N71-37371

SPACE SHUTTLE HIGH PRESSURE AUXILIARY PROPULSION SUBSYSTEM DEFINITION

EXECUTIVE SUMMARY REPORT

CASE FILE COPY

CONTRACT NAS 9-11013

MARCH 31, 1971

PREPARED FOR
MANNED SPACECRAFT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HOUSTON, TEXAS

TRW
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ABSTRACT

This report presents a summary overview of the findings of the Space Shuttle High Pressure Auxiliary Propulsion Subsystem Definition studies carried out by TRW Systems and its subcontractor, AiResearch Manufacturing Company. The study was performed for the National Aeronautics and Space Administration, Manned Spacecraft Center (MSC), Houston, Texas, under Contract NAS 9-11013.

The study effort was divided into two subtasks. The first subtask was a conceptual definition effort designed to screen a number of possible auxiliary propulsion system (APS) candidates for application to both booster and orbiter elements selected as baseline vehicles. From this effort selected concepts were carried forward into the second subtask. The second subtask provided for a preliminary design to define the concept with respect to its component needs and operation.

This report presents the summary findings for the selected cycle which is a pumped liquid, dual gas generation cycle. It features separate gas generators for the turbine and heat exchanger functions. Judicious selection of thruster sizing for the orbiter and booster resulted in a common 1840 lbf thruster for each vehicle and allowed a common conditioner design between each vehicle with the same peak demand rates. The cycle also provides for high performance controllability logic as well as single purpose control logic for the low ΔV APS demands.

Complete results of the study are found in TRW Report 17611, the final report. A Design Handbook, TRW Report 17611.1, provides component data for the selected cycle.

CONTENTS

		Page
1.	SUMMARY	1-1
	1.1 Program Objectives	1-3
	1.2 Program Approach	1-5
	1.3 Subtask A Summary Effort	1-6
	1.4 Subtask B Summary Effort	1-11
	1.5 Cycle Selection	1-11
2.	CYCLE CHARACTERISTICS	2-1
	2.1 Operating Point Selection	2-1
	2.2 Commonality	2-5
	2.3 Conditioner Cycles	2-9
	2.4 Thermodynamic Balance for Dual Gas Generator Cycle	2-15
	2.5 Major Component Description	2-15
	2.5.1 Turbopumps	2-15
	2.5.2 Heat Exchangers	2-15
	2.5.3 Start Bottles	2-22
	2.5.4 Gas Generators	2-22
	2.6 Pressurization	2-23
	2.7 Liquid Acquisition and Tankage	2-26
	2.8 Controls	2-28
	2.9 Main Line Sizing and Accumulator Requirements	2-33
	2.9.1 Line Sizing	2-33
	2.9.2 Accumulations	2-33
	2.9.3 Mixture Ratio Variability Effects on Number of Starts	2-37
	2.10 Cycle Weight Comparison	2-37
3.	VEHICLE INTEGRATION, REDUNDANCY AND MAINTAINABILITY	3-1
	3.1 Integration	3-1
	3.2 Redundancy	3-1
	3.3 Maintainability Requirements	3-6
4.	CRITICAL TECHNOLOGY SUMMARY REQUIREMENTS	4-1
	4.1 Phase Acquisition	4-1
	4.2 Pressurization	4-1

CONTENTS (Continued)

		Page
4.3	Tank Insulation	4-2
4.4	Gas Generators	4-2
4.5	Thrusters	4-2
4.6	Turbopumps	4-3
4.7	Heat Exchangers	4-3
4.8	Regulators and Throttle Valves	4-4
4.9	Instrumentation	4-4
4.10	Dynamics/Control	4-5

1. SUMMARY

The Space Shuttle High Pressure Auxiliary Propulsion Subsystem Definition Study was an 8-month technical effort to define, for both booster and orbiter elements of the Space Shuttle Vehicle, oxygen-hydrogen auxiliary propulsion subsystems capable of meeting Space Shuttle APS requirements. The selected APS concepts should require a minimum of new technologies and exhibit potentially high reliabilities and minimum subsystem weight. Specifically, the effort was directed to investigate those systems whose operating pressures are in excess of on-board liquid propellant ullage vent pressures.

The selected system for the high pressure APS is a pumped liquid cycle with supercritical heat exchange to condition the propellants. The cycle utilizes individual turbopumps and parallel gas generators to drive the turbines and feed the heat exchangers. The conditioned propellants are fed into a high pressure distribution network. A regulator controls the pressure to the thrusters.

The selected operating point for the conditioner network is 265°R and 1100 psia for the hydrogen and 315°R and 1100 psia for the oxygen for the high energy missions. This selection insures against liquid propellants being delivered into the thruster. The selected point also is a minimum conditioner energy point for conditioning the propellants. For low energy orbiter missions where the quantity of propellants used is only 3921 pounds rather than 27,952 pounds needed for the high energy missions, propellant conditioning temperatures can be raised to maximum ambient conditions of 500°R on both propellants without paying an exorbitant conditioning propellant penalty.

The selected thruster operating pressure is 300 psia with mixture ratios of 4 to 6. The regulator controls pressure to 400 psia in the thruster feedlines while the main vehicle distribution loop is maintained at 1100 psia, in order to take maximum advantage of the propellant feed line volume as an accumulator. The hydrogen feed lines provide 3.1 ft^3 and the oxygen 4.3 ft^3 of accumulator volume. With these selections there is a minimized spherical oxygen accumulator volume of 5 ft^3. The

main spherical hydrogen accumulator is also minimized to approximately 20 ft^3. These accumulator volumes are applicable for the nominal high energy mission. For other mission profiles, the accumulator sizes can be varied to suit the mission.

The turbopumps have a startup time on the order of 0.3 second. This is accomplished through the use of negligible load starts. Separate accumulators of 2.1 ft^3 for the hydrogen and 0.16 ft^3 for the oxygen are used for starting the conditioner gas generators. The pumps are single-stage centrifugal with inducers and directly driven at turbine speeds. The hydrogen turbine speed is 50,000 rpm and the oxygen turbine speed is 32,000 rpm.

The gas generators operate at a nominal mixture ratio of 1:1 to supply hot gas for both the turbine and heat exchanger. Temperature trim and required total energy modulation are accomplished by trimming the oxygen and total flow respectively for the nominal high energy mission. For the low energy missions, a less sophisticated control could be implemented. This could include constant gas generator output flow and narrowing the range of APS thrust demands, or using a torque balanced turbopump over a somewhat wider thrust demand range.

The heat exchanger approach is a co-current flow design with operating conditions selected to minimize freezing blockage and starting thermal shock loading. Operation with inlet gas generator gases at a nominal mixture ratio of 1:1 enables the use of state-of-the-art construction techniques. The selected exit exhaust temperature is 750°F which virtually eliminates exhaust venting freezing problems.

Detailed dynamic analysis of the distribution loop resulted in a maximum line Mach number criteria of 0.075, in order to minimize pressure surging. The high pressure loop has a control pressure ratio of 1100/600 on both the hydrogen and oxygen sides. The accumulator volumes allow for the total mission limit cycle requirements and conditioner spin-up time with a full hard-over yaw maneuver occurring. The accumulator sizings also allow the stored gas volumes to heat to 500°R over a long dormant period with the system still meeting the limit cycle and hard-over yaw maneuver startup. The thermal heat-up

pressure vent requirement is set at 1100 + 50 psia on both propellants. This allows acceptable control of the thruster mixture ratio and the system never provides a mixture ratio control much greater than the design point during any startup. As a result, mixture ratio control is not required for safety. Thruster mixture ratio control does not appear to provide any major weight savings in any event.

The entire APS system is arranged in modules. The basic turbopump, gas generator, heat exchanger, and start bottle occupy approximately 27 ft^3. The regulator package is a separate module. The thruster clusters are also modularized. With this approach the fail operational/fail safe criteria are met by building system redundancy in the module arrangements in some cases and using redundant single component modules in others, which in turn are interconnected by switching and isolation networks. APS tankage, main line accumulators and distribution loops are not redundant. The overall approach is completely interchangeable between the booster and the orbiter. As a result, with the exception of the liquid storage tank requirements, the system is virtually independent of the vehicle in its operation. This approach provides the maximum of flexibility.

The system is compatible with propulsive venting as well as non-propulsive venting. Staged combustion heat exchangers are easily incorporated into the system to uprate its capability if desired. The independent pumping loops enable overall vehicle system integration with APU, ECS and OMS elements of the vehicle, since the system maximum flow rates and storage volumes are compatible with all these systems.

The total estimated weight of the all-maneuver APS is 34,912.4 pounds. The purely APS functional system weight is 8,434.4 pounds.

1.1 PROGRAM OBJECTIVES

The scope of this program was to define for both booster and orbiter elements O_2/H_2 auxiliary propulsion subsystems capable of meeting space shuttle APS requirements wherein the APS would perform the following:

(1) Euler angle maneuvers
(2) All X, Y, Z maneuvers
(3) All translation maneuvers except single +X burns >50 ft/sec
(4) All translation maneuvers except single +X burns >10 ft/sec

This provided three ΔV ranges of interest for the orbiter. A single ΔV requirement was imposed on the study for the booster. For all selected concepts which were to be examined each cycle was to be evaluated in terms of:

- Minimum new technology requirements
- Simplicity
- Reliability
- System performance.

Following the above evaluation selected cycles were evaluated in some detail to establish final APS design requirements. The final program task was identification of required critical technology for the selected APS design.

The contract was divided into two subtasks to accomplish the above objectives. In subtask A, the effort was guided by the requirements outlined in the NASA Space Shuttle Vehicle Design and Requirements Document (SSVDRD) for the APS, dated July 1, 1970. In this task the following tasks were undertaken:

- Establish cycle schematics
- Determine thermodynamic balances
- Provide component performance and weight parametrics
- Determine preliminary operating points
- Identify critical technology needs
- Recommend baseline systems.

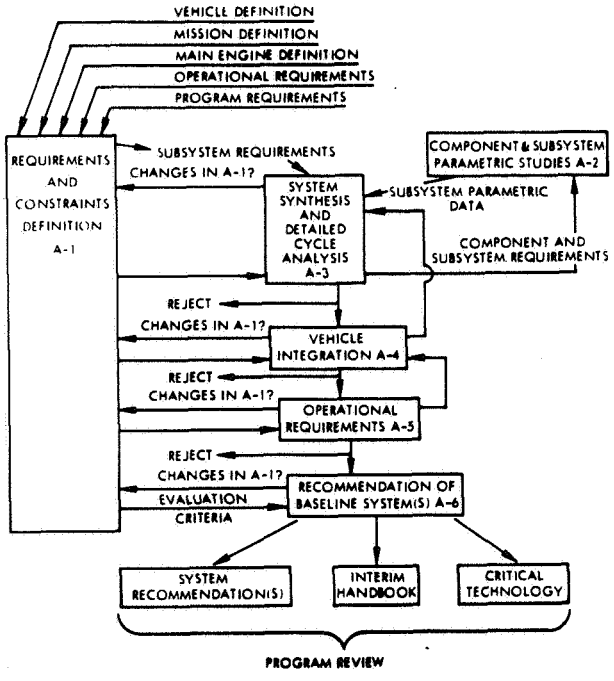
In subtask B, selected cycles were carried through preliminary design and analysis, based upon the updated SSVDRD requirements of 15 October 1970, to accomplish the following:

- Subsystem definition
- Thermodynamic balance
- APS cycle dynamics/control
- Reliability/maintainability definition
- Vehicle integration
- Identification of critical technology.

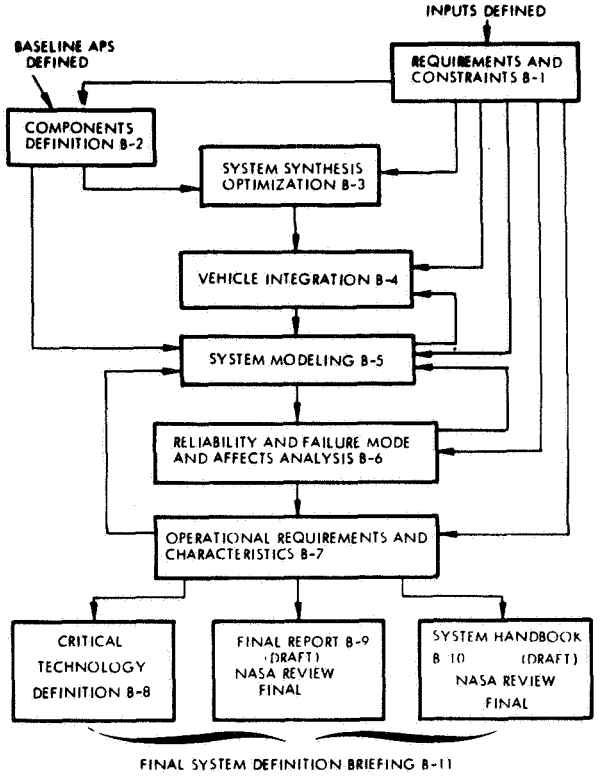
In addition, the subtask B effort included a concerted effort to provide commonality between the booster and orbiter APS elements to meet both vehicle propulsion requirements with a minimum of performance penalty in either vehicle.

1.2 PROGRAM APPROACH

Because of the expected variability in the original vehicle requirements it was necessary to organize the study effort with the capability to absorb vehicle changing requirements with a minimum impact on the final preliminary design efforts. The two subtasks were organized to operate as shown in Figure 1-1. Subtask A was highly paramentric to allow meaningful screening of possible APS concepts. As a result it called for a continued updating of requirements. Subtask B was organized to accept new vehicle requirements for a final system design investigations. The overall effort was carried out over a period of 7-1/2 months.



Subtask A: Conceptual Definition, Logic Diagram High Pressure SSAPS



Subtask B: Preliminary Design, Logic Diagram High Pressure SSAPS

Figure 1-1. Program Approach

1.3 SUBTASK A SUMMARY EFFORT

The original vehicle combinations which were evaluated are shown in Figure 1-2. The APS ΔV requirements for these vehicles resulted in conditioner flow requirements as summarized in Table 1-1. As seen from the table a wide range of flows were possible because of the widely differing vehicle requirements. It was recognized at this time that the vehicles would continue to vary in their APS requirements for some time and the program was organized to provide parametric data for the components which would be used in the various cycles as follows:

Regulators/Valves/Actuators	1 to 100 lb/sec
Pumps	2 to 100 lb/sec
Heat Exchangers	2 to 100 lb/sec
Thruster Assemblies	100 to 6000 lbf (50 to 700 psia)
Accumulators	600 to 4000 psia

In addition, the tankage requirements had to consider short-term storage as well as long-term storage, along with pressurization by either helium or autogenous systems.

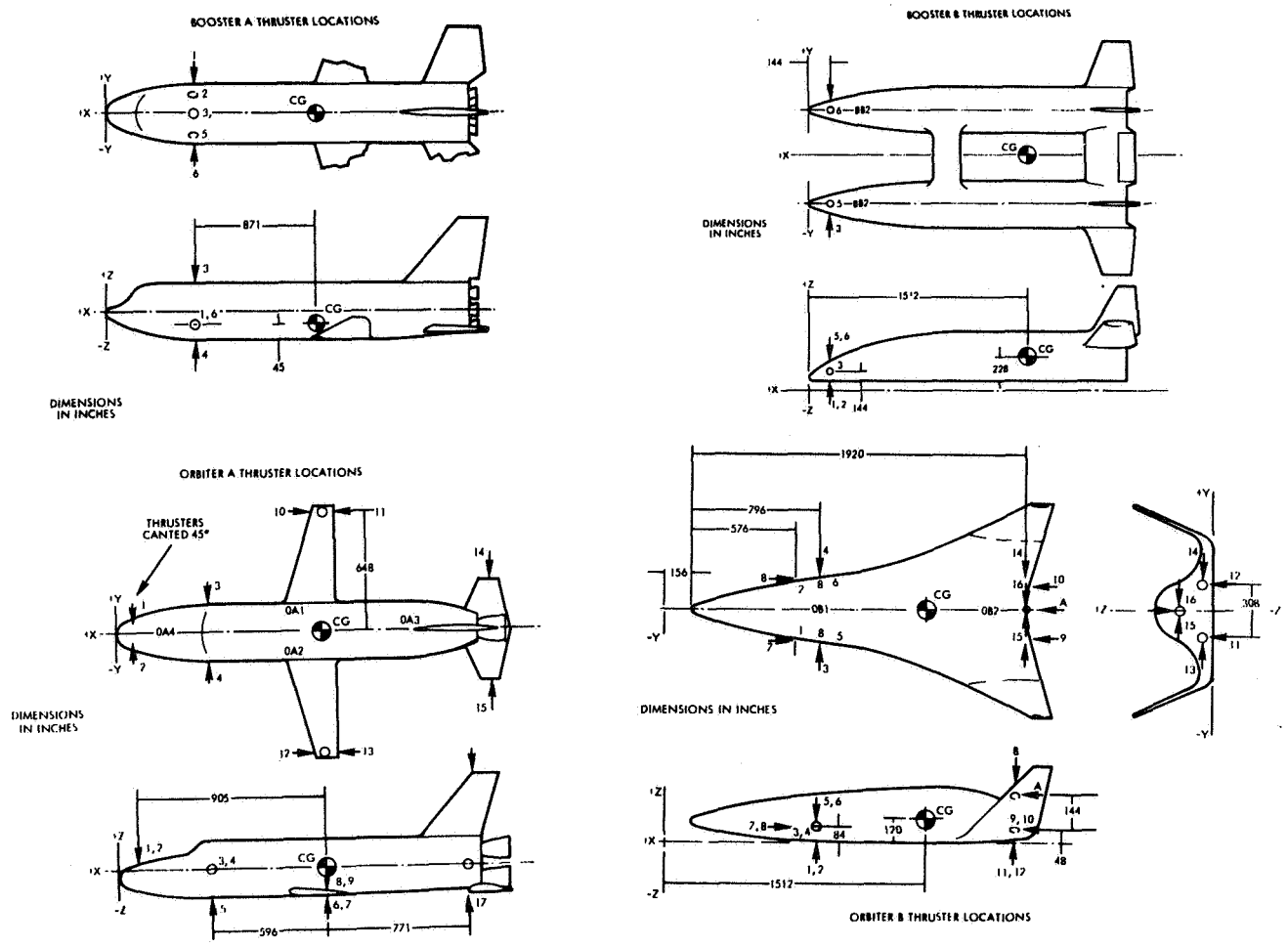


Figure 1-2. Subtask A Baseline Vehicle

Table 1-1. Subtask A Conditioner Flow Requirements

OPERATING FLOW RATES PER CONDITIONER[1]

Vehicle	Conditioner		Flow Rate, Lb/Sec					
	Number	Max Thrust	Isp = 416 MR = 6:1			Isp = 392 MR = 1:1		
			Total Flow	O_2	H_2	Total Flow	O_2	H_2
Booster A	Single Unit	23,760	57.00	48.85	8.15	60.6	30.3	30.3
Orbiter A	OA1	517	1.24	1.06	.18	1.32	.66	.66
	OA2	517	1.24	1.06	.18	1.32	.66	.66
	OA3	2,425	5.83	4.99	.84	6.19	3.09	3.09
	OA4	2,425	5.83	4.99	.84	6.19	3.09	3.09
	Single Unit	5884	14.14	12.10	2.04	15.00	7.50	7.50
Booster B	Single Unit	13,810	33.20	28.45	4.75	35.25	17.62	17.62
Orbiter B	OB1	4,108	9.86	8.45	1.41	10.48	5.24	5.24
	OB2	8,440	20.29	17.39	2.90	21.50	10.75	10.75

[1] Assumes pitch, roll and yaw and translation can occur during a maneuver.

To provide order in the study the candidate cycles were divided into the major areas as given in Table 1-2: super-critical, stored gas, gas compression and liquid pumping cycles. Each of these areas were further subdivided as shown in Tables 1-3 through 1-6. Based upon weight criteria the applicability of 12 selected cycles was determined as given in Table 1-7. Complete performance parametrics for each of the 12 cycles were determined and final cycles for subtask B efforts were selected.

