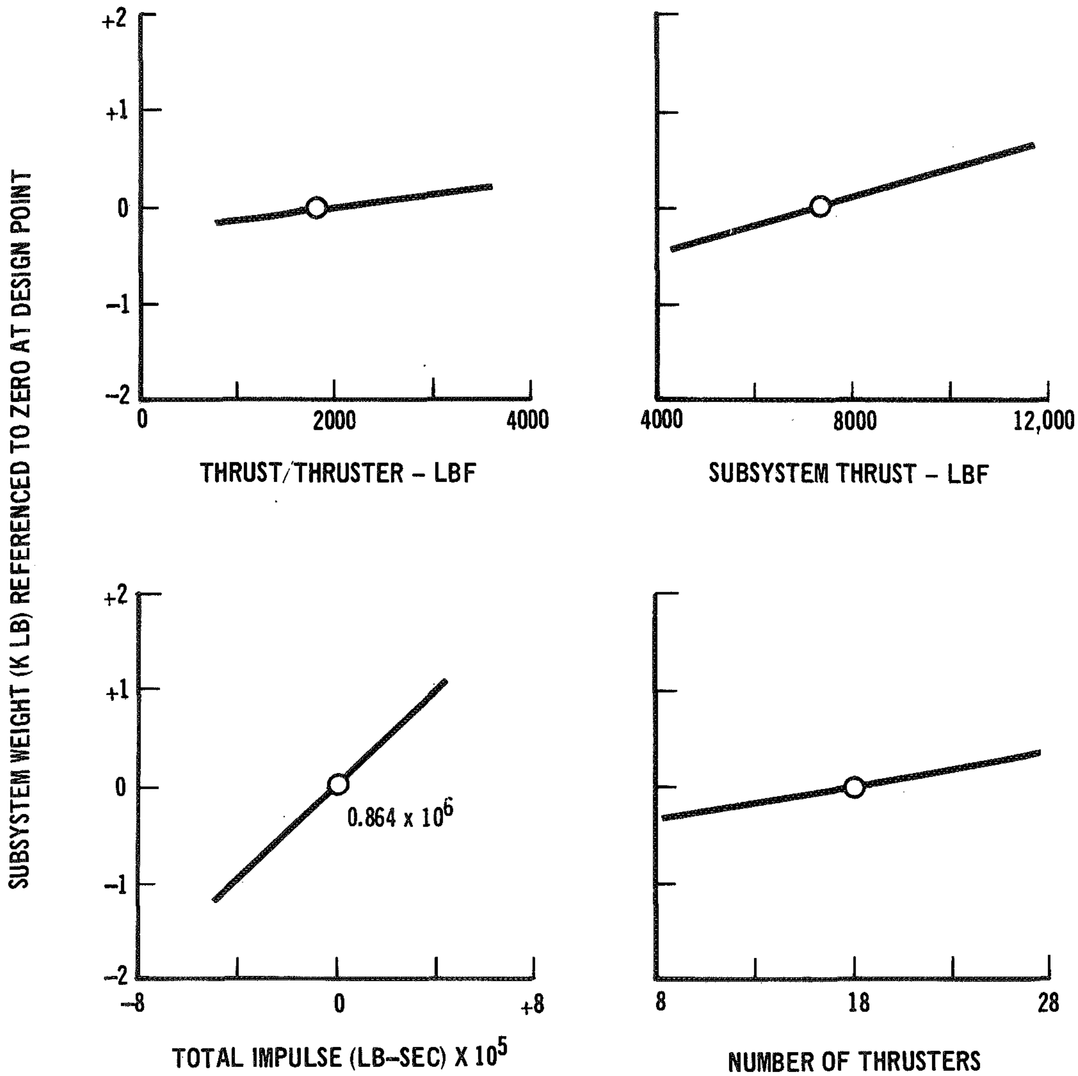
FIGURE 2–29



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS

Orbiter C

FIGURE 2–30



WEIGHT SENSITIVITY TO DESIGN REQUIREMENTS
BOOSTER

FIGURE 2-31

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	THRUSTER MIXTURE RATIO					
	2		4		6	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	10222	20462	6334	23552	4960	26462
PROPELLANT TANKAGE	1426	387	1036	417	884	445
PRESSURANT AND TANKAGE	733	69	450	79	349	89
INSULATION	267	48	248	50	240	52
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	342	287	255	297	225	305
TURBOPUMPS	173	112	76	124	49	136
GAS GENERATOR	39		37		36	
FEED ASSEMBLY						
ACCUMULATORS	1122	280	679	321	524	360
LINES	177	143	146	152	132	160
REGULATORS	36	26	26	29	22	31
VALVES	140	83	105	90	91	97
VENT ASSEMBLY						
LINES	346	118	210	135	162	152
VALVES	92	44	65	49	55	53
THRUSTER ASSEMBLY	917		917		917	
TOTAL SUBSYSTEM	38091		35879		36986	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
ORBITER B

FIGURE 2–32

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	ATTITUDE THRUSTER EXPANSION RATIO					
	40		60		80	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6341	23577	6334	23552	6331	23535
PROPELLANT TANKAGE	1037	418	1036	417	1036	417
PRESSURANT AND TANKAGE	450	79	450	79	450	79
INSULATION	248	50	248	50	247	50
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	257	298	255	297	254	296
TURBOPUMPS	77	125	76	124	75	123
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	686	324	679	321	673	318
LINES	147	153	146	152	146	152
REGULATORS	26	29	26	29	26	29
VALVES	106	91	105	90	105	90
VENT ASSEMBLY						
LINES	210	135	210	135	210	135
VALVES	65	49	65	49	65	49
THRUSTER ASSEMBLY	872		917		962	
TOTAL SUBSYSTEM	35887		35879		35889	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
ORBITER B

FIGURE 2-33

SUBSYSTEM ELEMENTS \ DESIGN VARIABLE	TRANSLATION THRUSTER EXPANSION RATIO					
	60		120			
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6434	23934	6334	23552		
PROPELLANT TANKAGE	1047	421	1036	417		
PRESSURANT AND TANKAGE	457	80	450	79		
INSULATION	248	50	248	50		
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	255	297	255	297		
TURBOPUMPS	76	124	76	124		
GAS GENERATOR	37		37			
FEED ASSEMBLY						
ACCUMULATORS	679	321	679	321		
LINES	146	152	146	152		
REGULATORS	26	29	26	29		
VALVES	105	90	105	90		
VENT ASSEMBLY						
LINES	213	138	210	135		
VALVES	66	49	65	49		
THRUSTER ASSEMBLY	872		917			
TOTAL SUBSYSTEM	36346		35879			

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES

ORBITER B

FIGURE 2–34

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	CHAMBER PRESSURE (LBF/IN^2A)					
	300		500		700	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6230	23755	6334	23552	6460	23548
PROPELLANT TANKAGE	1025	419	1036	417	1050	417
PRESSURANT AND TANKAGE	442	80	450	79	459	79
INSULATION	247	50	248	50	248	50
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	256	304	255	297	256	296
TURBOPUMPS	39	96	76	124	118	153
GAS GENERATOR	42		37		37	
FEED ASSEMBLY						
ACCUMULATORS	619	321	679	321	749	332
LINES	162	173	146	152	137	139
REGULATORS	33	37	26	29	23	26
VALVES	117	107	105	90	99	80
VENT ASSEMBLY						
LINES	199	141	210	135	246	131
VALVES	63	50	65	49	73	47
THRUSTER ASSEMBLY	1165		917		784	
TOTAL SUBSYSTEM	36170		35879		36037	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES

ORBITER B

FIGURE 2–35

SUBSYSTEM ELEMENTS \ DESIGN VARIABLE	HYDROGEN TANK PRESSURE (LBF/IN^2 A)					
	20		25		30	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6337	23551	6334	23552	6333	23552
PROPELLANT TANKAGE	1034	417	1036	417	1038	417
PRESSURANT AND TANKAGE	213	79	450	79	687	79
INSULATION	248	50	248	50	248	50
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	255	297	255	297	255	297
TURBOPUMPS	497	124	76	124	22	124
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	679	321	679	321	679	321
LINES	146	152	146	152	146	152
REGULATORS	26	29	26	29	26	29
VALVES	105	90	105	90	105	90
VENT ASSEMBLY						
LINES	210	135	210	135	209	135
VALVES	65	49	65	49	65	49
THRUSTER ASSEMBLY	917		917		917	
TOTAL SUBSYSTEM	36063		35879		36062	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES

ORBITER B

FIGURE 2-36

SUBSYSTEM ELEMENTS \ DESIGN VARIABLE	OXYGEN TANK PRESSURE (LBF/IN^{2}A)					
	25		30		35	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6334	23552	6334	23552	6334	23552
PROPELLANT TANKAGE	1036	417	1036	417	1036	418
PRESSURANT AND TANKAGE	450	54	450	79	450	104
INSULATION	248	50	248	50	248	50
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	255	297	255	297	255	297
TURBOPUMPS	76	214	76	124	76	93
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	679	321	679	321	679	321
LINES	146	152	146	152	146	152
REGULATORS	26	29	26	29	26	29
VALVES	105	90	105	90	105	90
VENT ASSEMBLY						
LINES	210	135	210	135	210	135
VALVES	65	49	65	49	65	49
THRUSTER ASSEMBLY	917		917		917	
TOTAL SUBSYSTEM	35943		35879		35872	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES

ORBITER B

FIGURE 2-37

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	HYDROGEN MINIMUM THRUSTER INLET TEMPERATURE (°R)					
	100		200		300	
PROPELLANT AND COMPONENTS	H_2	O_2	H_2	O_2	H_2	O_2
TOTAL PROPELLANT	6395	23371	6334	23552	6277	23948
PROPELLANT TANKAGE	1043	416	1036	417	1030	421
PRESSURANT AND TANKAGE	454	78	450	79	446	80
INSULATION	248	50	248	50	247	50
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	204	296	255	297	315	298
TURBOPUMPS	77	123	76	124	75	126
GAS GENERATOR	36		37		38	
FEED ASSEMBLY						
ACCUMULATORS	498	318	679	321	958	327
LINES	116	153	146	152	160	152
REGULATORS	26	29	26	29	26	29
VALVES	84	91	105	90	116	90
VENT ASSEMBLY						
LINES	141	137	210	135	314	134
VALVES	50	49	65	49	86	48
THRUSTER ASSEMBLY	917		917		917	
TOTAL SUBSYSTEM	35400		35879		36708	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
ORBITER B

FIGURE 2–38

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	OXYGEN MINIMUM THRUSTER INLET TEMPERATURE (°R)					
	300		350		400	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6314	23519	6334	23552	6351	23576
PROPELLANT TANKAGE	1034	417	1036	417	1038	418
PRESSURANT AND TANKAGE	448	79	450	79	451	79
INSULATION	247	50	248	50	248	50
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	255	295	255	297	256	295
TURBOPUMPS	75	124	76	124	76	124
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	676	268	679	321	681	368
LINES	147	139	146	152	146	160
REGULATORS	26	29	26	29	26	29
VALVES	105	80	105	90	105	97
VENT ASSEMBLY						
LINES	210	116	210	135	210	152
VALVES	65	43	65	49	65	53
THRUSTER ASSEMBLY	917		917		917	
TOTAL SUBSYSTEM	35715		35879		36008	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
ORBITER B

FIGURE 2-39

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	LINE PRESSURE DROP (LBF/IN^2 A)					
	20		40		60	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6326	23554	6334	23552	6344	23551
PROPELLANT TANKAGE	1035	418	1036	417	1037	417
PRESSURANT AND TANKAGE	449	79	450	79	451	79
INSULATION	248	50	248	50	248	50
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	255	297	255	297	255	297
TURBOPUMPS	73	121	76	124	79	126
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	673	319	679	321	683	322
LINES	170	177	146	152	134	139
REGULATORS	26	29	26	29	26	29
VALVES	124	110	105	90	96	80
VENT ASSEMBLY						
LINES	207	135	210	135	212	135
VALVES	65	48	65	49	66	49
THRUSTER ASSEMBLY	917		917		917	
TOTAL SUBSYSTEM	35741		35879		35858	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
ORBITER B

FIGURE 2–40

DESIGN REQUIREMENT / SUBSYSTEM ELEMENTS	THRUST/THRUSTER (LBF)					
	925		1850		3700	
PROPELLANT AND COMPONENTS	H_2	O_2	H_2	O_2	H_2	O_2
TOTAL PROPELLANT	6393	23778	6334	23552	6277	23330
PROPELLANT TANKAGE	1043	420	1036	417	1030	415
PRESSURANT AND TANKAGE	454	80	450	79	446	78
INSULATION	248	50	248	50	247	50
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	255	297	255	297	255	297
TURBOPUMPS	76	124	76	124	76	124
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	679	321	679	321	679	321
LINES	146	152	146	152	146	152
REGULATORS	26	29	26	29	26	29
VALVES	105	90	105	90	105	90
VENT ASSEMBLY						
LINES	210	135	210	135	210	135
VALVES	65	49	65	49	65	49
THRUSTER ASSEMBLY	719		917		1489	
TOTAL SUBSYSTEM	35981		35879		36158	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
ORBITER B

FIGURE 2–41

DESIGN REQUIREMENT / SUBSYSTEM ELEMENTS	SUBSYSTEM THRUST (LBF)					
	3700		7400		14800	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6334	23552	6334	23552	6334	23552
PROPELLANT TANKAGE	1036	417	1036	417	1036	417
PRESSURANT AND TANKAGE	450	79	450	79	450	79
INSULATION	248	50	248	50	248	50
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	190	251	255	297	387	344
TURBOPUMPS	22	83	76	124	235	243
GAS GENERATOR	34		37		42	
FEED ASSEMBLY						
ACCUMULATORS	339	160	679	321	1357	641
LINES	114	118	146	153	188	196
REGULATORS	18	20	26	29	40	44
VALVES	126	120	105	90	102	74
VENT ASSEMBLY						
LINES	105	77	210	135	419	270
VALVES	40	30	65	49	105	78
THRUSTER ASSEMBLY	917		917		917	
TOTAL SUBSYSTEM	34929		35879		37847	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
ORBITER B

FIGURE 2-42

SUBSYSTEM ELEMENTS / DESIGN REQUIREMENT	TOTAL IMPULSE (LB - SEC)					
	12.0×10^6		12.7×10^6		13.0×10^6	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6016	22329	6334	23552	6493	24164
PROPELLANT TANKAGE	1002	405	1036	417	1053	423
PRESSURANT AND TANKAGE	427	75	450	79	461	81
INSULATION	245	49	248	50	249	50
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	255	297	255	297	255	297
TURBOPUMPS	76	124	76	124	76	124
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	679	321	679	321	679	321
LINES	146	153	146	153	146	153
REGULATORS	26	29	26	29	26	29
VALVES	105	90	105	90	105	90
VENT ASSEMBLY						
LINES	210	135	210	135	210	135
VALVES	65	49	65	49	65	49
THRUSTER ASSEMBLY	917		917		917	
TOTAL SUBSYSTEM	34262		35879		36688	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES

ORBITER B

FIGURE 2–43

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	THRUSTER MIXTURE RATIO					
	2		4		6	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	9505	20634	6486	23748	5102	26683
PROPELLANT TANKAGE	1731	446	1338	477	1185	505
PRESSURANT AND TANKAGE	739	69	454	80	352	90
INSULATION	338	61	318	63	310	65
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	341	288	255	297	225	305
TURBOPUMPS	172	112	75	124	48	136
GAS GENERATOR	39		37		36	
FEED ASSEMBLY						
ACCUMULATORS	1158	290	700	332	540	373
LINES	196	158	162	169	146	177
REGULATORS	36	26	26	29	22	31
VALVES	147	88	111	96	95	103
VENT ASSEMBLY						
LINES	337	115	204	131	157	148
VALVES	92	44	65	49	55	52
THRUSTER ASSEMBLY	1244		1244		1244	
TOTAL SUBSYSTEM	38406		37070		38185	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES

ORBITER C

FIGURE 2-44

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	ATTITUDE THRUSTER EXPANSION RATIO					
	40		60		80	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6494	23775	6486	23748	6483	23732
PROPELLANT TANKAGE	1339	478	1338	477	1338	477
PRESSURANT AND TANKAGE	454	80	454	80	453	80
INSULATION	318	63	318	63	318	63
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	256	298	255	297	254	296
TURBOPUMPS	76	125	75	124	74	123
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	708	336	700	332	695	329
LINES	163	169	162	169	161	168
REGULATORS	26	29	26	29	26	29
VALVES	111	97	111	96	110	96
VENT ASSEMBLY						
LINES	204	131	204	131	204	131
VALVES	65	49	65	49	65	49
THRUSTER ASSEMBLY	1177		1244		1312	
TOTAL SUBSYSTEM	37058		37070		37103	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
ORBITER C

FIGURE 2-45

SUBSYSTEM ELEMENTS / DESIGN VARIABLE	TRANSLATION THRUSTER EXPANSION RATIO					
	60		120			
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6587	24132	6486	23748		
PROPELLANT TANKAGE	1349	481	1338	477		
PRESSURANT AND TANKAGE	461	81	454	80		
INSULATION	319	63	318	63		
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	255	297	255	297		
TURBOPUMPS	75	124	75	124		
GAS GENERATOR	37		37			
FEED ASSEMBLY						
ACCUMULATORS	700	332	700	332		
LINES	162	169	162	169		
REGULATORS	26	29	26	29		
VALVES	111	96	111	96		
VENT ASSEMBLY						
LINES	207	134	204	131		
VALVES	66	49	65	49		
THRUSTER ASSEMBLY	1199		1244			
TOTAL SUBSYSTEM	37541		37070			

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
ORBITER C

FIGURE 2–46

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	CHAMBER PRESSURE (LBF/IN^2A)					
	300		500		700	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6382	23952	6486	23748	6613	23745
PROPELLANT TANKAGE	1327	479	1338	477	1352	477
PRESSURANT AND TANKAGE	446	80	454	80	463	80
INSULATION	317	63	318	63	318	63
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	256	304	255	297	256	296
TURBOPUMPS	38	96	75	124	117	153
GAS GENERATOR	42		37		37	
FEED ASSEMBLY						
ACCUMULATORS	639	332	700	332	774	343
LINES	179	192	162	169	152	153
REGULATORS	33	37	26	29	23	26
VALVES	123	114	111	96	104	85
VENT ASSEMBLY						
LINES	193	137	204	131	239	128
VALVES	63	50	65	49	73	47
THRUSTER ASSEMBLY	1578		1244		1065	
TOTAL SUBSYSTEM	37452		37070		37182	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES

ORBITER C

FIGURE 2–47

SUBSYSTEM ELEMENTS \ DESIGN VARIABLE	HYDROGEN, TANK PRESSURE (LBF/IN^{2}A)					
	20		25		30	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6489	23748	6486	23748	6485	23748
PROPELLANT TANKAGE	1336	477	1338	477	1342	477
PRESSURANT AND TANKAGE	215	80	454	80	693	80
INSULATION	318	63	318	63	318	63
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	255	297	255	297	255	297
TURBOPUMPS	494	124	75	124	22	124
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	700	332	700	332	700	332
LINES	162	169	162	169	162	169
REGULATORS	26	29	26	29	26	29
VALVES	111	96	111	96	111	96
VENT ASSEMBLY						
LINES	204	131	204	131	203	131
VALVES	65	49	65	49	65	49
THRUSTER ASSEMBLY	1244		1244		1244	
TOTAL SUBSYSTEM	37251		37070		37256	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
ORBITER C

FIGURE 2-48

SUBSYSTEM ELEMENTS \ DESIGN VARIABLE	OXYGEN TANK PRESSURE (LBF/IN^2A)					
	20		30		40	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS	6486	23748	6486	23748	6486	23748
TOTAL PROPELLANT	1338	476	1338	477	1338	478
PROPELLANT TANKAGE	454	30	454	80	454	130
PRESSURANT AND TANKAGE	318	63	318	63	318	63
INSULATION						
CONDITIONING ASSEMBLY	255	297	255	297	255	297
HEAT EXCHANGERS	75	689	75	124	75	79
TURBOPUMPS						
GAS GENERATOR	37		37		37	
FEED ASSEMBLY	700	332	700	332	700	332
ACCUMULATORS	162	169	162	169	162	169
LINES	26	29	26	29	26	29
REGULATORS	111	96	111	96	111	96
VALVES						
VENT ASSEMBLY	204	131	204	131	204	131
LINES	65	49	65	49	65	49
VALVES						
THRUSTER ASSEMBLY	1244		1244		1244	
TOTAL SUBSYSTEM	37584		37070		37076	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
Orbiter C

FIGURE 2-49

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	HYDROGEN MINIMUM THRUSTER INLET TEMPERATURE (°R)					
	100		200		300	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS	6548	23567	6486	23748	6428	24146
TOTAL PROPELLANT	1345	475	1338	477	1332	481
PROPELLANT TANKAGE	458	79	454	80	449	81
PRESSURANT AND TANKAGE	318	63	318	63	317	63
INSULATION						
CONDITIONING ASSEMBLY	204	296	255	297	315	298
HEAT EXCHANGERS	76	123	75	124	75	125
TURBOPUMPS						
GAS GENERATOR	36		37		38	
FEED ASSEMBLY	514	329	700	332	989	338
ACCUMULATORS	129	169	162	169	177	168
LINES	26	29	26	29	26	29
REGULATORS	88	97	111	96	122	96
VALVES						
VENT ASSEMBLY	137	134	204	131	305	131
LINES	50	49	65	49	86	48
VALVES						
THRUSTER ASSEMBLY	1244		1244		1244	
TOTAL SUBSYSTEM	36583		37070		37907	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
Orbiter C

FIGURE 2-50

SUBSYSTEM ELEMENTS \ DESIGN VARIABLE	OXYGEN MINIMUM THRUSTER INLET TEMPERATURE (°R)					
	300		350		400	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS	6467	23715	6486	23748	6504	23774
TOTAL PROPELLANT	1336	477	1338	477	1340	477
PROPELLANT TANKAGE	452	80	454	80	455	80
PRESSURANT AND TANKAGE	318	63	318	63	318	63
INSULATION						
CONDITIONING ASSEMBLY	255	295	255	297	256	295
HEAT EXCHANGERS	75	123	75	124	76	124
TURBOPUMPS						
GAS GENERATOR	36		37		37	
FEED ASSEMBLY	697	278	700	332	703	381
ACCUMULATORS	162	154	162	169	162	178
LINES	26	29	26	29	26	29
REGULATORS	111	86	111	96	111	103
VALVES						
VENT ASSEMBLY	204	112	204	131	204	148
LINES	65	43	65	49	65	52
VALVES						
THRUSTER ASSEMBLY	1244		1244		1244	
TOTAL SUBSYSTEM	36903		37070		37205	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
Orbiter C

FIGURE 2-51

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	LINE PRESSURE DROP (LBF/IN^{2}A)					
	20		40		60	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS	6478	23750	6486	23748	6496	23745
TOTAL PROPELLANT	1338	477	1338	477	1339	477
PROPELLANT TANKAGE	453	80	454	80	454	80
PRESSURANT AND TANKAGE	318	63	318	63	318	63
INSULATION						
CONDITIONING ASSEMBLY	255	297	255	297	255	297
HEAT EXCHANGERS	72	121	75	124	78	126
TURBOPUMPS						
GAS GENERATOR	37		37		37	
FEED ASSEMBLY	695	330	700	332	706	334
ACCUMULATORS	188	196	162	169	148	154
LINES	26	29	26	29	26	29
REGULATORS	131	117	111	96	101	86
VALVES						
VENT ASSEMBLY	201	131	204	131	206	131
LINES	65	49	65	49	66	49
VALVES						
THRUSTER ASSEMBLY	1244		1244		1244	
TOTAL SUBSYSTEM	37141		37070		37045	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
Orbiter C

FIGURE 2-52

SUBSYSTEM ELEMENTS / DESIGN REQUIREMENT	THRUST/THRUSTER (LBF)					
	925		1850		3700	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS	6546	23977	6486	23748	6428	23525
TOTAL PROPELLANT	1345	479	1338	477	1332	475
PROPELLANT TANKAGE	458	80	454	80	449	79
PRESSURANT AND TANKAGE INSULATION	318	63	318	63	317	63
CONDITIONING ASSEMBLY	255	297	255	297	255	297
HEAT EXCHANGERS	75	124	75	124	75	124
TURBOPUMPS						
GAS GENERATOR	37		37		37	
FEED ASSEMBLY	700	332	700	332	700	332
ACCUMULATORS	162	169	162	169	162	169
LINES	26	29	26	29	26	29
REGULATORS	111	96	111	96	111	96
VALVES						
VENT ASSEMBLY	204	131	204	131	204	131
LINES	65	49	65	49	65	49
VALVES						
THRUSTER ASSEMBLY	967		1244		1852	
TOTAL SUBSYSTEM	37095		37070		37382	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
Orbiter C

FIGURE 2–53

DESIGN REQUIREMENT / SUBSYSTEM ELEMENTS	SUBSYSTEM THRUST (LBF)					
	3700		7400		14800	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6486	23748	6486	23748	6486	23748
PROPELLANT TANKAGE	1338	477	1338	477	1338	477
PRESSURANT AND TANKAGE	454	80	454	80	454	80
INSULATION	318	63	318	63	318	63
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	189	251	255	297	387	344
TURBOPUMPS	22	83	75	124	234	242
GAS GENERATOR	34		37		42	
FEED ASSEMBLY						
ACCUMULATORS	350	166	700	332	1400	664
LINES	126	131	162	169	208	217
REGULATORS	18	20	26	29	39	44
VALVES	137	132	111	96	104	76
VENT ASSEMBLY						
LINES	102	75	204	131	407	263
VALVES	41	30	65	49	105	78
THRUSTER ASSEMBLY	1244		1244		1244	
TOTAL SUBSYSTEM	36115		37070		39062	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES

ORBITER C

FIGURE 2-54

DESIGN REQUIREMENT / SUBSYSTEM ELEMENTS	TOTAL IMPULSE (LB - SEC)					
	12×10^6		12.8×10^6		13×10^6	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	6122	22343	6486	23748	6599	24177
PROPELLANT TANKAGE	1299	463	1338	477	1350	481
PRESSURANT AND TANKAGE	427	75	454	80	462	81
INSULATION	316	62	318	63	318	63
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	255	297	255	297	255	297
TURBOPUMPS	75	124	75	124	75	124
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	700	332	700	332	700	332
LINES	162	169	162	169	162	169
REGULATORS	26	29	26	29	26	29
VALVES	111	96	111	96	111	96
VENT ASSEMBLY						
LINES	204	131	204	131	204	131
VALVES	65	49	65	49	65	49
THRUSTER ASSEMBLY	1244		1244		1244	
TOTAL SUBSYSTEM	35213		37070		37637	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES

ORBITER C

FIGURE 2–55

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	THRUSTER MIXTURE RATIO					
	2		4		6	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	762	1531	478	1741	378	1948
PROPELLANT TANKAGE	285	134	225	140	202	146
PRESSURANT AND TANKAGE	55	7	34	8	26	9
INSULATION	42	4	39	4	37	4
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	347	288	259	297	228	306
TURBOPUMPS	196	90	86	98	56	105
GAS GENERATOR	39		37		37	
FEED ASSEMBLY						
ACCUMULATORS	722	174	437	200	338	224
LINES	170	137	141	147	130	157
REGULATORS	37	26	28	29	24	32
VALVES	177	111	135	122	120	133
THRUSTER ASSEMBLY	609		609		609	
VENT ASSEMBLY	11	7	11	7	11	7
TOTAL SUBSYSTEM	5961		5310		5267	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES BOOSTER
Booster

FIGURE 2-56

SUBSYSTEM ELEMENTS \ DESIGN VARIABLE	EXPANSION RATIO					
	20		40		60	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	495	1808	478	1741	472	1722
PROPELLANT TANKAGE	229	142	225	140	224	139
PRESSURANT AND TANKAGE	35	8	34	8	33	8
INSULATION	39	4	39	4	39	4
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	265	300	259	297	258	296
TURBOPUMPS	92	100	86	98	85	97
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	454	207	437	200	432	197
LINES	143	149	141	147	141	147
REGULATORS	28	30	28	29	27	29
VALVES	138	124	135	122	135	121
THRUSTER ASSEMBLY	564		609		654	
VENT ASSEMBLY	11	7	11	7	11	7
TOTAL SUBSYSTEM	5409		5310		5313	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES BOOSTER
Booster

FIGURE 2–57

SUBSYSTEM ELEMENTS \ DESIGN VARIABLE	CHAMBER PRESSURE (LBF/IN^2 A)					
	300		500		700	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	469	1753	478	1741	488	1747
PROPELLANT TANKAGE	223	140	225	140	227	140
PRESSURANT AND TANKAGE	33	8	34	8	35	8
INSULATION	39	4	39	4	39	4
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	260	303	259	297	260	296
TURBOPUMPS	45	81	86	98	133	116
GAS GENERATOR	42		37		37	
FEED ASSEMBLY						
ACCUMULATORS	398	199	437	200	484	207
LINES	156	167	141	147	133	134
REGULATORS	35	37	28	29	24	26
VALVES	151	143	135	122	127	108
THRUSTER ASSEMBLY	762		609		531	
VENT ASSEMBLY	11	7	11	7	11	7
TOTAL SUBSYSTEM	5466		5310		5326	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES BOOSTER
Booster