Table 1-2. Top Level APS Cycles

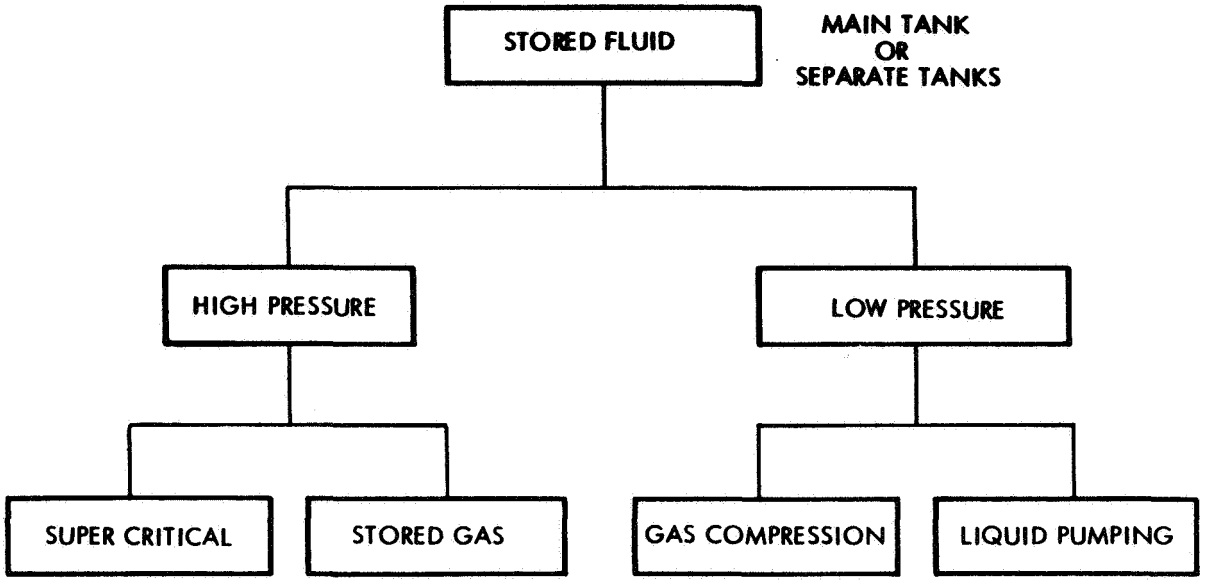


Table 1-3. Liquid Pumping APS Cycle Variations

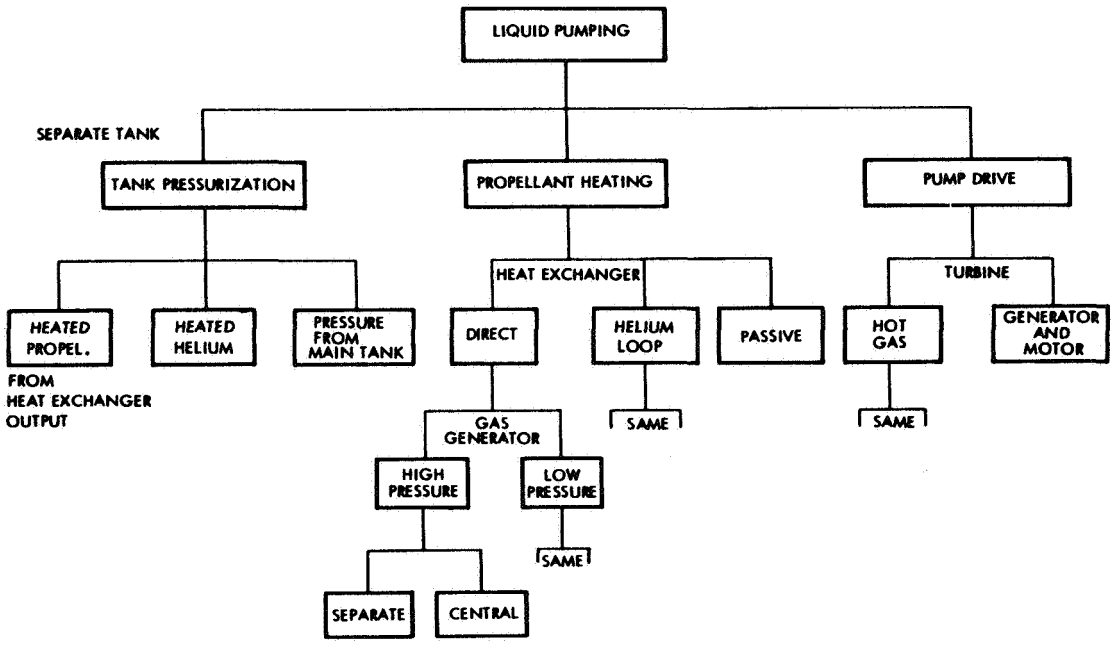


Table 1-4. Gas Compression Cycles

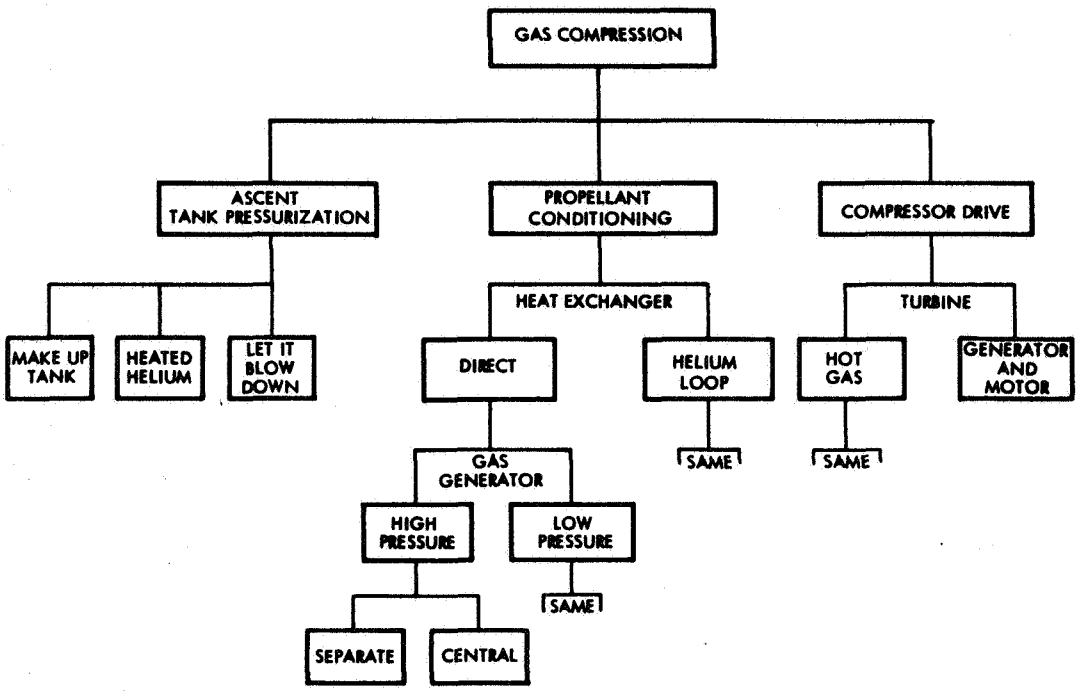


Table 1-5. Stored Gas Cycles

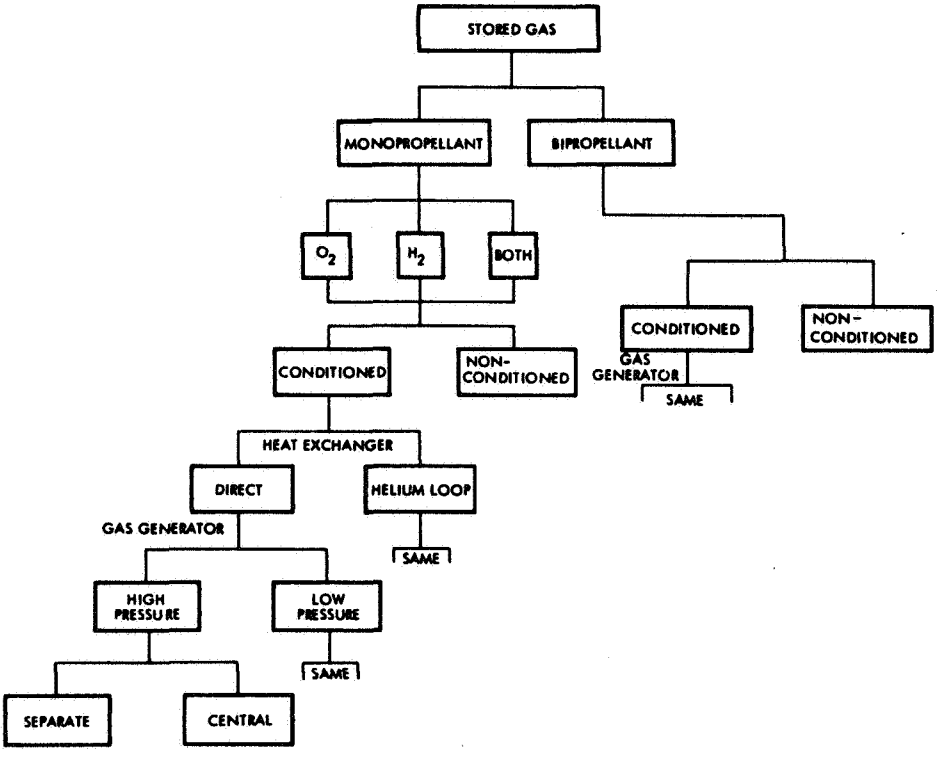


Table 1-6. Supercritical Cycles

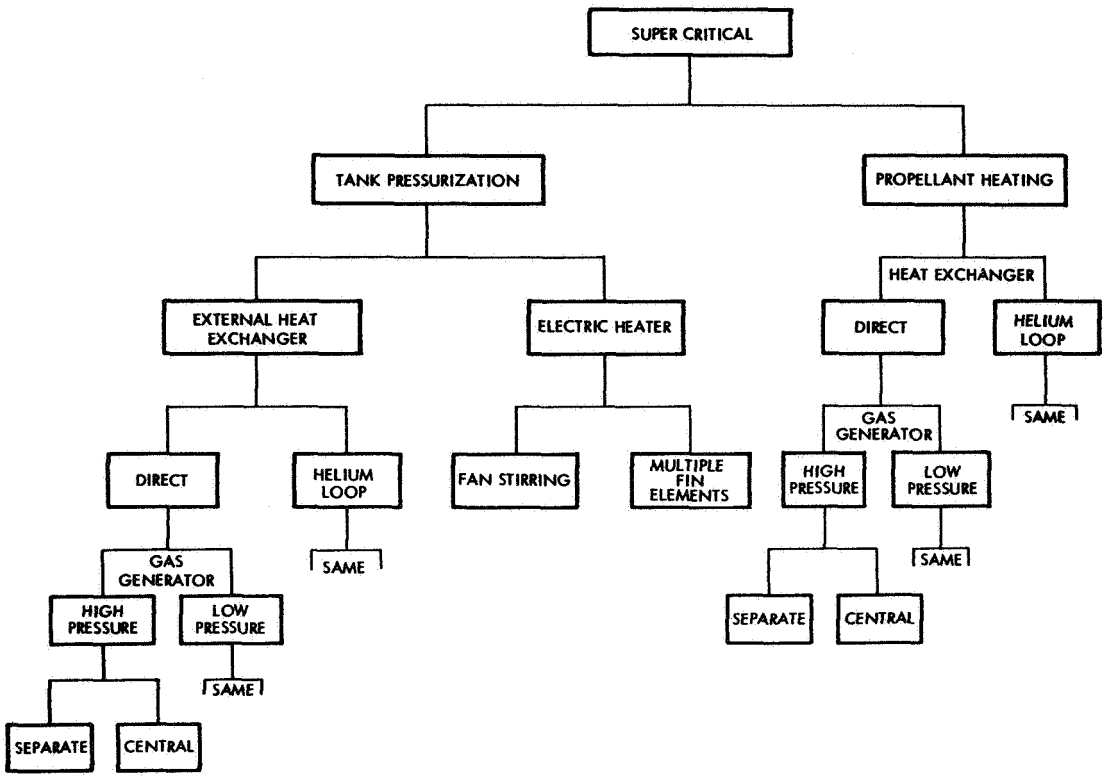


Table 1-7. High Pressure Cycles and Vehicle Applicability

	Cycle Number	Basic Cycle	Variations of Basic Cycle	Applicability							
				Bipropellant				Monopropellant			
				Booster	Orbiter			Booster	Orbiter		
					L	I	H		L	I	H
(1) Pumped Liquid	1	High Pressure Gas Generator for Propellant Heating	Indirect Heating	X	X	X	X				
	2			X	X	X	X				
	3	Low Pressure Gas Generator for Propellant Heating	Direct Heating	X	X	X	X				
Gas Compression	4		No Heating	X	X						
	5		No Heating					X			
	6	High Pressure Gas Generator for Propellant Heating	Direct Heating	X	X						
	7	Low Pressure Gas Generator for Propellant Heating	Direct Heating	X	X				(2)		
	8		Direct Heating					X	X		
Stored Gas	9	Low Pressure Gas Generator for Propellant Heating	No Heating	X							
	10		Direct Heating	X	X						
(1) Supercritical	11	High Pressure Gas Generator for Propellant Heating	Direct Heating	X	X						
	12	Low Pressure Gas Generator for Propellant Heating	Direct Heating	X	X	X					

(1) Pumped liquid and supercritical cycles can also use small propellant storage tanks refillable from the orbit maneuvering engine turbopumps for L (low) and I(intermediate) orbiter velocity increment.

(2) Separate makeup tanks using the structure as a passive heat exchanger can extend the range still further. Most applicable as a monopropellant oxygen system.

1.4 SUBTASK B SUMMARY EFFORT

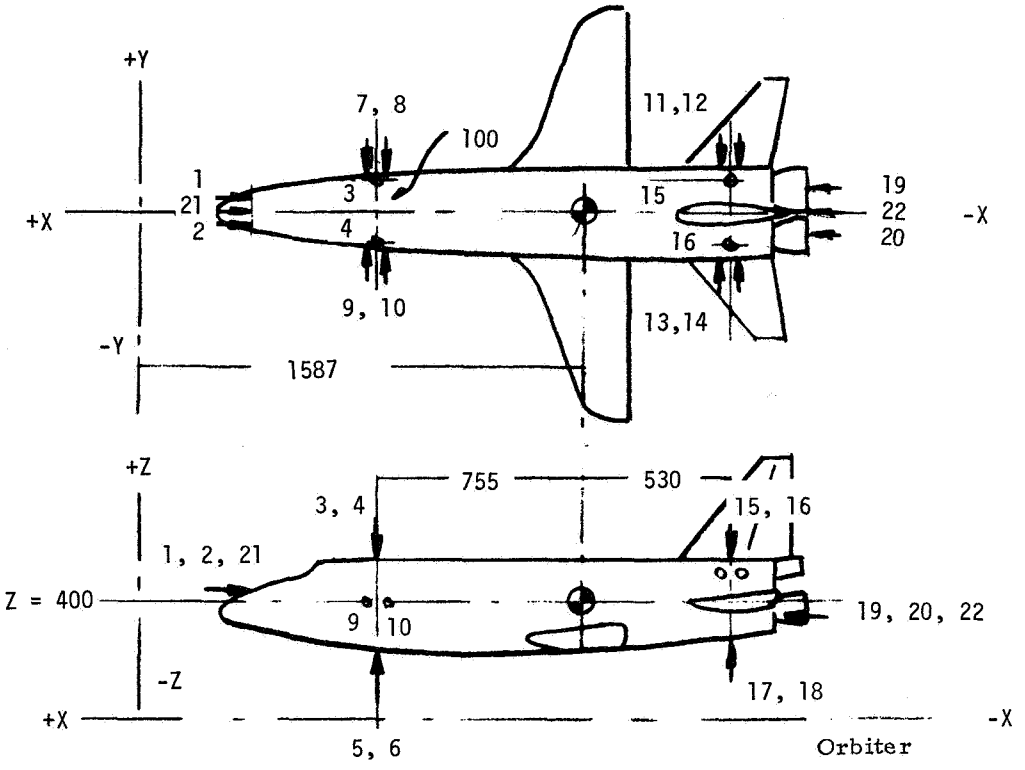
To begin the subtask B effort, an updated SSVDRD document (15 October 1970) was provided; the selected vehicles are those shown in Figure 1-3. A comparison of requirements between the subtask A and B efforts is shown in Tables 1-8 and 1-9. For the subtask B effort, the cycle analysis was restricted to the orbiter all and low ΔV and the booster requirements. Primary emphasis was placed on the high ΔV system performance with some consideration to the required changes for a low ΔV system.

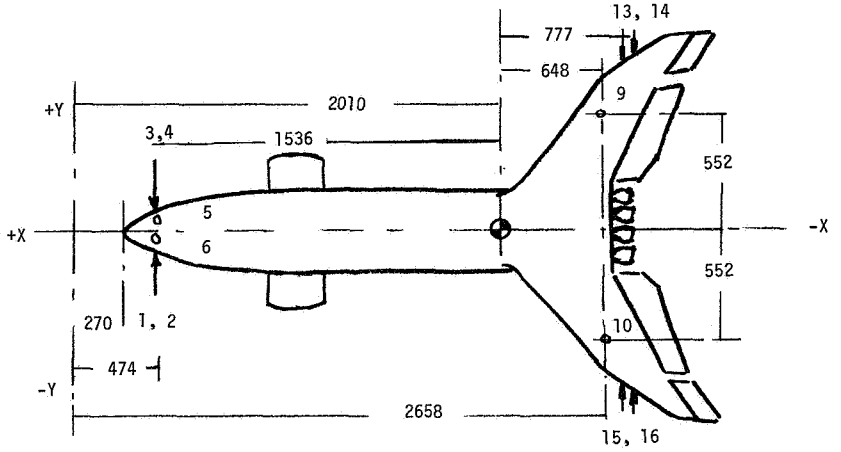
1.5 CYCLE SELECTION

The selected cycles were (1) a basic turbopump cycle for both orbiter and booster, and (2) a brief evaluation of a compressor cycle for the booster.

The final selected cycle for overall evaluation is given in Figure 1-4. It features dual gas generators with small start bottles to provide optimum matching of equipment transients with control requirements. The basic cycle is completely adaptable to several control logics to feature (1) performance in the high ΔV cycle, and (2) simplicity in the low ΔV cycle. Also illustrated is the capability to incorporate propulsive venting into the APS by oxygen drawoff from the ascent tank residuals.

The overall performance aspects and needs of the cycle as applied to both high and low ΔV requirements are illustrated in Figure 1-5. As is seen in the high ΔV application, the overall weight sensitivity to performance by the thrusters (also to conditioning loss) is approximately 100 lb/sec Isp. In the low ΔV application, the sensitivity is only ~9 lb/sec Isp. As a consequence, the high ΔV system demands high performance optimal control, a high turbine pressure ratio, and an optimum conditioner outlet temperature. On the other hand, the low ΔV system suffers only minimal penalties when it conditions to the environment temperature and a low pressure ratio, constant gas power turbine is used.





Booster

DIMENSIONS IN INCHES

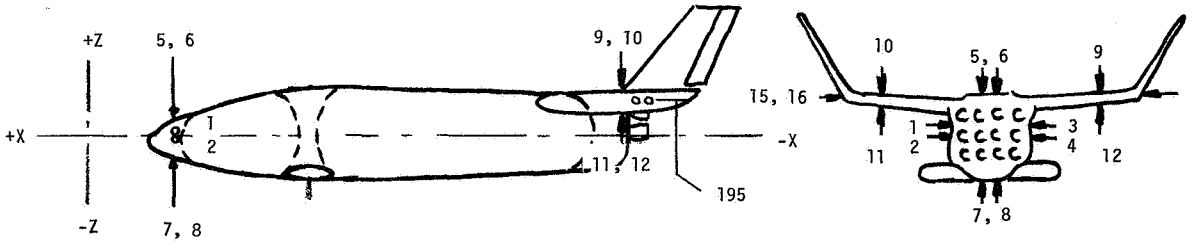


Figure 1-3. Subtask B Vehicle Selection

Table 1-8. Comparison of Subtask A and B Vehicle and Mission Requirements

	BOOSTER		ORBITER	
	SUBTASK A	SUBTASK B	SUBTASK A	SUBTASK B
WEIGHT AT BURNOUT, LBS	458,600	474,876	224,900	248,058
TOTAL IMPULSE REQUIREMENTS, FPS				
BOOSTER	455,750	862,750	---	---
LOW DELTA-V ORBITER	---	---	1,190,000	1,267,000
INTERMEDIATE DELTA-V ORBITER	---	---	3,000,000	N/A
HIGH DELTA-V ORBITER	---	---	14,126,000	10,260,000
ANGULAR ACCELERATION, DEG/SEC^2				
NOMINAL	0.5 P; 1.0 R, Y	0.5 P; 1.0 R, Y	0.5 P; 1.0 R, Y	1.0 P, R; 1.3 Y
MINIMUM	0.3 P, R, Y	0.3 P, R, Y	0.3 P, R, Y	0.5 P, R; 0.9 Y
TRANSLATIONAL ACCELERATION, FT/SEC^2				
NOMINAL	---	---	0.1 X, Y, Z	0.65 X 0.2 Y, Z
MINIMUM	---	---	0.07 X, Y, Z	0.5 X; 0.1 Y, Z

Table 1-9. Characteristics of Vehicle and Mission

BOOSTERS

- SHORT MISSION TIME, FEW HOURS
- LARGE RESIDUAL PROPELLANTS

	PHASE A				PHASE B			
	HYDROGEN		OXYGEN		HYDROGEN		OXYGEN	
	GAS	LIQUID	GAS	LIQUID	GAS	LIQUID	GAS	LIQUID
BOOSTER A	3,552	3,710	12,402	14,800	826	6,060	4,506	14,290
BOOSTER B	2,511	589	7,000	13,000	NOT APPLICABLE			

- LOW VELOCITY INCREMENT, FT/SEC: PHASE A - 32.0
  PHASE B - 58.5

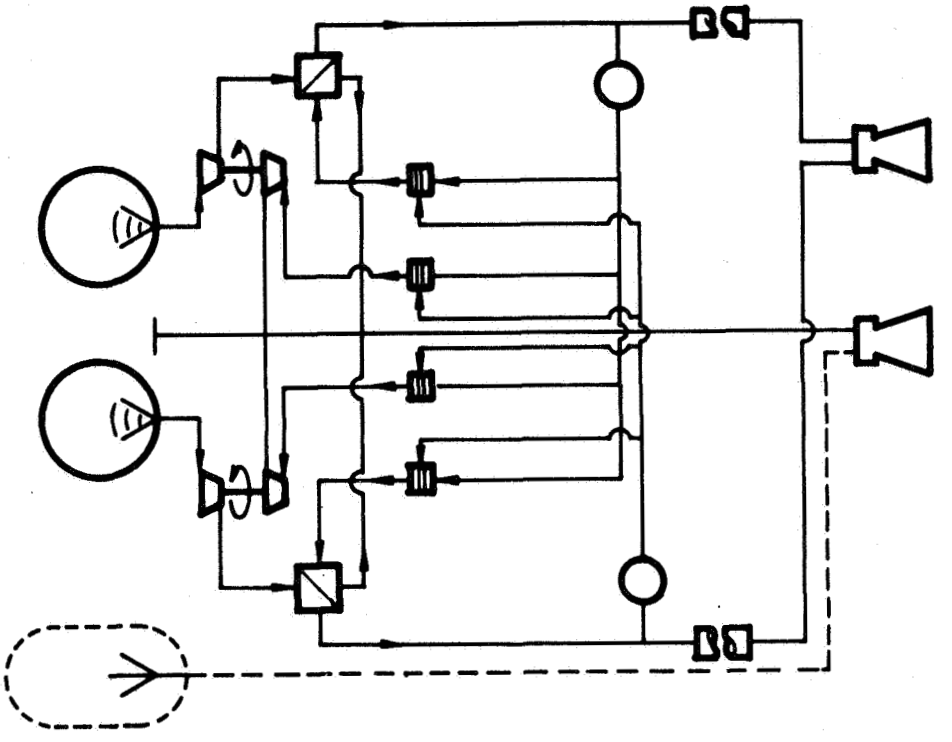
ORBITER

- LONG MISSION TIME, 7 DAYS AND 30 DAYS
- SMALL RESIDUAL PROPELLANTS

	PHASE A				PHASE B			
	HYDROGEN		OXYGEN		HYDROGEN		OXYGEN	
	GAS	LIQUID	GAS	LIQUID	GAS	LIQUID	GAS	LIQUID
ORBITER A	594	511	2,155	1,834	826	6,060	4,506	14,290
ORBITER B	297	31	2,185	585	NOT APPLICABLE			

- RANGE OF VELOCITY INCREMENTS

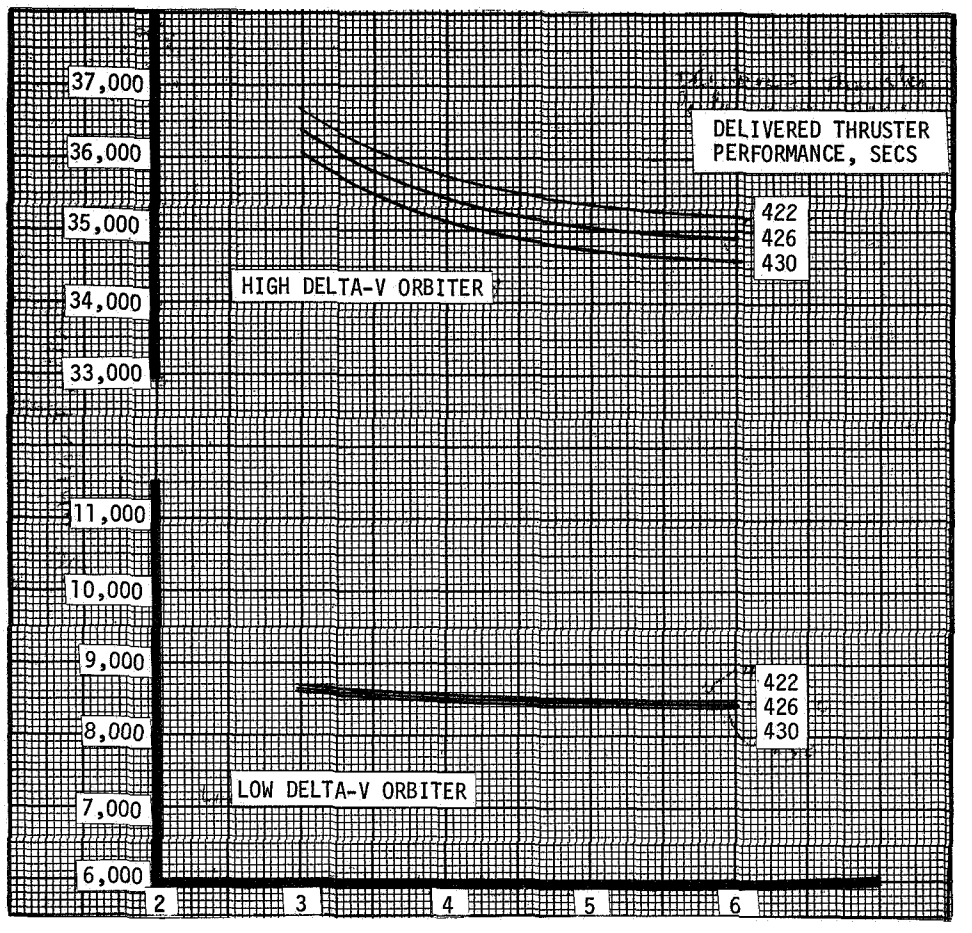
	PHASE A	PHASE B
LOW DELTA-V, FT/SEC	170.5	169.5
INTERMEDIATE DELTA-V, FT/SEC	429.5	NOT APPLICABLE
HIGH DELTA-V, FT/SEC	2002.5	1458.5



CYCLE FEATURES

- SEQUENCE CONTROLS TO MATCH EQUIPMENT DEMANDS
- OFF-LINE START ACCUMULATORS TO OPTIMIZE STARTUP, PROVIDE SAFING STARTUP
- ABSORBS THRUSTER CYCLING MR VARIABILITY
- ADAPTABLE TO SEVERAL CONTROL LOGICS
  - (1) HIGH ΔV - PERFORMANCE
  - (2) LOW ΔV - SIMPLICITY

Figure 1-4. Selected Dual Gas Generator Cycle and Features



- Minimize Conditioner Loss
- Propulsive Vent
- $P_{R,T} = 100$
- Condition to $500^{\circ}R$, ΔW = 300 pounds
- Pressure Ratio to 15, ΔW = 20 pounds

Figure 1-5. Overall System Performance Aspects

2. CYCLE CHARACTERISTICS

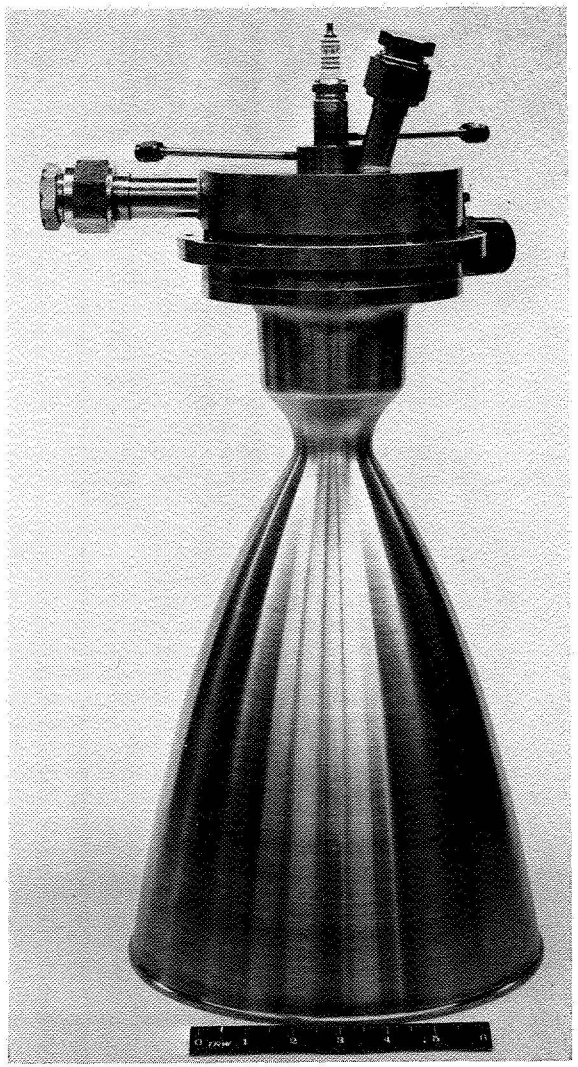
2.1 OPERATING POINT SELECTION

The major general considerations which are important to the determination of the APS operating point are summarized below:

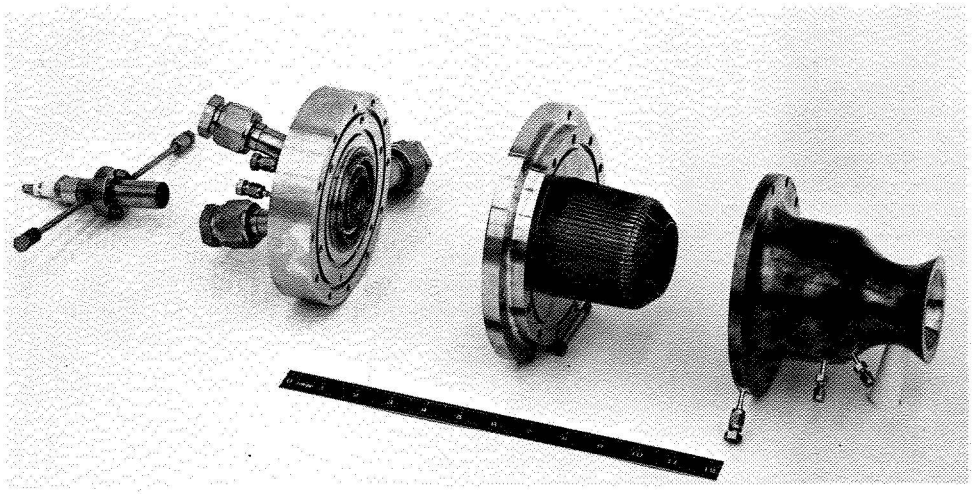
- Performance — Optimize thruster chamber pressure with coolant requirements
- Thrusters — Mixture ratio shifts caused by temperature excursions
- Propulsive vent — Use as high a pressure as possible
- Phychrometric — Reaction products condensation and freezing vents, gas generators, thrusters and heat exchangers
- Propellant Properties — Oxygen compressibility and two-phase flow
- Ignition — Two-phase flow effects
- Distribution System Constraints — Propellant condensation
- Accumulator Blowdown Ratios — Rapid drawoff, isothermal drawoff, recompression
- Environmental — Reactor soakout, environmental soakout
- Propellant Use MR Variability — Sizing and placement of storage bottles
- Cycle Performance Requirements — High ΔV versus low ΔV

The thruster selected for the performance determination was the TRW duct-cooled thruster (Figure 2-1). Its performance with ambient propellants at 300 psia is expected to be ~442 sec Isp, with a structural temperature dependance as shown in Figure 2-2. This approach features an all elastic design with no parts subjected to plastic deformation. No complicated geometries result in uncertainties of design calculations, and the concept requires no particular emphasis on tolerance control.