FIGURE 2–58

SUBSYSTEM ELEMENTS / DESIGN VARIABLE	HYDROGEN TANK PRESSURE (LBF/IN^2 A)					
	20		25		30	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	478	1741	478	1741	478	1741
PROPELLANT TANKAGE	225	140	225	140	225	140
PRESSURANT AND TANKAGE	16	8	34	8	51	8
INSULATION	39	4	39	4	39	4
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	259	297	259	297	259	297
TURBOPUMPS	559	98	86	98	26	98
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	437	200	437	200	437	200
LINES	141	147	141	147	141	147
REGULATORS	28	29	28	29	28	29
VALVES	135	122	135	122	135	122
THRUSTER ASSEMBLY	609		609		609	
VENT ASSEMBLY	11	7	11	7	11	7
TOTAL SUBSYSTEM	5765		5310		5207	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES BOOSTER
Booster

FIGURE 2-59

DESIGN VARIABLE / SUBSYSTEM ELEMENTS	OXYGEN TANK PRESSURE (LBF/IN^2 A)					
	20		35		45	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	478	1741	478	1741	478	1741
PROPELLANT TANKAGE	225	140	225	140	225	140
PRESSURANT AND TANKAGE	34	2	34	8	34	12
INSULATION	39	4	39	4	39	4
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	259	297	259	297	259	297
TURBOPUMPS	86	771	86	98	86	74
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	437	200	437	200	437	200
LINES	141	147	141	147	141	147
REGULATORS	28	29	28	29	28	29
VALVES	135	122	135	122	135	122
THRUSTER ASSEMBLY	609		609		609	
VENT ASSEMBLY	11	7	11	7	11	7
TOTAL SUBSYSTEM	5977		5310		5290	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES BOOSTER
Booster

FIGURE 2-60

SUBSYSTEM ELEMENTS \ DESIGN VARIABLE	HYDROGEN MINIMUM THRUSTER INLET TEMPERATURE (°R)					
	100		200		300	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	481	1725	478	1741	475	1777
PROPELLANT TANKAGE	226	140	225	140	224	141
PRESSURANT AND TANKAGE	34	8	34	8	33	8
INSULATION	39	4	39	4	39	4
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	206	297	259	297	321	299
TURBOPUMPS	88	97	86	98	85	99
GAS GENERATOR	36		37		39	
FEED ASSEMBLY						
ACCUMULATORS	318	197	437	200	622	204
LINES	123	147	141	147	158	147
REGULATORS	28	29	28	29	27	29
VALVES	114	122	135	122	148	122
THRUSTER ASSEMBLY	609		609		609	
VENT ASSEMBLY	11	7	11	7	11	7
TOTAL SUBSYSTEM	5087		5310		5628	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
Booster

FIGURE 2-61

SUBSYSTEM ELEMENTS / DESIGN VARIABLE	OXYGEN MINIMUM THRUSTER INLET TEMPERATURE (°R)					
	300		350		400	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	476	1737	478	1741	479	1745
PROPELLANT TANKAGE	225	140	225	140	225	140
PRESSURANT AND TANKAGE	34	8	34	8	34	8
INSULATION	39	4	39	4	39	4
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	259	296	259	297	260	294
TURBOPUMPS	86	97	86	98	87	98
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	435	166	437	200	439	230
LINES	141	139	141	147	141	154
REGULATORS	28	29	28	29	28	29
VALVES	135	114	135	122	135	136
THRUSTER ASSEMBLY	609		609		609	
VENT ASSEMBLY	11	7	11	7	11	7
TOTAL SUBSYSTEM	5252		5310		5369	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
Booster

FIGURE 2-62

SUBSYSTEM ELEMENTS / DESIGN VARIABLE	LINE PRESSURE DROP (LBF/IN^2 A)					
	20		40		60	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	477	1741	478	1741	478	1742
PROPELLANT TANKAGE	225	140	225	140	225	140
PRESSURANT AND TANKAGE	34	8	34	8	34	8
INSULATION	39	4	39	4	39	4
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	259	297	259	297	259	297
TURBOPUMPS	83	96	86	98	90	99
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	434	198	437	200	440	201
LINES	164	171	141	147	129	134
REGULATORS	28	30	28	29	27	29
VALVES	161	149	135	122	122	108
THRUSTER ASSEMBLY	609		609		609	
VENT ASSEMBLY	11	7	11	7	11	7
TOTAL SUBSYSTEM	5402		5310		5269	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
Booster

FIGURE 2-63

DESIGN REQUIREMENT / SUBSYSTEM ELEMENTS	THRUST/THRUSTER (LBF)					
	925		1850		3700	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	482	1758	478	1741	473	1725
PROPELLANT TANKAGE	226	140	225	140	224	140
PRESSURANT AND TANKAGE	34	8	34	8	33	8
INSULATION	39	4	39	4	39	4
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	259	297	259	297	259	297
TURBOPUMPS	86	98	86	98	86	98
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	437	200	437	200	437	200
LINES	110	115	141	147	182	190
REGULATORS	19	20	28	29	42	44
VALVES	94	86	135	122	196	173
THRUSTER ASSEMBLY	456		609		915	
VENT ASSEMBLY	11	7	11	7	11	7
TOTAL SUBSYSTEM	4555		5310		5818	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
Booster

FIGURE 2-64

SUBSYSTEM ELEMENTS \ DESIGN REQUIREMENT	SUBSYSTEM THRUST (LBF)					
	3700		7400		14800	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	478	1741	478	1741	478	1741
PROPELLANT TANKAGE	225	140	225	140	224	140
PRESSURANT AND TANKAGE	34	8	34	8	34	4
INSULATION	39	4	39	4	39	4
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	192	251	259	297	394	344
TURBOPUMPS	26	73	86	98	266	171
GAS GENERATOR	34		37		43	
FEED ASSEMBLY						
ACCUMULATORS	218	100	437	200	874	399
LINES	110	115	141	147	182	190
REGULATORS	19	20	28	29	42	44
VALVES	94	86	135	122	196	173
THRUSTER ASSEMBLY	609		609		609	
VENT ASSEMBLY	11	7	11	7	11	7
TOTAL SUBSYSTEM	4634		5310		6614	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES
Booster

FIGURE 2–65

DESIGN REQUIREMENT / SUBSYSTEM ELEMENTS	TOTAL IMPULSE (LB - SEC)					
	4.00×10^5		8.64×10^5		12×10^5	
	H_2	O_2	H_2	O_2	H_2	O_2
PROPELLANT AND COMPONENTS						
TOTAL PROPELLANT	242	842	478	1741	647	2392
PROPELLANT TANKAGE	166	111	225	140	262	157
PRESSURANT AND TANKAGE	16	4	34	8	47	11
INSULATION	35	2	39	4	41	5
CONDITIONING ASSEMBLY						
HEAT EXCHANGERS	259	297	259	297	259	297
TURBOPUMPS	86	98	86	98	86	98
GAS GENERATOR	37		37		37	
FEED ASSEMBLY						
ACCUMULATORS	437	200	437	200	437	200
LINES	141	147	141	147	141	147
REGULATORS	28	29	28	29	28	29
VALVES	135	122	135	122	135	122
THRUSTER ASSEMBLY	609		609		609	
VENT ASSEMBLY	11	7	11	7	11	7
TOTAL SUBSYSTEM	4059		5310		6203	

TURBOPUMP APS COMPONENT WEIGHT SENSITIVITIES

BOOSTER

FIGURE 2–66

DESIGN VARIABLES			SUBSYSTEM PERFORMANCE AND OPERATION***																
			SUBSYSTEM SPECIFIC IMPULSE (SEC)		SUBSYSTEM MIXTURE RATIO	ACCUMULATOR PRESSURES P_{MAX}/P_{MIN} (LBF/IN^2 A)		PUMP DISCHARGE PRESSURE (LBF/IN^{2}A)		FLOW RATE* (LB/SEC)		BYPASS FLOW** (LB/SEC)		TURBINE PRESSURE RATIO		CONDITIONER MIXTURE RATIO		OUTLET TEMPERATURE (°R)	
			TRANS	ATT		H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2
		BASELINE	424	416	3.87	2318/1021	2066/914	1182	1040	3.66	14.18	0.734	0.473	16.70	4.65	2.55	2.69	253	425
THRUSTER MIXTURE RATIO	2	4	410	402	2.04					6.06	12.34	1.213	0.414						
	6		403	396	5.63					2.82	15.88	0.566	0.531						
ATTITUDE THRUSTER EXPANSION RATIO	40	60		411						3.69	14.31								
	80			419						3.63	14.12								
TRANSLATION THRUSTER EXPANSION RATIO	60	120	416									0.747	0.482						
CHAMBER PRESSURE (LBF/IN^2 A)	300	500	423	416	3.97	1444/636	1290/571	744	652	3.58	14.26	0.696	0.494		1.57	4.60		252	428
	700		420	413	3.79	3194/1407	2841/1257	1619	1427	3.79	14.36	0.861	0.460		18.97	1.93		255	426
HYDROGEN TANK PRESSURE (LBF/IN^2 A)	20	25	424	416	3.87					3.66	14.18	0.736				2.53			
	30		424	416	3.87					3.66	14.18	0.732				2.56			
OXYGEN TANK PRESSURE (LBF/IN^2 A)	25	30	424	416	3.87					3.66	14.18		0.473		4.80				
	35		424	416	3.87					3.66	14.18		0.473		4.51				
HYDROGEN MINIMUM INJECTOR INLET TEMPERATURE (°R)	100	200	426	418	3.80					3.62	14.08	0.494	0.482		4.03	1.37		132	
	300		418	410	3.97					3.63	14.42	1.098	0.470		5.37	4.34		374	
OXYGEN MINIMUM INJECTOR INLET TEMPERATURE (°R)	300	350	425	417	3.88					3.64	14.11	0.733	0.404		10.01	2.56			359
	400		423	415	3.86					3.66	14.14	0.734	0.533		2.83	2.53			491
LINE PRESSURE DROP (LBF/IN^2 A)	20	40	424	416	3.88	2254/993	2002/886	1149	1008	3.65	14.19	0.725	0.473		3.94	2.61		253	423
	60		423	416	3.86	2384/1050	2131/943	1214	1073	3.67	14.17	0.743	0.474		5.52	2.48		254	427
THRUST/THRUSTER (LBF)	925	1850	420	412						3.69	14.28	0.370	0.239						
	3700		428	420						3.61	13.99	1.453	0.937						
SUBSYSTEM THRUST (LBF)	3700	7400								1.83	7.09	0.367	0.237						
	14800									7.32	28.36	1.468	0.946						
TOTAL IMPULSE (10^6 LB-SEC)		12.7																	

*TOTAL FLOW RATE SIZED BY ATTITUDE SPECIFIC IMPULSE
**BYPASS FLOW SIZED BY TRANSLATION SPECIFIC IMPULSE
***UNLISTED VALUES ARE THE SAME AS THE BASELINE

DESIGN CONDITIONS FOR WEIGHT SENSITIVITIES – ORBITER B

FIGURE 2-66

DESIGN VARIABLES			SUBSYSTEM PERFORMANCE AND OPERATION***																
			SUBSYSTEM SPECIFIC IMPULSE (SEC)		SUBSYSTEM MIXTURE RATIO	ACCUMULATOR PRESSURES P_{MAX}/P_{MIN} (LBF/IN^2 A)		PUMP DISCHARGE PRESSURE (LBF/IN^{2}A)		FLOW RATE* (LB/SEC)		BYPASS FLOW** (LB/SEC)		TURBINE PRESSURE RATIO		CONDITIONER MIXTURE RATIO		OUTLET TEMPERATURE (^oR)	
			TRANS	ATT		H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2
		BASELINE	424	416	3.87	2307/1021	2056/914	1176	1035	3.66	14.18	0.733	0.473	16.70	4.67	2.54	2.69	253	425
THRUSTER MIXTURE RATIO		4																	
	2		410	402	2.04					6.06	12.34	1.212	0.413						
	6		403	396	5.63					2.82	15.88	0.566	0.531						
ATTITUDE THRUSTER EXPANSION RATIO		60																	
	40			411						3.69	14.31								
	80			419						3.63	14.12								
TRANSLATION THRUSTER EXPANSION RATIO		120																	
	60		416									0.747	0.482						
CHAMBER PRESSURE (LBF/IN^2 A)		500																	
	300		424	416	3.97	1437/636	1285/571	741	649	3.58	14.26	0.694	0.494		1.57	4.58		252	427
	700		421	413	3.79	3180/1407	2828/1257	1612	1421	3.79	14.36	0.861	0.459		19.00	1.93		254	426
HYDROGEN TANK PRESSURE (LBF/IN^2 A)		25																	
	20		424	416	3.87					3.66	14.18	0.735				2.53			
	30		424	416	3.87					3.66	14.18	0.731				2.55			
OXYGEN TANK PRESSURE (LBF/IN^2 A)		30																	
	20		424	416	3.87					3.66	14.18		0.473		4.97				
	40		424	416	3.87					3.66	14.18		0.473		4.39				
HYDROGEN MINIMUM INJECTOR INLET TEMPERATURE (^oR)		200																	
	100		426	419	3.80					3.68	13.97	0.494	0.481		4.04	1.37		132	
	300		418	410	3.97					3.63	14.42	1.096	0.470		5.39	4.33		373	
OXYGEN MINIMUM INJECTOR INLET TEMPERATURE (^oR)		350																	
	300		425	417	3.88					3.64	14.11	0.732	0.404		10.04	2.55			359
	400		423	415	3.86					3.66	14.14	0.734	0.533		2.84	2.53			491
LINE PRESSURE DROP (LBF/IN^2 A)		40																	
	20		424	416	3.88	2244/993	1994/886	1144	1004	3.65	14.19	0.724	0.473		3.95	2.61		253	423
	60		424	416	3.86	2373/1050	2122/943	1209	1068	3.67	14.17	0.742	0.473		5.54	2.48		253	426
THRUST/THRUSTER (LBF)		1850																	
	925		420	412						3.69	14.28	0.370	0.239						
	3700		428	420						3.61	13.99	1.452	0.937						
SUBSYSTEM THRUST (LBF)		7400																	
	3700									1.83	7.09	0.367	0.237						
	14800									7.32	28.36	1.466	0.946						
TOTAL IMPULSE (10^6 LB-SEC)		12.8																	

*TOTAL FLOW RATE SIZED BY ATTITUDE SPECIFIC IMPULSE
**BYPASS FLOW SIZED BY TRANSLATION SPECIFIC IMPULSE
***UNLISTED VALUES ARE THE SAME AS THE BASELINE

DESIGN CONDITIONS FOR WEIGHT SENSITIVITIES – ORBITER C

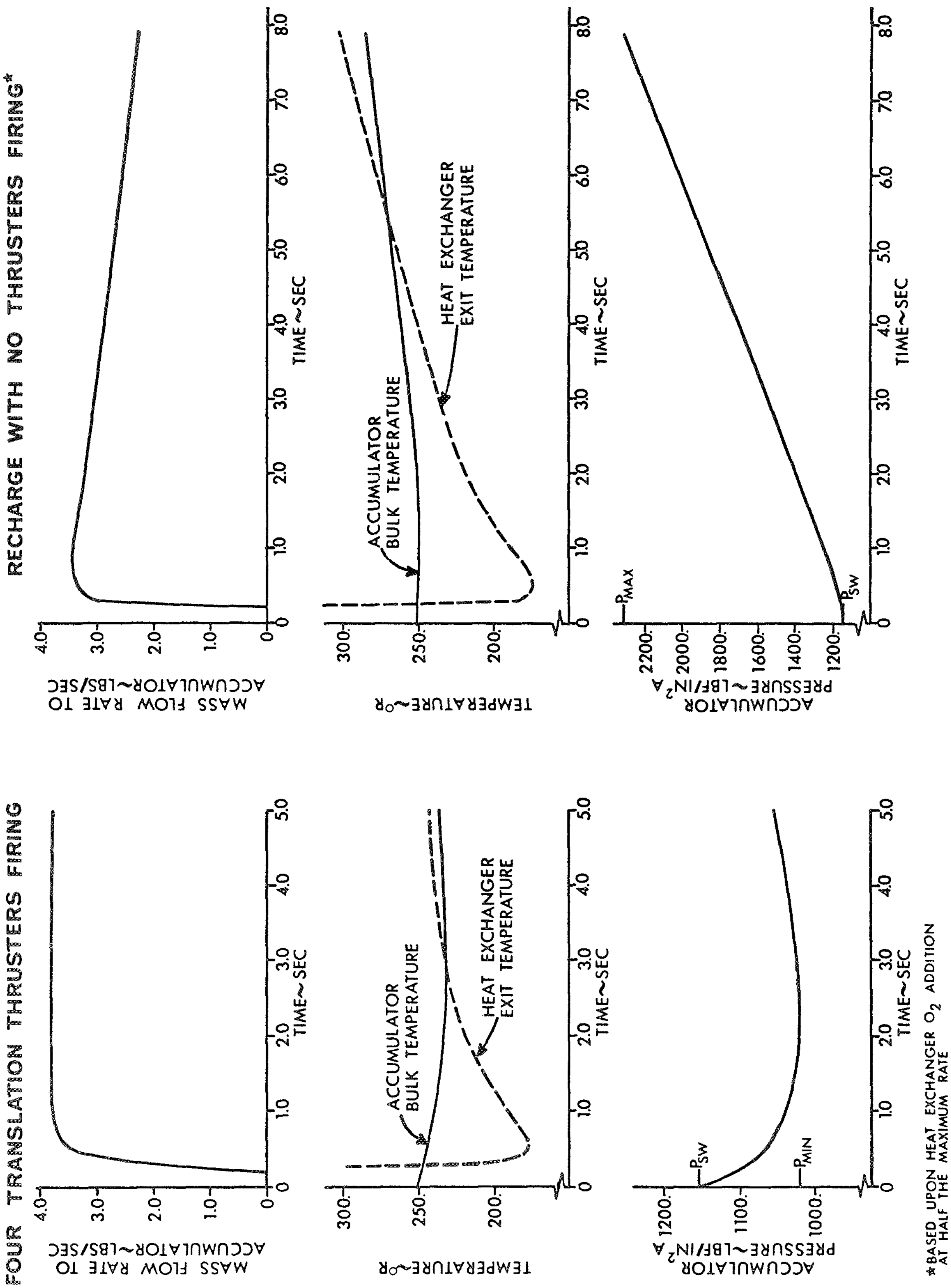
FIGURE 2-66b

DESIGN VARIABLES			SUBSYSTEM PERFORMANCE AND OPERATION*															
			SUBSYSTEM SPECIFIC IMPULSE (SEC)	SUBSYSTEM MIXTURE RATIO	ACCUMULATOR PRESSURES P_{MAX}/P_{MIN} (LBF/IN^2 A)		PUMP DISCHARGE PRESSURE (LBF/IN^{2}A)		FLOW RATE (LB/SEC)		BYPASS FLOW (LB/SEC)		TURBINE EXPANSION RATIO		CONDITIONER MIXTURE RATIO		OUTLET TEMPERATURE (°R)	
					H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2	H_2	O_2
		BASELINE	411	3.87	2532/1021	2267/914	1288	1140	3.70	14.31	0.771	0.495	16.70	4.21	2.61	2.69	260	433
THRUSTER MIXTURE RATIO	2 6	4	397 391	2.05 5.63					6.11 2.85	12.54 16.05	1.273 0.595	0.433 0.556						
THRUSTER EXPANSION RATIO	20 60	40	395 416						3.85 3.66	14.85 14.12	0.801 0.762	0.514 0.489						
CHAMBER PRESSURE (LBF/IN^2 A)	300 700	500	410 408	3.98 3.79	1577/636 3489/1407	1416/571 3117/1257	811 1767	715 1566	3.63 3.79	14.42 14.36	0.744 0.902	0.517 0.481		1.55 18.05	4.81 1.98		259 261	436 434
HYDROGEN TANK PRESSURE (LBF/IN^2 A)	20 30	25	411 411	3.87 3.87					3.70 3.70	14.31 14.31	0.772 0.769				2.60 2.63			
OXYGEN TANK PRESSURE (LBF/IN^2 A)	20 45	35	411 411	3.87 3.87					3.70 3.70	14.31 14.31		0.495 0.495		4.60 3.97				
HYDROGEN MINIMUM INJECTOR INLET TEMPERATURE (°R)	100 300	200	413 405	3.80 3.98					3.74 3.67	14.18 14.60	0.517 1.176	0.503 0.492		3.68 4.86	1.41 4.55		136 384	
OXYGEN MINIMUM INJECTOR INLET TEMPERATURE (°R)	300 400	350	412 410	3.88 3.87					3.68 3.71	14.27 14.34	0.770 0.771	0.422 0.558		9.27 2.67	2.62 2.60			364 502
LINE PRESSURE DROP (LBF/IN^2 A)	20 60	40	411 411	3.88 3.87	2463/993 2604/1050	2197/886 2339/943	1253 1324	1106 1176	3.69 3.70	14.32 14.31	0.762 0.780	0.494 0.495		3.61 4.97	2.68 2.55		259 260	431 435
THRUST/THRUSTER (LBF)	925 3700	1850	407 415						3.73 3.66	14.42 14.17	0.389 1.526	0.250 0.980						
SUBSYSTEM THRUST (LBF)	3700 14800	7400							1.85 7.40	7.16 28.62	0.386 1.542	0.248 0.990						
TOTAL IMPULSE (10^6 LBF-SEC)		0.864																

*UNLISTED VALUES ARE THE SAME AS THE BASELINE.

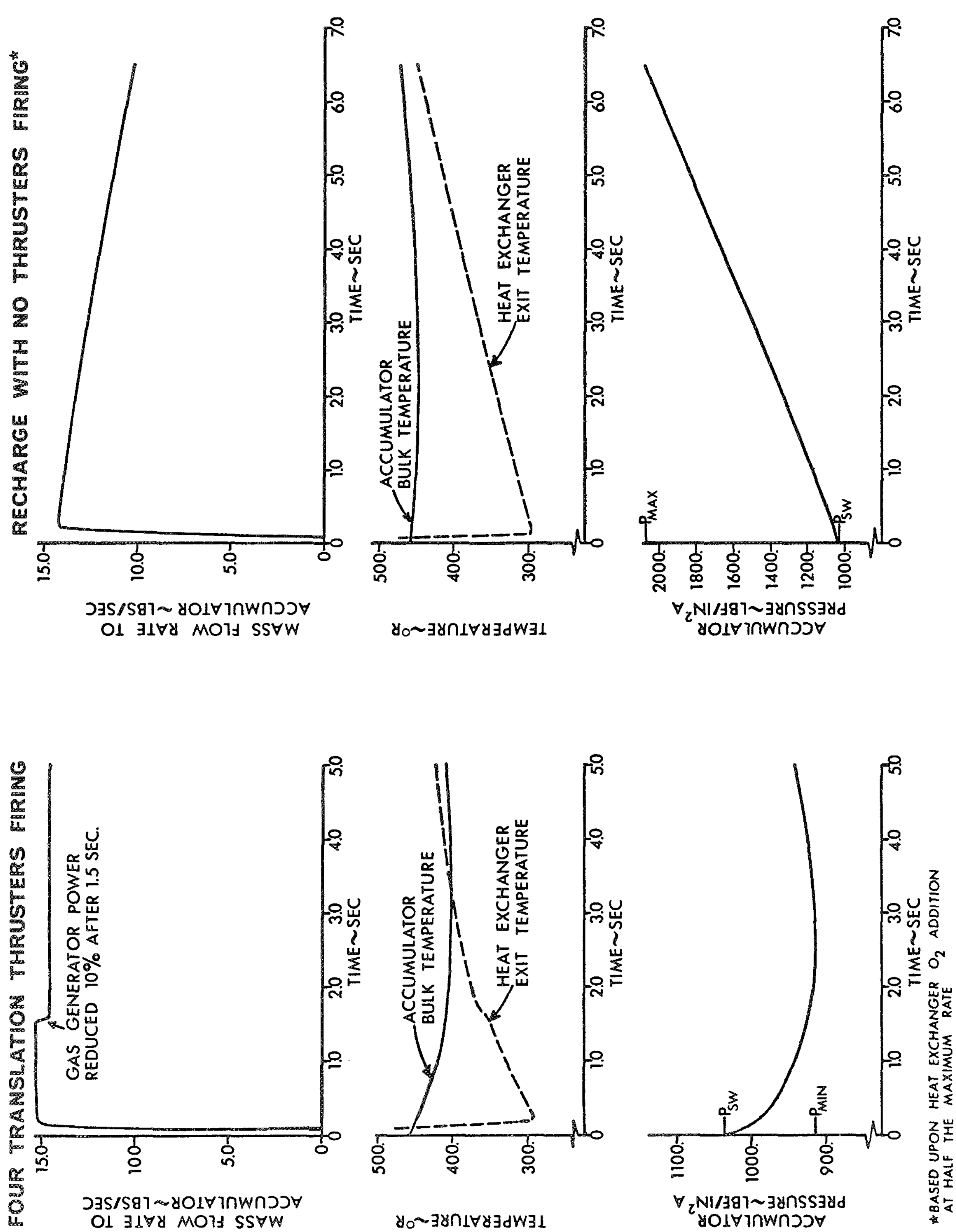
DESIGN CONDITIONS FOR WEIGHT SENSITIVITIES – BOOSTER

FIGURE 2-66c



HYDROGEN CONDITIONING ASSEMBLY PERFORMANCE

FIGURE 2-67



OXYGEN CONDITIONING ASSEMBLY PERFORMANCE

FIGURE 2-67a

turbopump spin-up is initiated. The oxygen valve in the heat exchanger is delayed until turbopump speed has reached approximately half design speed. The conditioner assembly control concept was established to satisfy three independent design criteria:

(1) rapid start transients; (conditioner response time is a primary factor in accumulator sizing as it is directly related to accumulator volume. Slow conditioner response characteristics result in excessive accumulator weight penalties; hence, high turbine power for starting was desirable).

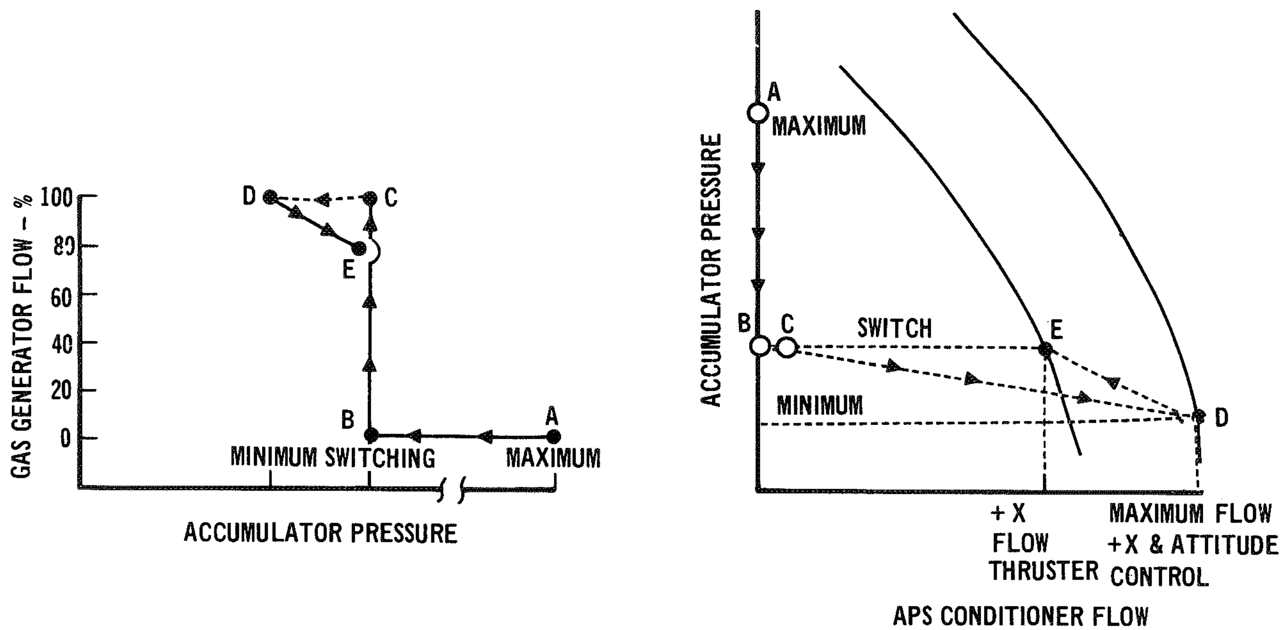
(2) minimum operating power; (the amount of gas generator flow required for steady state conditioner operation directly relates to the effective specific impulse of the APS. Hence, it was desirable to operate with minimum turbine power under normal conditions.

(3) conditioner flow variability; (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 would cycle on-off during steady state operation requiring additional life capability. Therefore it was desirable to control conditioner flow in such a way that accumulators would not recharge during +X maneuvers.

The control concept selected to satisfy these criteria provides a high gas generator flow for turbopump starting and adjusts flow, according to accumulator pressure during steady state operation. Recharge is accomplished at minimum turbine power and thus with minimum bypass flow.