Based upon sensitivity tradeoffs such as illustrated in Figure 2-3, a chamber pressure of 300 psia was selected for this thruster which would enable it to perform between mixture ratios of 4 and 6. The importance

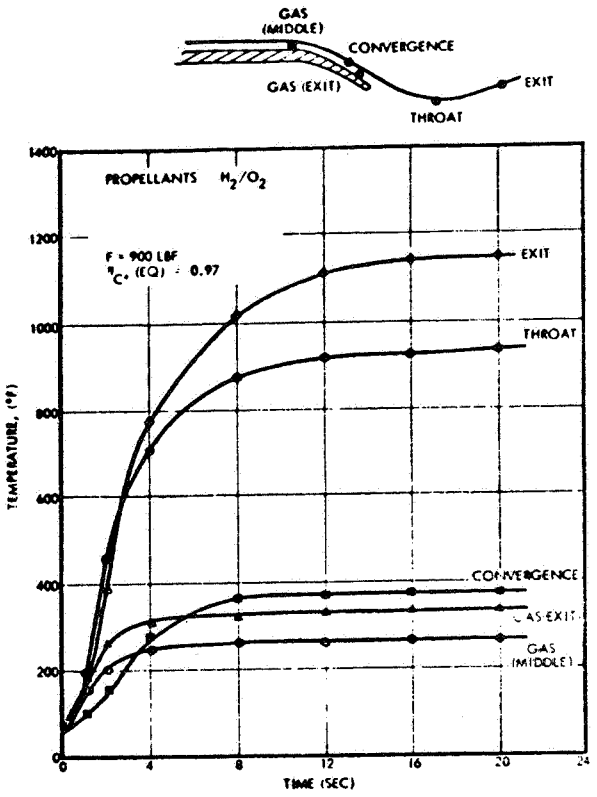


Assembly



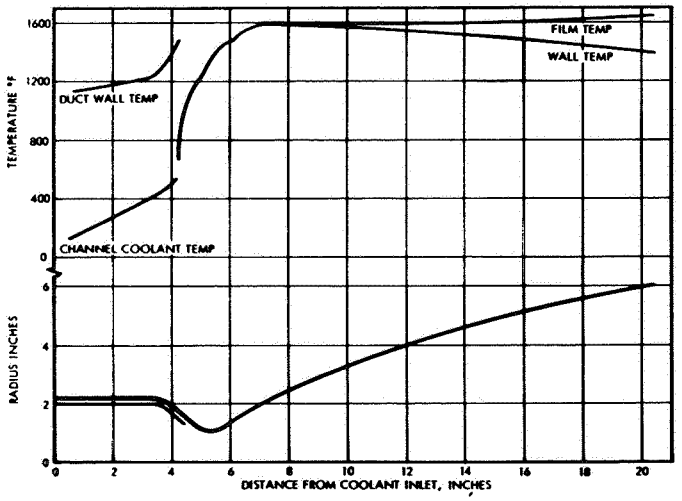
Disassembly

Figure 2-1. TRW Duct-Cooled Experimental Thruster Featuring Thin Wall Stainless Steel Chamber



Typical Temperature-Time Response of TRW Duct Cooled Engine

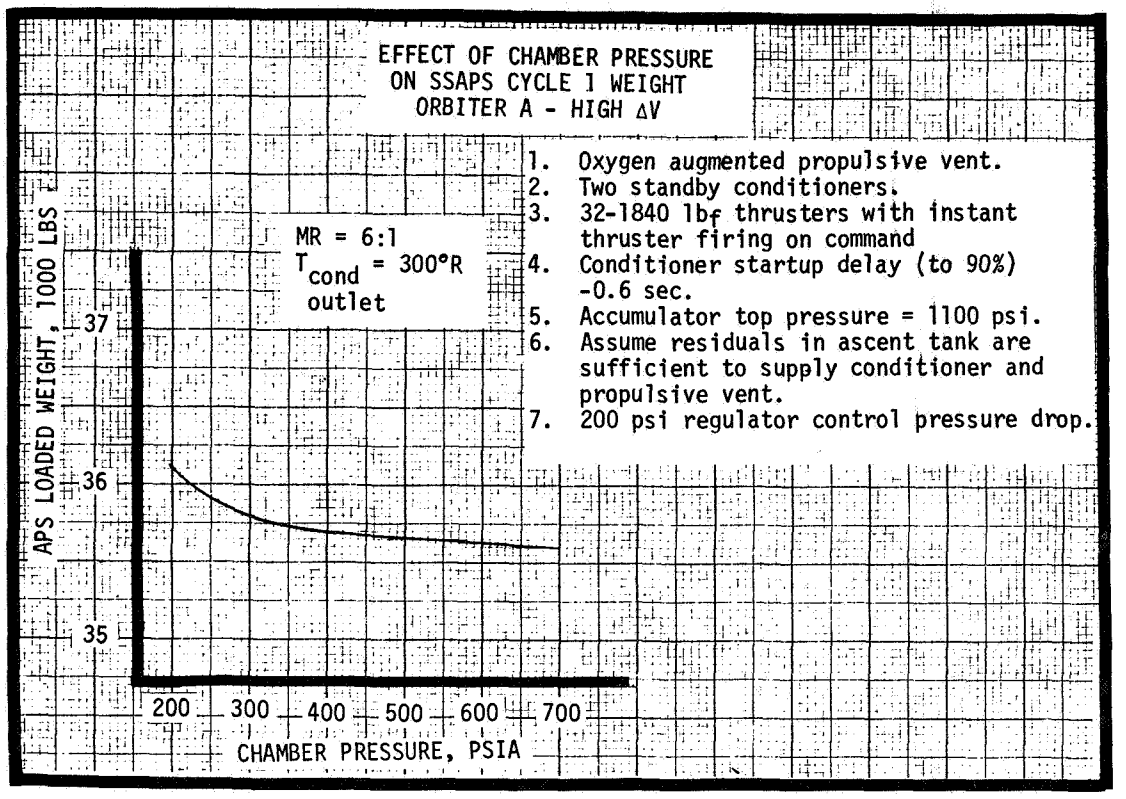
- THRUST = 1500 LB_F @ ϵ = 40:1
- CHAMBER PRESSURE = 300 PSIA
- COOLANT FLOW RATE = 20% OF FUEL
- AMBIENT TEMPERATURE PROPELLANTS
- INSULATED (ADIABATIC) CHAMBER



Duct Cooled Thruster Steady State Operating Characteristics

- IN ACTUAL MISSION, THRUSTER SELDOM FIRES LONG ENOUGH OR OFTEN ENOUGH TO REACH STEADY STATE
- INJECTOR SOAKOUT SUFFICIENT TO PREVENT 2-Ø FLOW AFTER FIRST FIRING

Figure 2-2. Thruster Structural Temperature Dependence, Experimental and Theoretical



- Selected 300 psia as Thruster Chamber Pressure
- Reasonable from Thruster Life Standpoint

Figure 2-3. Thruster Chamber Pressure Selection

of thruster performance is illustrated in Figure 1-3. The all ΔV APS has a thruster performance sensitivity coefficient of ~100 lb/sec Isp, while the low ΔV APS coefficient is only 9 lb/sec Isp.

The requirement for maintaining gaseous flow into the thrusters and gas generators requires that the propellant properties be carefully examined, particularly on the O_2 side. O_2 will condense in the storage system if the conditioner outlet temperature is incompatible with the storage accumulation blowdown pressure ratio. Further, O_2 is far removed from being an ideal gas in the regions of interest here and its large $(\partial T/\partial P)_H$ coefficient must be carefully considered in selecting the O_2 conditioner point. On the other side, the H_2 takes large energies to condition it; consequently, it is desirable to minimize the H_2 conditioner temperature. However, the allowable H_2 and O_2 temperatures are intimately related to prevent condensing of O_2 in the combustors of the system.

Within the distribution network some thermal management may be necessary depending upon the environment. The O_2 and H_2 lines will always be in close proximity and, therefore, at nearly the same temperature. Further, the storage accumulators and lines will equilibrate out in relatively short times (Figure 2-4). It is necessary to allow venting of the accumulators and lines in the high performance on all ΔV systems at a pressure which minimizes the thruster MR shift.

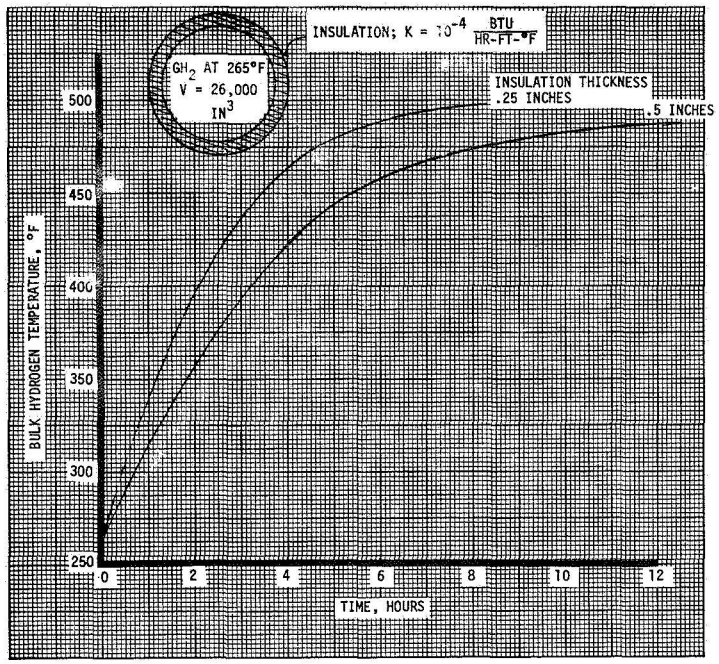
The effects of recompression of the residual gases in the propellant lines as the conditioner comes on line are also important. Because the system rapidly fills, the residual gases will compress nearly adiabatically. As a consequence, the allowable blowdown pressure ratio should be minimized to prevent undesirable temperature excursions.

Finally, optimum pressures exist for the storage of the gaseous propellants when conditioning and fluid properties are taken into account. For O_2 this optimum occurs at approximately 2000 psia, and for H_2 it occurs at nearly 1500 psia; however, in both cases the curves are nearly flat from 1100-1200 to 2500 psia (Figure 2-5).

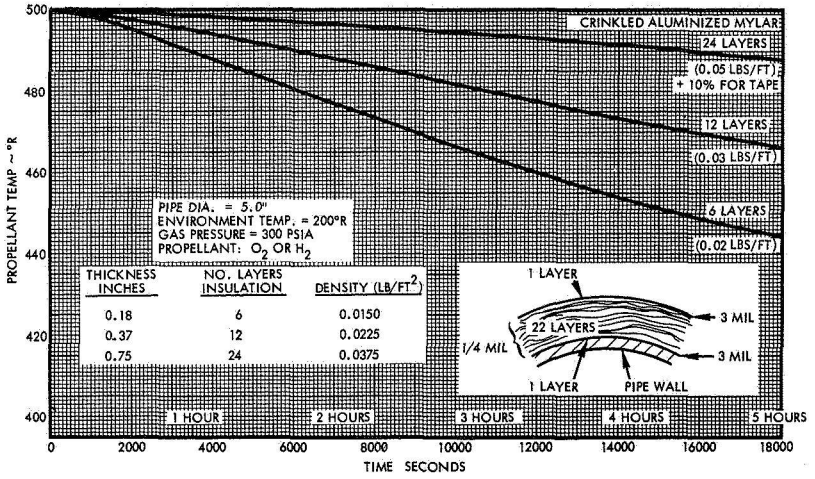
When all the above factors were considered the summary findings resulted in the selections given in Table 2-1. The premium on performance forces the selection in the all ΔV case, while performance is secondary in the low ΔV system and a selection as shown here minimizes the need for control.

2.2 COMMONALITY

A concerted effort was made to make the fundamental APS conditioners and thrusters common between the booster and orbiter elements. To accomplish this required selection of thruster size and number with a minimum weight penalty which still met the acceleration requirements for both vehicles. By a judicious choice of the thruster sizings it is also possible to size the conditioner flows to be identical between the vehicles. The results of this commonality tradeoff are shown in Figure 2-6. It results in a common thruster thrust selection of 1840 lbf with 32 thrusters for the orbiter and 26 for the booster. Note that the maximum conditioner flow of 34.3 pounds is also matched for the two vehicles. In the all ΔV cases it is desirable is provided for two flow rates from the conditioner to match the major demands. For the +X maneuvers this results in ~17 lb/sec. Therefore, a two-flow rate pumping system is desirable here.



STORAGE

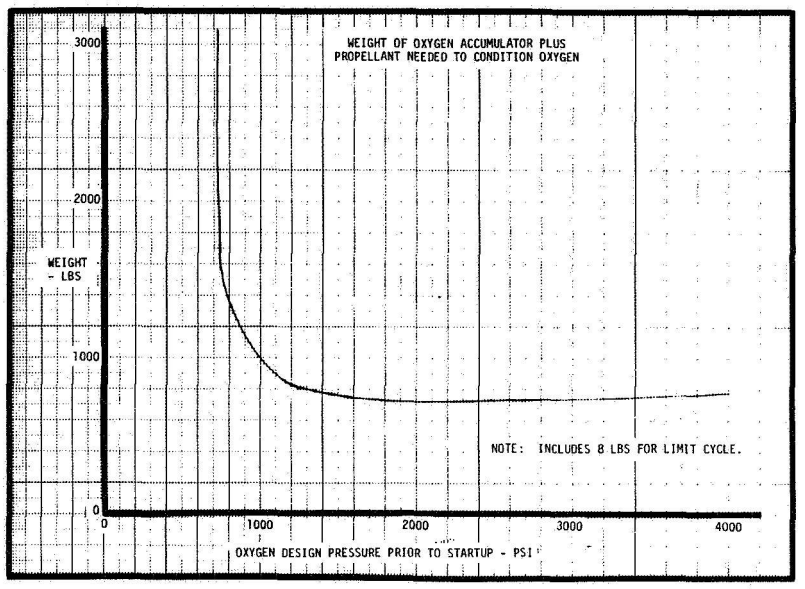


LINES

SUMMARY

- IF NO PERFORMANCE PREMIUM CONDITION TO ENVIRONMENT TEMPERATURE
- FOR PERFORMANCE SELECT P_c, T_c TO MINIMIZE MR EXCURSIONS ON SOAKOUT
- DEPENDING ON ENVIRONMENT, MAY REQUIRE LINE HEATERS ~10-20 WATTS

Figure 2-4. Environmental Soakout Effects



Oxygen

- 1140 psia Selected for Start Accumulators
- 1100 psia for line accumulators
- Selection Dependent on P_C, T_C Relation

Hydrogen

- 1140 psia Selected for Start Accumulators
- 1100 psia for line Accumulators

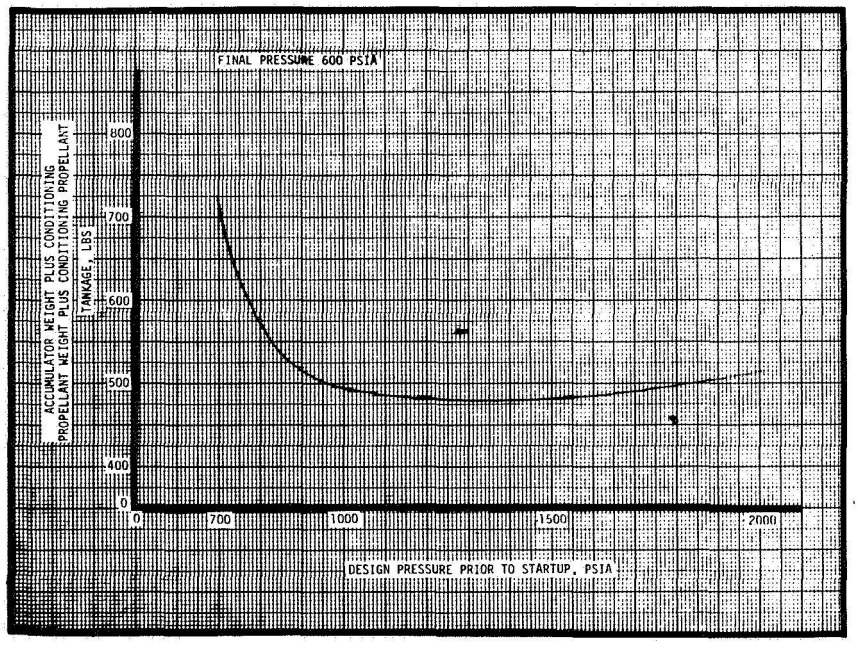


Figure 2-5. Accumulator Pressure Optimization for Nominal SSVDRD Mission

Table 2-1. Summary APS Conditioner Operating Point Findings

MIXTURE RATIO

- LOW DELTA-V 4 ⟵ MIXTURE RATIO ⟶ 6 HIGH DELTA-V

THRUSTER CHAMBER PRESSURE

- 300 PSIA

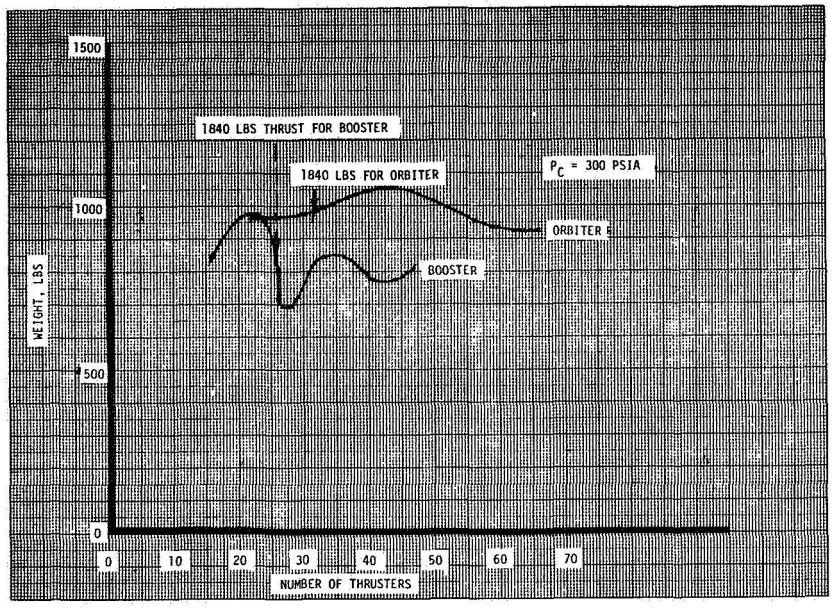
REGULATOR PRESSURE

- EXIT - 400 PSIA
- MINIMUM INLET - 600 PSIA

CONDITIONER

- HIGH DELTA-V:
  - P_{COND} = 1140 PSIA
  - T_H = 265°R
  - T_O = 315°R
- LOW DELTA-V:
  - P_{COND} = 1140 PSIA
  - T_H = 400-500°R
  - T_O = 400-500°R

DETAILED PERFORMANCE TRADES REQUIRED TO FINALIZE SELECTIONS



Vehicle	Booster			Orbiter			
Maneuver	Yaw	Pitch	Roll	Yaw	Pitch	Roll	X Translation
Number of Thrusters Per Axis For Maneuvering in One Direction	8	4	2	8	4	4	4*
Thruster Flow Rates	34.5	17.25	8.67	34.5	17.25	17.25	17.25

32 THRUSTERS ORBITER
26 THRUSTERS BOOSTER

Figure 2-6. Commonality Study Results

2.3 CONDITIONER CYCLES

In selecting the conditioner cycles and the control logics associated with them, it is necessary to consider the amount of propellant processed and the mode in which it is used. The high ΔV orbiter APS will process up to 27,000 pounds of propellant. Nearly 50 percent of this propellant goes into X-axis translation over steady burn periods at a flow rate approximately one-half of the maximum propellant demand. Because of the large propellant quantities involved and the duty cycle, there is incentive to go to the minimum energy conditioning points ($265^{\circ}R$ H_2, $315^{\circ}R$ O_2). Further, the system should be highly controlled to match the duty cycle requirements. As a result there is a justified incentive to investigate advanced technology components.

On the other hand, in the low ΔV orbiter and booster, the APS will process less than 3900 pounds of propellant. As a result, efficiency is not critical and control requirements can be minimized. The conditioner output can be matched to the vehicle environment with little penalty. As a result, there is little incentive for advanced technology components.

In this effort, the need for commonality between booster and orbiter was respected at all times. In application, the cycles had to be capable of rapid startup, have the ability to absorb cyclic, wide range operation, and provide for continuous on-line readiness (including individual propellant processing).

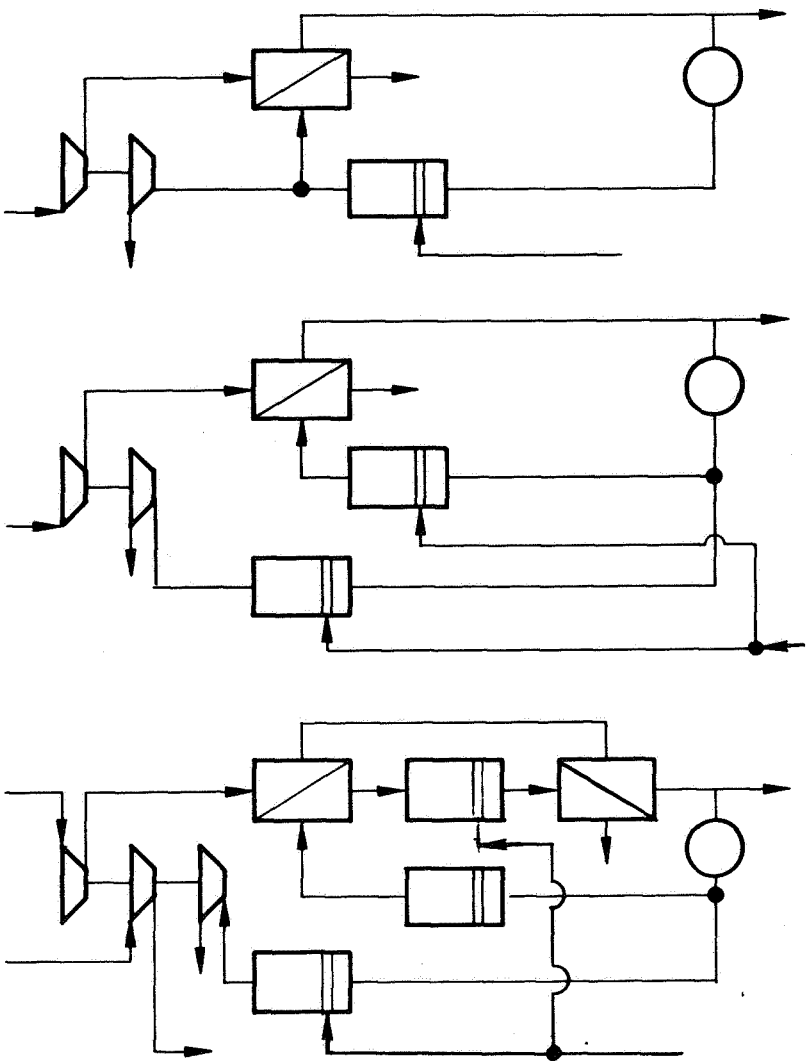
In considering the various possible pumped liquid cycles, consideration was given to:

- Equipment arrangement—series versus parallel turbine/heat exchanger
- Conditioner O/F—minimize conditioner penalty.

The parallel turbine-heat exchanger arrangements which were selected for final analysis are shown in Figure 2-7 along with pertinent comments. The final selected cycle was the second one with individual gas generators for the primary reasons of growth capability and wide range of flow rate capability. Staged heat exchanger combustion can be seriously considered if the processed propellant quantities are high.

The in-line arrangements that were considered are shown in Figures 2-8 and 2-9. As indicated in all these cycles, off design flow rates will complicate their control (primarily because of nonlinearity of turbine efficiency effects competing with the linearity of the heat exchangers). Even in fixed flow rate systems, it is seen that these systems still possess problems not associated with the parallel arrangements. As will be seen shortly, the heat exchangers control the response of the control loops. As a result, a decoupling of the turbine and heat exchanger power fluids is desirable.

A comparison of in-line and parallel cycles with single-stage combustion is shown in Figure 2-10 for both conditioner penalty and weight differential. It is seen that from a thermodynamics standpoint, there is little to choose from in either type of arrangement. Therefore, the choice is to be made on other bases.