Primary conditioner control is provided by throttling of the gas generator valves. These flow control valves are effectively two separate valves. One is a fast-acting, pneumatically controlled on-off valve, while the other is a slower, electrically controlled, vernier throttle valve. The vernier is located downstream of the primary valve and provides up to 20 percent flow reduction. During steady state, accumulator pressure controls the position of the throttling valves. However, the gas generator mixture ratio at any flow is also controlled by sensing combustion temperature and throttling the oxygen flow to maintain proper mixture ratio and thus temperature. Operation of these valves for conditioner control is illustrated in Figure 2-68.

Operation of the conditioner during the start transient is shown pictorially in Figure 2-68a. When the accumulator is fully charged, conditions are at point A. There is no conditioner flow and the primary gas generator valves are closed while

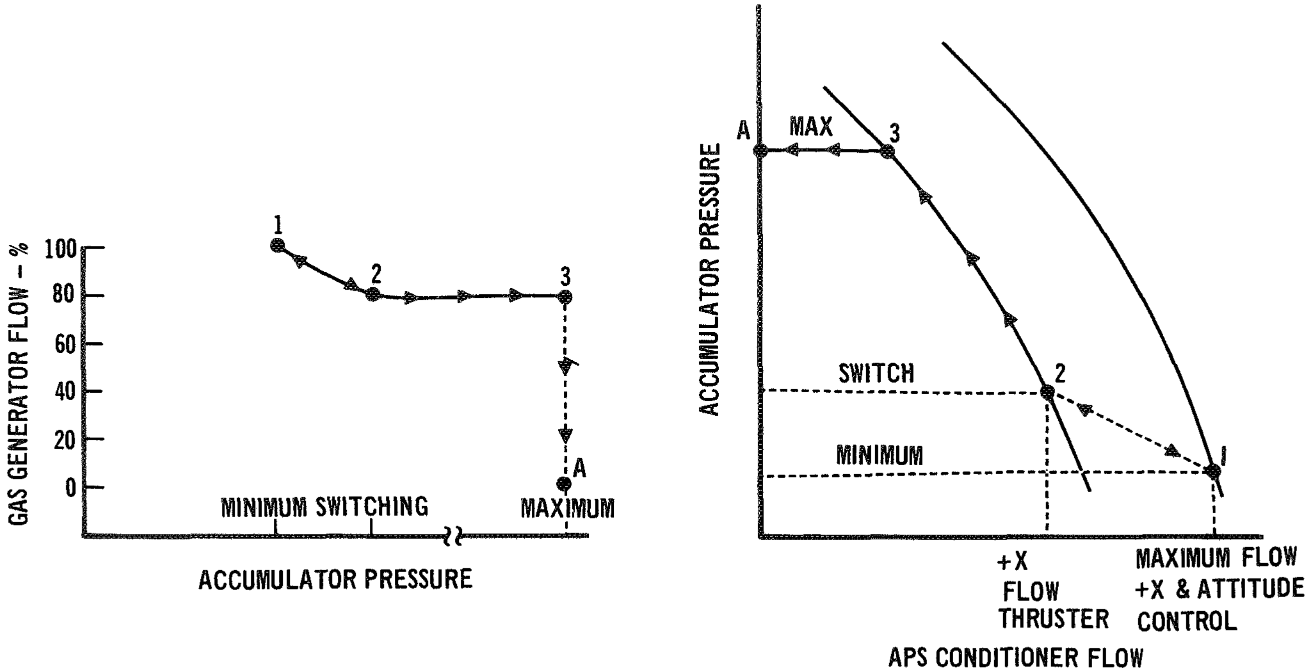


START TRANSIENT
(a)

FIGURE 2-68

throttle valves are full open. With thruster usage, accumulator pressure will decay until the switching pressure is reached (point B). The primary gas generator valves will immediately open full (point C). During the start transient the accumulator pressure continues to decay and the slower response throttle valves will seek their commanded flow rate along path C-D. The accumulator immediately starts to recharge after reaching point D and will either recharge to point E or operate steady state with gas generator valve modulation between points D-E depending on flow demands.

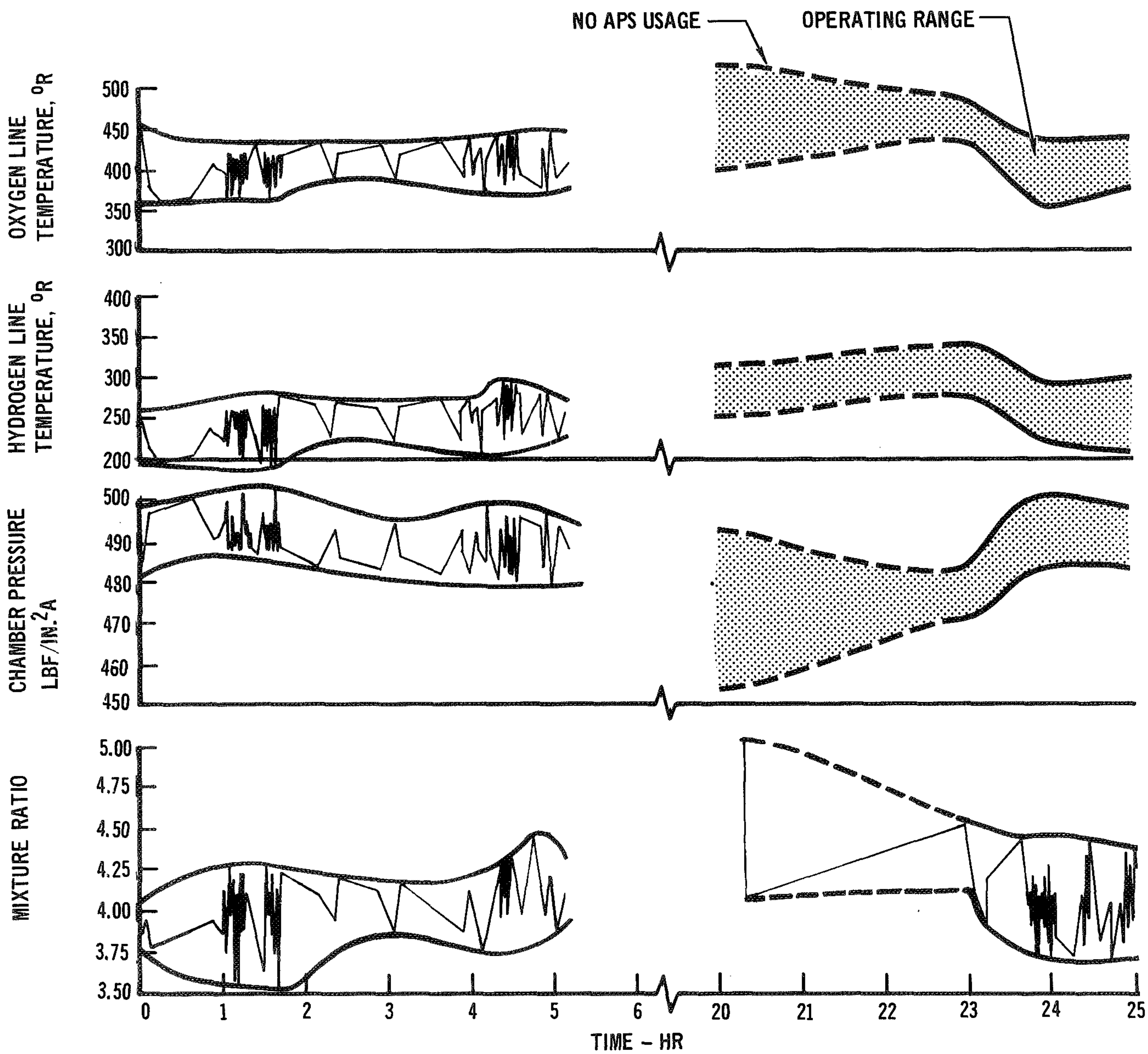
The steady state operation and recharge can be described by reference to Figure 2-68b. Steady state operation is with the gas generator valves modulating flow and thus turbine horsepower between points 1-2 dependent on thruster flow requirements. During recharge with no or low thruster flow requirements, the turbine operates at minimum power along path 2-3. After full charge is reached, the gas generator main valves close and the assembly is reset to point A by opening the gas generator throttling valves.



STEADY STATE AND RECHARGE
(b)

FIGURE 2-68

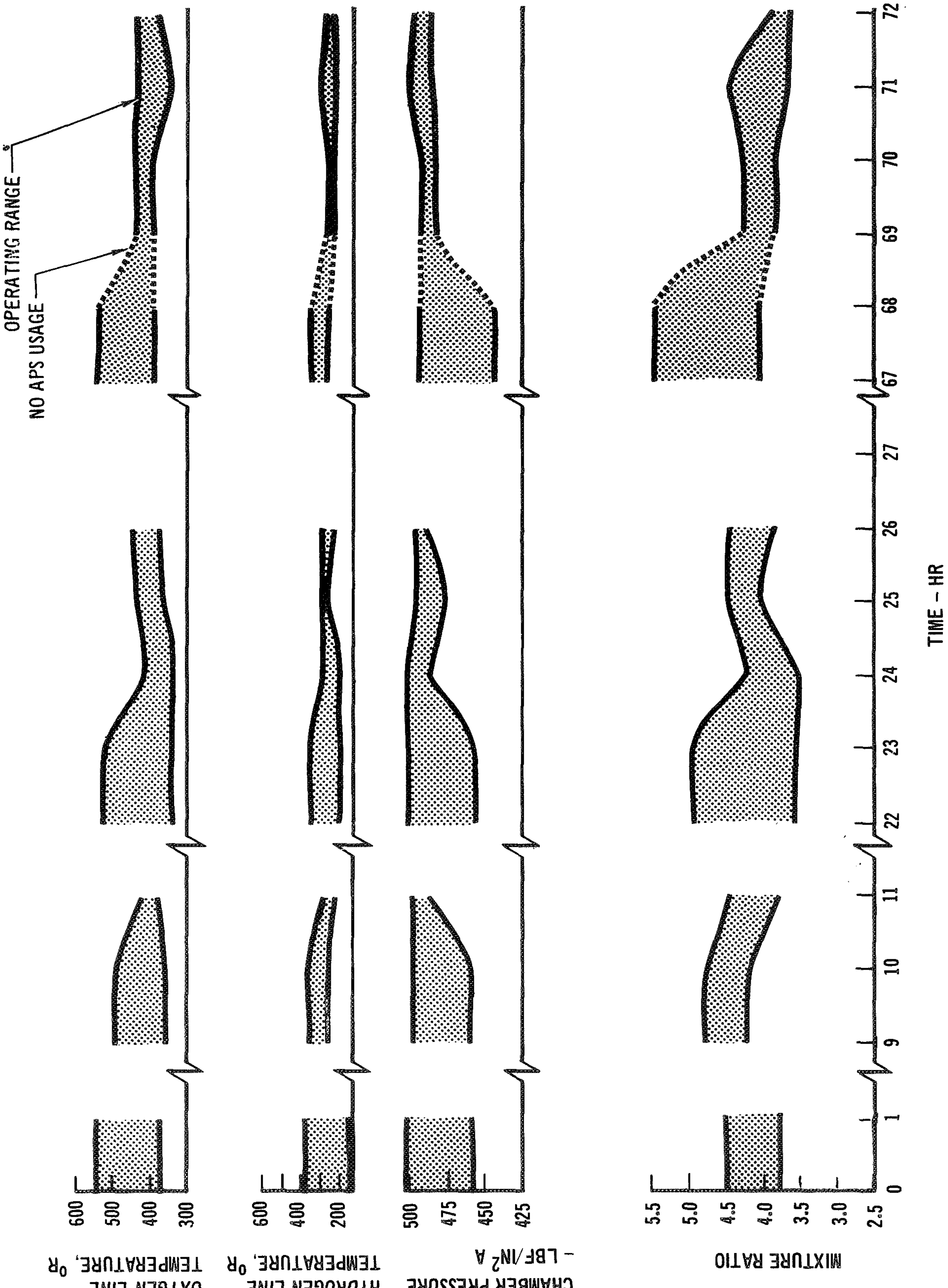
2.4 Mission Performance Analysis at Nominal and Off Design Conditions - Parametric analyses defined the APS operational characteristics under simulated mission operation. These analyses included investigation of the impact of variances in propellant conditioning temperatures, and pressure regulator performance. Analytical results are shown in Figures 2-69 through 2-80. Figures 2-69 and 2-70 illustrate subsystem operation during nominal missions, i.e. with all components and assemblies operating at their design values and with no commanded venting. Lines and accumulators are vented, however, to limit maximum pressure. Figure 2-69 shows the variation in mixture ratio during a typical third orbit rendezvous mission. As shown, during the initial phase of the mission (before docking) mixture ratio variation due to blowdown/charging of accumulators, and line/accumulator heating, are minimal. During the long period in which the orbiter is docked to the space station, propellant supply line and accumulator gas temperatures increase appreciably, which results in high mixture ratios at separation from the space station. Figures 2-71 and 2-72 show the mixture ratio which results if lines are completely vented prior to separation from the station. When vented, the system rapidly returns to design conditions and continues to operate at design conditions so long as usage is of any significance. Based on these



SUBSYSTEM OPERATING CHARACTERISTICS

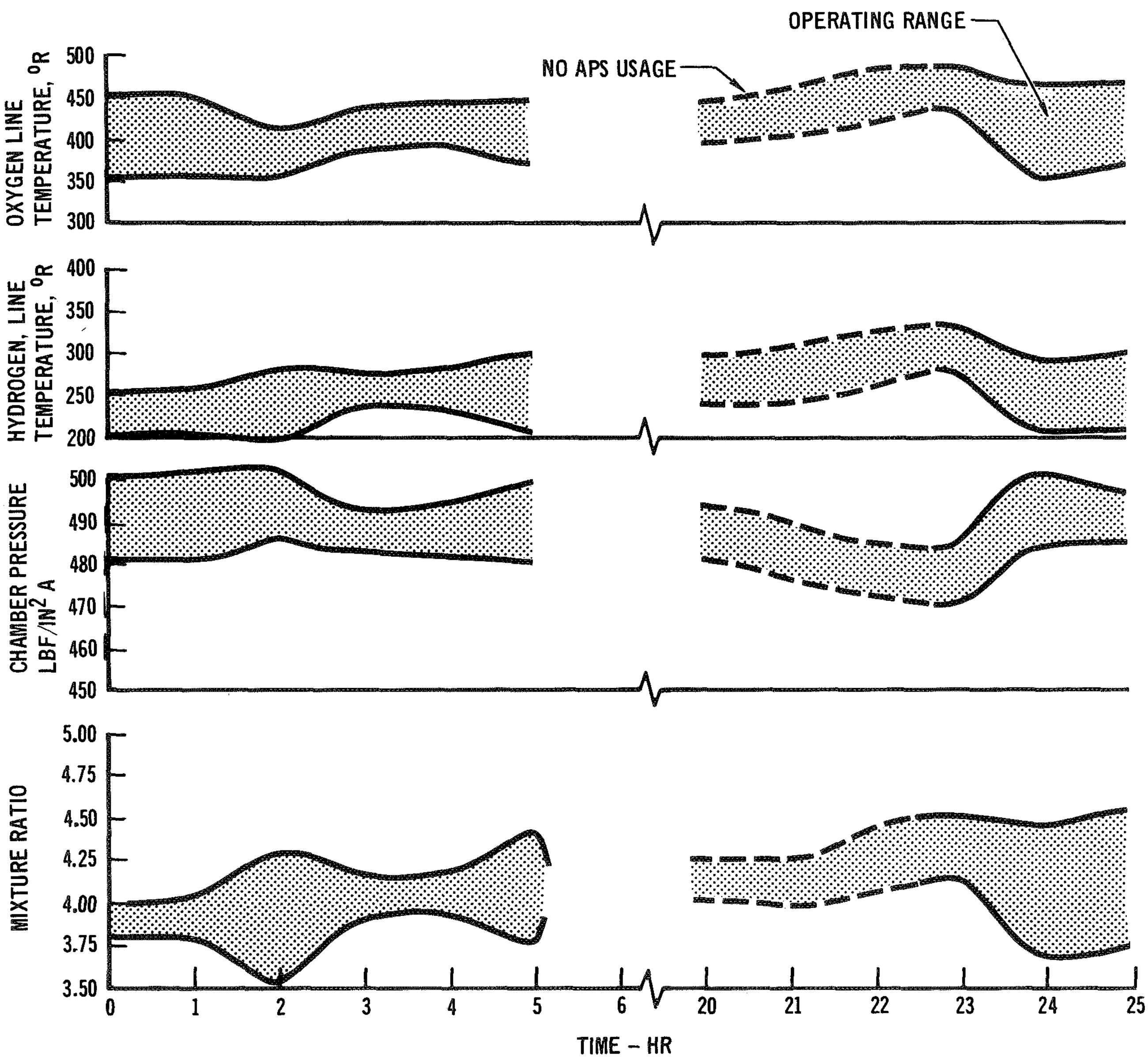
NOMINAL DESIGN CONDITIONS (NO VENT)
3RD ORBIT RENDEZVOUS

FIGURE 2–69



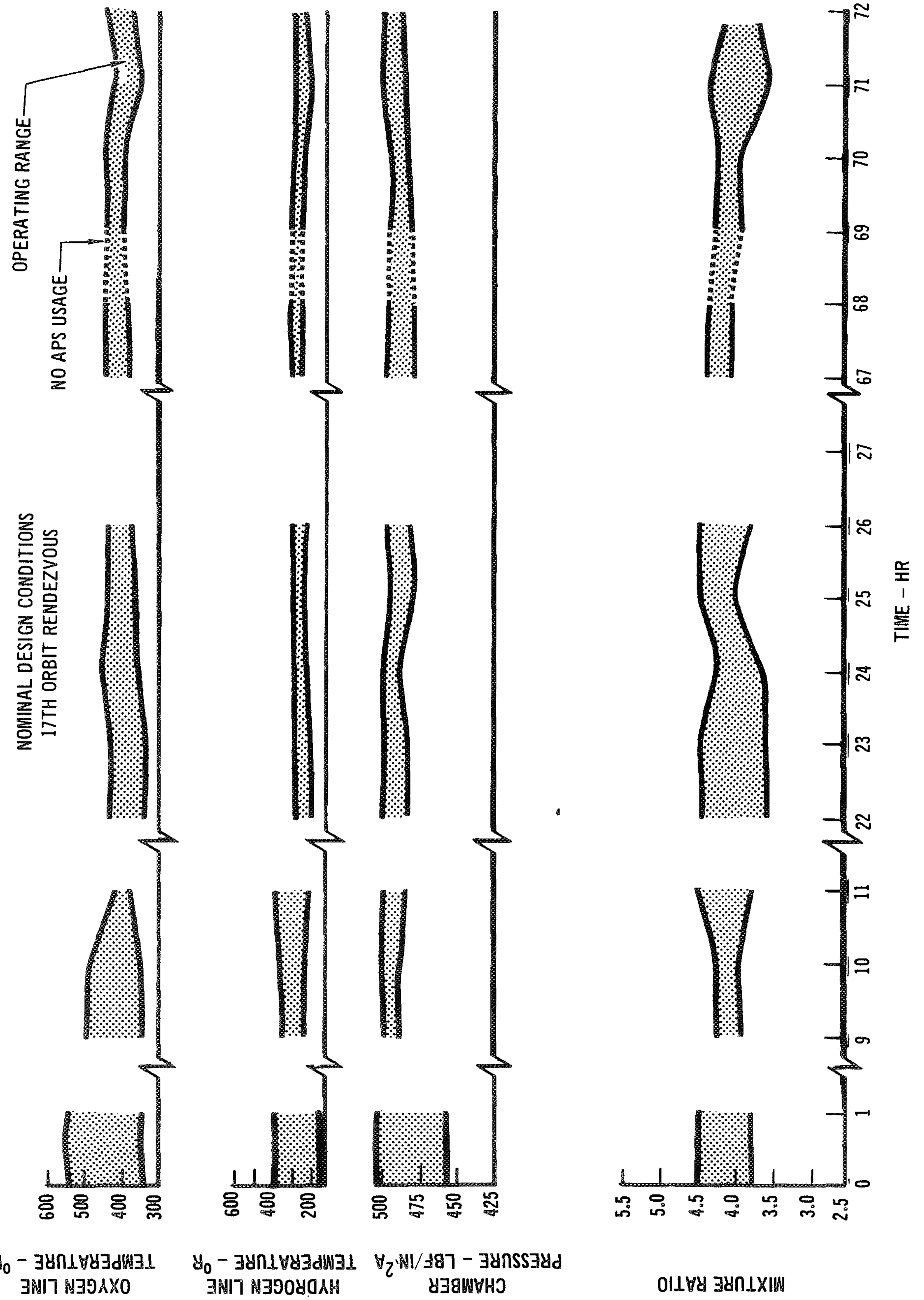
SUBSYSTEM OPERATING CHARACTERISTICS
Nominal No Vent
17 Orbit Rendezvous

FIGURE 2–70



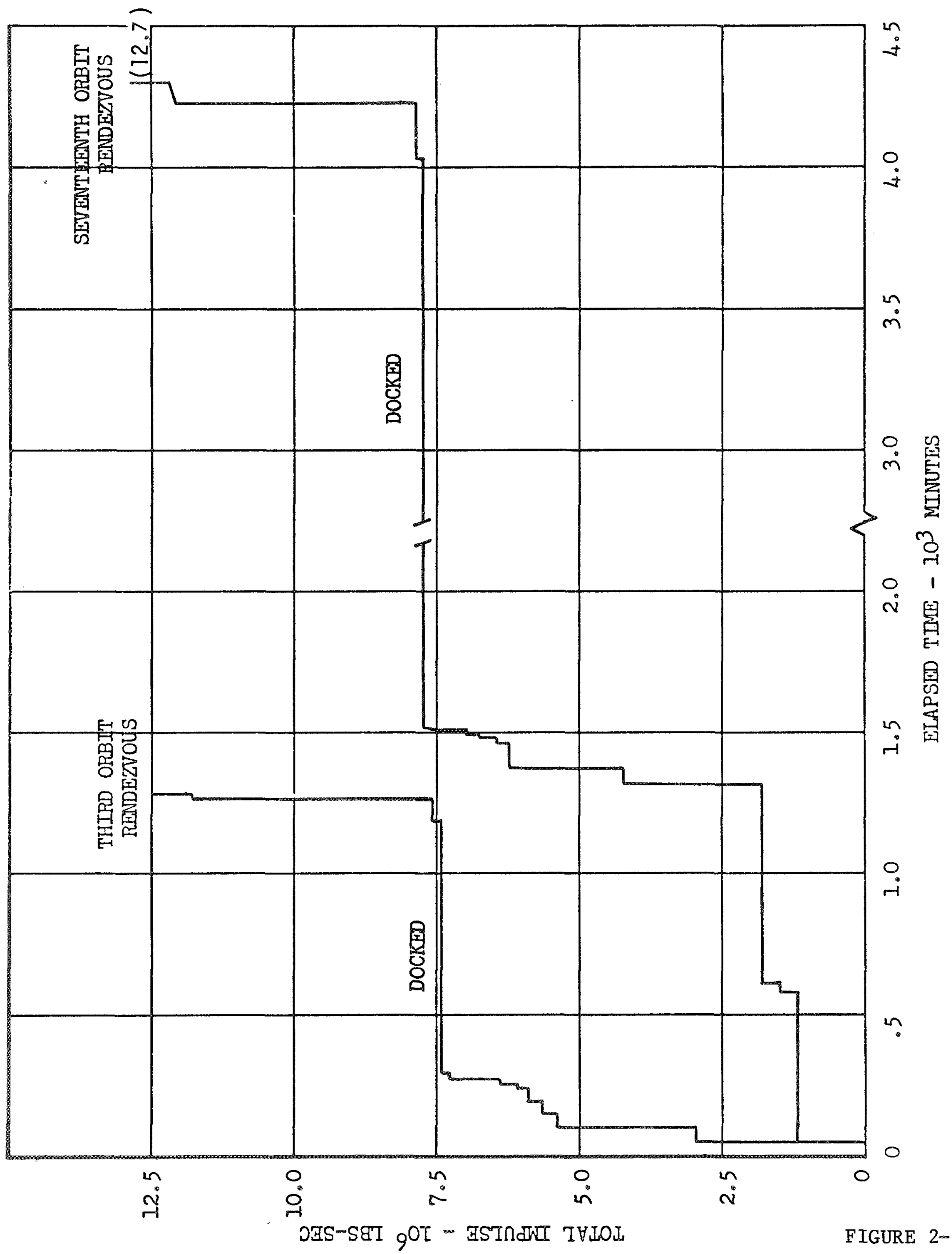
SUBSYSTEM OPERATING CHARACTERISTICS
NOMINAL DESIGN CONDITIONS -VENTED
Third Orbit Rendezvous

FIGURE 2–71



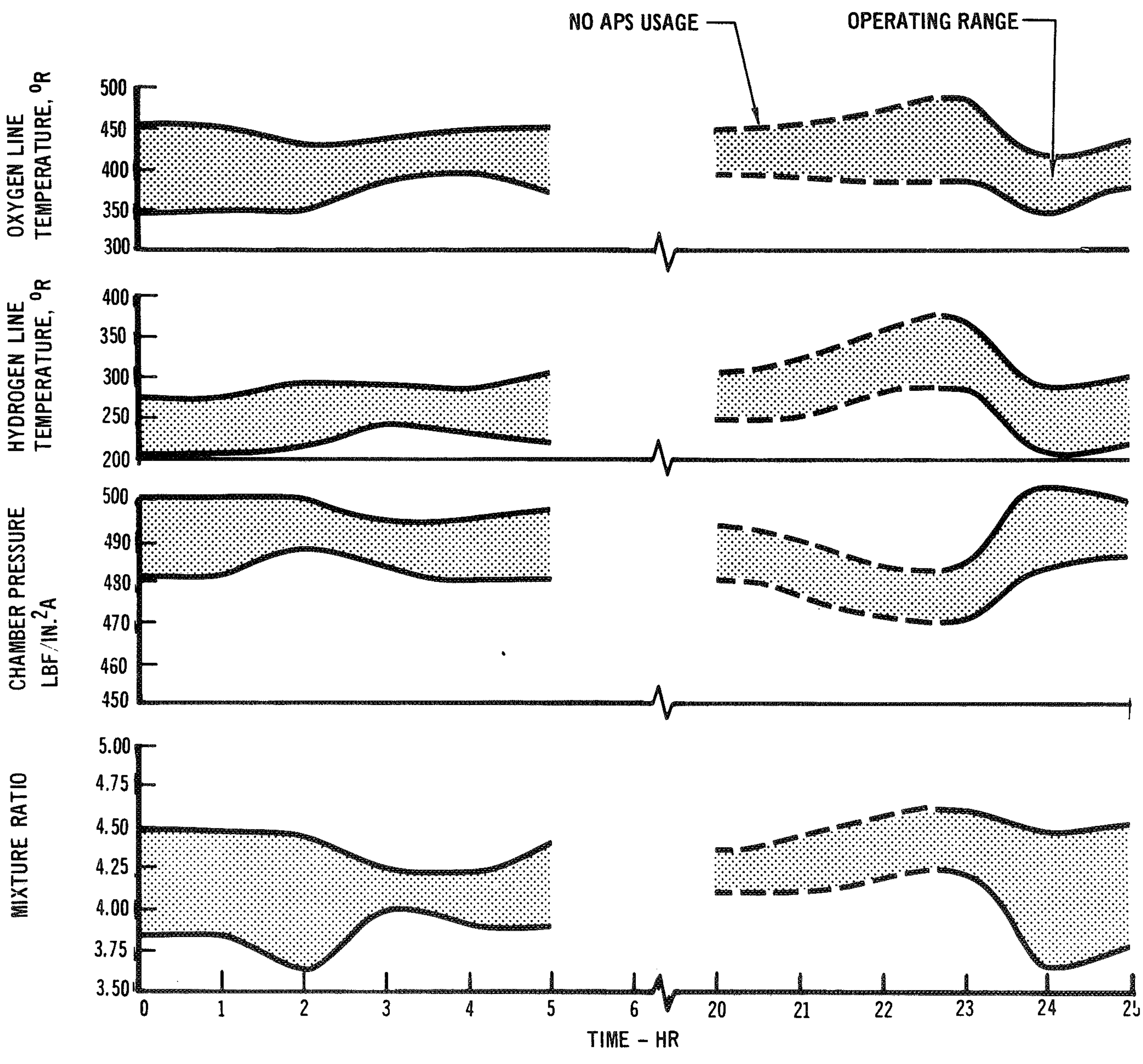
SUBSYSTEM OPERATING CHARACTERISTICS
NOMINAL DESIGN CONDITIONS – VENTED
17TH ORBIT RENDEZVOUS

FIGURE 2–72



IMPULSE TIME HISTORY - ORBITER B

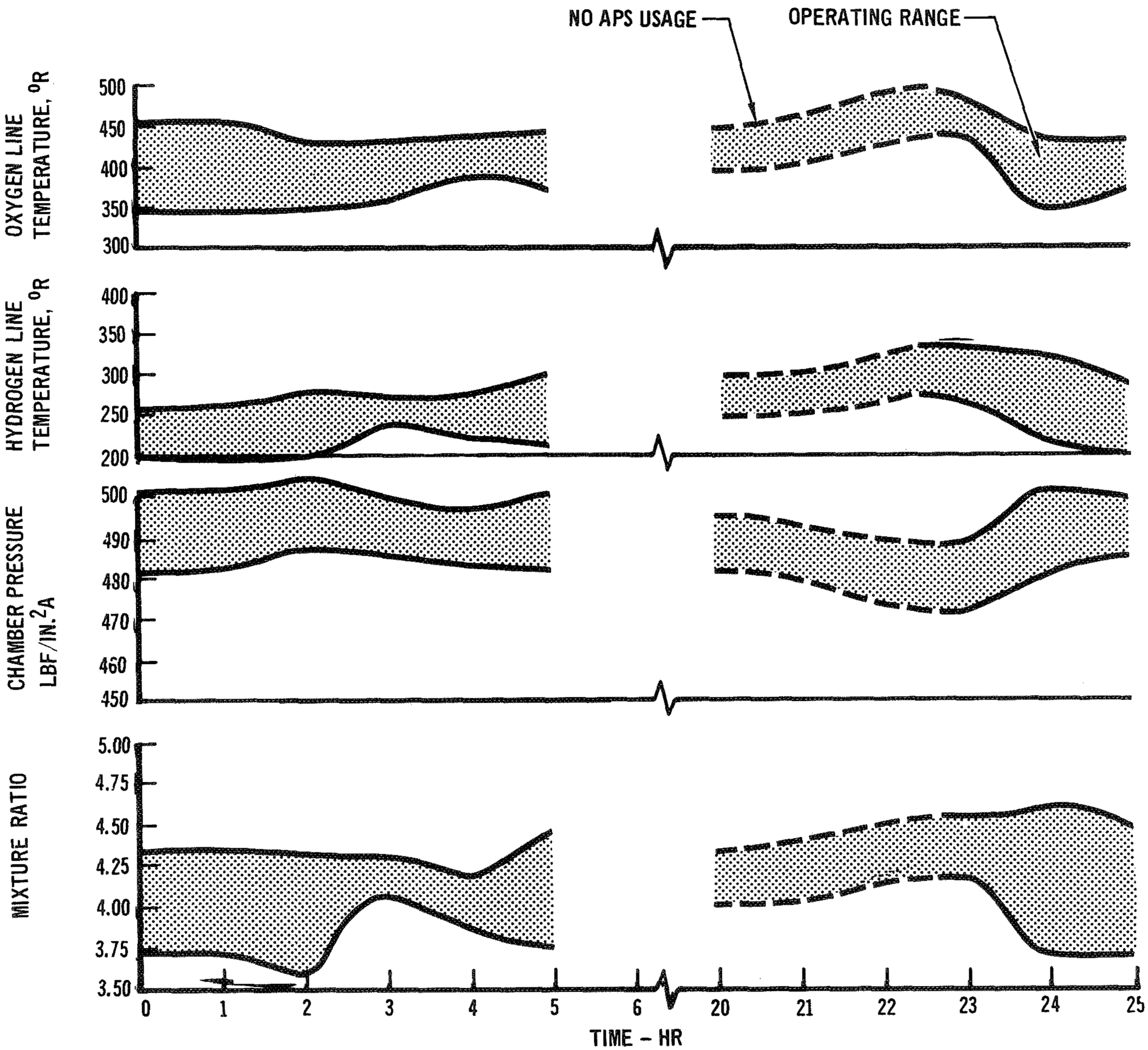
FIGURE 2-72a



SUBSYSTEM OPERATING CHARACTERISTICS

HYDROGEN CONDITIONING TEMPERATURE INCREASED 5 PERCENT –VENTED
3RD ORBIT RENDEZVOUS

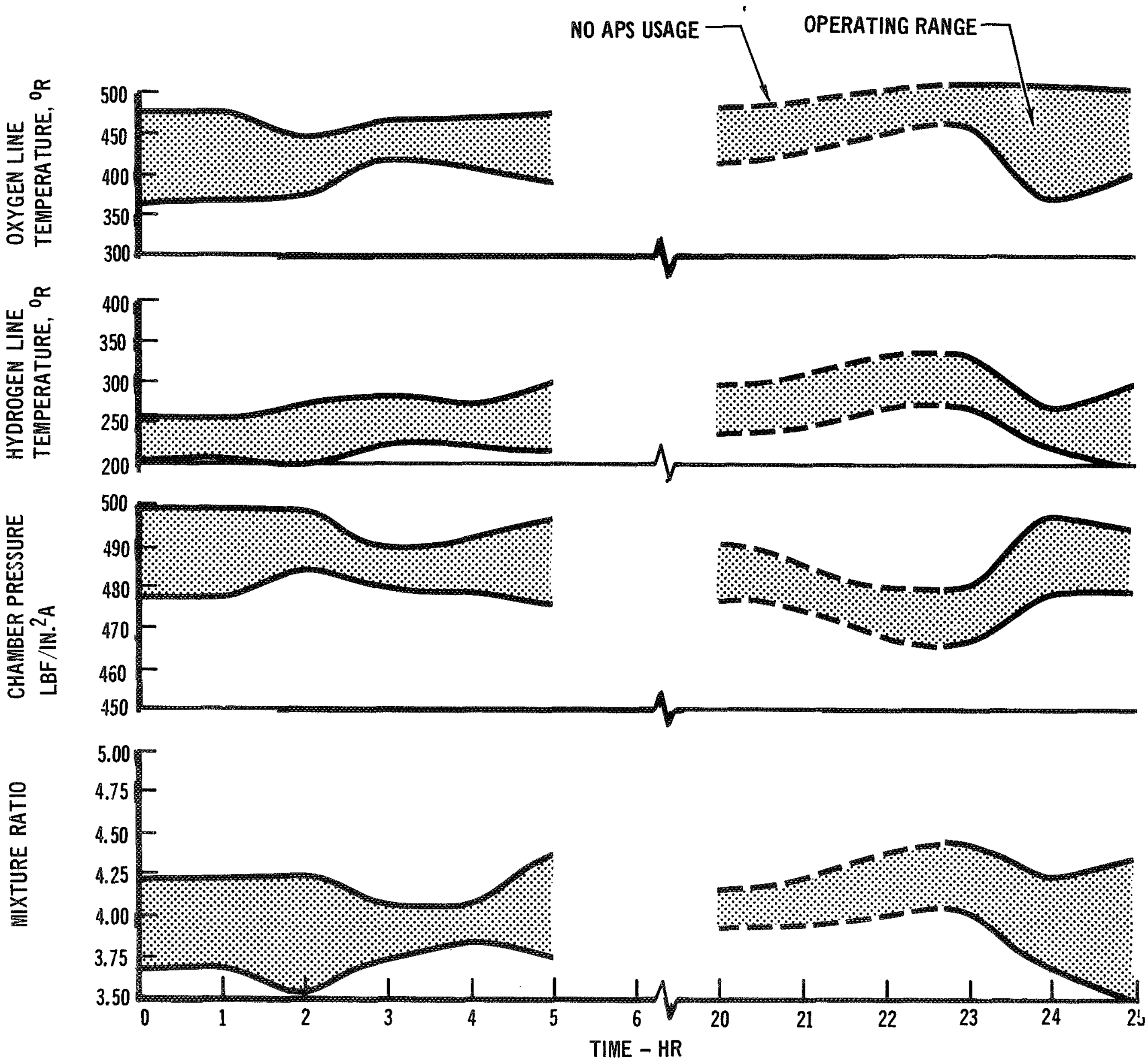
FIGURE 2–73



SUBSYSTEM OPERATING CHARACTERISTICS

HYDROGEN REGULATION PRESSURE INCREASED 5 PERCENT –VENTED
3RD ORBIT RENDEZVOUS

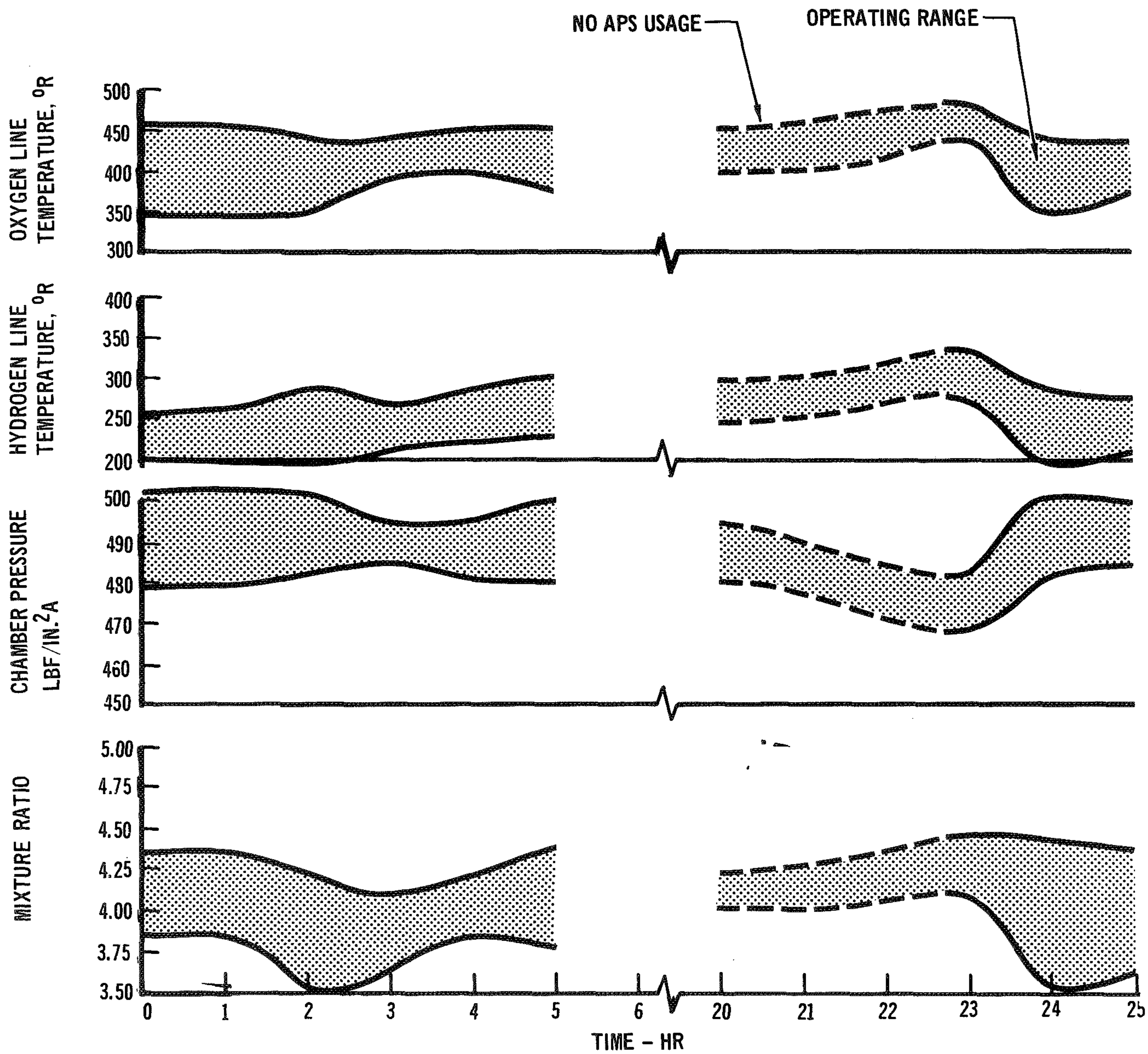
FIGURE 2–74



SUBSYSTEM OPERATING CHARACTERISTICS

OXYGEN CONDITIONING TEMPERATURE INCREASED 5 PERCENT - VENTED
3RD ORBIT RENDEZVOUS

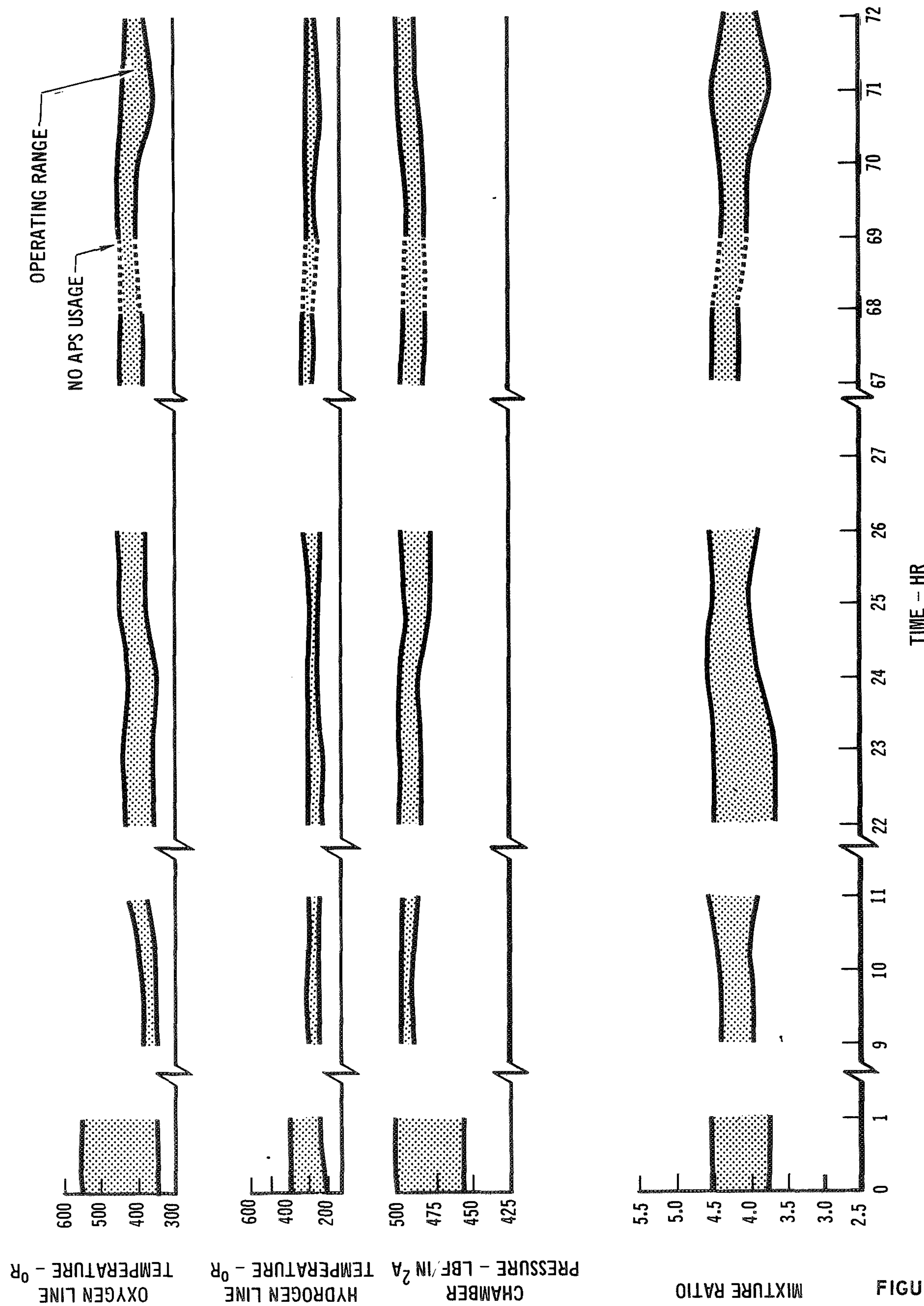
FIGURE 2-75



SUBSYSTEM OPERATING CHARACTERISTICS

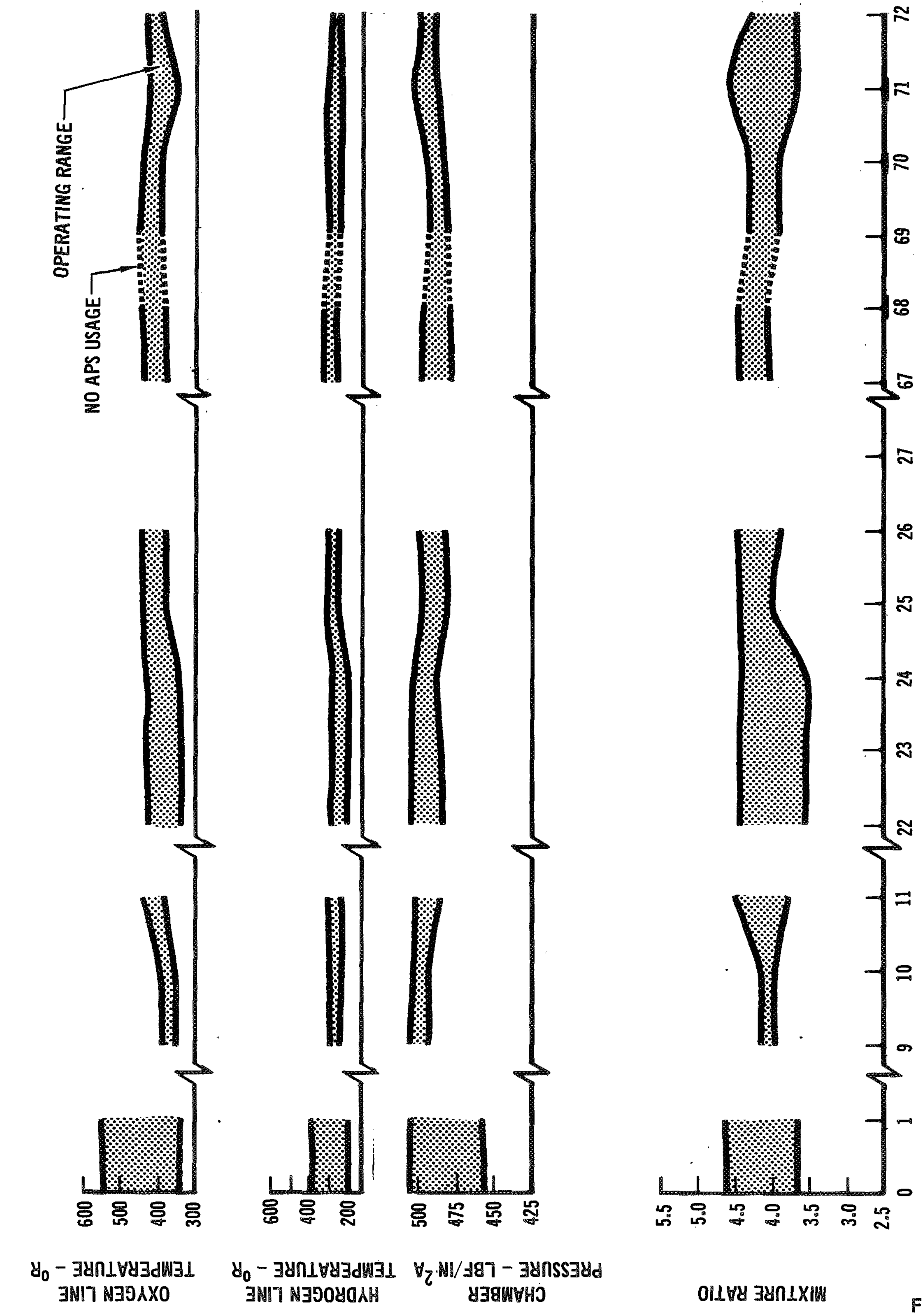
OXYGEN REGULATION PRESSURE INCREASED 5 PERCENT –VENTED
3RD ORBIT RENDEZVOUS

FIGURE 2–76



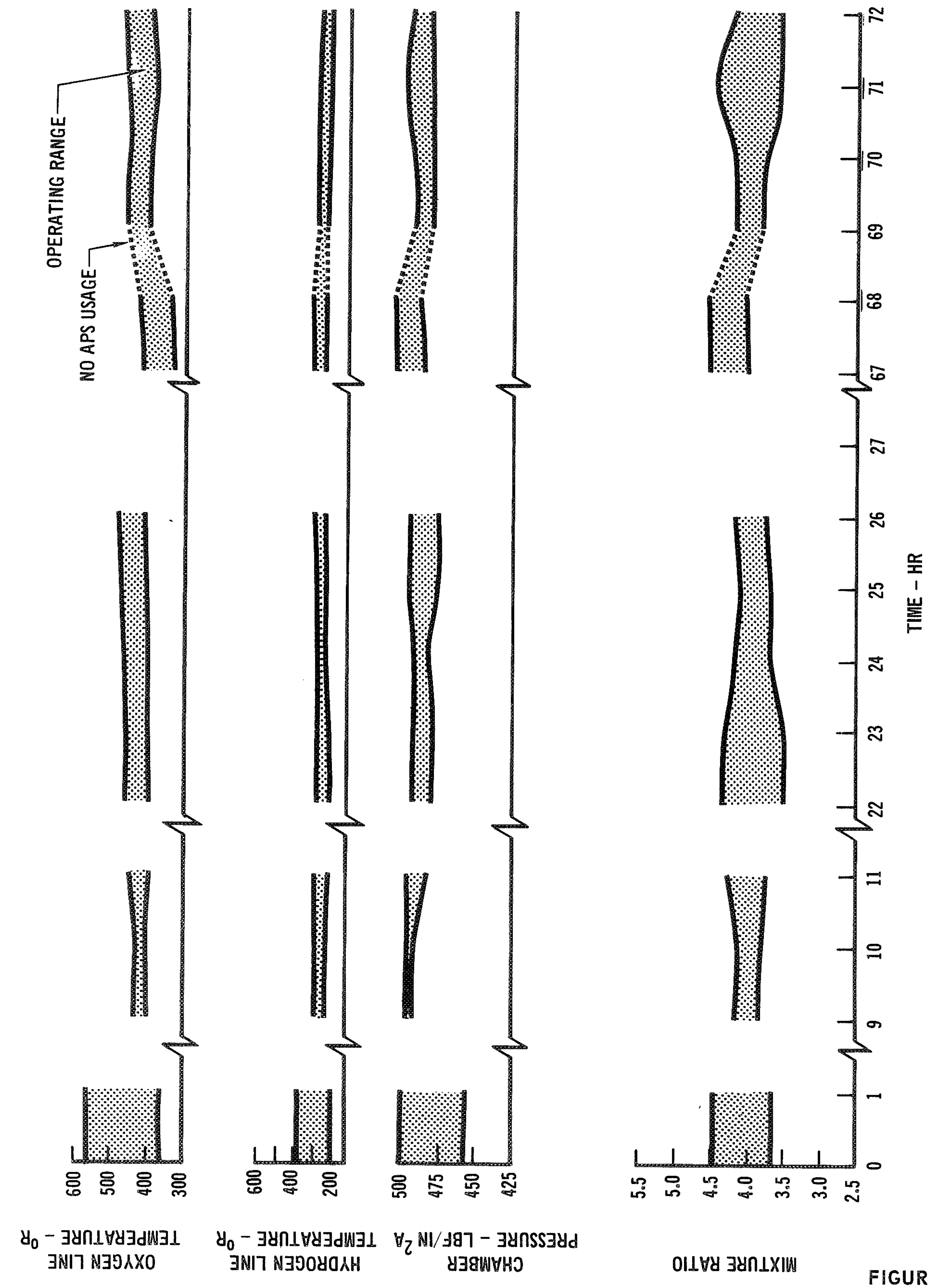
SUBSYSTEM OPERATING CHARACTERISTICS
HYDROGEN CONDITIONING TEMPERATURE INCREASED 5 PERCENT – VENTED
17TH ORBIT RENDEZVOUS

FIGURE 2–77



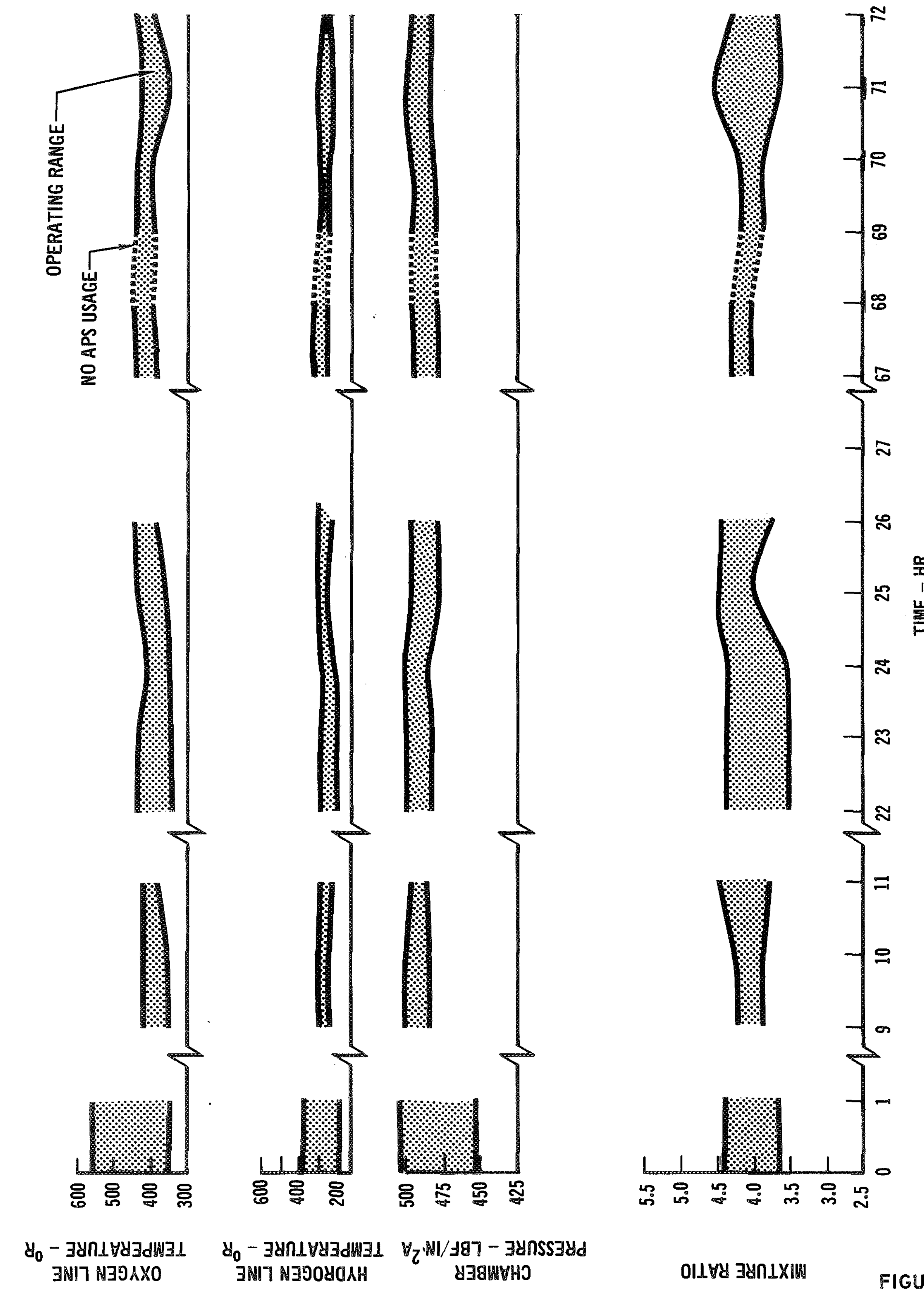
SUBSYSTEM OPERATING CHARACTERISTICS
HYDROGEN REGULATION PRESSURE INCREASED 5 PERCENT –VENTED
17TH ORBIT RENDEZVOUS

FIGURE 2–78



SUBSYSTEM OPERATING CHARACTERISTICS
OXYGEN CONDITIONING TEMPERATURE INCREASED 5 PERCENT – VENTED
17TH ORBIT RENDEZVOUS

FIGURE 2-79



SUBSYSTEM OPERATING CHARACTERISTICS
OXYGEN REGULATION PRESSURE INCREASED 5 PERCENT – VENTED
17TH ORBIT RENDEZVOUS

FIGURE 2–80

results, it is considered mandatory to vent the lines after long periods of low usage. Also shown are variances in thruster chamber pressure and hydrogen and oxygen line temperatures. None of the variations is severe. Comparison of Figures 2-71 and 2-72 shows that there are no marked differences in APS variations during the third or seventeenth orbit rendezvous missions. Figure 2-72a shows the corresponding impulse expenditure histories for Orbiter B.

Investigation of APS operation in the presence of off-design conditions shows results similar to the nominal case. Regulator output pressure variations of ±5 percent and conditioning temperature excursions of ±5 percent do not have large effects on subsystem operating characteristics, and, when compared with the nominal case, results are very similar, as shown in Figures 2-73 through 2-76 for the third orbit rendezvous mission and Figures 2-77 through 2-80 for the seventeenth orbit rendezvous mission.