SINGLE GAS GENERATOR PER SIDE

- SIMPLE GAS GENERATOR CONTROL
- GAS GENERATOR OUTLET TEMPERATURE LIMIT 2000°R (O/F ~1)
- NARROW FLOW RANGE CAPABILITY

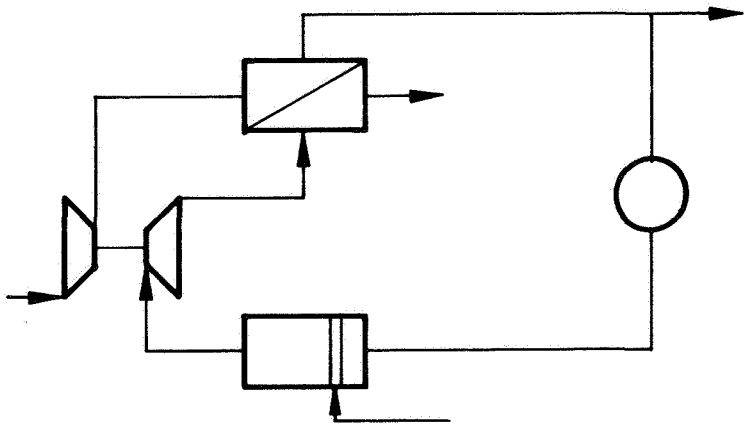
INDIVIDUAL GAS GENERATORS FOR TURBOPUMPS AND HEAT EXCHANGERS

- CAN SELECT OPTIMUM TURBINE AND HEAT EXCHANGER INLET TEMPERATURES (GROWTH POTENTIAL)
- WIDE FLOW RANGE CAPABILITY
- FINE OUTLET TEMPERATURE CONTROL POSSIBLE

MULTIPLE STAGE COMBUSTION WITH COMBINED TURBOPUMP

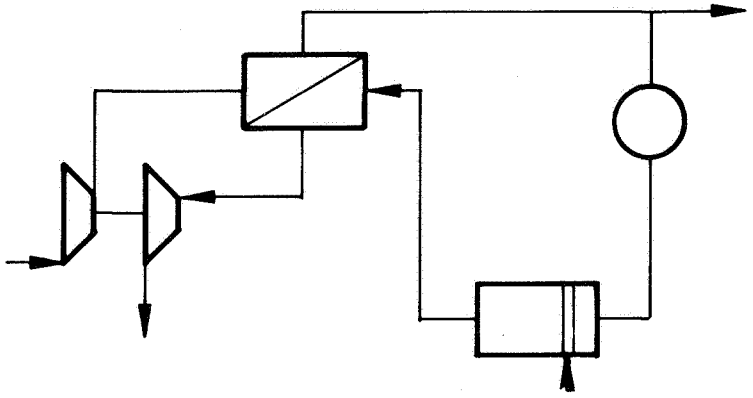
- HIGH O/F OPERATION WITH MINIMUM NUMBER OF GAS GENERATORS (PARALLEL)
- CAN SELECT OPTIMUM TURBINE AND HEAT EXCHANGER INLET TEMPERATURES
- WIDE FLOW RANGE CAPABILITY
- LIMITED FLEXIBILITY FOR ONE-SIDE OPERATION

Figure 2-7. Parallel Turbine/Heat Exchanger Arrangements Considered in Final Design Analysis



SINGLE STAGE COMBUSTION WITH TURBINE UPSTREAM OF HEAT EXCHANGER

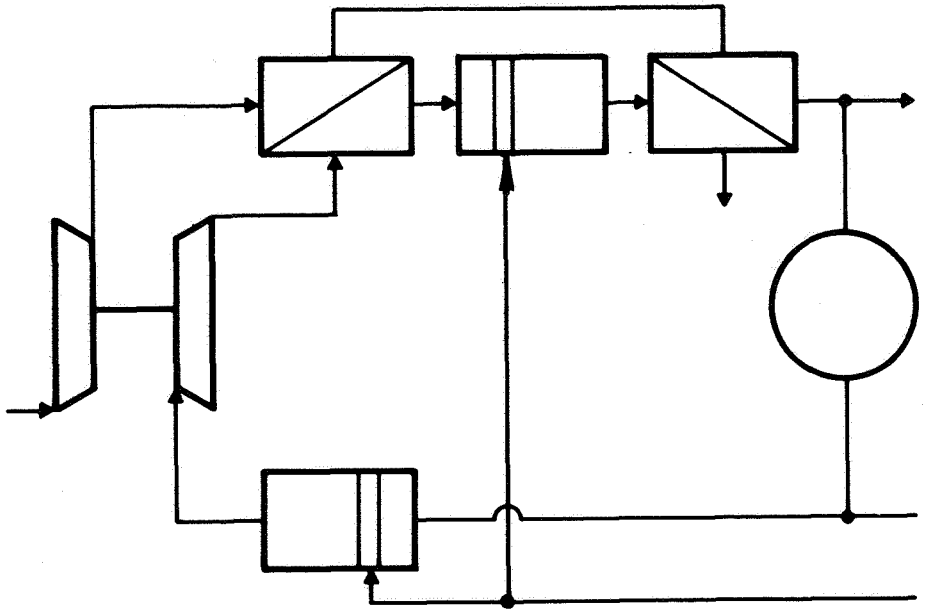
- FAST STARTUP CAPABILITY
- GAS GENERATOR TEMPERATURE LIMIT 2260°R (HIGHER O/F THAN PARALLEL)
- TURBINE RUNS HOTTER THAN IN PARALLEL ARRANGEMENT (COOLING COMPLEXITY)
- LOWER HEAT EXCHANGER TEMPERATURE DIFFERENTIAL THAN PARALLEL ARRANGEMENT
- LOW PRESSURE HEAT EXCHANGER
- COMPLICATED OFF-DESIGN CONTROL



SINGLE STAGE COMBUSTION WITH TURBINE DOWNSTREAM OF HEAT EXCHANGER

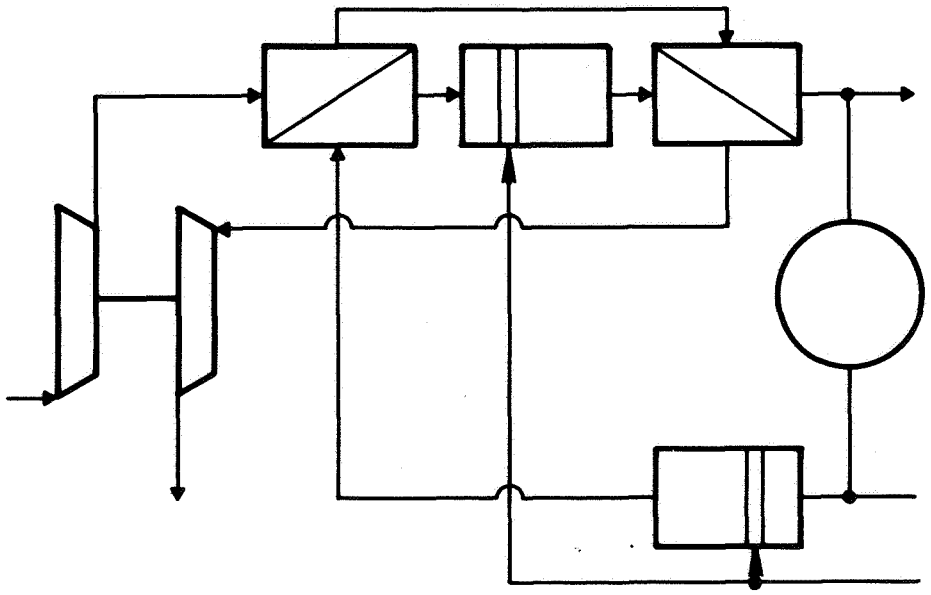
- LOW TEMPERATURE TURBINE DESIGN POSSIBLE
- BETTER DYNAMIC COUPLING OF TURBINE AND HEAT EXCHANGER
- REDUCED START CAPABILITY
- POSSIBLE MOISTURE CARRYOVER INTO TURBINE - EROSION/ CORROSION

Figure 2-8. In-Line Turbine/Heat Exchanger Arrangements (with no staged combustion) Considered in Final Design Analysis



MULTIPLE STAGE COMBUSTION WITH UPSTREAM TURBINE

- FAST STARTUP CAPABILITY
- HIGH O/F POSSIBLE IN SECOND HEAT EXCHANGER
- LOW PRESSURE HEAT EXCHANGERS
- HIGH TEMPERATURE TURBINE
- OFF-DESIGN COMPLEXITY



MULTIPLE STAGE COMBUSTION WITH DOWNSTREAM TURBINE

- REDUCED STARTUP CAPABILITY
- HEAT EXCHANGER TEMPERATURE LIMIT 2000°R
- LOW TEMPERATURE TURBINE
- POSSIBLE MOISTURE CARRY-OVER PROBLEMS

Figure 2-9. In-Line Turbine/Heat Exchanger Arrangement with Staged Combustion Considered in Final Design Analysis

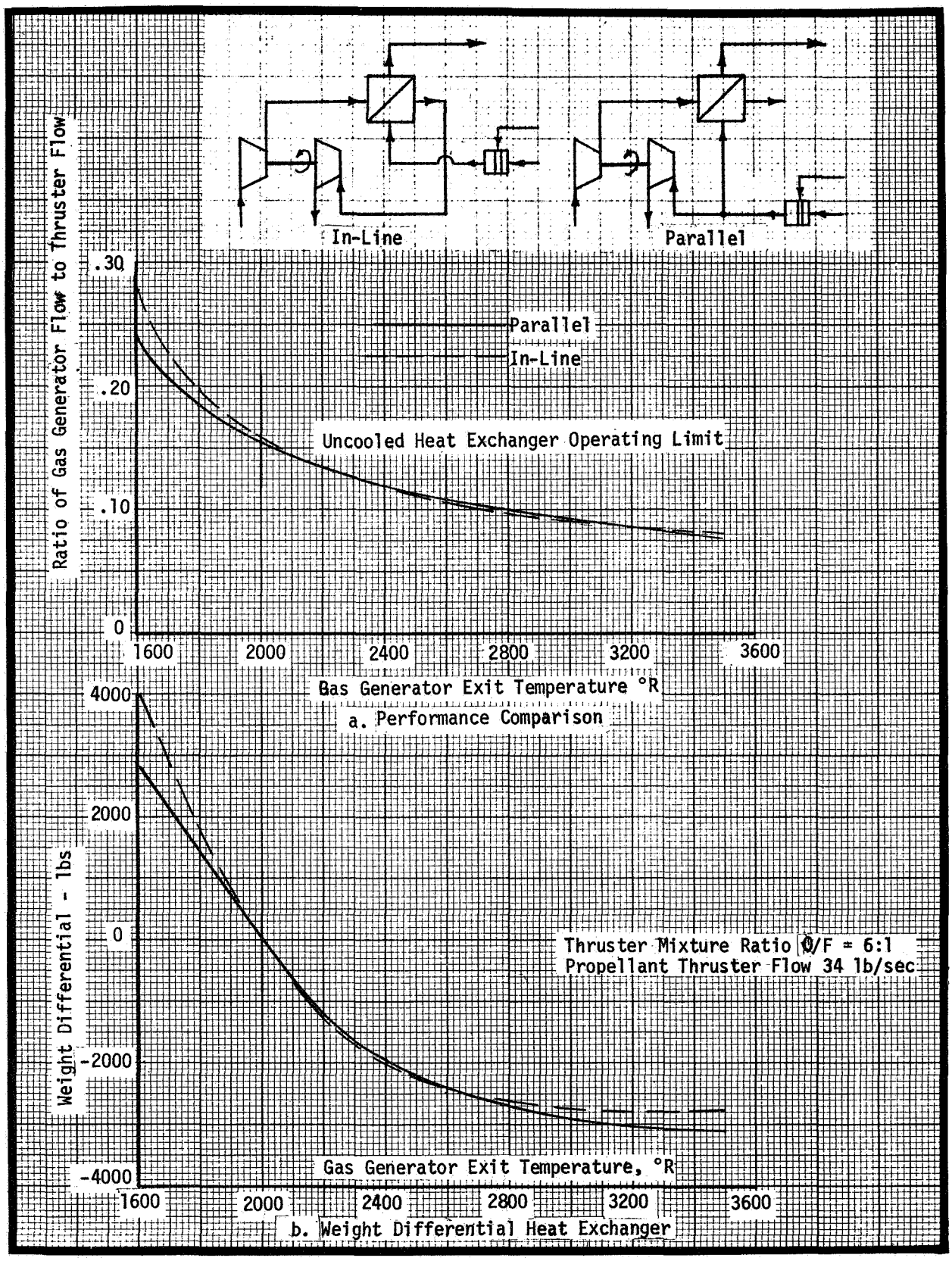


Figure 2-10. Comparison of In-Line and Parallel Cycles, Single-Stage Combustion

With respect to staging, an examination of the number of stages of combustion shows that the major gain occurs with two stages, and there is really no premium to offset the complexity of the multiple staging beyond two stages (Figure 2-11).

2.4 THERMODYNAMIC BALANCE FOR DUAL GAS GENERATOR CYCLE

The overall thermodynamic balance for the dual gas generator cycle is given in Figure 2-12 for a total demand flow of 34 lb/sec to the thrusters. As noted, the cycle indicates small start bottles for the gas generators.

2.5 MAJOR COMPONENT DESCRIPTION

2.5.1 Turbopumps

A detailed analysis of the turbopumps and their startup modes was carried out in this program. The final design summaries for the high ΔV application are given in Tables 2-2 and 2-3. The turbopumps are shown in cross-section in Figures 2-13 and 2-14. The bearing and seal performance summary for the turbopumps is given in Table 2-4.

The thermal management requirements are summarized in Table 2-5. Using a thermodynamic vent results in a requirement of 60 pounds of H_2 and 235 pounds of O_2 for a 7-day mission. It may also be required to provide electrical heating of the turbine and of the pumps to minimize thermal problems.

2.5.2 Heat Exchangers

Parallel flow tubular configurations were selected for these applications, in order to provide self-curing of water condensation and freezing problems. The use of thin walled tubing provides maximum response and minimum core weight. Design considerations show that a 2000°R limitation allows the units to be designed for dry starts and requires no uncooled structure. A temperature of 3500°R is probably feasible, but it requires the heat exchanger to start with propellant flow and also results in a requirement for a cooled external structure.

The selected configurations for this study are shown in Figures 2-15 and 2-16. Hastalloy X is called out. There may be some problems with it in the cold end of the H_2 heat exchanger. If upon further analysis this proves to be so, it appears that a stainless steel can be used.

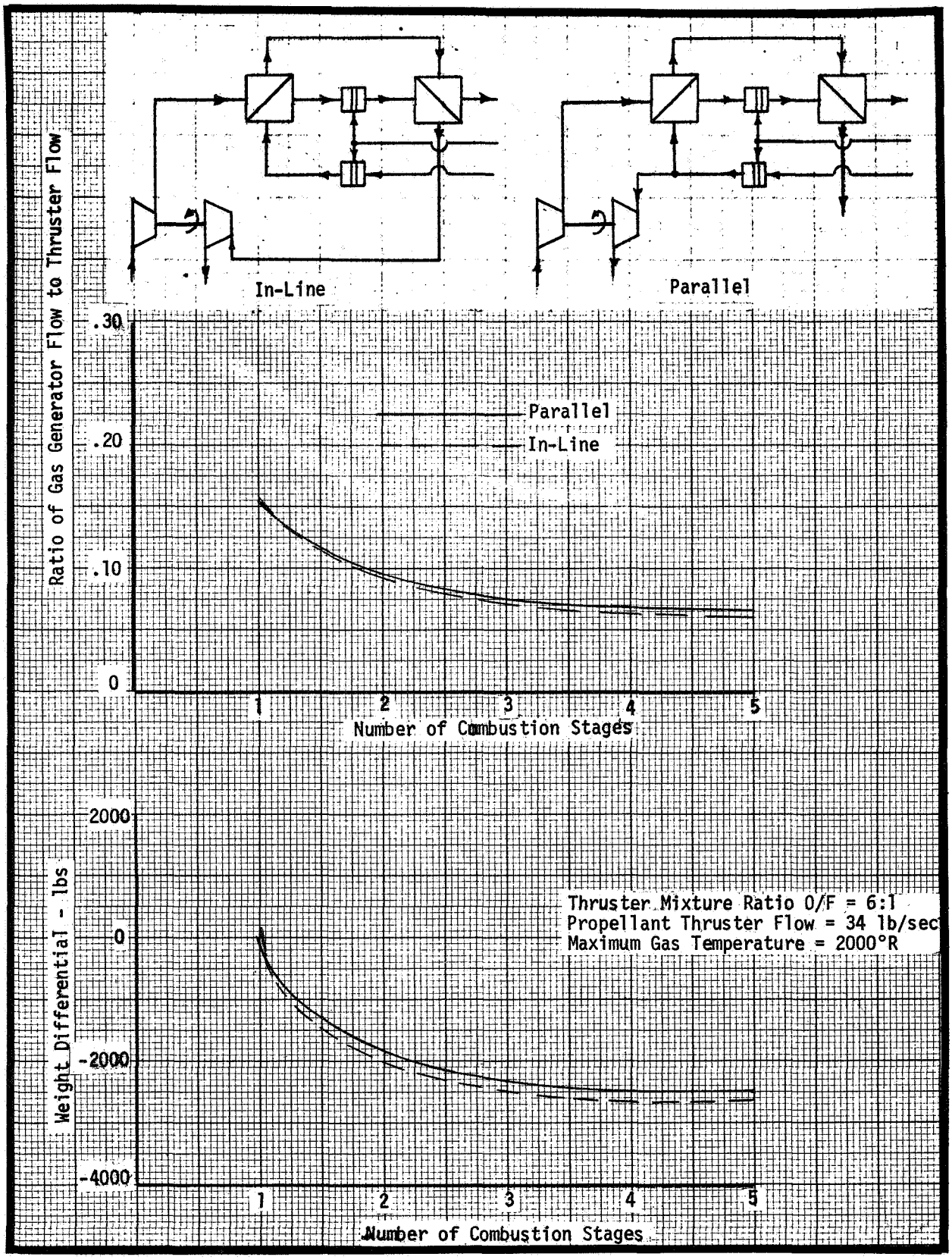


Figure 2-11. Effect of Combustion Staging

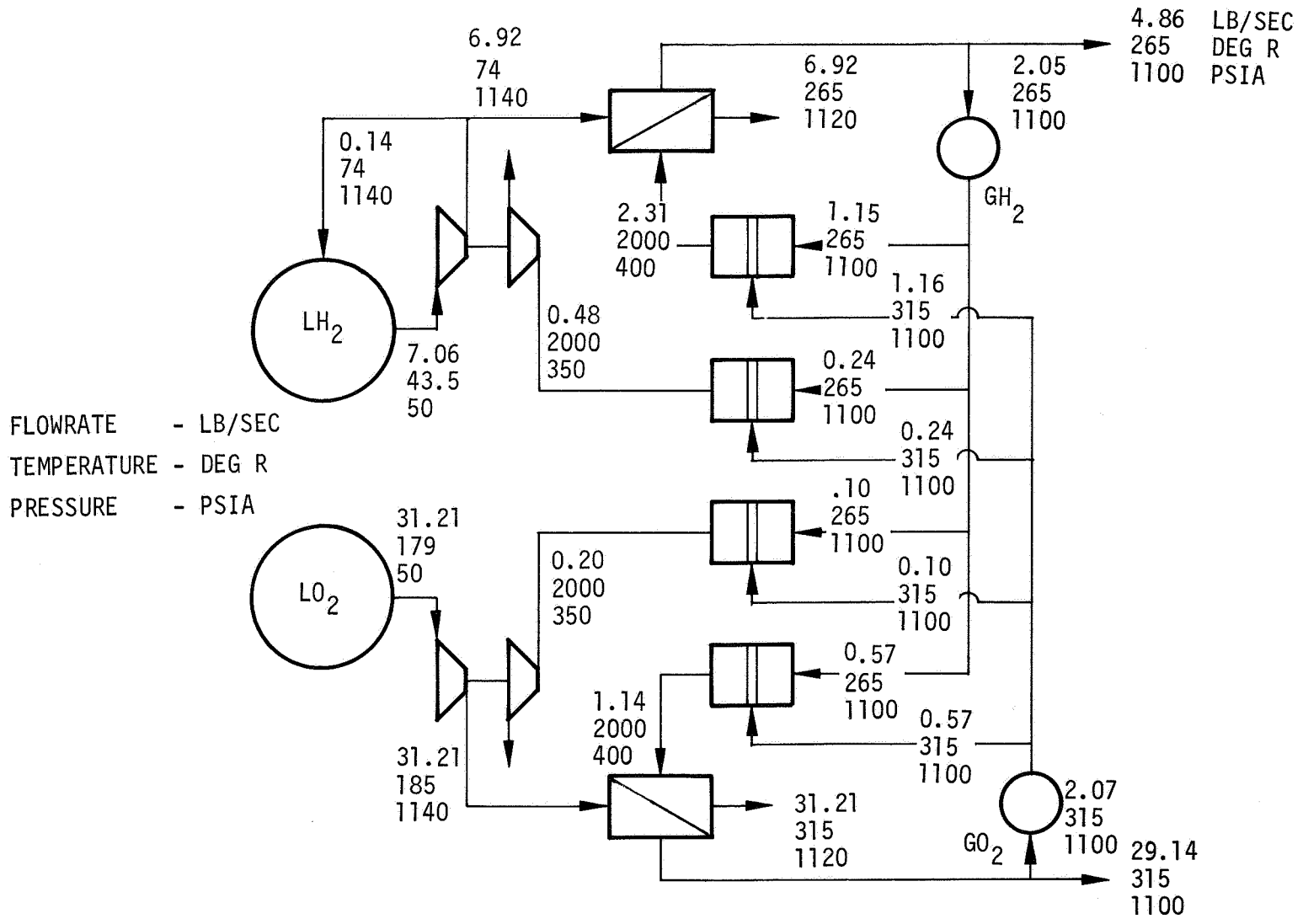


Figure 2-12. Thermodynamic Balance for Dual Gas Generator Cycle

Table 2-2. Selected Pump Design Characteristics

	HYDROGEN	OXYGEN
CONDITIONER REQUIREMENTS		
FLOW RATE, LB/SEC	7.06	31.2
INLET PRESSURE, PSIA	47	47
INLET TEMPERATURE, DEG. R	43.5	179
OUTLET PRESSURE	1140	1140
PUMP TYPE	SINGLE STAGE RADIAL AXIAL INDUCER	SINGLE STAGE RADIAL AXIAL INDUCER
DESIGN BASIS	SST/HRC FUEL PUMPS NASA INDUCER	NEW DESIGN NASA INDUCER
ROTATIONAL SPEED, RPM	50,000	32,000
TIP DIAMETER, IN.	7.45	3.35
DESIGN POINT EFFICIENCY, PERCENT	50	70

Table 2-3. Nominal Turbine Design (High ΔV application)

	HYDROGEN LOOP	OXYGEN LOOP
NOZZLE INLET TEMPERATURE	2000°R	2000°R
NOZZLE INLET PRESSURE	350 PSIA	350 PSIA
ROTATIONAL SPEED	50,000 RPM	32,000 RPM
POWER	984 HP	190.5 HP
NUMBER OF STAGES	2	1
PITCH VELOCITY	1800 FT/SEC	1150 FT/SEC
FIRST STAGE		
FLOW RATE	0.45 LB/SEC	0.195 LB/SEC
ADMISSION	42 PERCENT	68 PERCENT
TIP DIAMETER	8.65 IN.	8.65 IN.
BLADE HEIGHT	0.412 IN.	0.412 IN.
SECOND STAGE		
FLOW RATE	0.43 LB/SEC	-
ADMISSION	100 PERCENT	-
TIP DIAMETER	9.41 IN.	-
BLADE HEIGHT	1.170 IN.	-
OVERALL EFFICIENCY	56 PERCENT	25 PERCENT

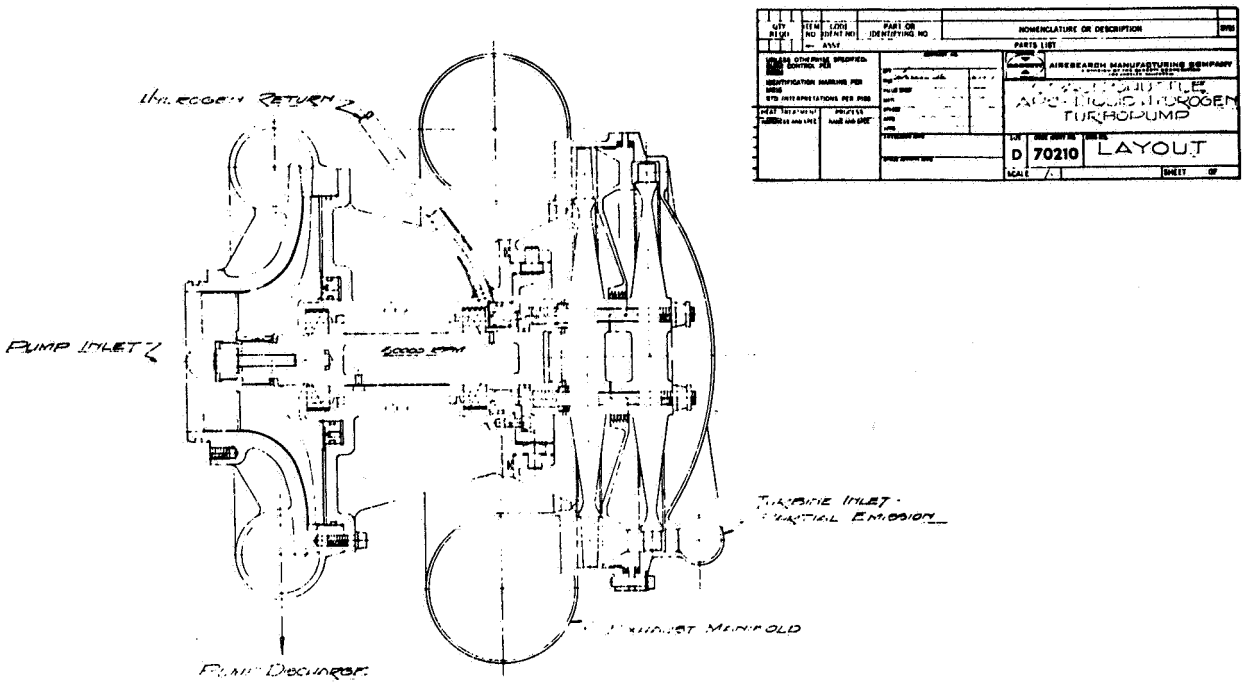


Figure 2-13. Preliminary Hydrogen Turbopump Design Layout

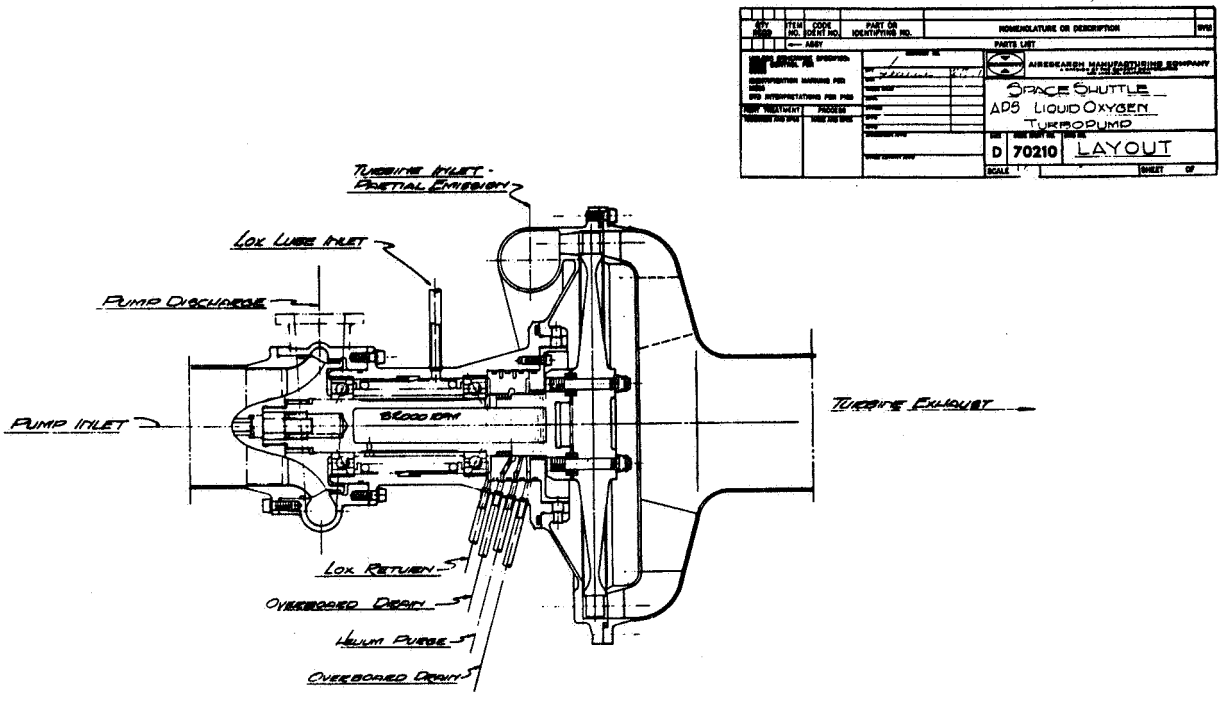


Figure 2-14. Preliminary Oxygen Turbopump Design Layout

Table 2-4. Bearing and Seals Performance

	HYDROGEN PUMP	OXYGEN PUMP
• SEALS		
TYPE	FACE	HYDROSTATIC
	MAXIMUM TIP SPEED = 400 FPS	
HEAT LOAD	0.841 BTU/SEC	1.272 BTU/SEC
• BEARINGS		
TYPE	BALL	BALL
MATERIALS	400 C (BALLS) TEFLON/GLASS - (ARMALON/SEPARATOR)	440 C (BALLS) TEFLON/GLASS - (ARMALON/SEPARATOR)
HEAT LOAD	0.931 BTU/SEC	0.548 BTU/SEC
BUFFER MEDIUM	NONE	HELIUM