3. ASSEMBLY AND COMPONENT DESCRIPTION

The APS consists of four primary assemblies:

(1) propellant storage assembly

(2) conditioning assembly

(3) gaseous propellant storage and distribution assemblies

(4) thruster assembly

3.1 Propellant Storage Assembly - The propellant storage assembly includes four primary subassemblies:

(1) tankage and insulation subassembly

(2) active vapor vent/cooling subassembly

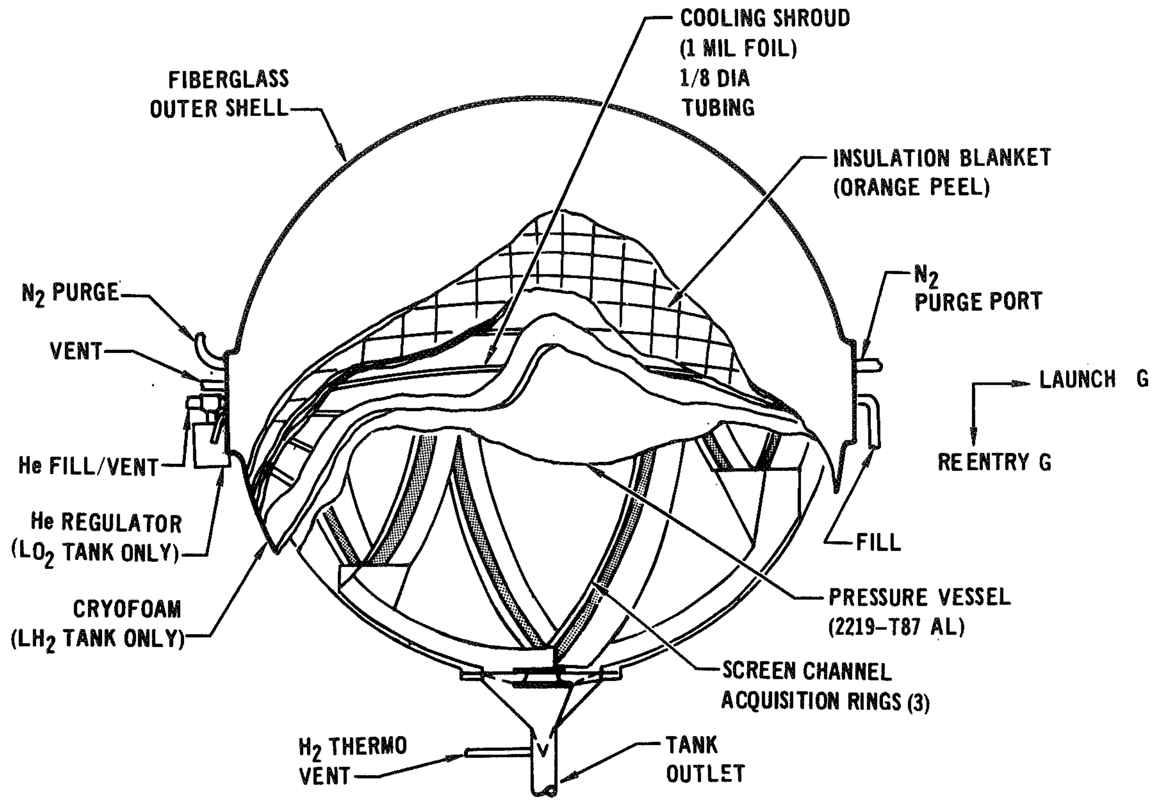
(3) propellant acquisition subassembly

(4) pressurization subassembly

Tankage and Insulation Subassembly - The propellant storage pressure vessels are fabricated of 2219-T87 aluminum. The tank and insulation assembly is shown in Figure 3-1. The fiberglass outer shell must be pressurized during entry to prevent collapse pressure loads and purged during grounds holds when propellants are loaded to prevent condensation and resultant insulation damage. Storage tank configuration design data for the two orbiters and the booster are presented in Figure 3-2.

Active Vapor Vent/Cooling Subassembly - Active thermal protection is provided to propellants by a heat shield around the propellant tanks. This shield consists of a thin metal foil shroud with attached cooling tubes. Liquid hydrogen from the acquisition screen channels is first throttled through a laminar flow throttling device to reduce temperature, then circulated through the hydrogen tank cooling tubes where heat to the propellant is intercepted through liquid vaporization. This coolant fluid cools the hydrogen turbopump enclosure. Finally, the gaseous hydrogen is used for oxygen tank and oxygen turbopump cooling. A flow schematic of the vent/cooling subassembly is illustrated in Figure 3-3 which shows the pressures, temperatures and flows.

Propellant Acquisition Subassembly - The propellant acquisition subassembly consists of passive surface tension screens mounted in annular trays which selectively pass liquid to the feed subassembly. The design of the propellant acquisition subassembly is illustrated in Figure 3-4. A detailed definition of the screen trays is shown in Figure 3-5. The trays are separated from the tank wall to prevent vaporization of the propellant within the positioning device, but are sufficiently close to the tank walls to allow contact with liquid for any propellant orientation.



PROPELLANT TANK INSULATION/COOLING CONCEPT

FIGURE 3-1

Pressurization Subassembly - The pressurization medium for both hydrogen and oxygen tanks is regulated pressure helium gas stored at 3000 lbf/in^2a in spherical aluminum tanks within the propellant tanks. Gas pressure is regulated to 25 lbf/in^2a for H_2 and 30 lbf/in^2a for O_2. The pressurization subassembly also includes a pressure relief and reseal capability to preclude tank overpressure failure.

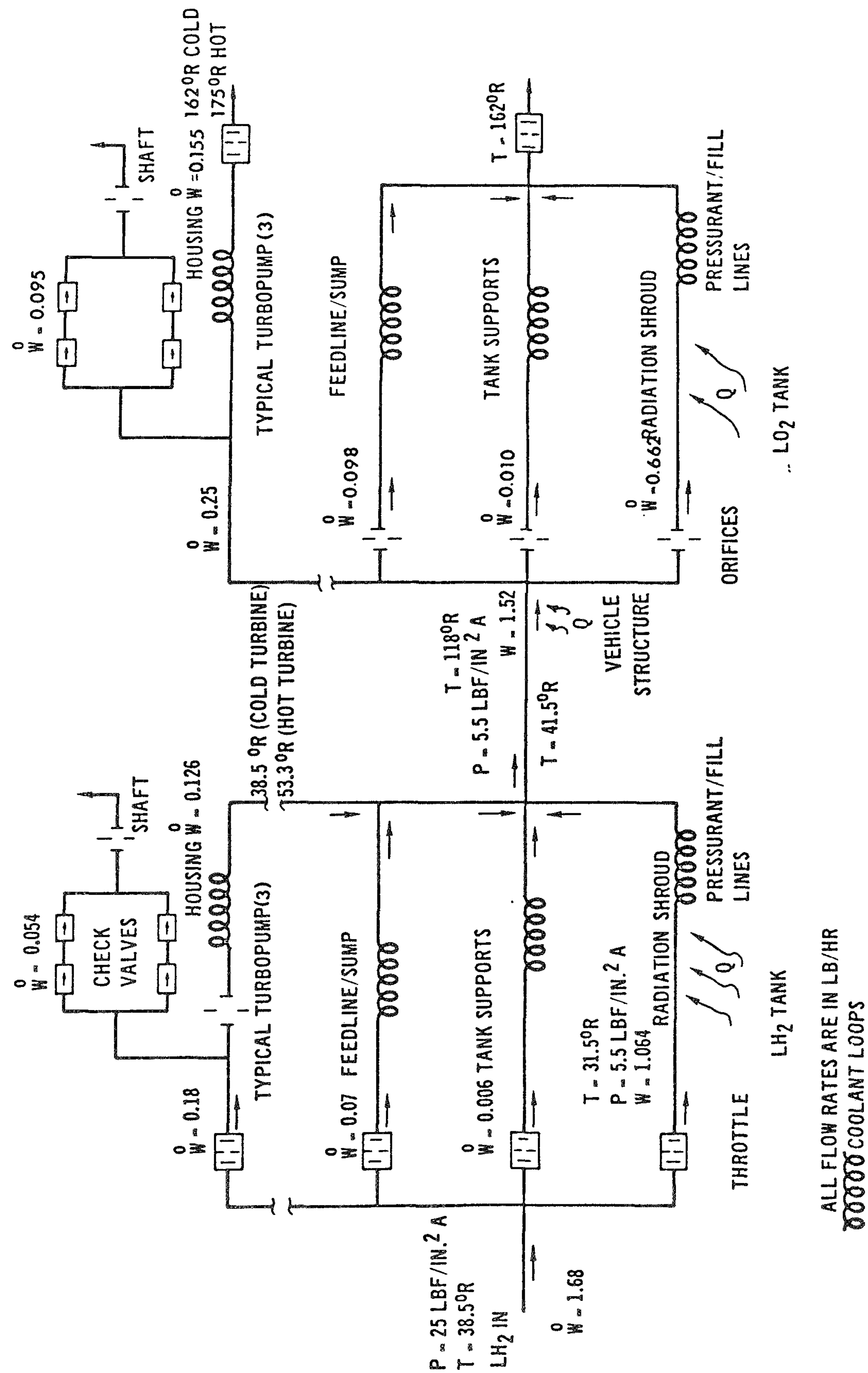
3.2 Conditioning Assembly - The conditioning assembly for both oxygen and hydrogen consists of three primary components; turbopump, gas generator, and reburn heat exchanger.

Turbopumps - The turbopump configurations are shown in Figures 3-6 and 3-7. The LO_2 turbopump consists of a single stage pump and a 2-stage, pressure compounded, axial flow turbine. Pump impeller and turbine rotors are mounted on a common shaft, supported by LO_2 cooled/lubricated element roller bearings. Bearing cooling/lubricating flow is tapped from the high pressure pump discharge, directed through the bearings, and reintroduced to the main stream flow at a low pressure station at the hub of the impeller backside. The magnitude of the bearing coolant

	ORBITER B		ORBITER C		BOOSTER	
	H_2	O_2	H_2	O_2	H_2	O_2
PRESSURIZATION	← COLD HELIUM →					
STORAGE PRESSURE, LBF/IN ^{2}A	← 3000 →					
STORAGE TEMPERATURE, ^{o}R	← 37 (H_2) AND 162 (O_2) →					
DELIVERY PRESSURE, LBF/IN ^{2}A	25	30	25	30	25	35
PROPELLANT TANK						
VOLUME, FT^3	1449	332	1485	335	108	25
MATERIAL	← 2219–T87 ALUMINUM →					
INSULATION	HPI/FOAM	HPI	HPI/FOAM	HPI	FOAM	NONE
THICKNESS, IN.	0.68/0.42	0.97	0.68/0.42	0.97	0.8	–
COOLING	← H_2 VENT →				← NONE →	
VENT RATE, LB/HR	1.68	–	2.01	–	N/A	N/A
SHROUD	ALUMINUM FOIL (0.005 IN. H_2, 0.001 IN. O_2)				N/A	N/A
TUBING	← 0.125 IN. DIAMETER, 0.010 IN WALL				N/A	N/A
PROPELLANT ACQUISITION	← SCREEN CHANNELS →					
NO. CHANNELS	4	3	4	3	1	1
EXTRACTION RATE, LB/SEC	3.84	14.84	3.83	14.84	3.88	15.03
EXPULSION EFFICIENCY, PERCENT	98.3	99.4	97.5	99.4	96.5	96.5

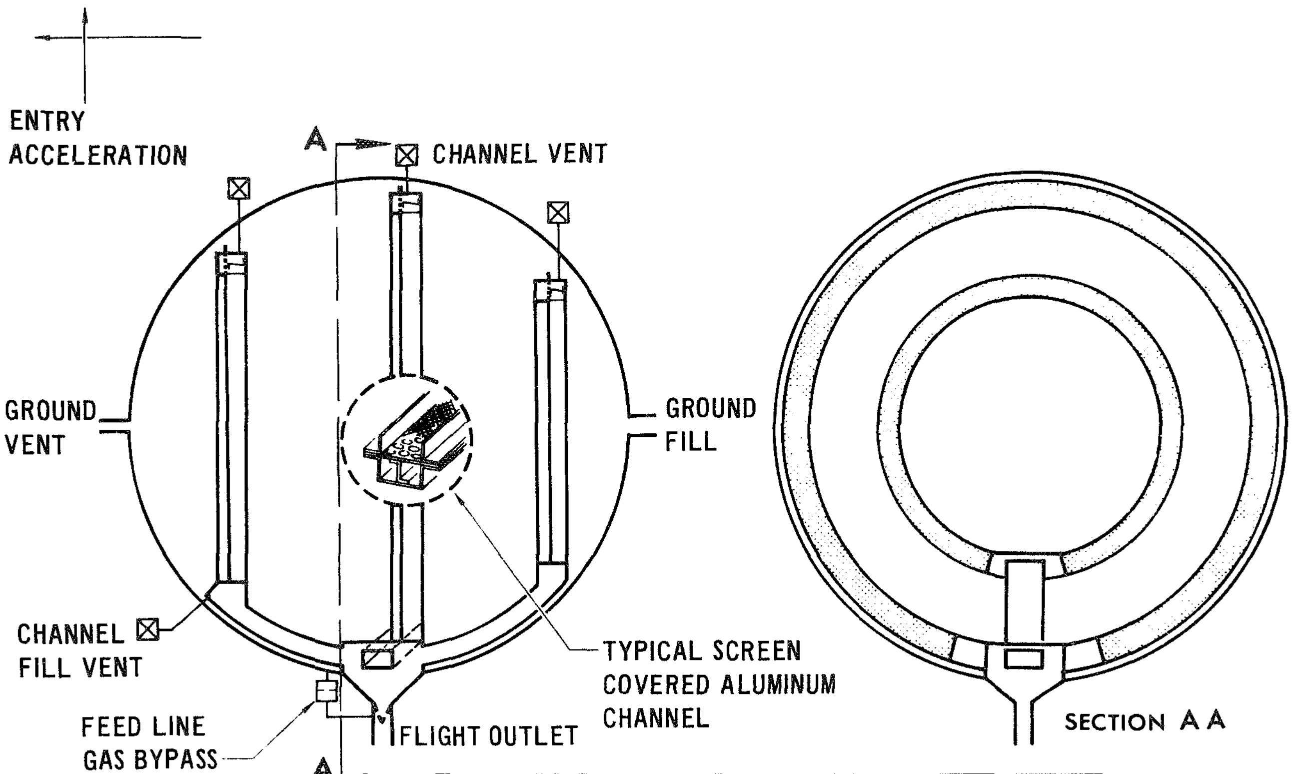
APS PROPELLANT STORAGE DESIGN SUMMARY

FIGURE 3–2



VENT SUBASSEMBLY SCHEMATIC

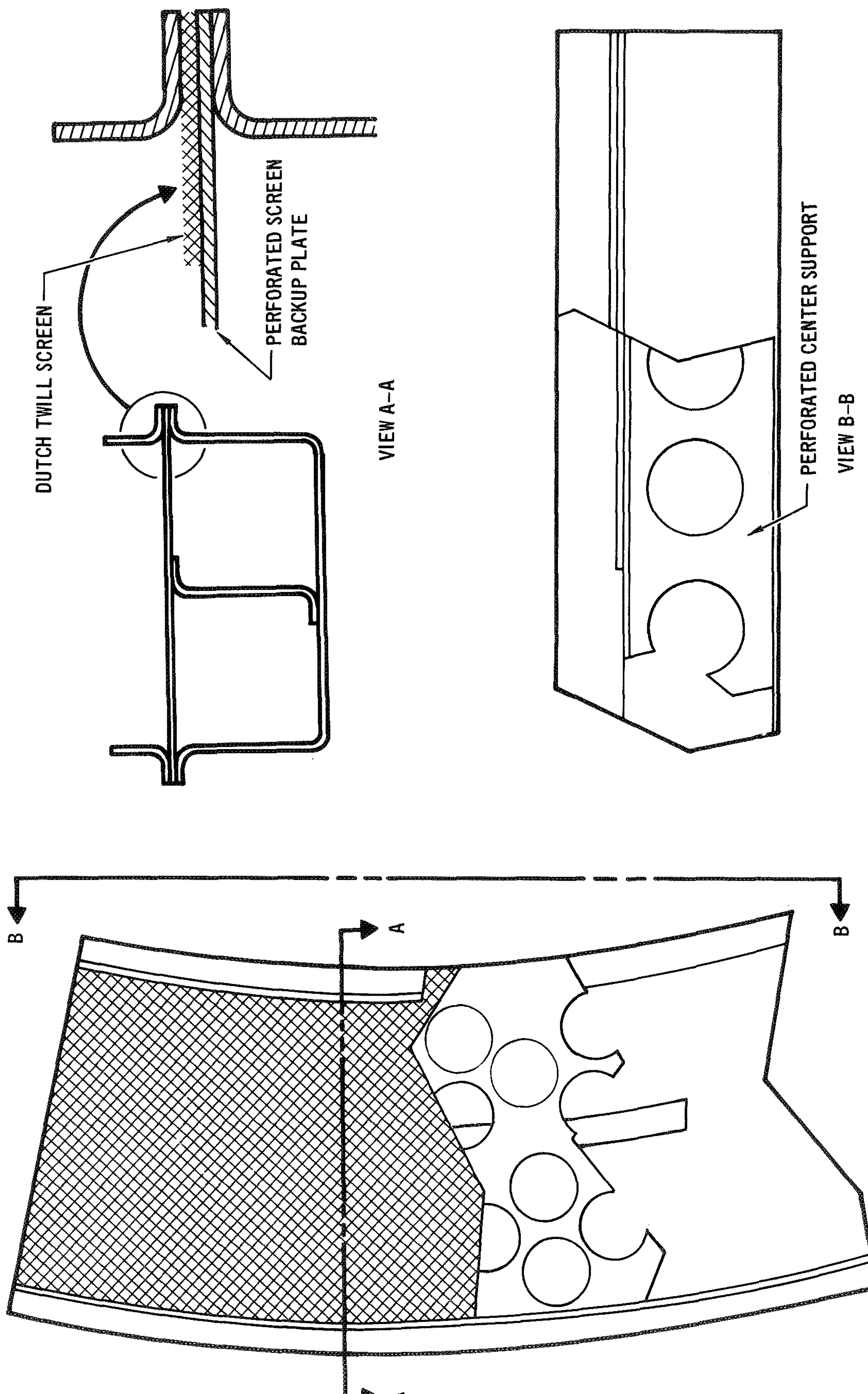
FIGURE 3-3



	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

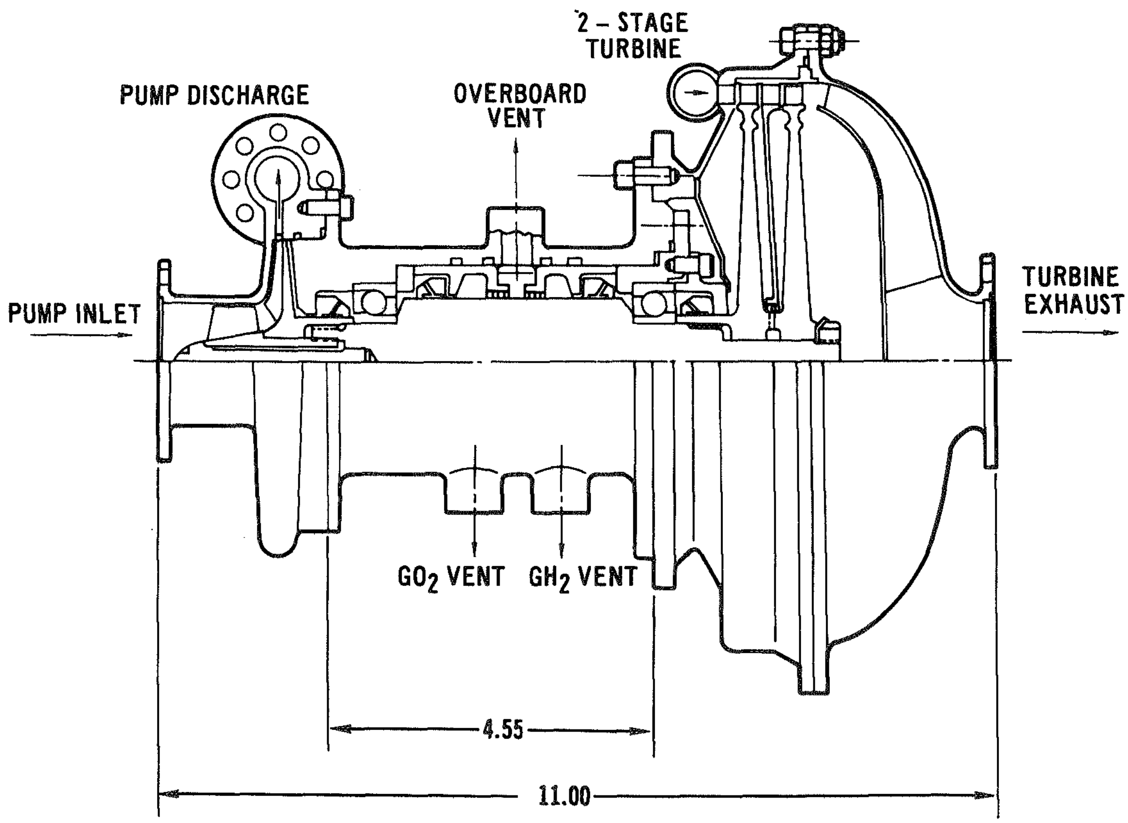
APS PROPELLANT ACQUISITION CONCEPT

FIGURE 3–4



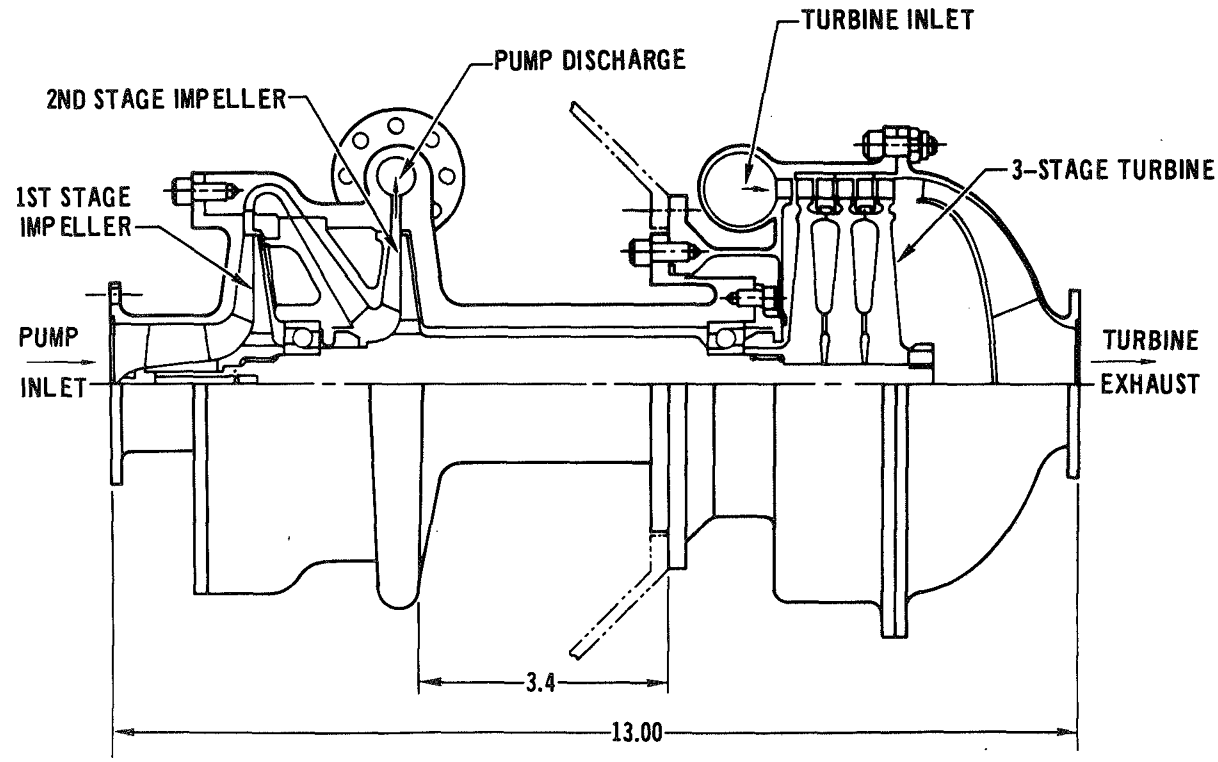
PROPELLANT ACQUISITION SCREEN
CHANNEL DESIGN

FIGURE 3-5



APS LO_2 TURBOPUMP

FIGURE 3-6



APS LH_2 TURBOPUMP

FIGURE 3-7

flow (5 percent allocated) is controlled by hydrostatic seals. The turbine end bearing is lubricated and cooled by gaseous hydrogen from the accumulator. The interpropellant seal which seals LO_2 from the hydrogen turbine bearing coolant uses a triple vent.

The fuel turbopump is similar to the LO_2 turbopump. Two pump stages are used to develop the required pressure and three pressure compounded axial flow stages are used in the turbine. The pump impellers and turbine rotors are mounted on a common shaft, supported by LH_2 cooled/lubricated roller element bearings. Hydrostatic, shaft riding seals are used to control bearing coolant. Like the LO_2 pump, 5 percent of the flow is used for cooling and lubrication and is recycled. The fuel turbopump does not require an interpropellant seal to separate propellant from the hot turbine gas, since LH_2 is nonreactive with the fuel rich turbine gases. Liquid hydrogen flow from the turbine end bearing to the turbine is minimized by use of a hydrostatic seal.

Figure 3-8 shows that the pump output pressures vary from approximately 1000 lbf/in^2a at steady state operation to approximately 2000 lbf/in^2a at the end of accumulator recharge. This is accomplished by permitting the turbopump shaft speed to increase, and flow to decrease, as the accumulator is recharged. During recharge, gas generator flow and power to the turbine are constant except for slight turbine power increases with speed (due to an increase in turbine efficiency).

Head, flow, efficiency, power, and torque characteristics of the pumps are shown in a normalized format in Figure 3-9. Since stage specific speeds of the LO_2 and LH_2 pump are nearly equal, their normalized characteristics will be the same. Use of these normalized characteristics resulted in the head/flow characteristics for values of constant shaft speed shown in Figures 3-10 and 3-11 for the oxidizer and fuel turbopumps, respectively. These figures show the pump operating characteristics during accumulator charge from the steady state operating point to maximum accumulator pressure. The dotted lines shown correspond to pump power requirements matched to turbine delivered power. A design efficiency less than the predicted maximum available at the operating point was used in APS design to provide a margin in the design and to limit the flow range to the heat exchangers during recharge.

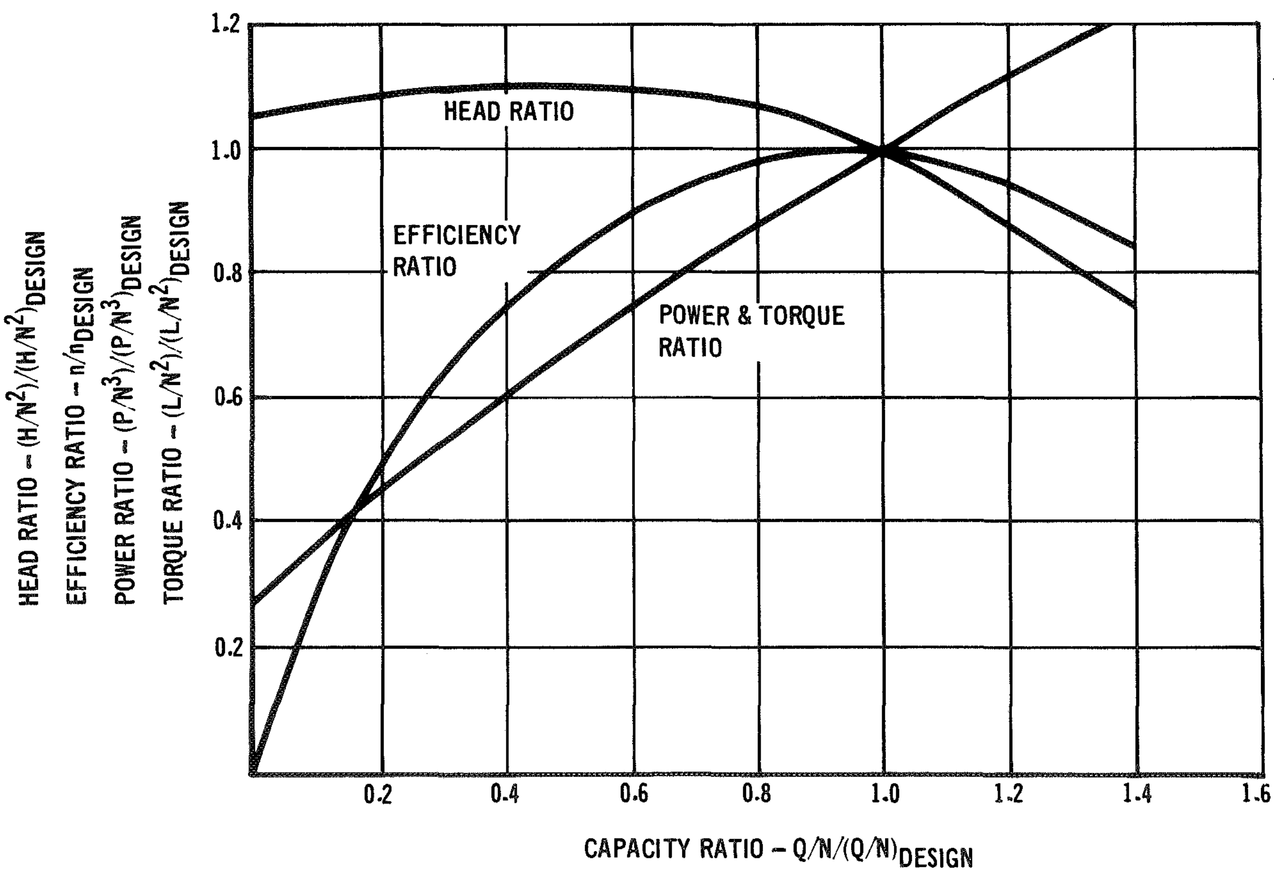
The turbopump fuel and oxidizer pump volumes are 10.58 and 6.05 in^3, respectively from the plane of the suction flange to the plane of the discharge flange.

The turbopump has been designed for a life of 100 missions with 50 starts required per mission, or 5000 cycles. Based on the thermal shock duty requirements of the turbine rotor, cycle fatigue life is predicted to be 6000 cycles.

	O_2		H_2	
	MIN ΔP	MAX. ΔP	MIN ΔP	MAX. ΔP
PUMP				
– PUMP FLOWRATE, LB/SEC	14.81	9.7	3.8	2.55
– SUCTION PRESSURE, LBF/IN^{2}A	30	30	25	25
– SUCTION TEMPERATURE, ^{o}R	162	162	37	37
– DISCHARGE PRESSURE, LBF/IN^{2}A	921	2082	1043	2340
– NUMBER OF CYCLES	50	–	50	–
TURBINE				
– FLOWRATE, LB/SEC	0.255	0.255	0.425	0.425
– INLET PRESSURE, LBF/IN^{2}A	500	500	500	500
– INLET TEMPERATURE, ^{o}R	2000	2000	2000	2000
– PRESSURE RATIO, –	5.55	5.55	16.7	16.7
– NUMBER OF CYCLES	50	–	50	–

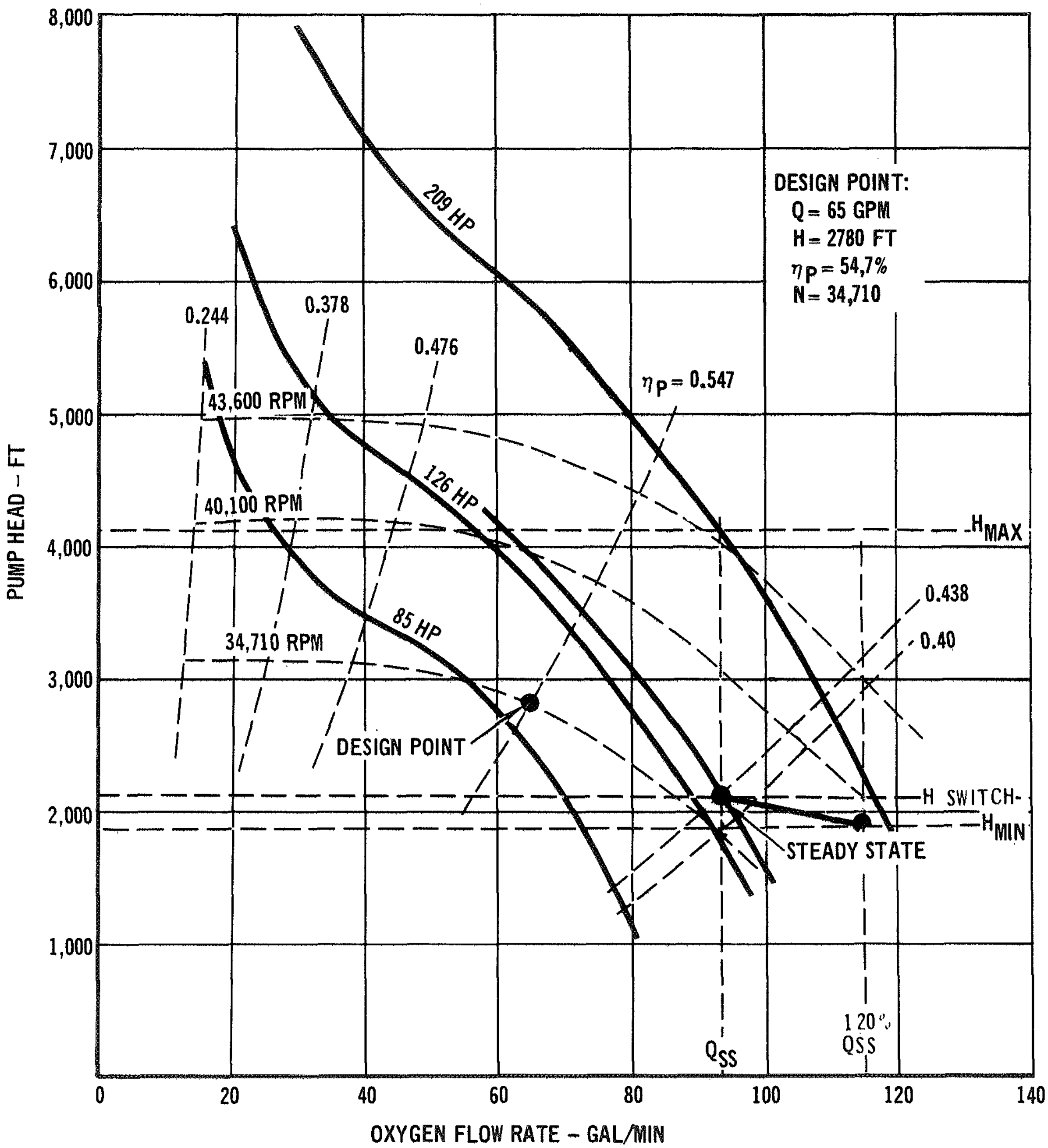
TURBOPUMP DESIGN SUMMARY
ORBITER B

FIGURE 3-8



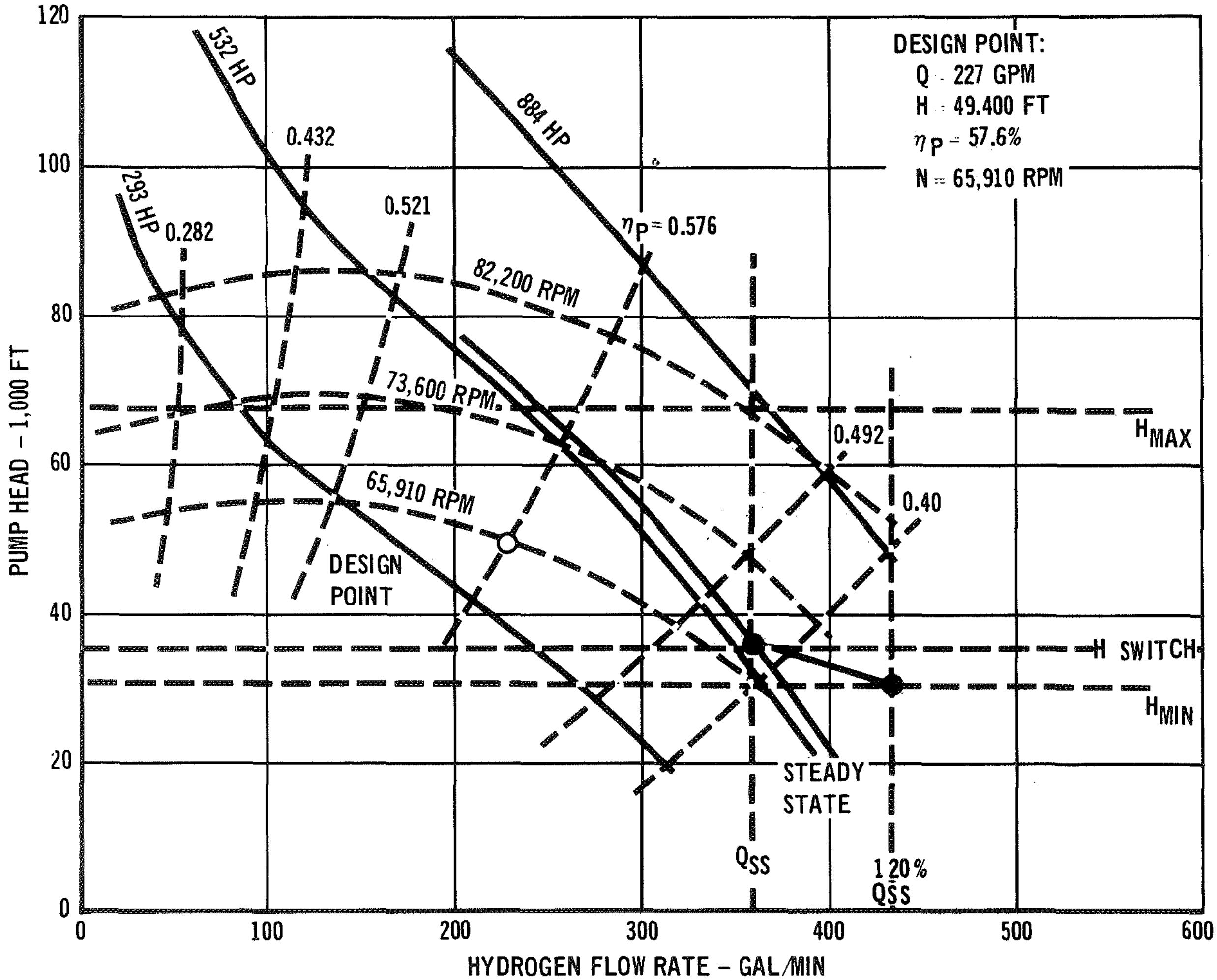
PUMP NORMALIZED PERFORMANCE PARAMETERS

FIGURE 3-9



OXYGEN PUMP

FIGURE 3-10



HYDROGEN PUMP

FIGURE 3-11

The turbine blading for both the fuel and oxidizer turbopump turbines is the axial flow impulse type. The blade design is symmetrical, utilizing neither taper or twist, with the inlet and outlet angles equal to 21 degrees.

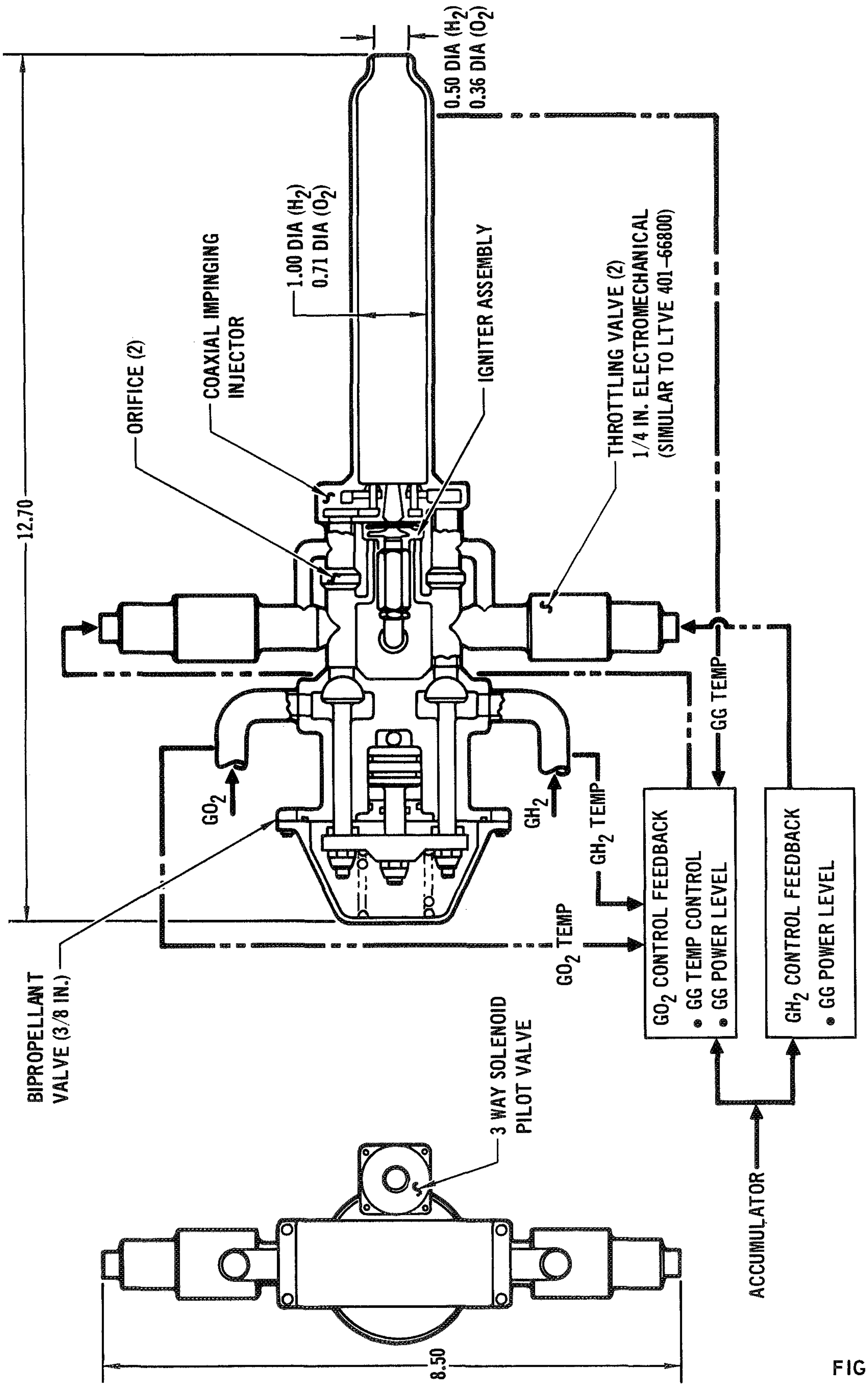
Both the fuel and oxidizer pump discharge volutes are designed for a proof pressure capability of 150% of maximum working pressure, and a burst pressure of 200% of proof. The hydrogen pump is designed to operate at 53,330 RPM, and the oxygen pump at 21,337 RPM. First shaft critical speeds for the hydrogen and oxygen pumps are 32,151 RPM and 33,550 RPM, respectively. This represents operation, with predicted bearing freedom, at 165% of critical for the fuel pump and 63.5% of critical for the oxidizer pump.

Both the fuel and oxidizer pump shaft support bearings operate at bearing DN values of 1.5×10^6.

Gas Generators - The gas generators provide 2000°R hot gas to the turbine at a nominal pressure level of 500 lbf/in^2a when operated with propellant inlet temperatures of 250°R (GH_2) and 400°R (GO_2).

The gas generator design concept was adapted from APS gas/gas thruster technology programs. Figure 3-12 shows the configuration and size of the hydrogen gas generator. The oxygen gas generator is the same configuration, but has a smaller injector and chamber since the required flow rate is lower. The oxygen gas generator size is also noted in Figure 3-12.

The gas generator operation is initiated with a signal to open the linked gas generator valves and a signal to the electrical igniter. The opening of the bipropellant valve sends gaseous oxygen and hydrogen through the parallel flow circuits of the igniter and the primary injecter. The gas generator valves are shown in Figure 3-12. Effectively, two valves are used; one is a primary, linked, pneumatically operated valve for on-off propellant control. The other is a vernier, electrically operated, throttle valve. A linked primary valve was selected to provide added assurance of proper propellant sequencing and to minimize potential mixture ratio variations. There are flow restrictions (orifices) in each propellant flow circuit between the linked bipropellant valve seats and the gas generator injector to limit operation to an 80 percent power level. A bypass flow circuit flows around each orifice, with individual throttling valves in each circuit. The throttle valve is an electric torque motor actuated design. The throttle valves allow propellant to be bypassed around the orifices for gas generator power level control. The oxygen throttle valve also provides combustion temperature and mixture ratio control, based on gas generator exhaust temperature measurements.



APS GAS GENERATOR

FIGURE 3-12

The APS design has a gaseous oxygen and gaseous hydrogen injector operating at a nominal mixture ratio of 1.0 to produce 2000°R gas. An electrical spark discharges and ignites a small torch flame down the center of the injector, which, in turn, ignites the main flow. The propellant to the electrical igniter is tapped from the primary inlet flow and secondary igniter valves are not used. The injector proposed is an impinging coaxial element concept. The element provides a uniform and homogeneous hot gas flow stream down the GG barrel and at the inlet to the turbine nozzles. The injector is fabricated of brazed 347 Stainless Steel. The propellant supply lines and injector manifolding is designed to provide propellant flow velocities of less than Mach 0.3 in the circuits up to the injector elements.

The flow velocities selected result in propellant feed lines of 3/8 in. internal flow diameter through the linked propellant control valves (on-off) for both the hydrogen and oxygen gas generators. The parallel bypass lines around the flow resistance orifice are 1/4 in. flow diameter through the throttling valves for the hydrogen gas generator and 1/8 in. for the oxygen gas generator. These flow circuits are sized to provide 40% greater flow capability than the flow through the primary orificed flow path. The flow orifices are sized for the primary flow of each gas generator. The manifold volumes for each propellant circuit from the linked propellant control valves to the injector face are:

$$\text{Manifold Volume} = 3'' \text{ flow length @ } 3/8'' \text{ I.D.} + \text{injector volume} + \left\{ \begin{array}{l} 2.5'' \text{ flow length @ } 1/4'' \text{ I.D. (Hydrogen GG)} \\ 2.5'' \text{ flow length @ } 1/8'' \text{ I.D. (Oxygen GG)} \end{array} \right\} + \text{throttling valve}$$

Injector Manifold Volumes = 2" dia - 1" dia x 1/2" thick = 1.6 cu. in.

Throttling Valve Volumes $\sim$ 0.2 cu. in.

Each Propellant Circuit for Hydrogen Gas Generator has 2.27 cu. in.

Each Propellant Circuit for Oxygen Gas Generator has 2.18 cu. in.

The injector is coupled to a subsonic chamber, having sufficient length to ensure complete propellant reaction and uniform hot gas temperatures at the turbine inlet. The insulated (adiabatic wall) chamber is fabricated of A286 alloy.

The chamber has a cylindrical barrel with a low hot gas velocity and a subsonic converging section at the exit to provide an exit Mach of 0.5.

The stress of the chamber is dependent upon the wall thickness. The wall thickness dictates the resultant hoop stress based upon the $\frac{P\ r}{t}$ relationship and the resultant thermal stress based upon the following:

$$\sigma(\text{thermal stress}) = \frac{E \cdot \alpha \cdot T_f}{(1 - \mu)\ (1.5 + \frac{3.25\ k}{h \cdot t})}$$

where; E = Young's modulus

α = Coefficient of Thermal Expansion

T_f = Suddenly applied film Temperature, °R

μ = Poisson's Ratio

k = thermal conductivity

h = heat transfer coefficient

t = material thickness

Based on a 1000°R assumed temperature at the worst gradient and a subsonic heat transfer coefficient of 7.55×10^{-4} BTU/in^2-sec-°R the resultant thermal stress for a 0.030 in. wall is 10,400 psi and for 0.050 in. wall in 16,900 psi. These levels compare to a hoop stress level of only 8,400 psi for the 0.03 in. wall thickness. The A286 has a yield strength of 20,000 psi at 1500°R. The creep stress rupture of the material is 17,000 psi sustained for 60 hours at 1500°R. These levels identify that the 0.05 in. wall thickness has sufficient design margin, however, additional thermal stress safety factor will be achieved by utilizing a 0.030 in. wall.

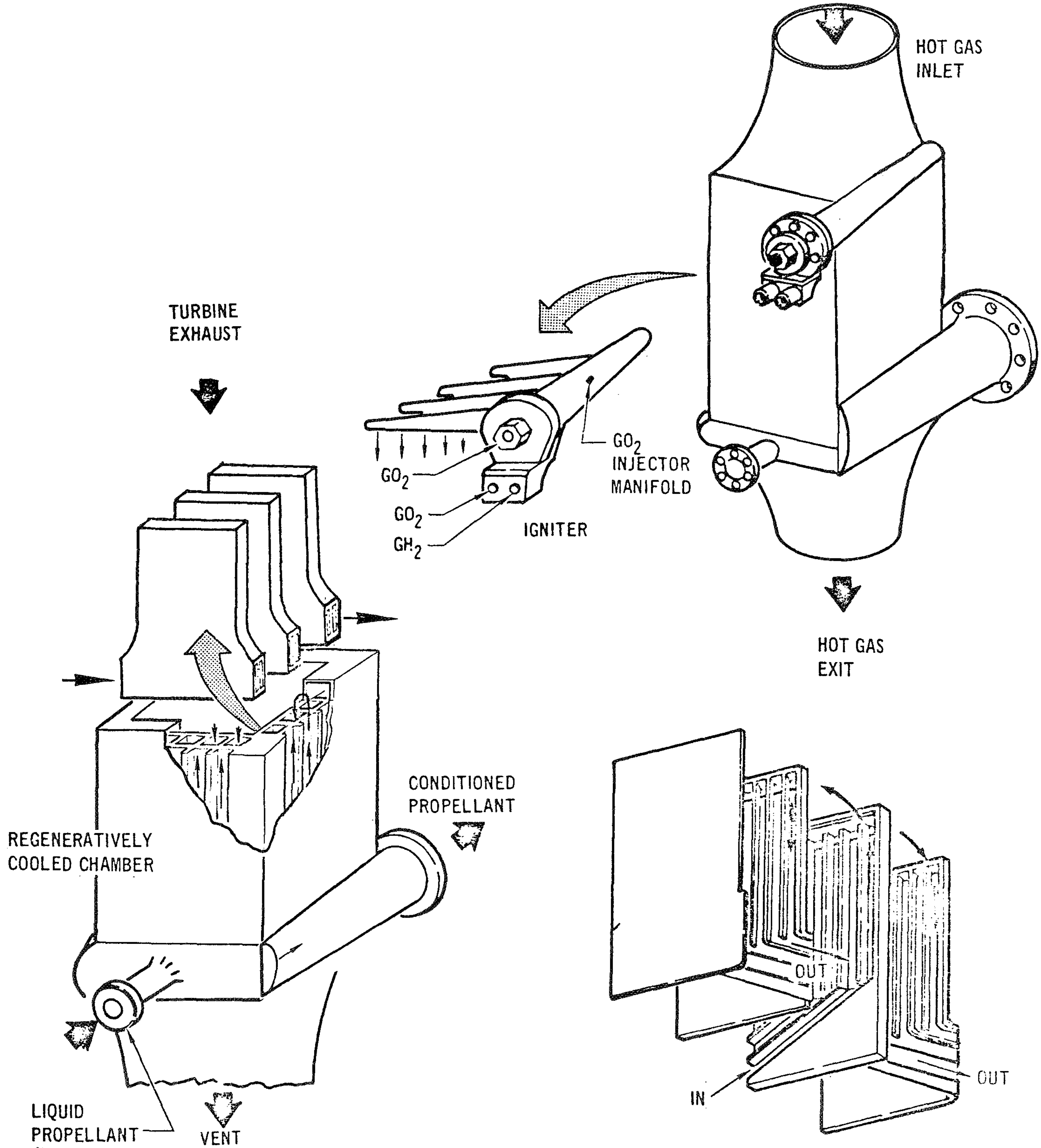
Reburn Heat Exchanger - The heat exchangers in the propellant conditioning assembly contain, in effect, second gas generators which initially reburn the fuel-rich turbine exhaust products. These hot gases then flow between the heat exchanger platelets to condition the propellants. Heat exchanger performance and weights are shown in Figure 3-13.

Heat exchanger design is illustrated in Figure 3-13a. The core consists of a series of liquid propellant platelet assemblies, each separated by a hot gas flow passage. Platelet construction techniques provide controlled heat trnnsfer coefficients for hot gas and cold propellant sides. The exploded view of the liquid propellant platelet assembly shows that the liquid propellant enters the center

		HYDROGEN	OXYGEN
HOT SIDE			
INLET PRESSURE (HEATING SECTION)	– PSIA	30.0	88.0
OUTLET PRESSURE (HEATING SECTION)	– PSIA	25.7	79.9
INLET TEMPERATURE (HEATING SECTION)	– °R	3757.2	4152.0
OUTLET TEMPERATURE (HEATING SECTION)	– °R	820.6	800.7
INLET VELOCITY (HEATING SECTION)	– FT/SEC	3012.9	1146.2
EXIT VELOCITY (HEATING SECTION)	– FT/SEC	1107.4	657.7
COLD SIDE			
INLET PRESSURE (HEATING SECTION)	– PSIA	1045.0	925.0
OUTLET PRESSURE (HEATING SECTION)	– PSIA	1034.8	874.3
INLET TEMPERATURE (HEATING SECTION)	– °R	60.0	170.0
OUTLET TEMPERATURE (HEATING SECTION)	– °R	250.4	461.3
INLET VELOCITY (HEATING SECTION)	– FT/SEC	97.0	43.3
OUTLET VELOCITY (HEATING SECTION)	– FT/SEC	61.1	68.1
$\dot{W}_{h_{DES}}$ (DESIGN HOT GAS FLOW RATE)	– LB/SEC	0.746	0.479
$\dot{W}_{c_{DES}}$ (DESIGN COLD SIDE FLOW RATE)	– LB/SEC	3.84	14.8
HEAT FLUX (TOTAL)	– BTU/SEC	2798.2	2139.0
HOT GAS MIXTURE RATIO	– $\dot{W}_O/\dot{W}_H$	2.55	2.7
A_h AND A_c (HEATING SURFACE)	– $IN.^2$	2271.36	1551.0
W_W (HOT/COLD METAL WEIGHT)	– LB	30.4	35.7
W_{PW} (INTERPROPELLANT METAL WEIGHT)	– LB	28.3	48.4
W_{MISC} (METAL STRUCTURE, MANIFOLD, ETC)	– LB	26.5	17.4
TOTAL HEAT EXCHANGER WEIGHT	– LB	85.2	101.5
MATERIAL	–	INCONEL 718	NICKEL 200

HEAT EXCHANGER PERFORMANCE AND WEIGHT

FIGURE 3–13



HIGH TEMPERATURE REBURN HEAT EXCHANGER

FIGURE 3-13a

of the platelet, is distributed across its width, directed up its length where the flow is split and directed back down the platelet stack. Heat exchange with the hot gas occurs on the downpass because the closure plate for the downpass channels is also the wall of a gas generator segment. At the bottom of the downpass, the conditioned propellant discharging from each of the platelets is gathered in a manifold assembly and directed to the accumulator.

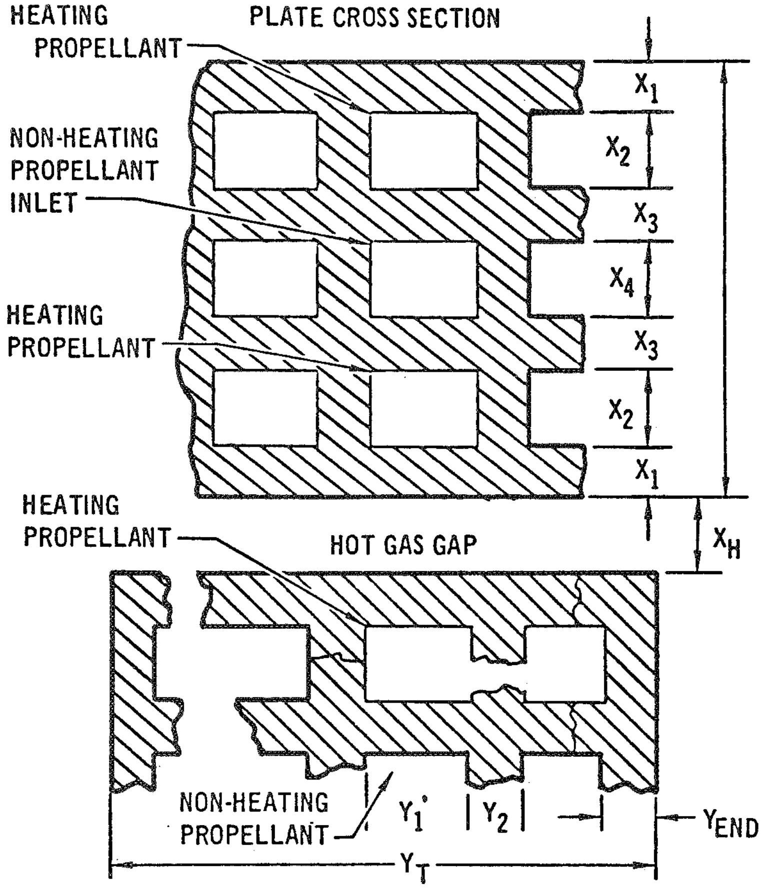
The heat exchanger shell is regeneratively cooled and is acutally one half of a main heat exchanger platelet. The liquid propellant flows up the outside passage of the shell and down the inside passage where it is conditioned. It is collected with the conditioned propellant from the main platelets.

The baseline internal configuration of the heat exchanger platelets is defined in Figure 3-13b. Using this configuration heat exchanger steady state performance operating maps were defined. Hydrogen heat exchanger operating maps are shown in Figure 3-13c for a hot gas inlet (turbine discharge) pressure of 30 LBF/in^2A and for a hydrogen inlet pressure of 1045 LBF/in^2A. The operating limits are defined by limiting the wall temperature to above 500°R, and limiting the velocity at the exit to less than sonic. A 500°R minimum wall temperature is required to preclude freezing of water on the heat exchanger surfaces. The steady state heat exchanger operating point for only +X thruster usage is shown in Figure 3-13c(a). At this point the conditioned hydrogen temperature is 250°R, the conditioning assembly is operating at an overall mixture ratio of 2.55 and the exhaust gas is above the condensation limit. Increasing the thruster usage by 25% to allow attitude control usage during +X thruster firing results in the operating map shown in Figure 3-13c(b).

During an accumulator charge cycle, heat exchanger cold side pressures will increase, and flow rate will decrease. This change in flow and pressure requires that heat exchanger oxygen flow rates be reduced to provide a corresponding reduction in the total enthalpy available in the hot gas. This is accomplished by throttling the heat exchanger oxygen flow to maintain the desired hot gas outlet temperature. The throttle will be continuously controlled on the basis of accumulator pressure. Near the end of the recharge cycle the hydrogen pressure will reach the 2000 psia shown in the performance maps defined in Figure 3-13d. The corresponding operating point is shown in Figure 3-13d(a).