Table 2-5. Turbopump Thermal Management

REQUIREMENTS

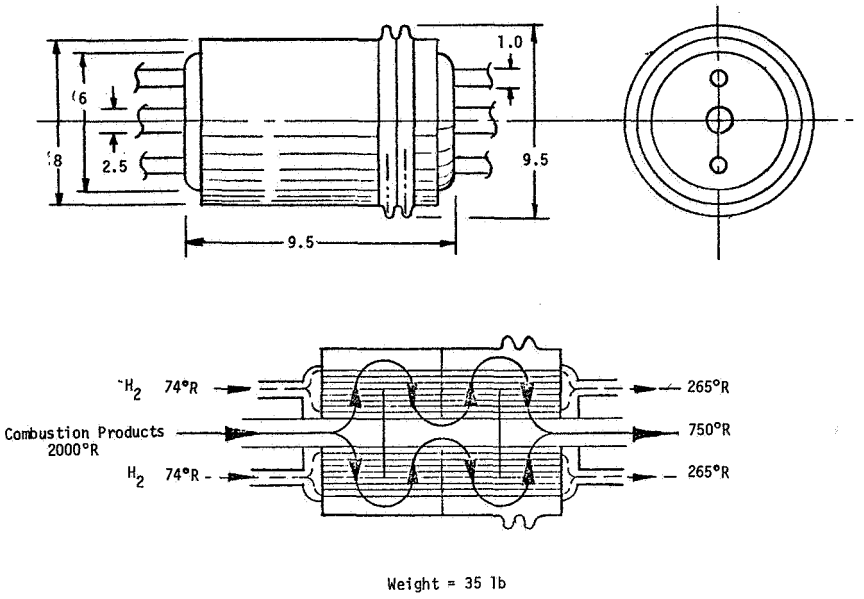
- INLET CONTROL - PREVENT VAPORIZATION OF PROPELLANT IN LINE
- PUMP CASING AND IMPELLER CONTROL - AVOID FLASHING ON STARTUP AND THERMAL SHOCK

APPROACH

- USE CONCENTRIC INSULATED LINES WITH PROPELLANT THERMODYNAMIC VENT
- CONTINUOUS COOLING OF INSULATED TURBOPUMP ASSEMBLY

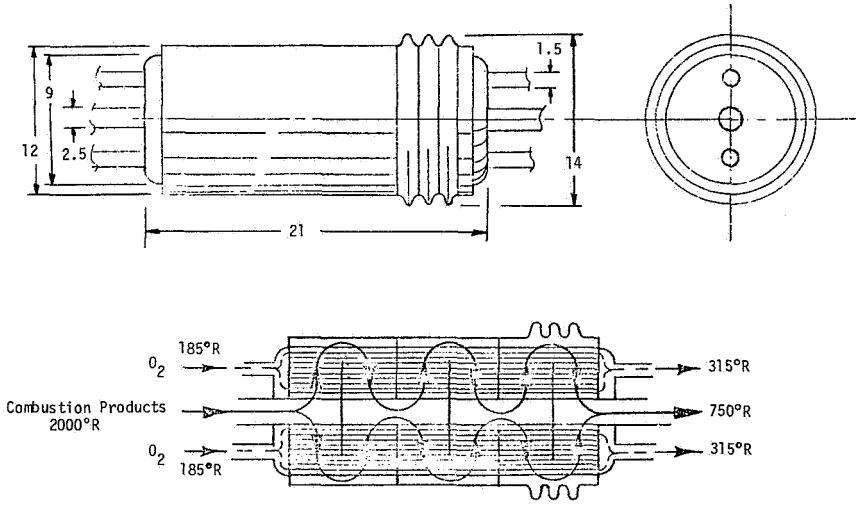
} 60 LB H_2, 235 LB O_2 FOR SEVEN-DAY MISSION

- POSSIBLE REQUIREMENT FOR TURBINE HEATING



HYDROGEN FLOW	6.92 LB/SEC
INLET PRESSURE	1140 PSIA
PRESSURE DROP	20 PSI
COMBUSTION GAS FLOW	2.31 LB/SEC
INLET PRESSURE	420 PSIA
PRESSURE DROP	40 PSI
TUBE O.D.	.125 IN
WALL THICKNESS	.008 IN
MATERIALS	HASTELLOY X

Figure 2-15. Hydrogen Heat Exchanger Characteristics



Weight = 165 lb

OXYGEN FLOW	31.21 LB/SEC
INLET PRESSURE	1140 PSIA
PRESSURE DROP	20 PSI
COMBUSTION GAS FLOW	
INLET PRESSURE	420 PSIA
PRESSURE DROP	7.5 PSI
TUBE O.D.	.125 IN
WALL THICKNESS	.008 IN
MATERIAL	HASTELLOY X

Figure 2-16. Oxygen Heat Exchanger Characteristics

2.5.3 Start Bottles

The start bottle concept was conceived as a means of providing a safe, rapid startup. The design analyses were conducted to provide for one ignition hangup in each gas generator. They could be dispensed with when large accumulations are used; however, their size and weight penalties are quite small and their safing qualities appear to be worth the small weight penalties. Their characteristics are summarized in Table 2-6.

Table 2-6. Start Bottle Characteristics

CONFIGURATION	HYDROGEN SPHERE		OXYGEN SPHERE	
MATERIAL	ALUMINUM 2219-T87		INCONEL 718	
STORAGE PRESSURE (NOMINAL)	1100 PSIA (265°R)		1100 PSIA (315°R)	
(VENT)	1600 PSIA		1600 PSIA	
(MINIMUM)	650		800 PSIA	
	1 START	2 STARTS	1 START	2 STARTS
DELIVERED MASS	0.48 LB	0.63 LB	0.49 LB	0.82 LB
BOTTLE WEIGHT	59 LB	79 LB	6 LB	8 LB
BOTTLE VOLUME	2.1 CU FT	2.8 CU FT	0.16 CU FT	0.27 CU FT
OUTER DIAMETER	20 IN	22 IN	9 IN	11 IN

2.5.4 Gas Generators

The gas generators for the selected cycle operate at an overall mixture ratio of unity. Their flow requirements and relative sizing are given in Table 2-7. As is seen, the power gas generators can probably be developed as identical units. The heat exchanger gas generator units are similar in this respect. It is suggested that the duct cooled thruster approach is satisfactory for these applications. The only additional requirements for the gas generators are (1) a need for dual ignition (for safety), (2) a fairly tightly controlled temperature profile ($\pm 100^{\circ}F$), (3) an ability to remain free of icing and condensation, and (4) a decoupling from the downstream using equipment to prevent surging.

Table 2-7. Gas Generator Requirements

GAS GENERATOR FLOW REQUIREMENTS

DUAL GAS GENERATORS (MR ≈ 1:1)

	$\dot{W}$, LBS/SEC	P_C, PSIA	SIZE RATIO
H_2 TURBINE POWER GG	0.48	350	0.46*
O_2 TURBINE POWER GG	0.20	350	0.30*
H_2 HEAT EXCHANGER	2.31	400	1.00**
O_2 HEAT EXCHANGER	1.14	400	0.70**

SINGLE GAS GENERATORS (MR ≈ 1:1)

H_2 (TURBINE PLUS HX)	2.79	400	1.0***
O_2 (TURBINE PLUS HX)	1.34	400	0.70

*POSSIBLE IDENTICAL GEOMETRIES, TURBINE UNITS

**POSSIBLE IDENTICAL GEOMETRIES, HX UNITS

***POSSIBLE IDENTICAL GEOMETRIES, COMBINED UNITS

2.6 PRESSURIZATION

The pressurization techniques which are applicable to the APS are illustrated in Figure 2-17. A weight comparison between helium and autogenous systems is shown in Figure 2-18. For the oxygen system no real premium results in selection between the two techniques from a weight standpoint. There is a clear weight advantage for the hydrogen system to use the autogenous system at large propellant loads. The final recommended systems were: He for all O_2 and the low ΔV H_2 system; autogenous for the high ΔV H_2 system.

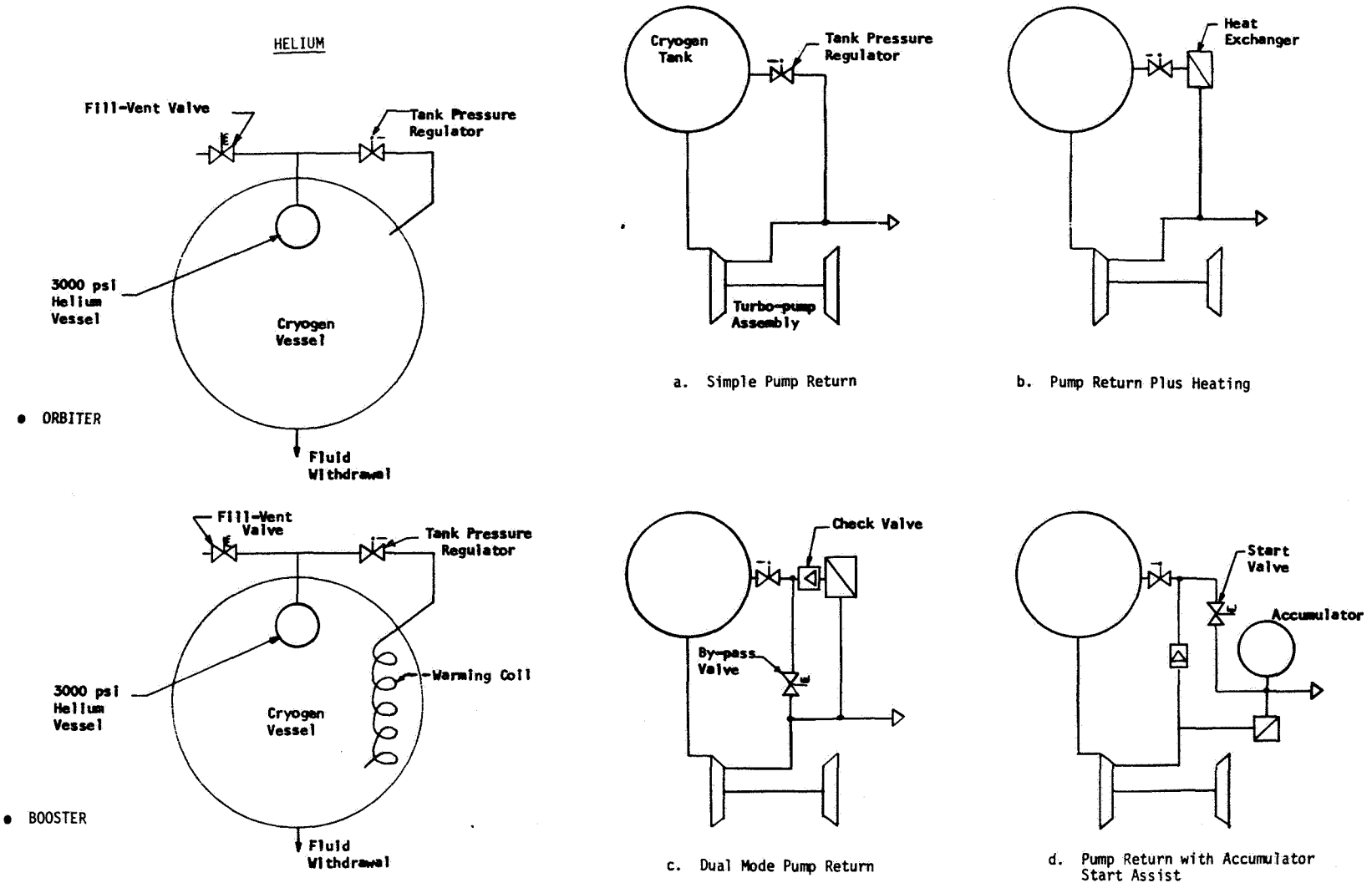
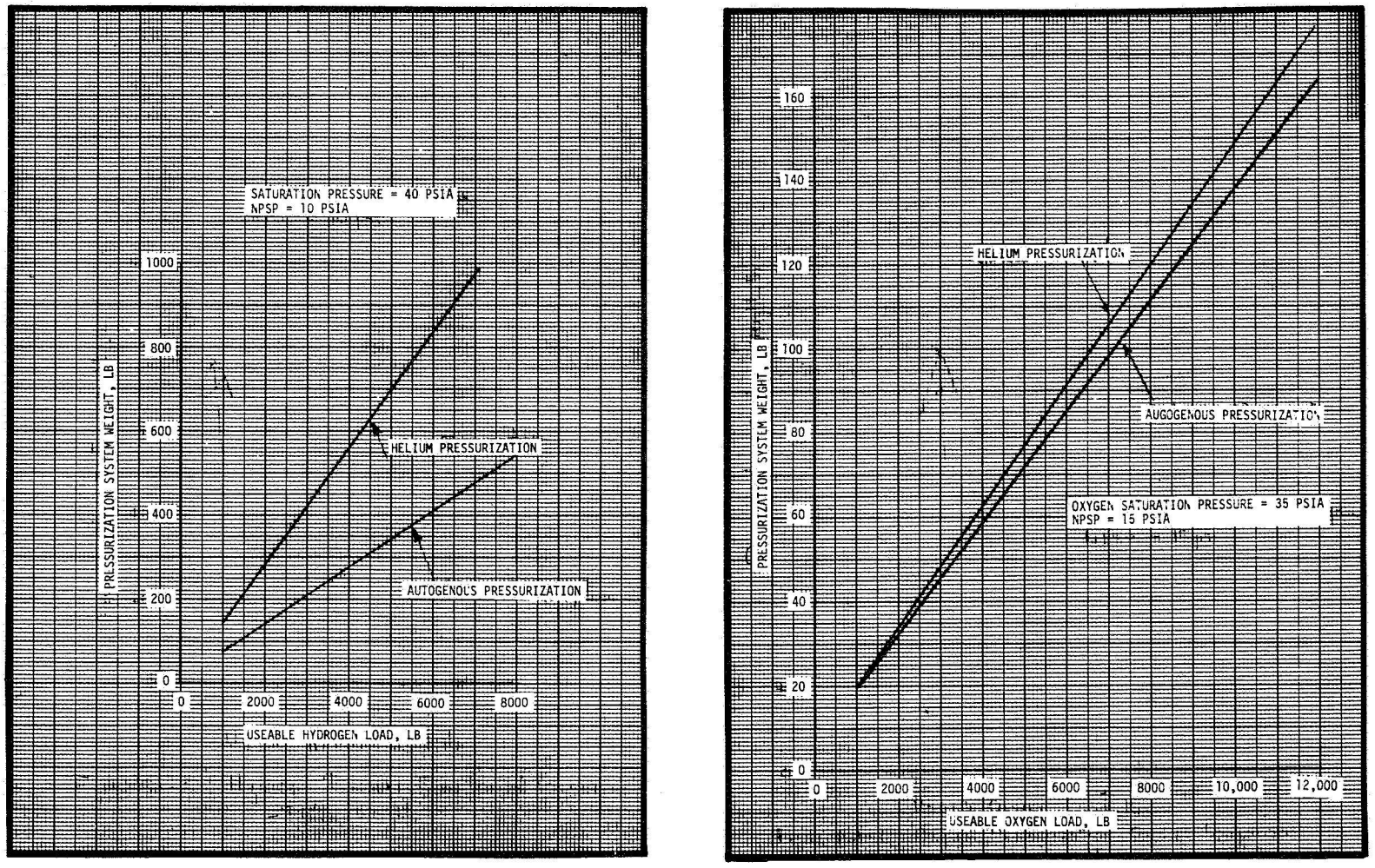


Figure 2-17. Final Pressurization Concepts Considered to be Applicable



- HELIUM FOR ALL O_2 , LOW DELTA-V H_2
- AUTOGENOUS FOR HIGH DELTA-V H_2

Figure 2-18. Pressurization System Weight Comparison

2.7 LIQUID ACQUISITION AND TANKAGE

The tankage configuration and liquid acquisition requirements and constraints are given in Tables 2-8 and 2-9. Tanks were restricted to 6-foot-diameter spheres. Larger volumes were relegated to cylinders. No venting was found to be necessary in the tank design with maximum pressure buildup to 50 psia for the nominal SSVDRD 7-day mission.

An assessment of liquid acquisition techniques resulted in selection of surface tension devices. A typical configuration is shown in Figure 2-19. Considerably more attention must be given to this area before final configurations are selected.

Similarly, the insulation and tankage support areas require specific design study to determine final selections.

Table 2-8. Propellant Storage Requirements

	BOOSTER	ORBITER	
		LOW DELTA-V	HIGH DELTA-V
PROPELLANT QUANTITIES, LBS			
H_2	350 - 450	600 - 800	4,800 - 5,400
O_2	1,700 - 1,900	2,800 - 3,300	20,000 - 23,000
TANKAGE CONFIGURATION			
H_2	1 SPHERE	1 SPHERE	2 CYLINDERS (6 FT DIA)
O_2	1 SPHERE	1 SPHERE	2 SPHERES
THERMAL DESIGN BASIS	PRELAUNCH	ON-ORBIT STANDBY	ON-ORBIT STANDBY
THERMAL DESIGN PHILOSOPHY	PRESSURE BUILDUP - NO VENTING (NOMINAL)		
TANK DESIGN PRESSURE, PSIA			
H_2	50	50	50
O_2	50	50	50
PUMP NPSP REQUIREMENTS, PSI			
H_2	15	15	15
O_2	10	10	10

Table 2-9. Liquid Acquisition Requirements and Constraints

VEHICLE	ACCELERATION FT/SEC^2	TYPE	FLUID	CONFIGURATION	SIZE FT	REQUIRED ACCELERATION FT^2/SEC^2	DESIGN VALVE ACCELERATION FT^2/SEC^2
BOOSTER	5.8	PITCH	LOX	1 SPHERICAL	3.6 DIA	10.5	20.0
BOOSTER	5.8	PITCH	LH_2	1 SPHERICAL	5.0 DIA	14.5	52.0
ORBITER	3.0*	± X	LOX	2 SPHERICAL	6.0 DIA	12.0	20.0
ORBITER	3.0*	± X	LH_2	2 CYLINDRICAL	6.0 DIA X 18.0	21.0	52.0

NOTE: RE-ENTRY ACCELERATIONS NOT INCLUDED.

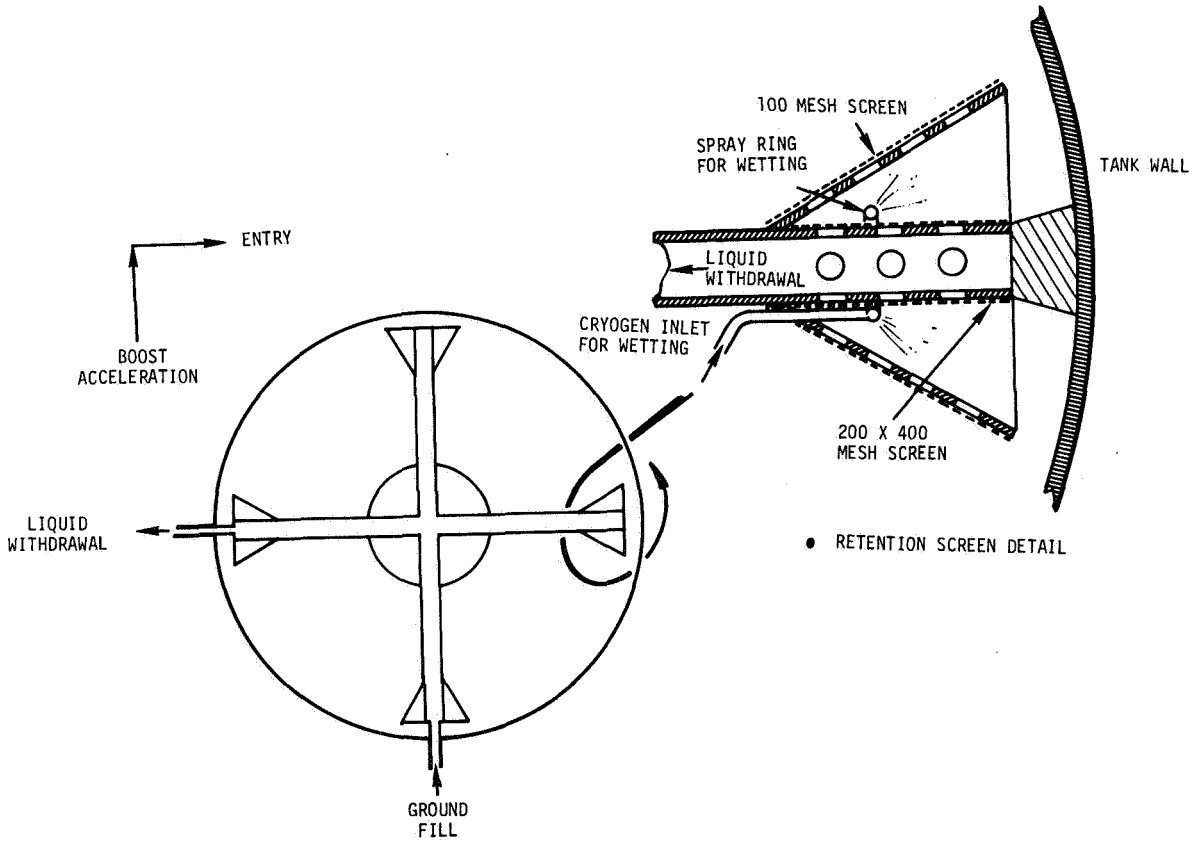


Figure 2-19. Acquisition Device Configuration

2.8 CONTROLS

Complete analog modeling was conducted on the conditioner cycle and the feed system. In the conditioner, both the single gas generator and dual gas generator cycles were examined. The nonlinearity demands of the power turbine competing with the linear demands of the heat exchanger resulted in the single gas generator system being unable to satisfy the demand in the 50 percent flow demand case. On the other hand, the dual gas generator cycle was able to follow the demands down to at least 41 percent of the full demand.

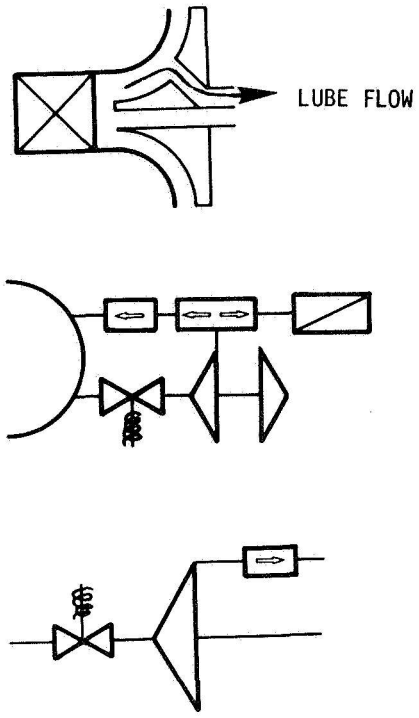
Three different pump start-up techniques were evaluated as shown in Figure 2-20. The resultant spinup times are illustrated in Figure 2-21. A minimum start-up time is desired, since it directly affects the accumulator sizing and operation.

The maximum control logic for the all ΔV requirement is shown in Figure 2-22 for the combined gas generator cycle. As indicated above, this cycle will not control deep into the flow rate demand. It will control quite adequately at a fixed demand rate. The controls consist of (1) speed control, (2) mixture ratio modulating control, and (3) power control to the gas generator.

Its counterpart in the dual gas generator cycle is shown in Figure 2-23. This cycle is fully capable of controlling across the entire range of flow demand.

In order to illustrate the control sequencing requirements, Figure 2-24 shows the various response times and a suggested sequence. The oxygen heat exchanger is primarily controlling. As a result its gas generator feed must overlap most of the other gas generator requirements, as well as the spinup time of the pumping equipment.

When the low ΔV requirements are considered and the flow rate demands are constant, it is possible to consider the use of constant pressure gas generators and constant mass flow gas generators in torque balanced turbopump cycles. When this approach and independent heat exchanger control are retained the control schematic of Figure 2-25 results. The constant pressure and mass flow regulator cycles are shown in Figures 2-26 and 2-27, respectively. In all cases, over speed control is retained.



"DRY" SPINUP

3 POSITION INLET VALVE, SPINUP TO 80 PERCENT SPEED WITH LUBRICATION CRYOGEN ONLY. LOW SPINUP TORQUE.

PARTIALLY LOADED SPINUP

PUMP SPINS UP WET. DIVERTER VALVES RETURN FLOW TO TANK UNTIL SET PRESSURE REACHED. LOW SPINUP TORQUE. RETURN FLOW AIDS TANK PRESSURIZATION.

DEADHEADED SPINUP

PUMP SPINS UP WET. LOW PUMP DELTA-P UNTIL LOAD VALVE OPENS.

- HEAT INPUT TO PUMP CAVITY WILL CAUSE PRESSURE BACKSURGE INTO FEEDLINE. MAY BLOW LIQUID OFF ACQUISITION DEVICE.

Figure 2-20. Pump Startup Techniques

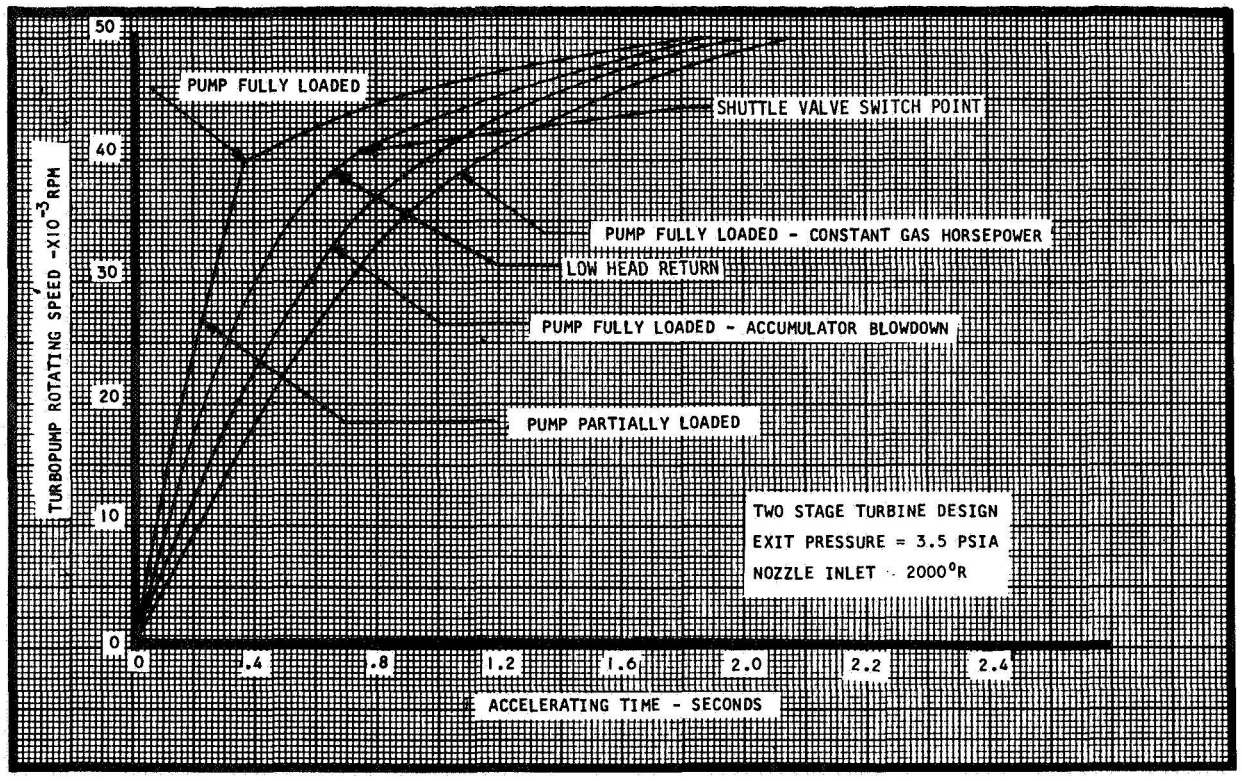


Figure 2-21. Pump Spinup Times

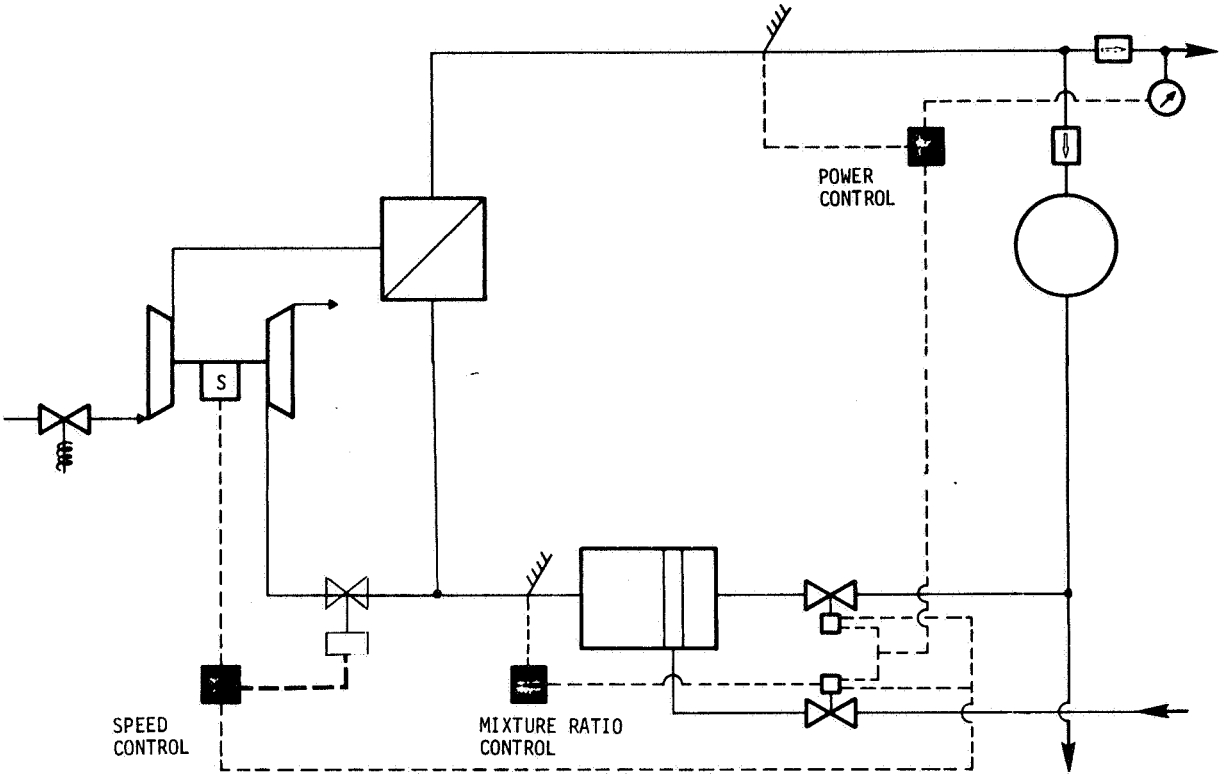


Figure 2-22. Maximum Control Logic for Combined Gas Generator Cycle

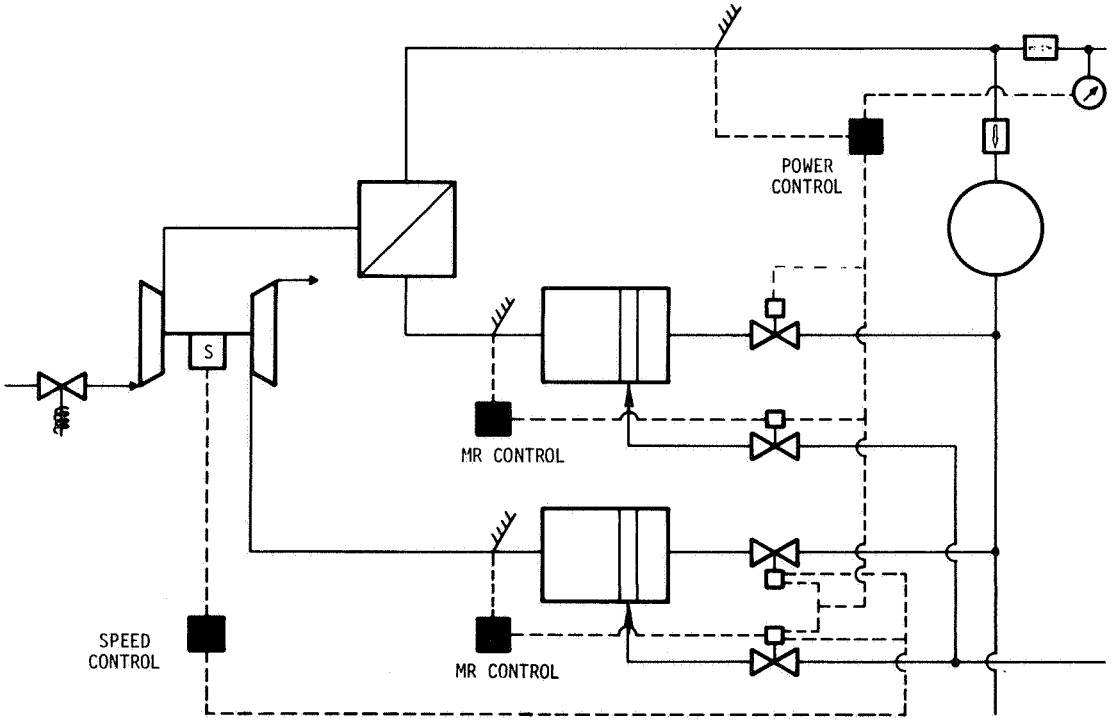
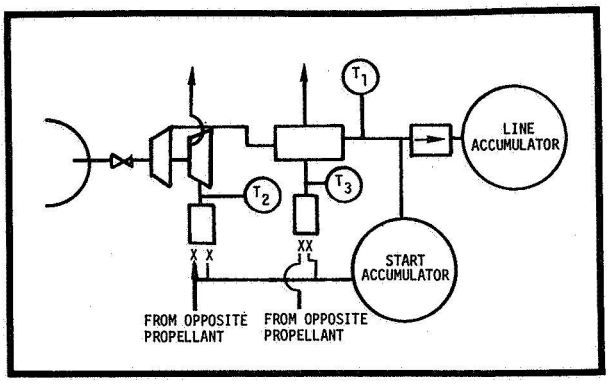


Figure 2-23. Control Logic for Dual Gas Generator Cycle

	RESPONSE, SECS	
	OXYGEN	HYDROGEN
HEAT EXCHANGER	0.693	0.166
TURBOPUMP	0.300	0.300
SENSOR T_1	0.032	0.066
SENSOR T_2	0.082	0.170
SENSOR T_3	0.082	0.170
MODULATING GAS GENERATOR VALVES	0.100	0.100
ON-OFF VALVES	0.040	



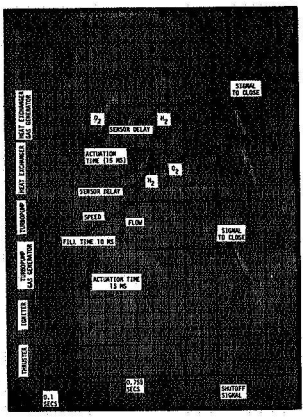


Figure 2-24. APS Component Response Times and Start Sequence

CONTROL MODIFICATIONS FOR LOW ΔV ORBITER

RETAIN HEAT EXCHANGER CONTROL, RUN TORQUE BALANCED TURBOPUMP

- WIDE RANGE OPERATION

NARROW RANGE OPERATION WITH MINIMUM GAS GENERATOR FLOW MODULATION

- CONSTANT PRESSURE GAS GENERATORS
- CONSTANT MASS FLOW GAS GENERATORS - VARIATIONS REQUIRED TO KEEP CONSTANT HEAT EXCHANGER INLET TEMPERATURE

Figure 2-25. Constant Flow Rate and Independent Heat Exchanger Control Cycle

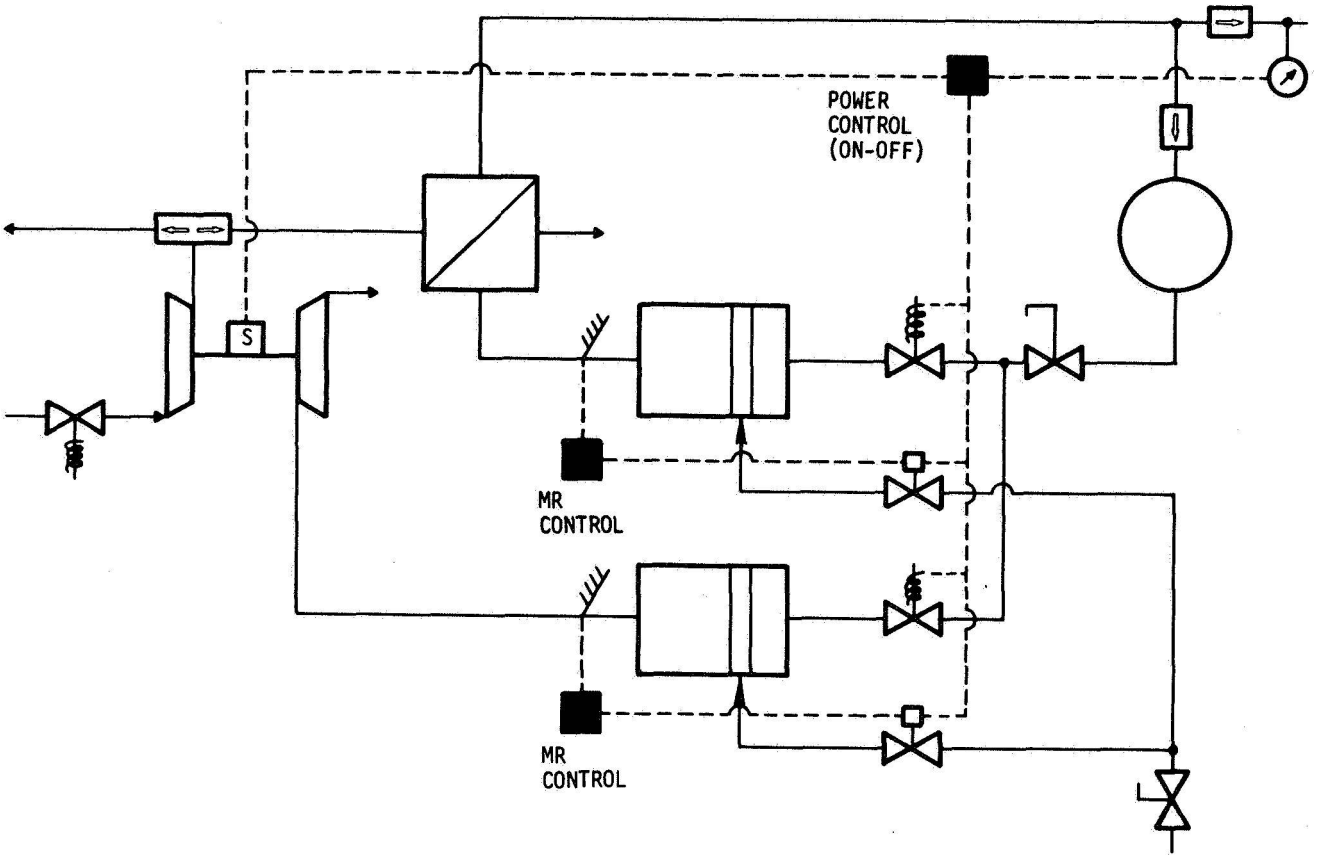


Figure 2-26. Torque Balanced System with Constant Pressure Gas Generator

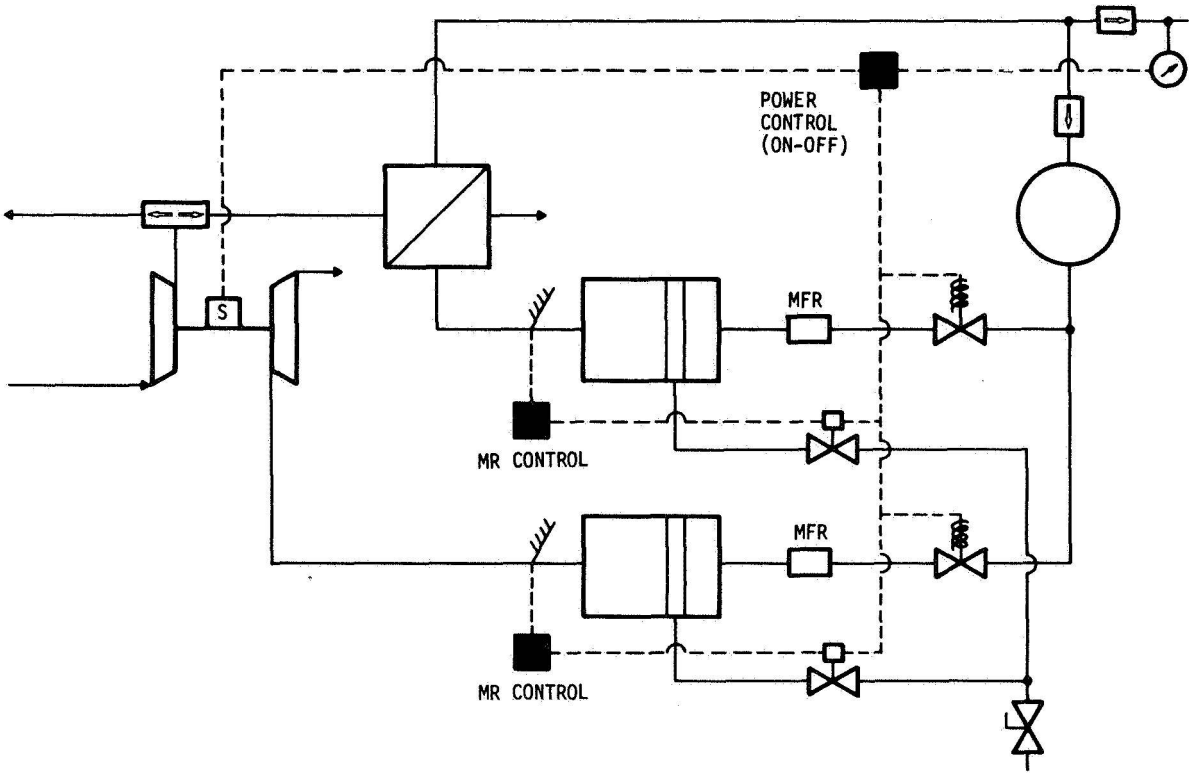


Figure 2-27. Torque Balanced System with Constant Mass Flow Gas Generators

A comparison of the pressure/speed variations for the various cycles is given in Table 2-10 for both wide and narrow range flow control. In the wide range, torque balanced turbopump the parenthetical values represent a different design point selection to minimize the low flow pressure/speed excursions.

All of the above systems use state-of-the-art control concepts. The high performance cycles have been shown to be fully controllable. In both high and low ΔV cycles, gas generator mixture ratio control is required. Constant mass flow regulators will not provide adequate temperature control in themselves. Indeed, they compete with the concept of temperature control.

2.9 MAIN LINE SIZING AND ACCUMULATOR REQUIREMENTS

2.9.1 Line Sizing

The original program effort commenced with a distribution line Mach number maximum specification of 0.3. A detailed dynamic analysis of the distribution network was conducted to determine the effects of line size on pressure surging. The results are shown in Figure 2-28. From these results, it was determined that the Mach number would be restricted to 0.075. Further, the major distribution artery in both vehicles was carried at high pressure to minimize the required accumulator storage volume (Figure 2-29).

2.9.2 Accumulators

The primary sizing criteria impact on the accumulators is that of minimizing the number of starts on the conditioning equipment. The effects of mission requirements are shown in Figures 2-30 and 2-31 for two different mixture ratios for the low ΔV requirement. For a one burn mission, the accumulator requires only sufficient propellant to start the conditioner. For the nominal mission specified in the SSVDRD, the conditioner was arbitrarily restricted to 25 starts as shown. For all limit cycles plus one start the results are shown as the parametric curves with various initial pressures. As seen, major weight penalties result as the number of allowable conditioner cycles are reduced. Because of these larger penalties, serious consideration should be given to the use of composite vessel structures, as well as maximizing the rotary machinery bearing and seal life.

Table 2-10. Cycle Pressure/Speed Variations

WIDE-RANGE CYCLES	FULLY CONTROLLED	TORQUE-BALANCED TURBOPUMP
P/N AT DESIGN FLOW, PSIA/RPM	1140/50,000	1140/50,000 (800/40,000)
P/N AT 25 PERCENT FLOW, PSIA/RPM	1280/50,000	1900/61,000 (1300/52,000)
NARROW-RANGE CYCLES	**CONSTANT PRESSURE GAS GENERATORS**	**CONSTANT MASS FLOW GAS GENERATORS**
EXPECTED GAS HORSEPOWER VARIATION, PERCENT	30	10
P/N AT DESIGN FLOW, PSIA/RPM	1140/50,000	1140/50,000
P/N AT MAX GHP, PSIA/RPM	1350/54,700	1210/51,700
MAX FLOW RATE VARIATION, PERCENT	9	3

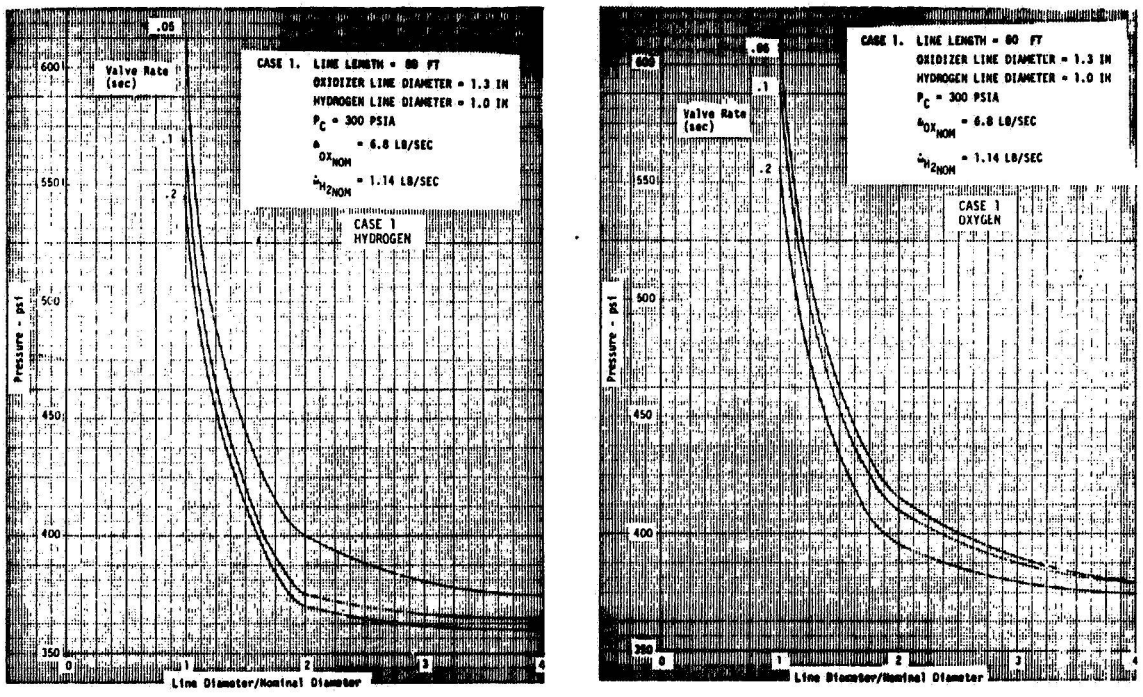


Figure 2-28. Amplitude of Pressure Fluctuations with Line Diameter and Valve Rate