The operating performance maps for the oxygen heat exchangers are shown in Figures 3-13e and 3-13f.

The gas generator portion of the reburn heat exchanger is illustrated by the igniter shown in Figure 3-13a. The turbine exhaust gas is mixed with oxygen along

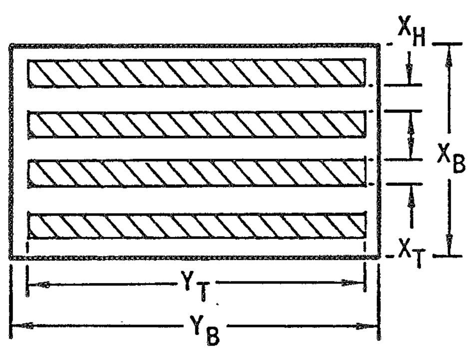


	HYDROGEN		OXYGEN	
STATION	0	19.5	0	23.5
T_{HOT} - °R	3757.2	820.6	4152.0	800.7
T_{COLD} - °R	60.0	250.4	170.0	461.3
X_1 = IN.	0.030	0.050	0.050	0.050
X_2 = IN.	0.015	0.125	0.022	0.130
X_3 = IN.	0.020	0.020	0.050	0.050
X_4 = IN.	0.220	0.015	0.176	0.060
X_T = IN.	0.350	0.405	0.420	0.520
X_H = IN.	0.115	0.070	0.130	0.030
Y_1 = IN.	0.115	0.125	0.075	0.100
Y_2 = IN.	0.030	0.020	0.075	0.050
Y_T = IN.	7.28	7.28	6.6	6.6
N_C -	800	800	420	420
N_H -	8	8	5	5
N_S -	16	16	10	10
A_{HOT} IN.^{2}	6.8998	4.3460	4.4764	1.36688
A_{COLD} IN.^{2}	1.380	12.5	0.693	5.46
HOT VELOCITY FT/SEC	3012.9	1107.4	1146.2	657.7
COLD VELOCITY FT/SEC	97.0	61.1	43.3	68.1
Y_{END} = IN.	0.030	0.025	0.1875	0.175

N_C = NO. OF COLD FLOW CHANNELS

N_H = NO. OF HOT FLOW GAPS

N_S = NO. HX SURFACES

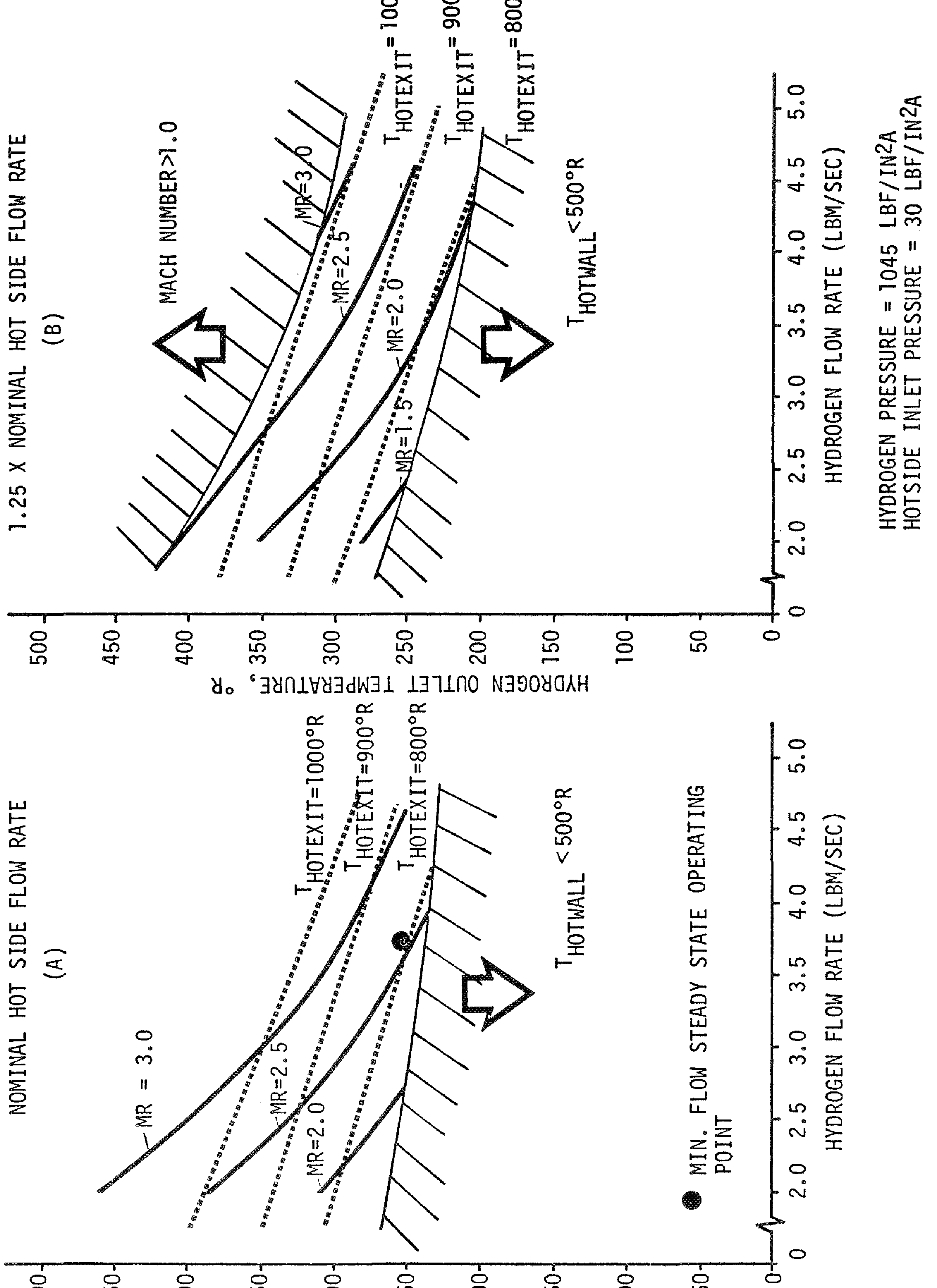


SHAPED AREAS INDICATE PLATE ELEMENTS IN CROSS SECTION OF HEAT EXCHANGER NORMAL TO HOT GAS & PROPELLANT FLOW DIRECTION.

X_T = IN.	0.350	0.405	0.420	0.530
X_H = IN.	0.115	0.070	0.130	0.030
N_H -	8	8	5	5
N_S -	16	16	10	10
X_B = IN.	3.370	3.395	2.33	2.23
Y_T = IN.	7.28	7.28		
Y_B = IN.	7.34	7.34	6.60	6.68
LENGTH OF PLATES (HEAT TRANSFER SURFACE ONLY)	19.5 IN		23.5 IN.	

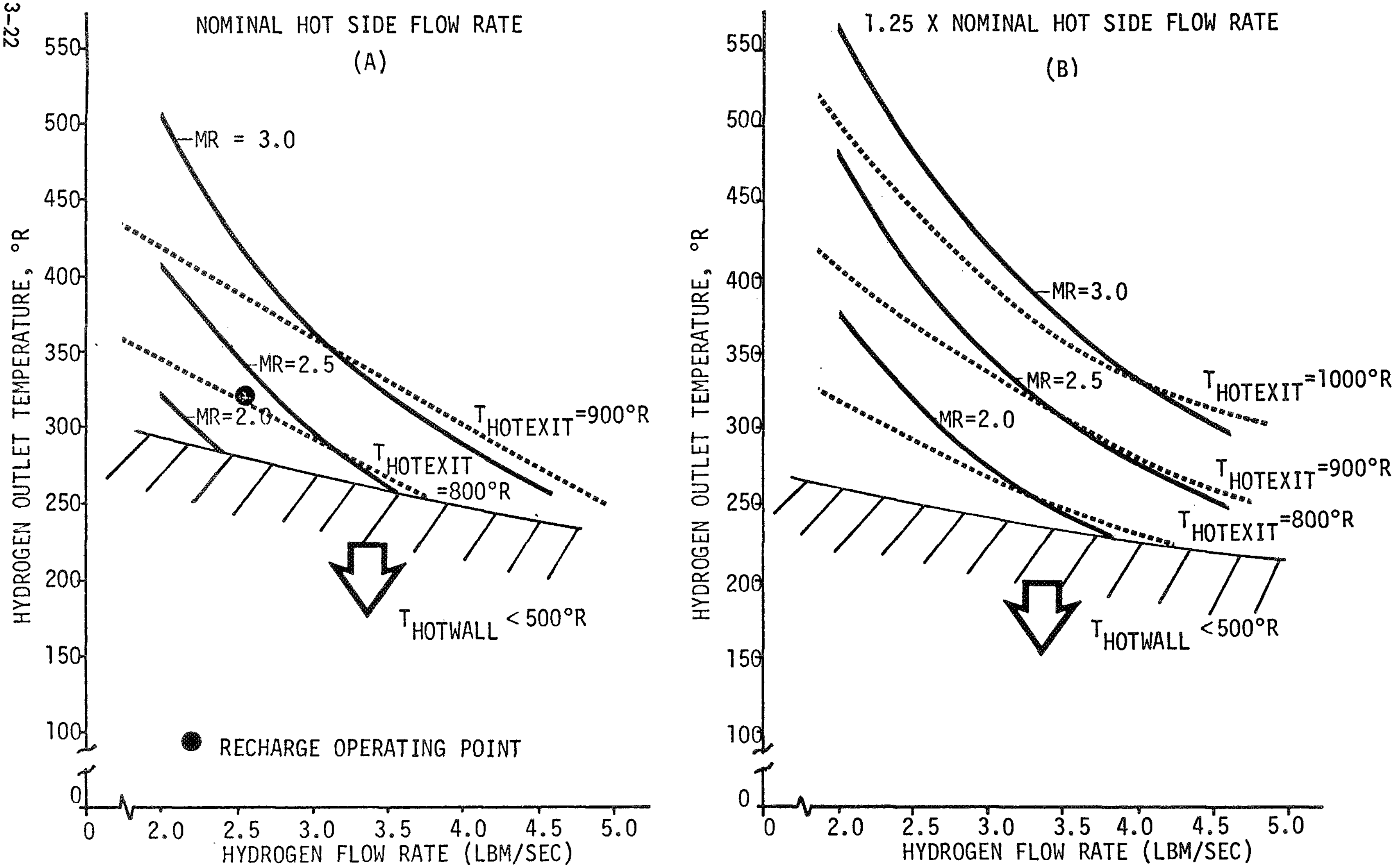
HEAT EXCHANGER DESIGN DATA

FIGURE 3-13b



HYDROGEN HEAT EXCHANGER OPERATING MAP

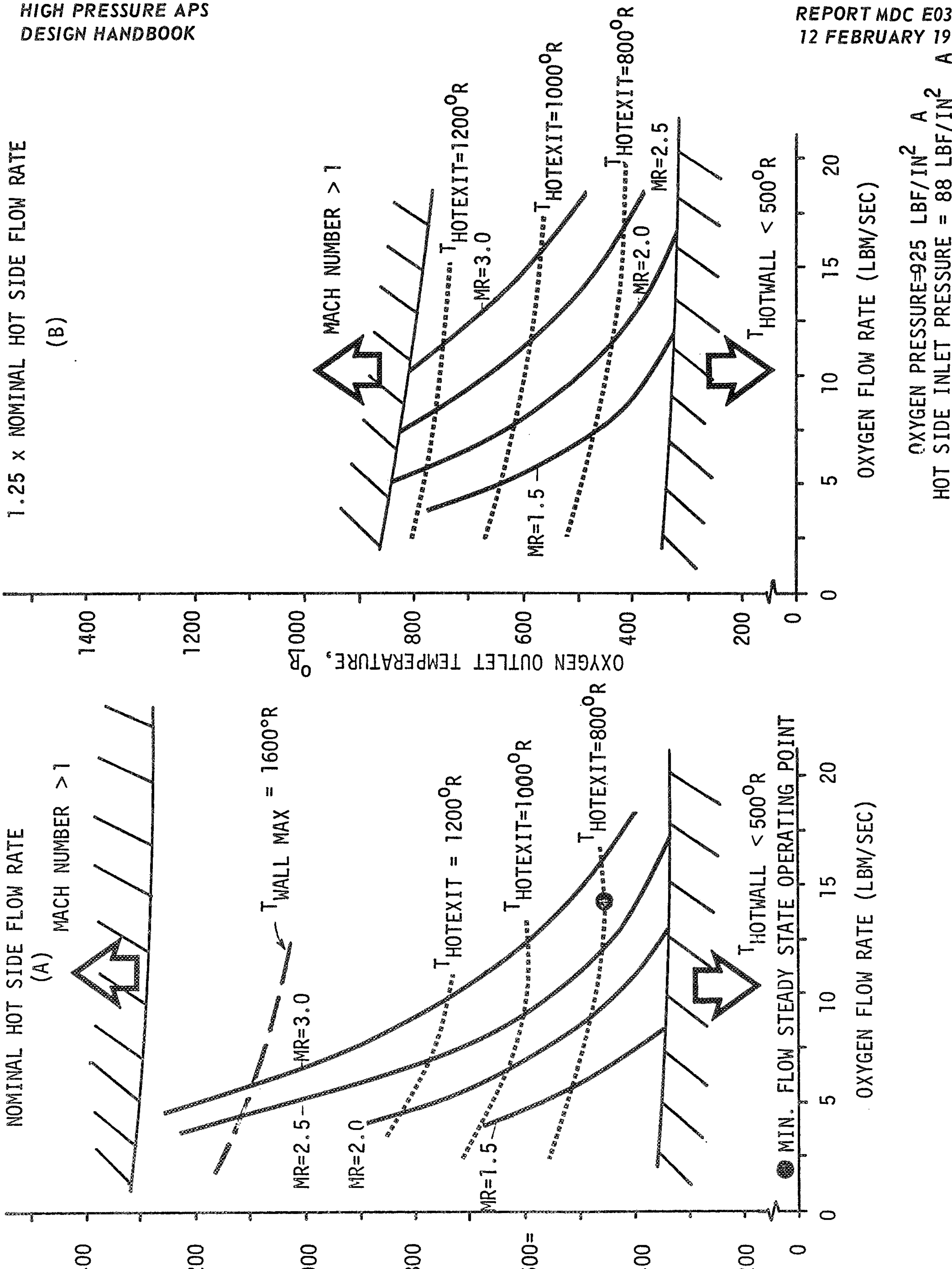
FIGURE 3-13c



HYDROGEN PRESSURE = 2000 LBF/IN^{2}A
HOTSIDE INLET PRESSURE = 30 LBF/IN^{2}A

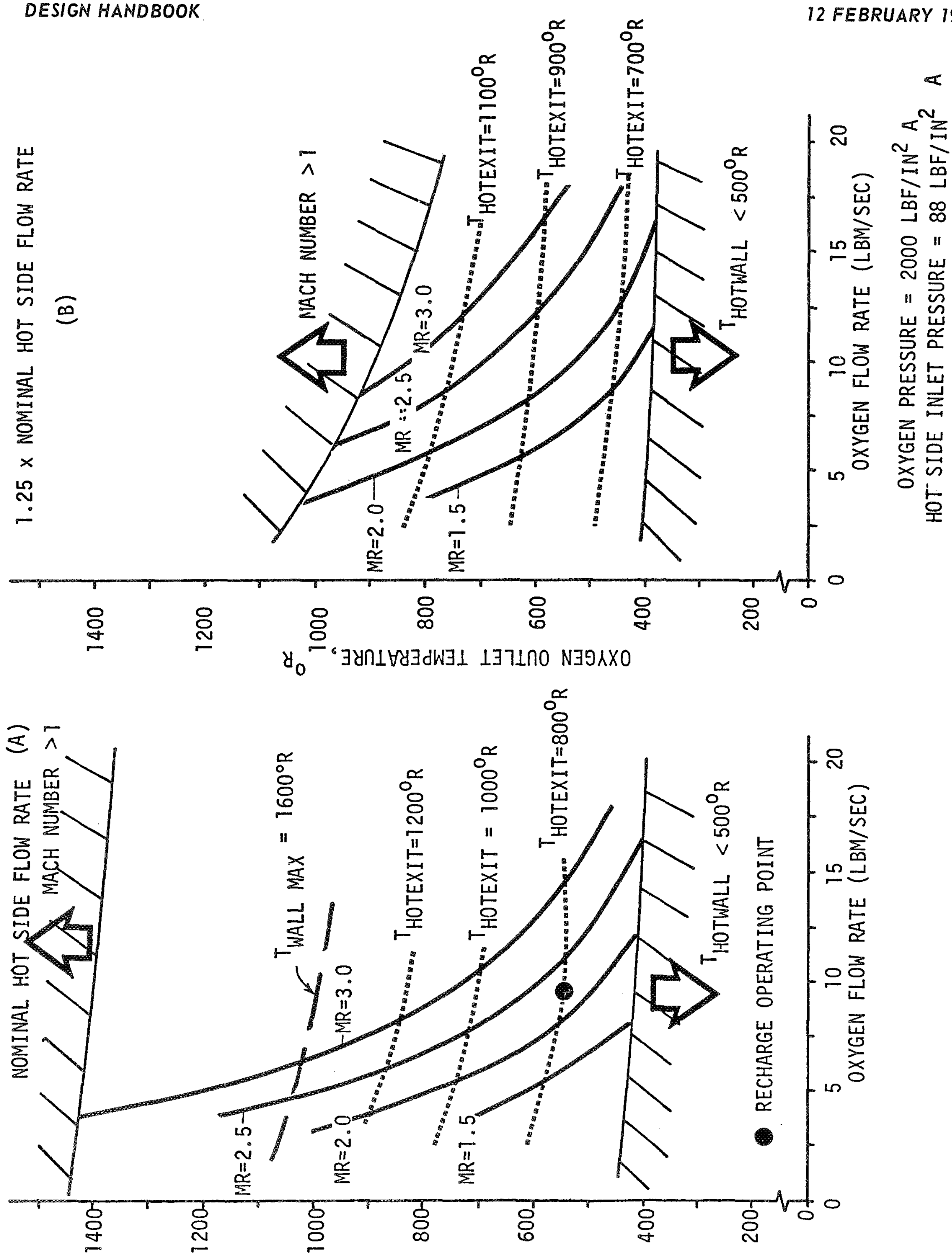
FIGURE 3-13d

HYDROGEN HEAT EXCHANGER OPERATING MAP



OXYGEN HEAT EXCHANGER OPERATING MAP

FIGURE 3-13e



OXYGEN HEAT EXCHANGER OPERATING MAP

FIGURE 3-13f

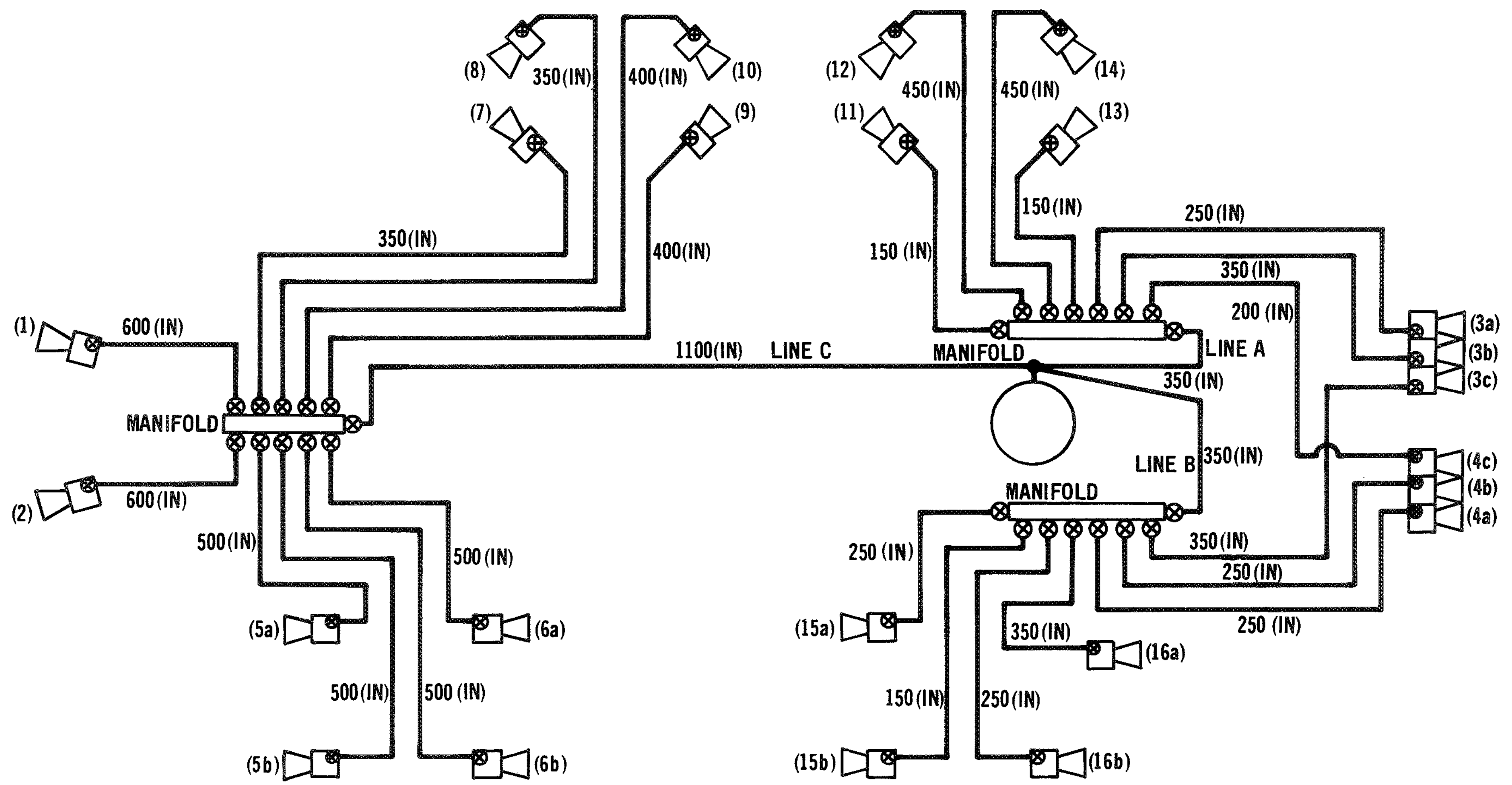
the width of each gas generator panel. The ignition source for the turbine exhaust gases and the GO_2 is a catalytic igniter in the GO_2 manifold, as shown in Figure 3-13a. Ignition in the GO_2 distribution manifold provides a short duration of high mixture ratio hot gas for ignition. This approach was used because a major concern is providing an ignition technique which allows uniform and consistent ignition between each of the closely spaced plate assemblies. The catalytic igniter is turned off after achieving uniform combustion downstream of each of the GO_2 injecters. This catalytic igniter concept requires the distribution, by the GO_2 injecter manifold, of approximately 2500 - 3000°R hot gas for short durations.

A stress analysis was conducted using steady state wall temperatures and a maximum pressure of 2475 LBF/in^{2}A, allowing for an over shoot of the design maximum pressure. The following results were obtained.

				MARGIN OF SAFETY	
		OXYGEN	HYDROGEN	OXYGEN	HYDROGEN
FLOW CHANNEL STRESSES (KSI)	SHEAR	2.4	4.7	2.4	>10
	BENDING	4.8	18.0	2.2	HIGH
	TENSION	4.8	15.5	2.2	HIGH
HOT SURFACE THERMAL STRAIN		1.3%	1.2%		

3.3 <u>Gaseous Propellant Storage Distribution Assembly</u> - The gaseous propellants are stored in 2219-T87 aluminum accumulators, which are insulated with aluminized mylar high performance insulation. These accumulators are pressure cycled a maximum of 50 times during each flight. The required orbiter B accumulator volumes are 29.0 ft^3 for the hydrogen and 11.6 ft^3 for the oxygen. The propellant distribution subassembly includes lines, valves, regulators, and manifolds. Line routings have been shown previously in Figures 2-13, 2-14, and 2-15. Line sizes and lengths are shown in Figures 3-14 through 3-16. Lines are aluminum and are insulated with aluminized mylar insulation. Manifolds provide a convenient method of distributing propellant to particular groups of thrusters and to provide isolation capability for banks of thrusters in the event two valves fail open in series.

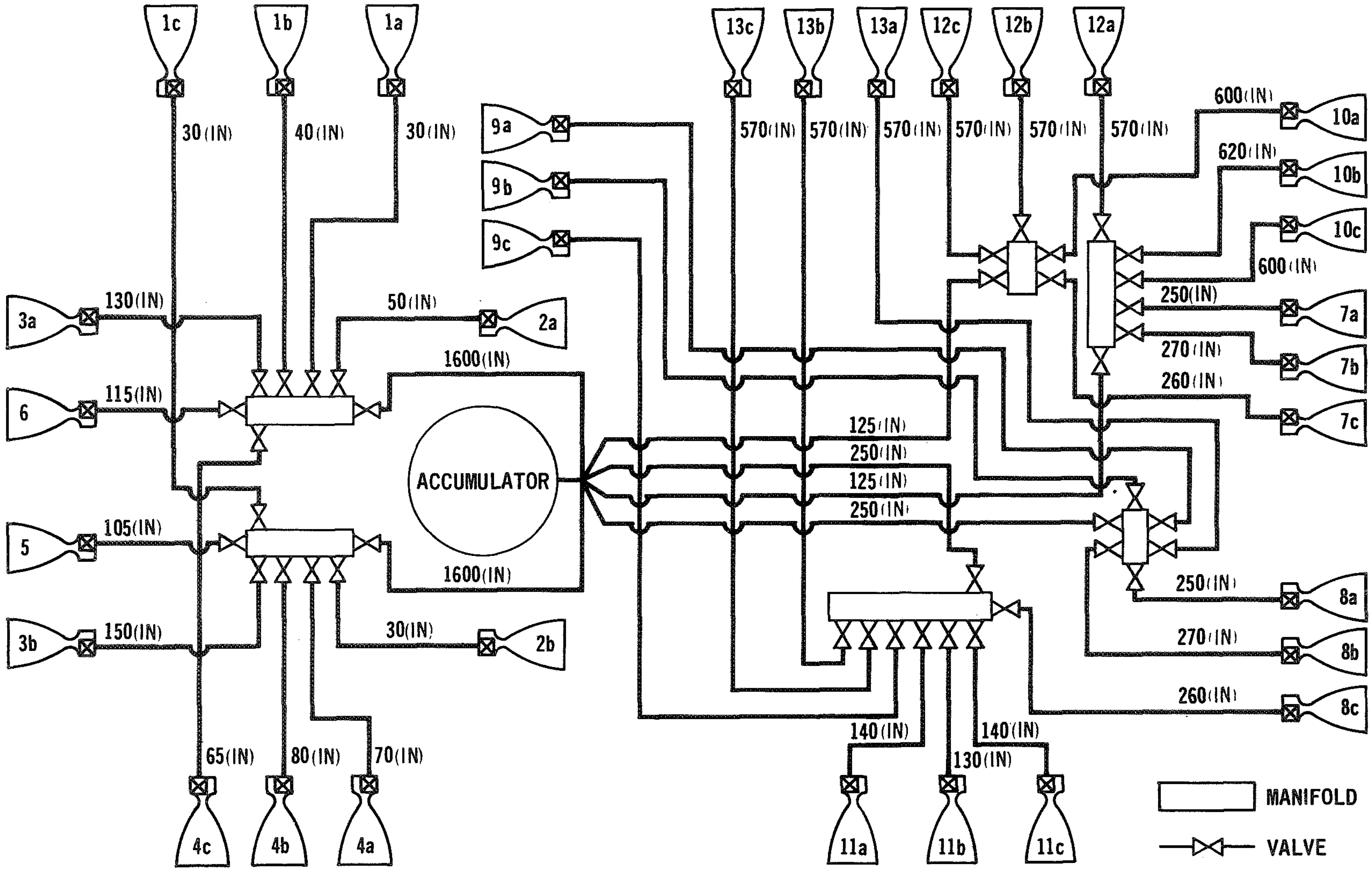
The regulators which control the pressure to the thrusters and to the gas



LINE TYPE	REQUIRED INNER DIAMETER	TUBE OUTER DIA USED	MIN WALL THICK REQ'D	ACTUAL WALL THICKNESS
MAIN A&B (H_2)	1.97(IN)	2.125(IN)	0.0316(IN)	0.042(IN)
MAIN A&B (O_2)	2.05(IN)	2.125(IN)	0.0316(IN)	0.042(IN)
MAIN C (H_2)	1.76(IN)	2.125(IN)	0.0316(IN)	0.042(IN)
MAIN C (O_2)	1.83(IN)	2.125(IN)	0.0316(IN)	0.042(IN)
BRANCH (H_2)	0.88(IN)	1.00(IN)	0.015(IN)	0.028(IN)
BRANCH (O_2)	0.92(IN)	1.00(IN)	0.015(IN)	0.028(IN)