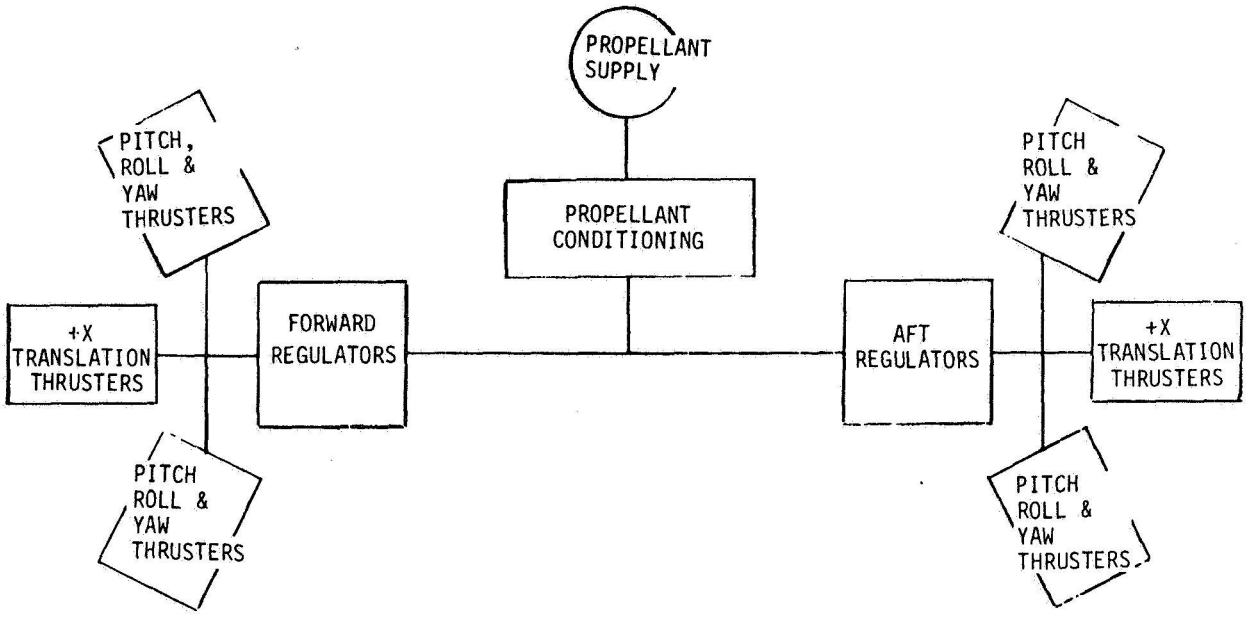


Figure 2-29. APS Functional Placements

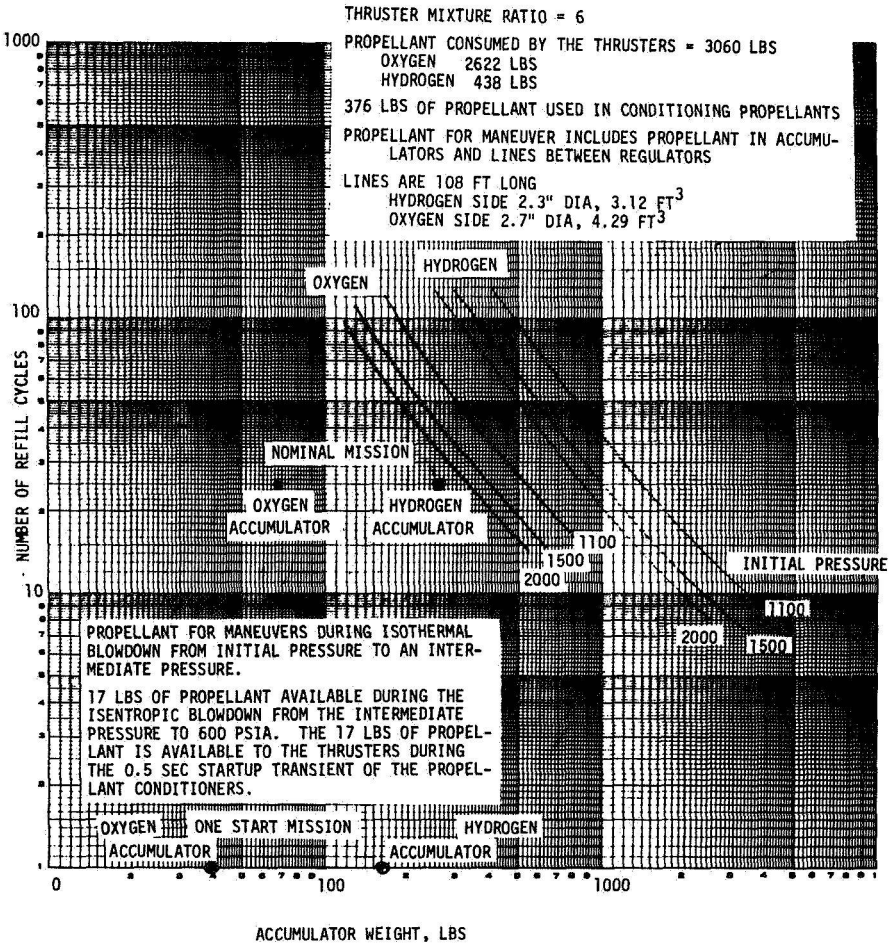


Figure 2-30. Accumulator Weight and Refill Cycles for Different Missions, Mixture Ratio = 6

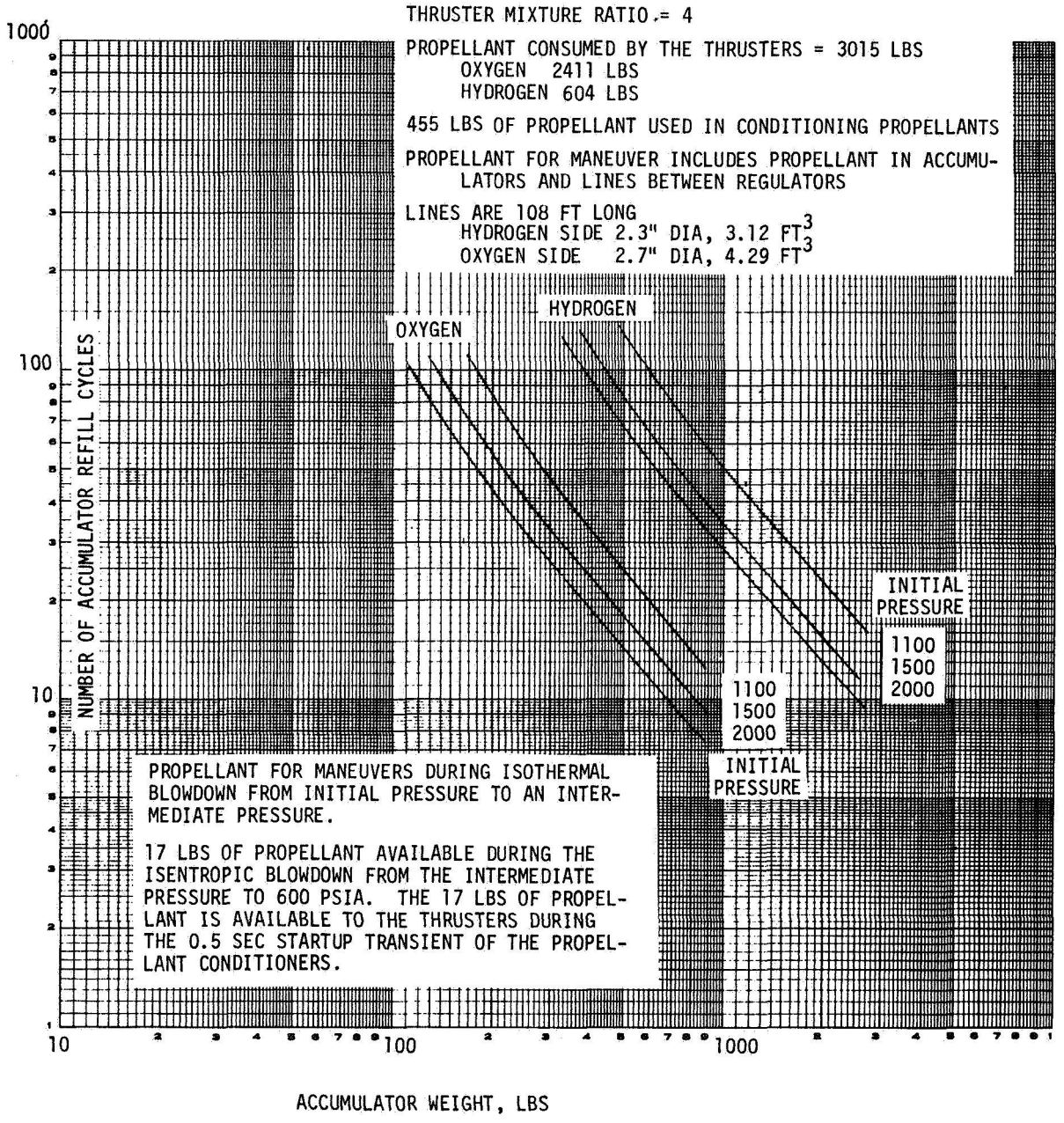


Figure 2-31. Effect on Accumulator Weight for All Stable Limit Cycle Mission, Mixture Ratio = 4

2.9.3 Mixture Ratio Variability Effects on Number of Starts

Mixture ratio variability in cycle use will result in the two conditioning loops operating at different times. An estimate of the maximum number of mismatched starts is given in Figures 2-32 and 2-33 for assumed off MR duty and selected nominal cycle operations/mission of 25, 50, 100. As is seen, the number of mismatches is not expected to be exorbitant. They will occur, however. No performance penalty for induced pump disturbance torque brought on by these starts was computed.

2.10 CYCLE WEIGHT COMPARISON

The various possible cycle configurations which result in major weight variations are compared on a weight basis in Table 2-11 for both the booster and orbiter at the minimum weight condition (highest allowable thruster mixture ratio of 6:1). The distribution loop and thruster weights are not included in these values. The distribution loop weight is dependent upon the allowable duty cycle for the conditioner and is summarized in this section. In Table 2-11, the comparisons to be made are against the single gas generator (2000°R limit), dual turbopump cycle.

It is of interest that the largest gains to be made are in the use of a propulsive vent for the all ΔV maneuvers. The addition of separate 3500°R gas generators for the heat exchanger or staged 2000°R gas generator cycles will result in a weight savings of up to ~2400 pounds in the all ΔV case; however, most of this occurs with the use of the propulsion vent with "free" oxygen addition from the ascent tanks. The use of staging combustion in the cycles results in a weight savings of up to ~700 pounds.

In the low ΔV cycles, staging or high temperature combustion can result in a maximum of ~620 pounds weight savings. Similarly, on the booster, the use of staging or high temperature in the gas generators results in a maximum weight savings of ~495 pounds.

In considering the use of high temperature gas generators or staged gas generators, it is cautioned that increased control and propellant sequencing requirements must be traded off against the weight savings. An independent decision must be made as to whether or not the weight savings enumerated merit the increased control requirements.

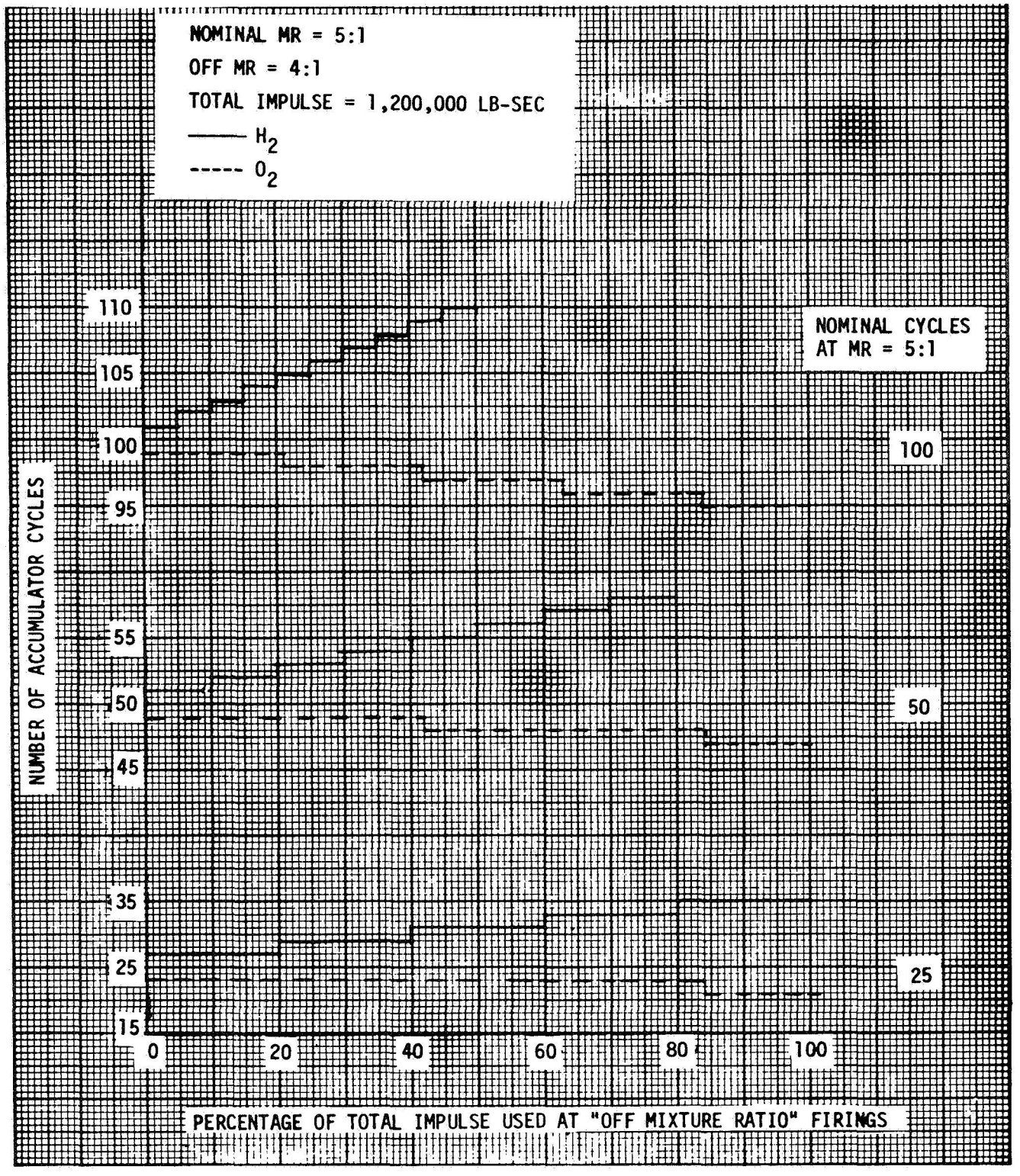


Figure 2-32. Effect of Thruster Mixture Ratio Shift on Conditioner Cycles for Fixed Accumulator Size, Off Mixture Ratio = 4:1

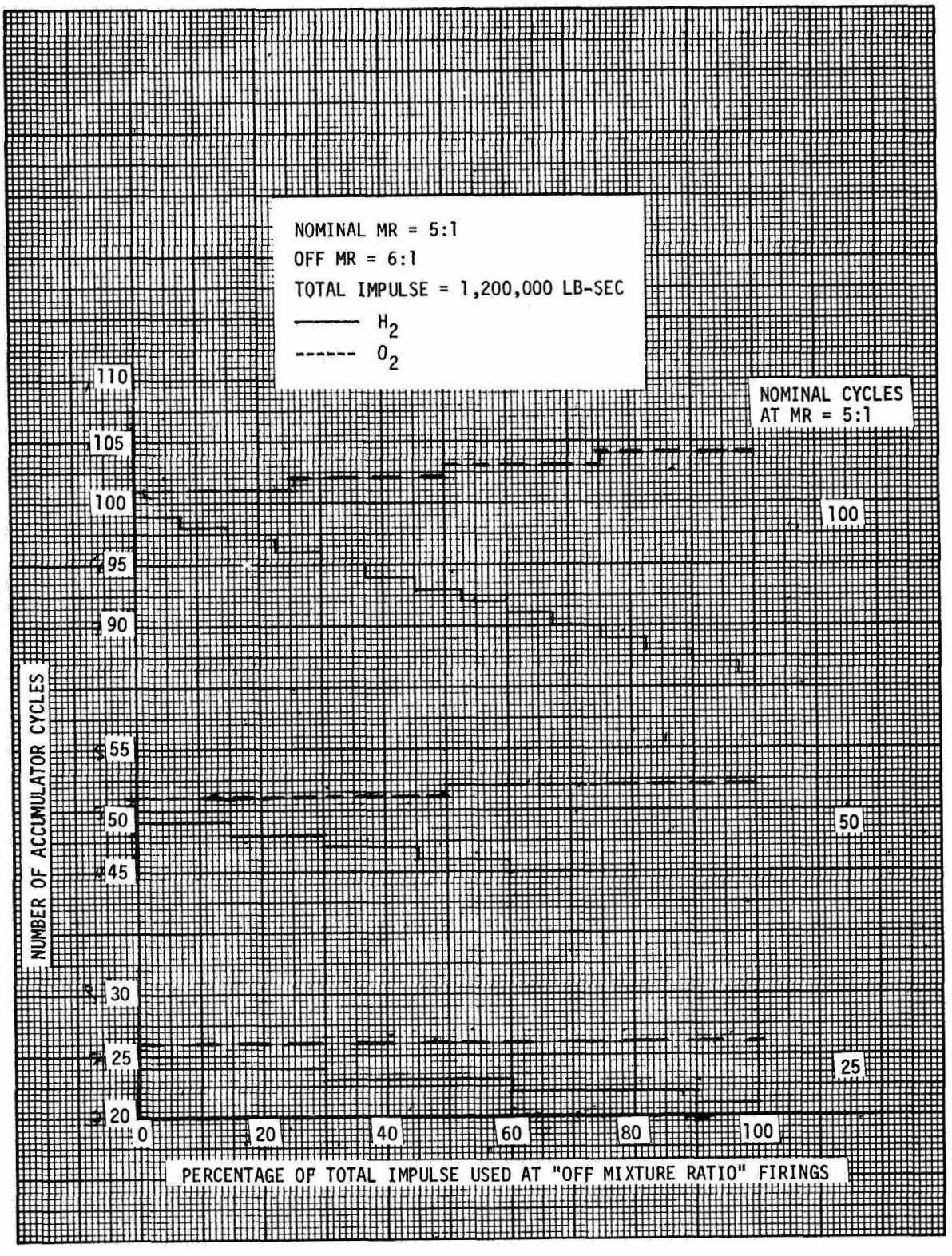


Figure 2-33. Effect of Thruster Mixture Ratio Shift on Conditioner Cycles for Fixed Accumulator Size, Off Mixture Ratio = 6:1

Table 2-11. Cycle Weight Comparisons for Booster and Orbiter

CYCLE	CONDITIONING PENALTY PERCENT	RELATIVE WEIGHT, LBS (INCLUDING PROPELLANT TANKAGE)
PARALLEL, ONE GAS GENERATOR PER SIDE, 2000°R GAS TEMPERATURE	12.1	CYCLE I-A AS BASE
PARALLEL, INDIVIDUAL TURBINE/ HEAT EXCHANGER GAS GENERATOR, 2000°R GAS TEMPERATURE	12.1	HIGH ΔV LOW ΔV BOOSTER
PARALLEL, INDIVIDUAL TURBINE/ HEAT EXCHANGER GAS GENERATORS, 3500°R GAS TEMPERATURE (hx)	7.1	WITHOUT PROPULSIVE VENT WITH PROPULSIVE VENT + O_2 ADDITION
IN-LINE, STAGED COMBUSTION, DOWNSTREAM TURBINE, 2000°R GAS TEMPERATURE	6.9	
PARALLEL, STAGED COMBUSTION, COMBINED TURBOPUMPS, 3500°R GAS TEMPERATURE (hx)	5.6	-400 0 400 800 1600 1200 2000

The propellant line weight summary is given below:

Item	Booster	Orbiter
Propellant Lines	370	356
Line Supports	22	20
Expansion Loops	56	50
Flanges	46	43
TOTAL	494	469

The entire low ΔV unit weight summary for baseline comparisons is given in Table 2-12.

Table 2-12. Low Velocity APS Inert Weight

COMPONENTS	Quantity of			Unit Weight, lbs		Total Weight		
	Component in Module	Modules in APS	Component in APS	H_2 Side	O_2 Side	H_2 Side	O_2 Side	Both Sides
Propellant Supply Module								674
Propellant Acquisition Device	1	2	2	16	11	16	11	27
Propellant Tank	1	2	2	87	37	87	37	124
Pressurization System	1	2	2	68	37	68	21	89
Vent Valves	3	2	6	1.7	1.7	5	5	10
Insulation	1	2	2	93	100	93	100	193
Lines and Valves	--	--	--	--	--	17	17	34
Outer Structure Weight	--	--	--	--	--	72	126	198
Propellant Distribution Module								1438
Propellant Conditioner Isolation Valves	16	2	32	4	4	64	64	128
Propellant Conditioner Isolation Valves	8	1	8	4	4	16	16	32
Vent Isolation Valves	5	4	20	1.5	1.5	15	15	30
Regulator Isolation Valves	5	6	30	3	3	45	45	90
Accumulator Tank	1	2	2	260	68	260	68	328
Check Valves	9	2	18	2	2	18	18	36
Vent Valves	3	6	18	2	2	18	18	36
Regulators	3	4	12	20	20	120	120	240
Acc. Fill & Drain Valves	1	2	2	2	2	2	2	4
Lines, Hangers, Expansionloops	--	--	--		469		469	469
Insulation	--	--	--	--	--	--	--	45
Propellant Conditioning Module								1093.7
Main Propellant Control Valve	2	3	6	14	20	42	60	102
Turbopumps	2	3	6	50	75	150	75	225
Heat Exchangers	2	3	6	32	85	96	255	351
Gas Generators for Heat Exchangers	2	3	6	7	6	21	18	39
Gas Generators for Turbopump	2	3	6	4.2	3.3	12.6	9.9	22.5
Gas Generator Propellant Control Valve for Heat Ex.	4	3	12	2.8	2.4	16.8	14.4	31.2
Gas Generator Propellant Control Valve for Turbopump	4	3	12	1.5	1.2	9	7.2	16.2
Start Accumulator Tank and Insulation	2	3	6	58	6	174	18	192
Vent Valve	2	3	6	2	2	6	6	12
Fill & Drain Valve	2	3	6	2	2	6	6	12
Regulators	2	3	6	10	10	30	30	60
Check Valves	2	3	6	1.8	1.8	5.4	5.4	10.8
Insulation	--	--	--	10	10	10	10	20
Thruster Module								1415.6
Thrusters	1	32	32		30.5		976	976
Propellant Control Valves	2	32	64					
Filters	2	32	64	2	2	64	64	128
Isolation Valves	4	32	128	2.1	2.3	134.4	147.2	281.6
Insulation	--	--	--	--	--	--	--	30
TOTAL APS								4622.3

Weight	
Total Inert	4622
Total Propellants	3911
Total	8533 lb

3. VEHICLE INTEGRATION, REDUNDANCY AND MAINTAINABILITY

3.1 INTEGRATION

The integration of the APS into the booster and orbiter elements is illustrated in Figures 3-1 and 3-2. In the booster, the entire conditioner and propellant storage is placed in the forward part of the vehicle, while these elements are placed in the aft end of the orbiter.

The APS is logically broken into modules as illustrated in Figure 3-3. Within the propellant supply module are included the primary tankage, pressurization, fill and vent valves and the acquisition concept. In the conditioner loop are included the turbopumps, heat exchangers, gas generators and start bottles. The main distribution network redundant regulators are also modularized. The thruster modules include valves, igniters and line filters.

Both booster and orbiter feature the use of a high pressure distribution network. This provides that a maximum storage volume is available for the gaseous propellants in a most advantageous manner. The thruster feeds are regulated down at the forward and aft regions of the vehicles. The lines are all sized for a maximum Mach number of 0.075 to prevent surging effects. The lines range in diameter requirements from 1.4 to 2.8 inches on the H_2 side and 1.7 to 3.8 inches on the O_2 side. Thermal expansion and contraction are provided for by the use of 2-foot diameter circular expansion loops. High performance insulation is suggested to prevent major temperature variations. All lines are aluminum.

The conditioner loop can be closely packaged, as illustrated in Figure 3-4. Here a single gas generator is shown for both turbine and heat exchanger feed. The entire unit can be placed in approximately a 3' x 3' x 3' cube.