ORBITER B LINE LENGTHS AND DIAMETERS

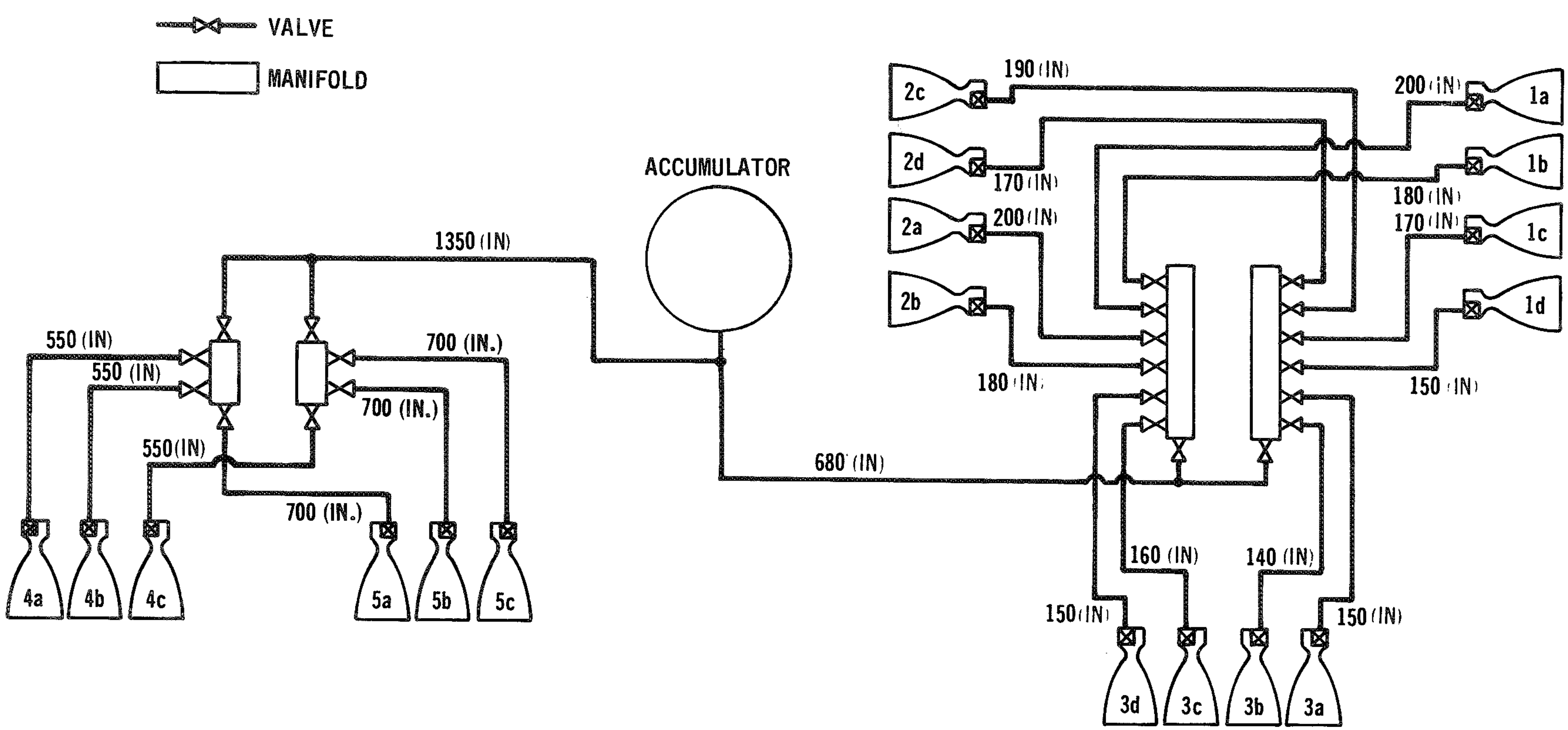
FIGURE 3-14



LINE TYPE	REQUIRED INNER DIAMETER	TUBE OUTER DIAMETER USED	MIN WALL THICK REQ'D	ACTUAL WALL THICKNESS
MAIN (H_2)	1.83 (IN)	2.12 (IN)	0.0316 (IN)	0.042 (IN)
MAIN (O_2)	1.90 (IN)	2.12 (IN)	0.0316 (IN)	0.042 (IN)
BRANCH (H_2)	0.92 (IN)	1.00 (IN)	0.015 (IN)	0.028 (IN)
BRANCH (O_2)	0.95 (IN)	1.00 (IN)	0.015 (IN)	0.028 (IN)

ORBITER C LINE LENGTHS AND DIAMETERS

FIGURE 3–15



LINE TYPE	REQUIRED INNER DIA	TUBE OUTER DIA USED	MIN WALL THICK REQ'D	ACTUAL WALL THICKNESS
MAIN (H_2)	2.49 (IN)	2.75 (IN)	0.0385 (IN)	0.042 (IN)
MAIN (O_2)	2.58 (IN)	2.75 (IN)	0.0385 (IN)	0.042 (IN)
BRANCH (H_2)	1.25 (IN)	1.38 (IN)	0.0186 (IN)	0.028 (IN)
BRANCH (O_2)	1.29 (IN)	1.38 (IN)	0.0186 (IN)	0.028 (IN)

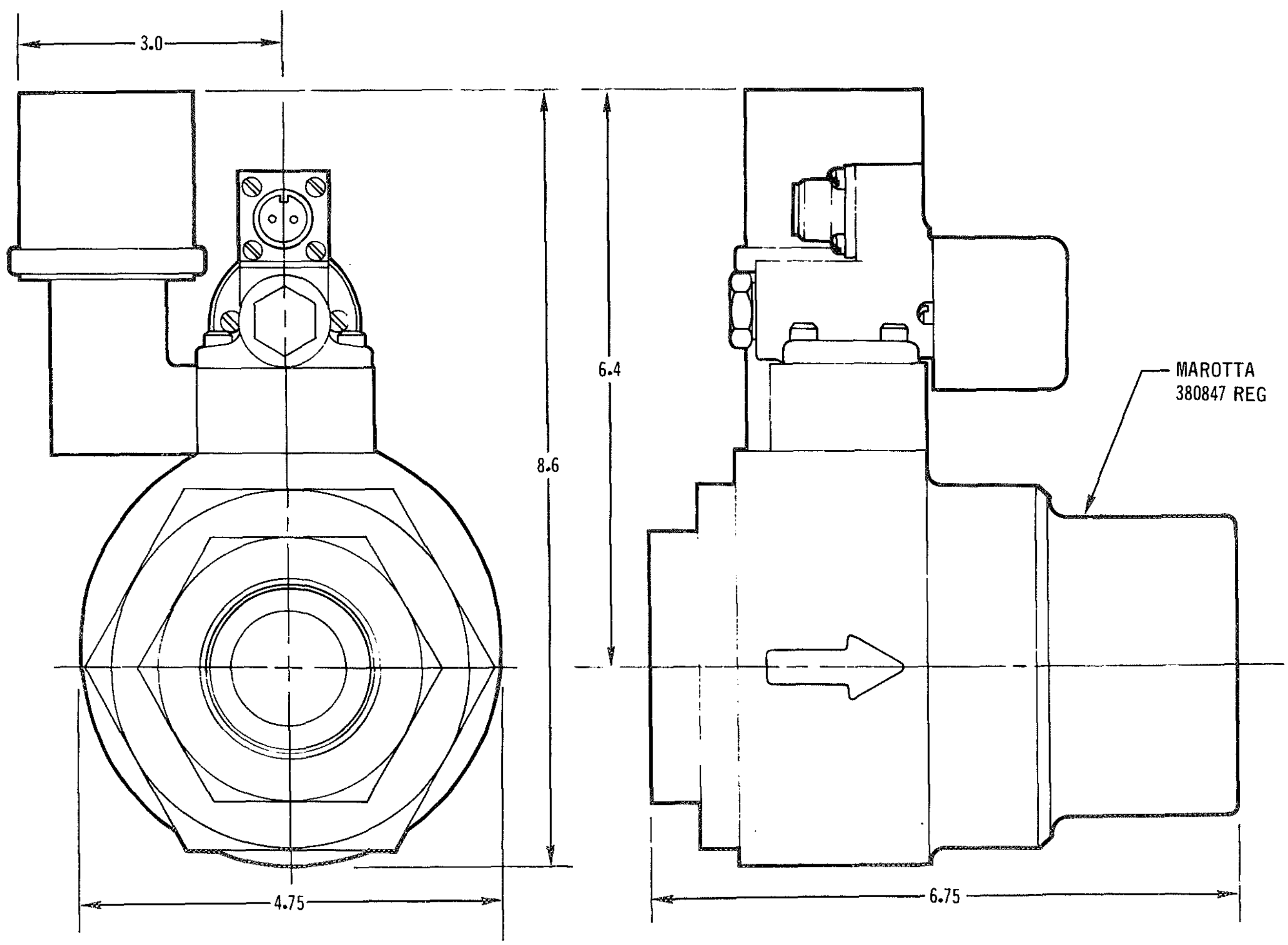
BOOSTER LINE LENGTHS AND DIAMETERS

FIGURE 3-16

generators are defined in outline by Figure 3-17. A small, dome loading, reference regulator is used to provide reference pressure to the main regulator. This configuration, proposed by Marotta Scientific Control, Inc., can provide the required regulation accuracy with adequate flow capability.

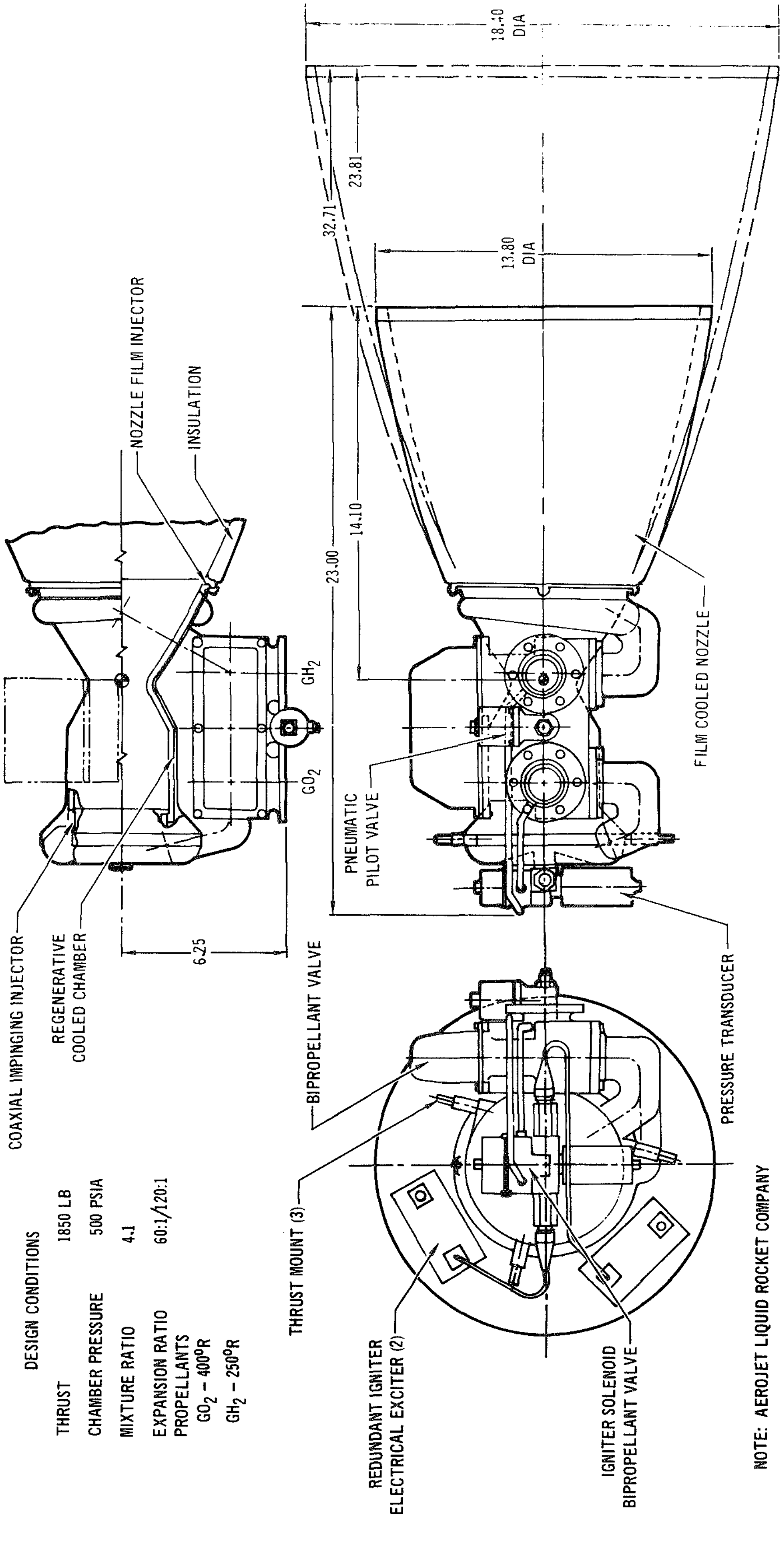
3.4 Thruster Assembly - The APS uses gaseous hydrogen-oxygen thrusters to provide the impulse necessary for space shuttle vehicle attitude control and orbital maneuvers. APS weight is very sensitive to the performance of these thrusters, due to the magnitude of APS total impulse requirements. Figure 3-18 shows the thruster design selected. Associated thruster performance is presented in Figures 3-19 and 3-20. The thruster design presented in Figure 3-18, consists of four primary components: propellant injector, combustion chamber, igniter, and propellant controls.

The injector concept selected for the high pressure APS thruster is an impinging coaxial design. This is a variation of the more conventional coaxial element,



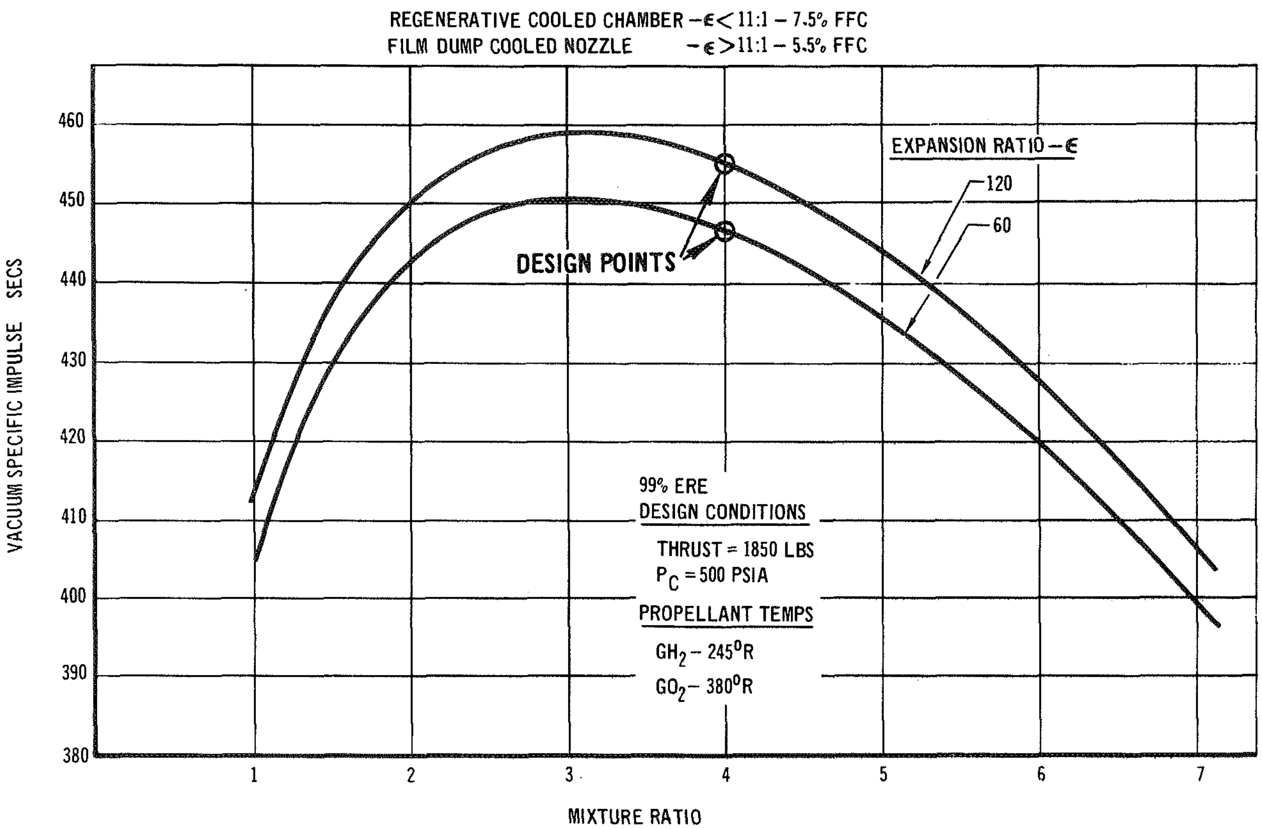
PRESSURE REGULATOR

FIGURE 3-17



HIGH PRESSURE APS THRUSTER

FIGURE 3-18



HIGH PRESSURE APS THRUSTER PERFORMANCE

FIGURE 3-19

DESIGN POINT		
THRUST, LBS	1850	1850
MIXTURE RATIO	4.0	4.0
CHAMBER PRESSURE, LBF/IN^{2}A	500	500
AREA RATIO	60	150
PROPELLANT TEMP, °R		
HYDROGEN	245	245
OXYGEN	380	380
CHAMBER COOLING, % ($\epsilon < 11:1$)	7.6	7.6
NOZZLE COOLING, % ($\epsilon > 11:1$)	5.4	5.4
PERFORMANCE		
THEORETICAL I_{SP} VACUUM, SEC	472.5	481.7
COOLING LOSS, SEC	7.9	7.9
IMPURITY LOSS, SEC	1.0	1.0
CURVATURE-DIVERGENCE LOSS, SEC	3.9	2.9
KINETICS LOSS, SECS	2.7	3.0
ENERGY RELEASE LOSS, SEC	4.6	4.6
BOUNDARY LAYER LOSS, SEC	5.9	7.5
DELIVERED VACUUM SPECIFIC IMPULSE, SEC	446.5	454.8

HIGH PRESSURE APS THRUSTER PERFORMANCE SUMMARY

FIGURE 3-20

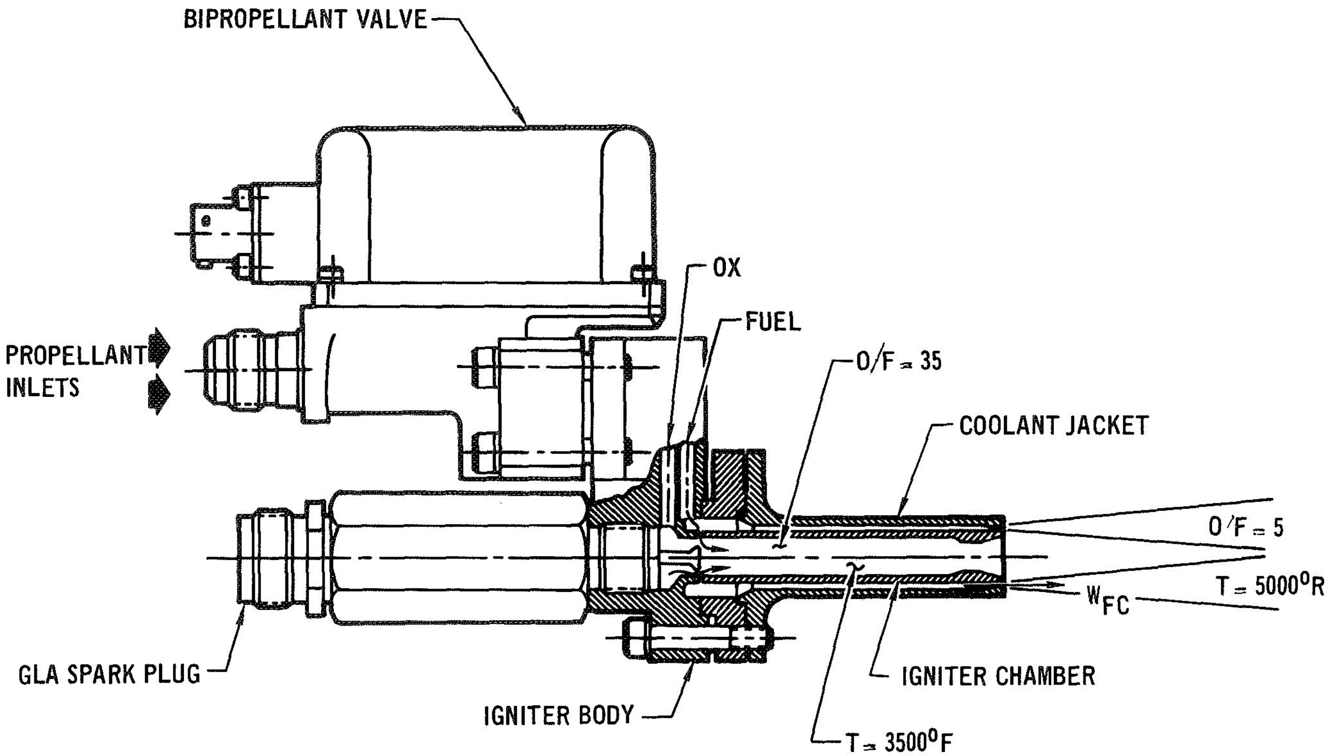
wherein fuel is injected normal to the axially directed oxidizer stream. The impinging coaxial design uses a concentric ring manifold attached to a free plate assembly containing internal fuel passages. The oxidizer channels discharge through the face plate parallel to the chamber axis. The fuel channels feed into a labyrinth of passages in the face plate which provide regenerative and transpiration cooling of the face as well as fuel entry into each element.

The combustion chamber is composed of a regeneratively cooled section, extending from the injector to a nozzle area ratio of 11:1, and a separate film cooled expansion nozzle. The regeneratively cooled chamber employs a rectangular channel geometry and is fabricated of a high conductivity copper alloy. The design is a single pass concept with hydrogen entering the chamber at an area ratio of 11:1 and flowing forward toward the injector and discharging into an injector manifold. The manifold also supplies hydrogen to a fuel film coolant ring which distributes a small percentage of fuel down along the chamber wall. The nozzle extension is attached to the regeneratively cooled chamber at an area ratio of 11:1 and extends to the exit diameters of 12.9 in. and 18.2 in. for area ratios of 60 and 120, respectively. Cooling of the nozzle is achieved by introducing 4 to 5 percent fuel flow, depending on the area ratio, at the point of attachment to the regeneratively cooled chamber.

The igniter for the high pressure APS thruster utilizes the spark discharge technique. Electrical ignition is attained by a spark discharge across the oxidizer flow stream. The immediate downstream addition and mixing of a small quantity of fuel to the spark-excited oxygen causes ignition within the igniter chamber. Figure 3-21 depicts this basic design.

The sequenced electrical igniter provides positive, fast ignition of primary injector propellant. The initial valve signal opens the thrust-chamber-valve pilot valve, the igniter valves, and initiates the spark current for the electrical sequencer. The igniter torch is established in 0.025 sec. The primary thrust chamber valves begin to open in 0.035 sec and are fully open 0.010 sec later. The thrust trace parallels valve opening rate and full thrust is achieved 0.045 sec after initial valve signal. The cycle is reversed for shutdown.

The propellant control valve for the APS thruster is a linked parallel poppet type with pneumatic actuation. The pneumatic actuation is provided by hydrogen gas from the feed lines. The valve is shown in Figure 3-22. This configuration has been tested under NASA-Lewis contract Number NAS 3-14354 and has demonstrated repeatable travel times of 0.010 sec. This type of valve provides the response

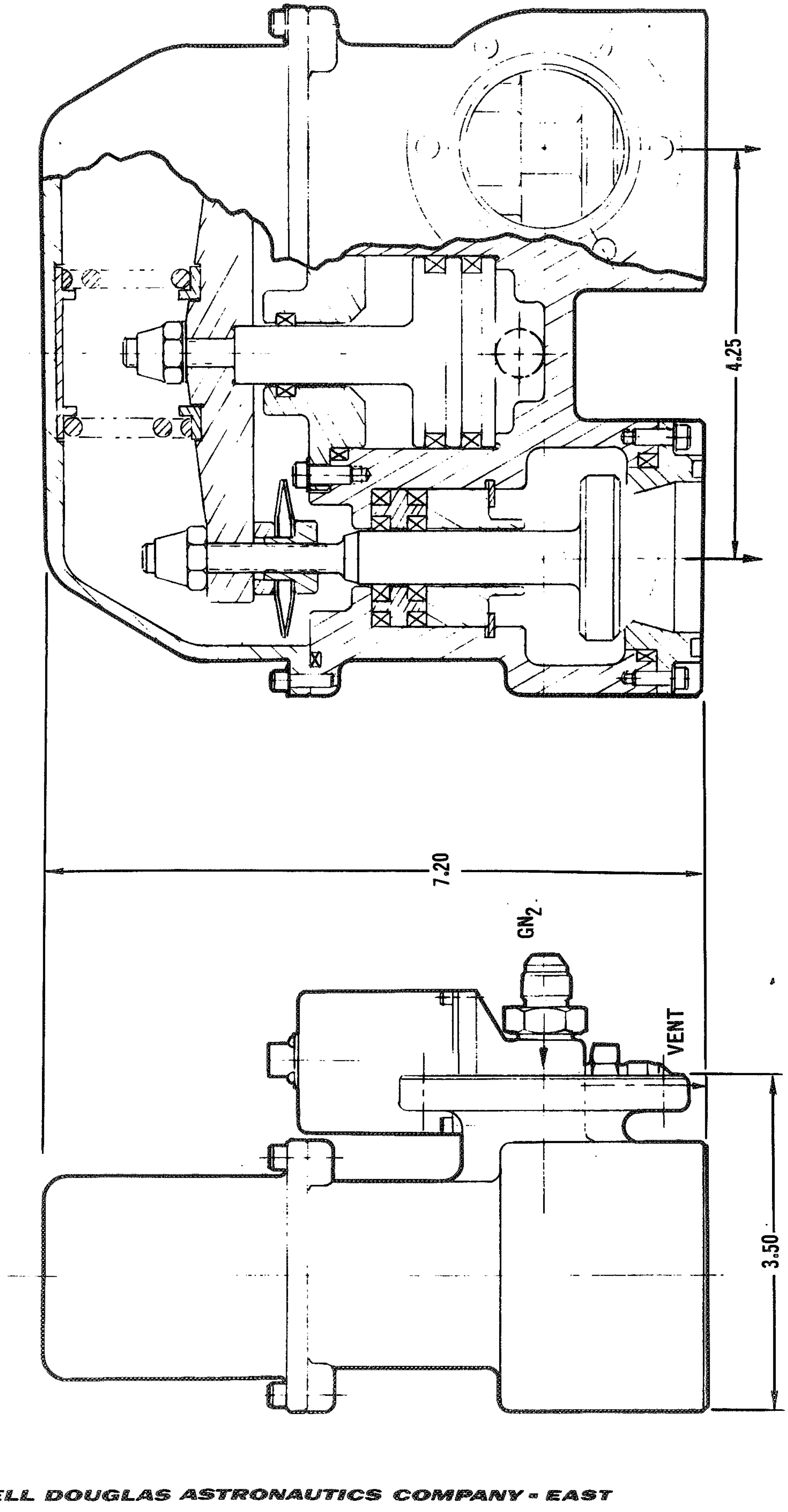


APS SPARK IGNITER

FIGURE 3-21

capability required for pulse mode operation. The poppet type valve also seals with a minimum of sealing surface wiping or surface shear, a desirable feature from a cycle-life standpoint.

The poppet seat material is KEL-F, which exhibits excellent compatibility with the propellants. Reasonable seal stress levels are achieved by control of seat surface area, and by balancing actuator spring force. The single pneumatic actuator is coupled to both the poppet shafts with a common link. The fast response pilot valve sequences regulated hydrogen line pressure into the pneumatic actuator to open the valve. The actuator cavity is vented when the pilot valve is sequenced closed and the actuator spring closes the valve. Venting is accomplished internally through the thruster assembly.



APS HIGH PRESSURE BIPROPELLANT VALVE

FIGURE 3-22

4. CONCLUSIONS

Data presented in the preceding paragraphs provide a complete description of the high pressure APS configurations defined for space shuttle high and low cross range orbiters and the booster. These definitions are the result of effort conducted under Contract No. NAS 8-26248. Although APS configurations were based on requirements defined in Reference (e), weight sensitivity data included in the study allows APS weight definition for a range of design and mission variables.

5. REFERENCES

(a) MDAC-East Report E-0299, "High Pressure Auxiliary Propulsion Subsystem Definition Summary Report", dated 12 February 1971.

(b) MSFC, "Space Shuttle Vehicle Description and Requirements Document", dated 15 July 1970.

(c) MDAC-East Report E0297, "High Pressure Auxiliary Propulsion Subsystem Definition Subtask A Report", dated 12 February 1971.

(d) MDAC-East Report E-0258, "Interim Subsystem Description Handbook", dated 27 October 1970.

(e) MSFC, "Space Shuttle Vehicle Description and Requirements Document", dated 1 October 1970.

(f) MDAC-East Report E-0298, "High Pressure Auxiliary Propulsion Subsystem Definition Subtask B Report", dated 12 February 1971.

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