3.2 REDUNDANCY

To meet fail operational/fail safe redundancy requirements as indicated in the SSVDRD, the approach taken was that the thrusters would provide functional redundancy. The conditioner loop would provide

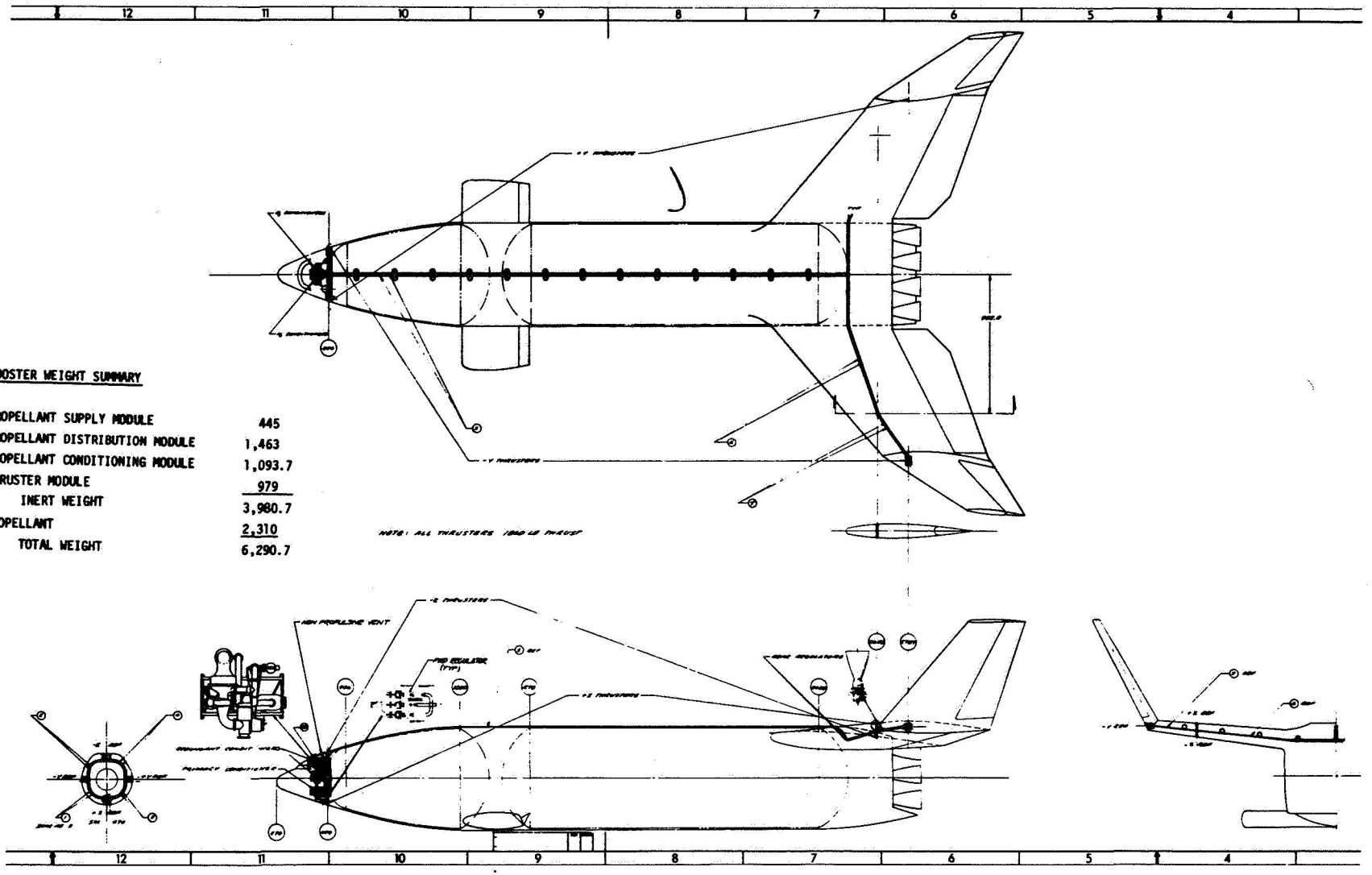


Figure 3-1. Booster Propellant Distribution and Component Location

ORBITER WEIGHT SUMMARY

	LOW DELTA-V	ALL DELTA-V
PROPELLANT SUPPLY MODULE	675	3,122
PROPELLANT DISTRIBUTION MODULE	1,438	1,438
PROPELLANT CONDITIONING MODULE	1,093.7	1,093.7
THRUSTER MODULE	1,415.6	1,415.6
INERT WEIGHT	4,622.3	7,069.3
PROPELLANT	3,921	27,952
TOTAL WEIGHT	8,543.3	35,021.3

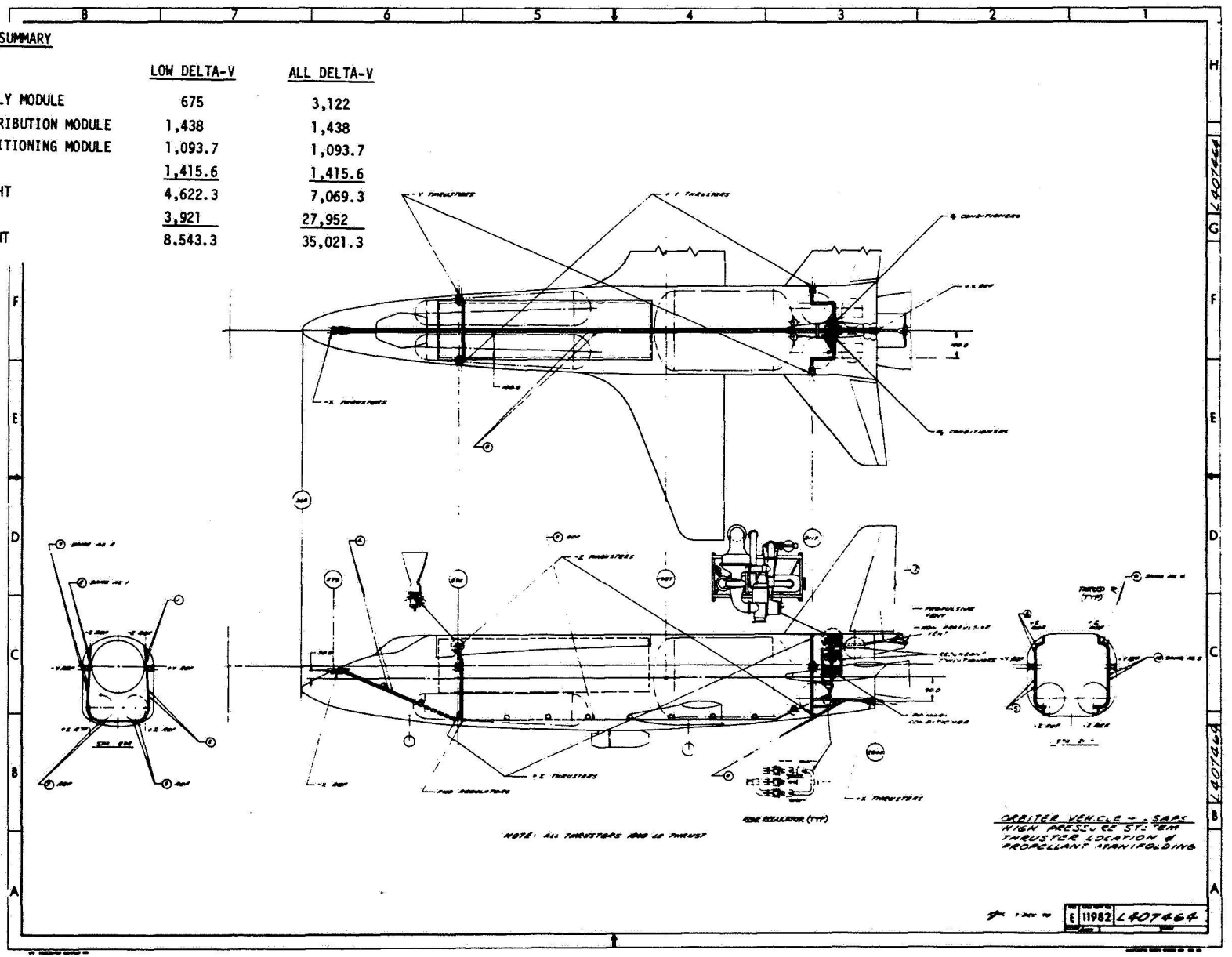


Figure 3-2. Orbiter Propellant Distribution and Component Location

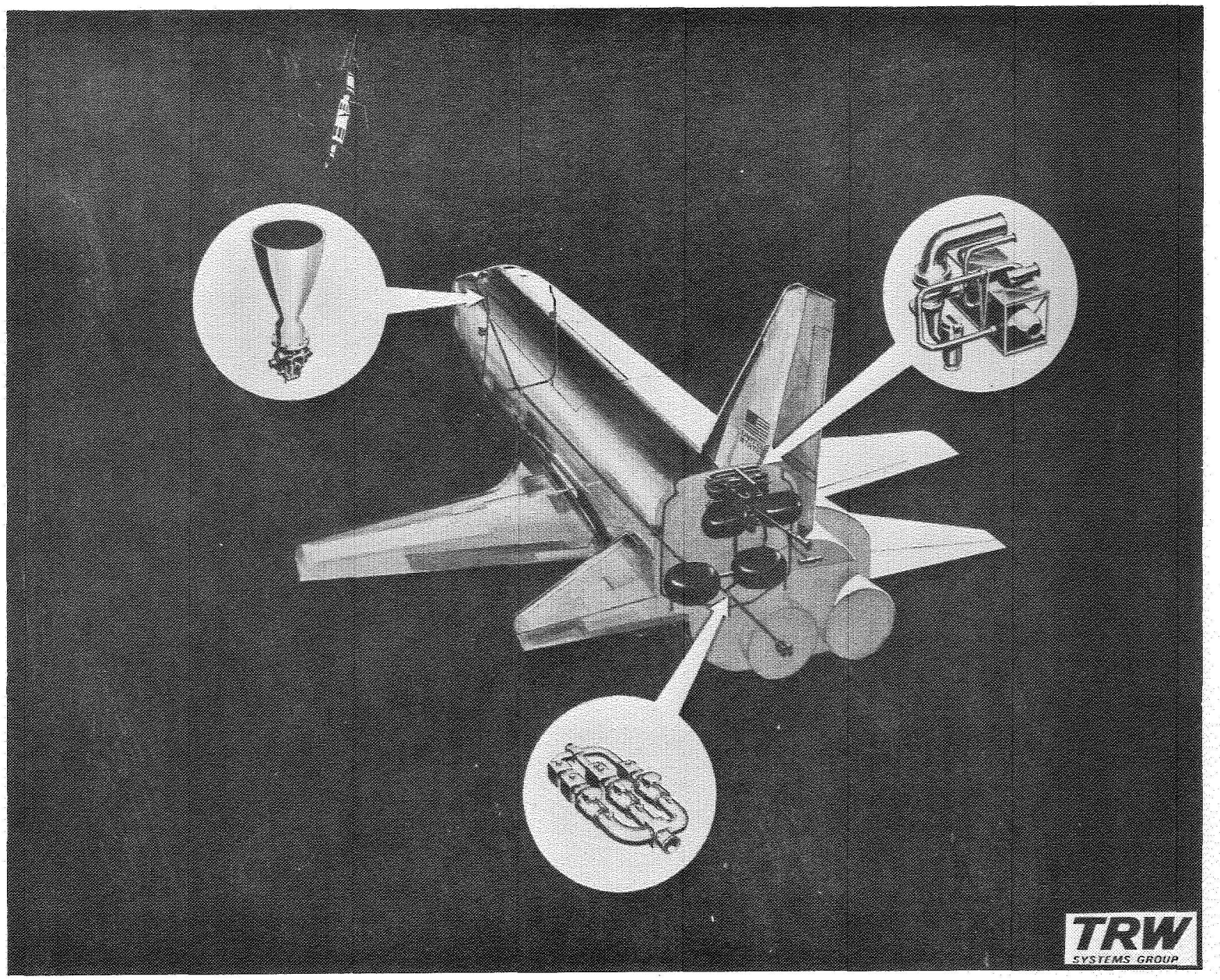


Figure 3-3. APS Installation Low Cross-Range Orbiter

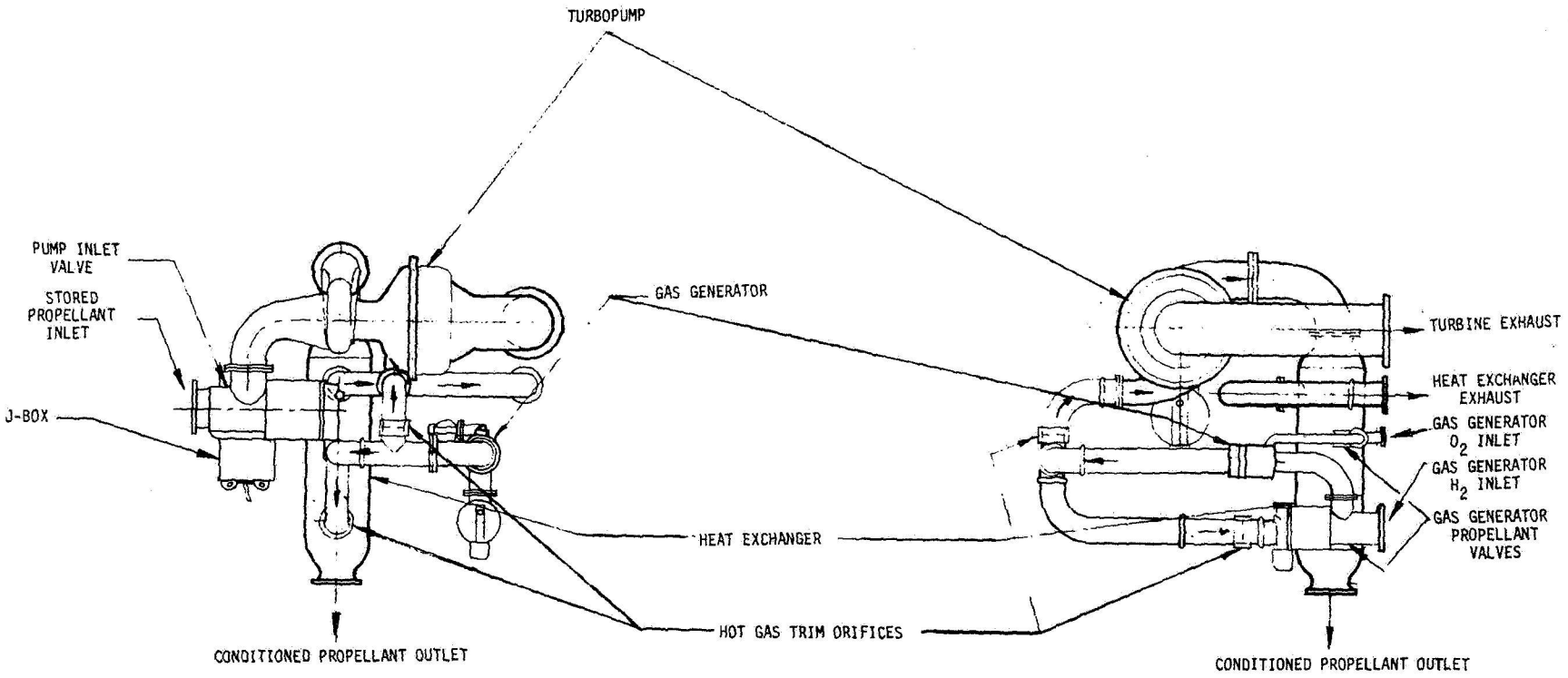


Figure 3-4. Single Gas Generator Conditioner Package for APS (Size is ~3 x 3 x 3 feet)

redundancy by module redundancy. The remaining areas of redundancy needed would be assessed on a component-by-component basis. This judicious approach in the entire APS results in an overall system which insures a safe and successful mission with minimum weight impact.

The 1840 lbf thruster selection and location selections meet all acceleration requirements as shown in Table 3-1 with 1 and 2 failures in the orbiter and booster vehicles.

The selected pressure relief vent module selection configuration, its probability of failure and weight are summarized in Figure 3-5a. The regulator module is shown in Figure 3-5b, and the thruster isolation system is given in Figure 3-5c. The entire orbiter APS redundant system is shown in Figure 3-6. Note that the conditioner loops are complete with start bottles and are switched with external switching networks. The tanks and main line accumulators are, of course, not made redundant. The overall approach results in reliability equal to or exceeding that of the unit results in the system.

3.3 MAINTAINABILITY REQUIREMENTS

A brief analysis of the APS system as modularized shows that major maintainability considerations need be directed only at the conditioner loop and the main regulator modules, both of which contain the major share of expected high failure rate items. The effects on overall reliability are illustrated in Figure 3-7 for several policies. Figure 3-8 shows the results of replacing the used conditioner module under several policies, while Figure 3-9 shows the results, including the regulator modules. In summary, it would appear that the selected maintainability policy will require maintenance of these modules every two to six missions, in order to maintain overall high reliability.

Table 3-1. Thruster Functional Redundancy

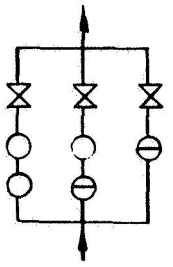
	Thruster Failure Location	Minimum Required Acceleration, deg/sec^2		Acceleration* Available, deg/sec^2	
		1 Failure	2 Failures	1 Failure	2 Failures
BOOSTER					
YAW	FORWARD	1.0	0.3	1.19	0.95
PITCH	FORWARD	0.5	0.3	0.71	0.46
ROLL	AFT	1.0	0.3	**	***
PITCH	AFT	0.5	0.3	0.86	0.74
YAW	AFT	1.0	0.3	1.31	1.18
ORBITER					
YAW	FORWARD	1.3	0.9	2.32	1.91
PITCH	FORWARD	1.0	0.5	1.0	0.58
ROLL	FORWARD	1.0	0.5	1.32	0.88
ROLL	AFT	1.0	0.5	1.32	0.88
PITCH	AFT	1.0	0.5	1.12	0.83
YAW	AFT	1.3	0.9	2.43	2.16

*1840 LBS THRUST COMMON ENGINE
16 YAW
4 AFT
6 FORWARD PITCH

**1.17 AVAILABLE WHEN ONE ROLL THRUSTER FIRED WITH TWO AFT YAW THRUSTERS

***0.475 AVAILABLE USING TWO AFT YAW THRUSTERS

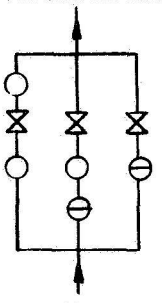
CONSIDERING FAIL OPERATIONAL/
FAIL SAFE AND EXTERNAL LEAKAGE



TOTAL WEIGHT OF COMPONENT	19	
PROBABILITY OF RELIEF VALVE EXTERNAL LEAKAGE	0.32×10^{-12}	(1 RELIEF VALVE EXTERNAL LEAKAGE PLUS 2 ISOLATION VALVE NON-FIRE)
	0.067×10^{-12}	(2 RELIEF VALVES--FIRST, ANY MODE; SECOND, EXTERNAL LEAKAGE PLUS 1 ISOLATION VALVE NON-FIRE)
CATASTROPHIC FAILURE OF ALL THREE RELIEF VALVES	7.4×10^{-12}	(FAIL OPEN OR CLOSE)

(a) Pressure Relief Valve Module Configuration Selection

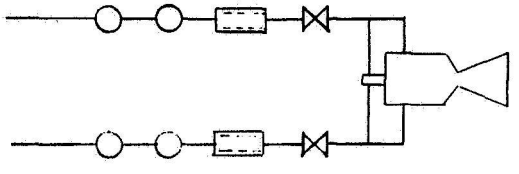
CONSIDERING FAIL OPERATIONAL/FAIL SAFE
AND PROVIDING FOR EXTERNAL LEAKAGE



TOTAL COMPONENT WEIGHT	75	
PROBABILITY OF REGULATOR EXTERNAL LEAKAGE	19.3×10^{-9}	(TWO REGULATOR FAILURES)*
CATASTROPHIC FAILURE**	17.6×10^{-9}	(TWO REGULATOR + ONE ISOLATION VALVE)

*ONE IN ANY MODE, OTHER IN EXTERNAL LEAKAGE.
**FAILURE OF ALL THREE REGULATORS TO OPERATE.

(b) Regulator Module Configuration



	NO ISOLATION VALVES	ONE ISOLATION VALVE	TWO ISOLATION VALVES
EXTERNAL LEAKAGE	602.67×10^{-9}	5.4×10^{-12}	4.88×10^{-20}
CATASTROPHIC FAILURE	$25,213 \times 10^{-9}$	22×10^{-9}	20×10^{-12}

(c) Thruster Module Configuration Selection

Figure 3-5. Fundamental Redundant Configuration

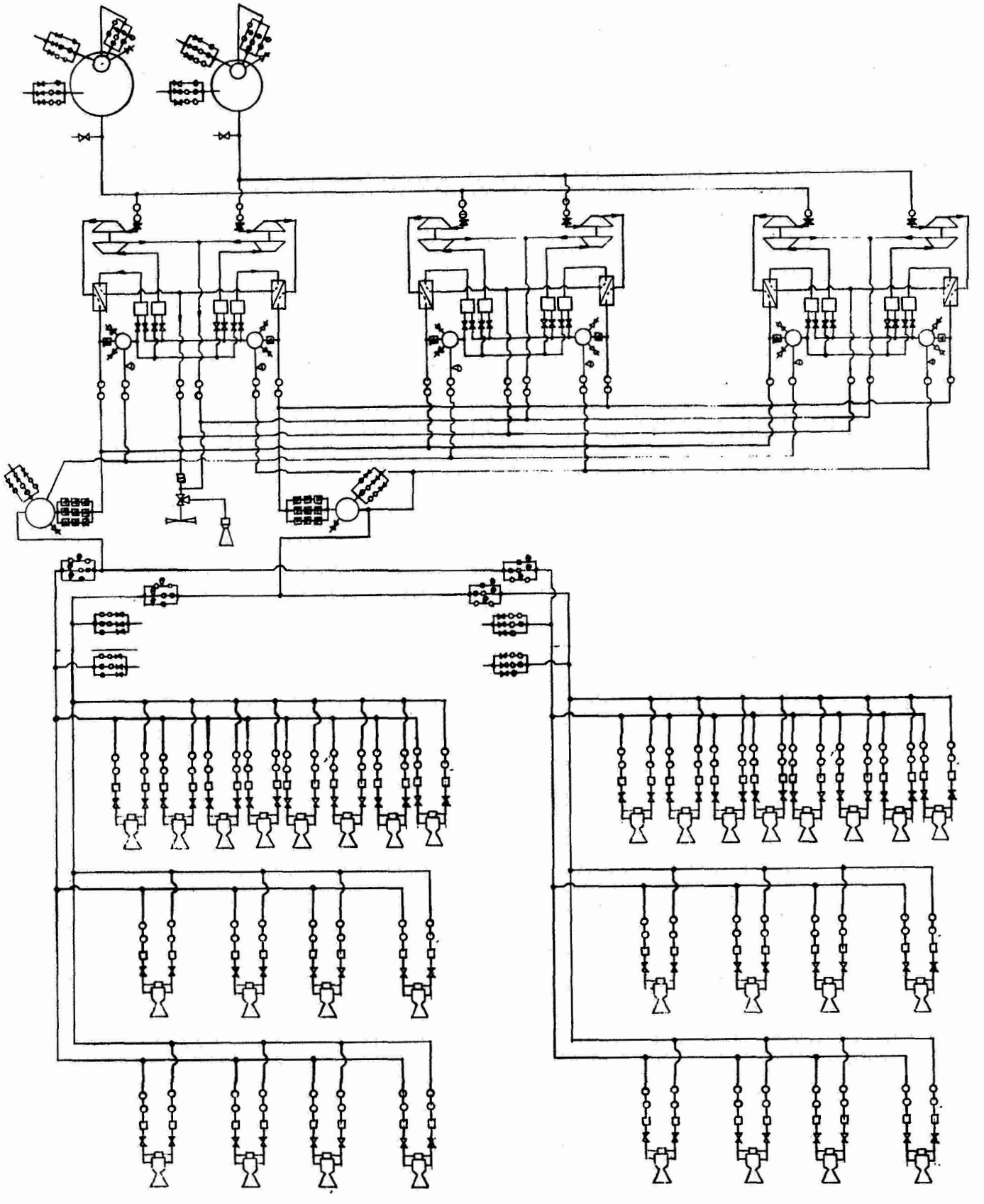


Figure 3-6. F/O-F/S Redundant APS for Orbiter

- REASONS FOR IMPLEMENTING MAINTAINABILITY.
- DETERMINE MAJOR MISSION INFLUENCES ON RELIABILITY.
- MAINTAINABILITY INTERACTION
-

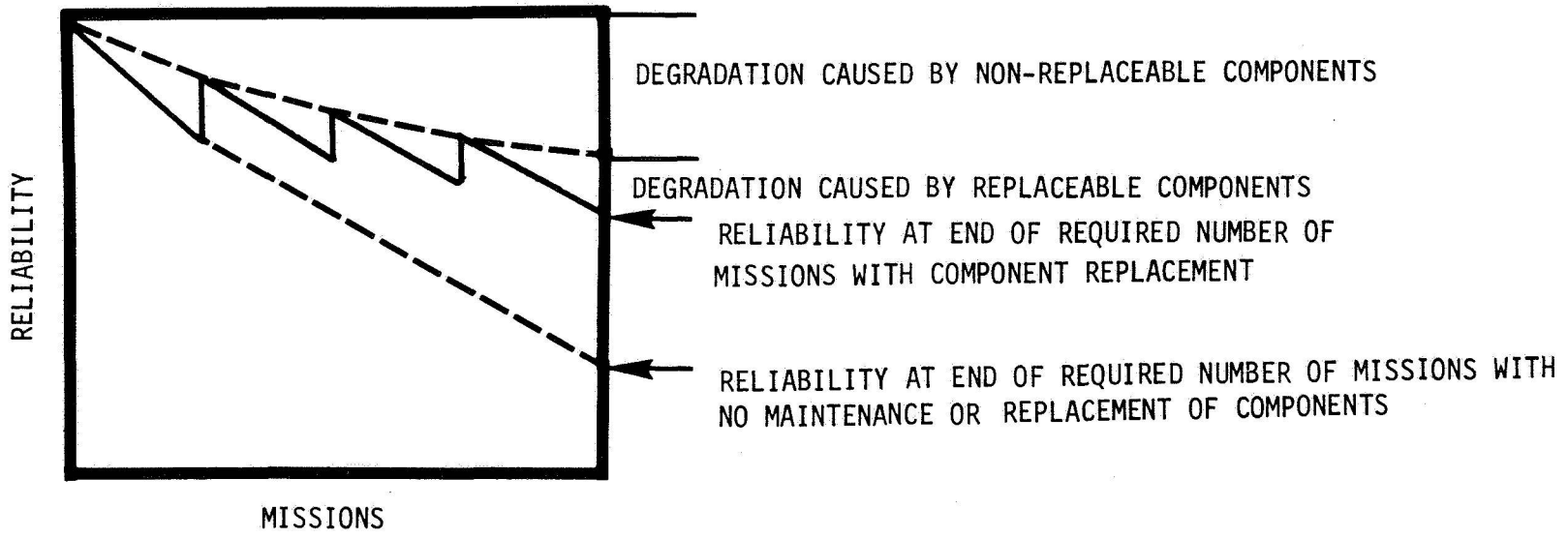


Figure 3-7. Illustration of Maintainability/Reliability Interaction

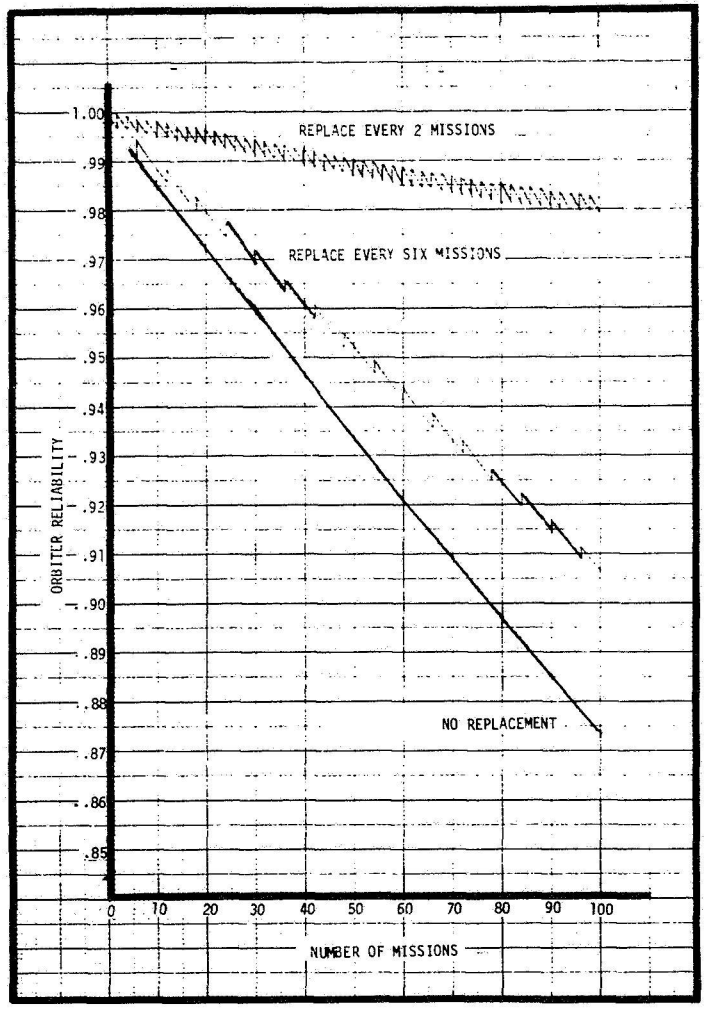


Figure 3-8. Effect on Orbiter Reliability of Replacing the On-Line Propellant Conditioning Module

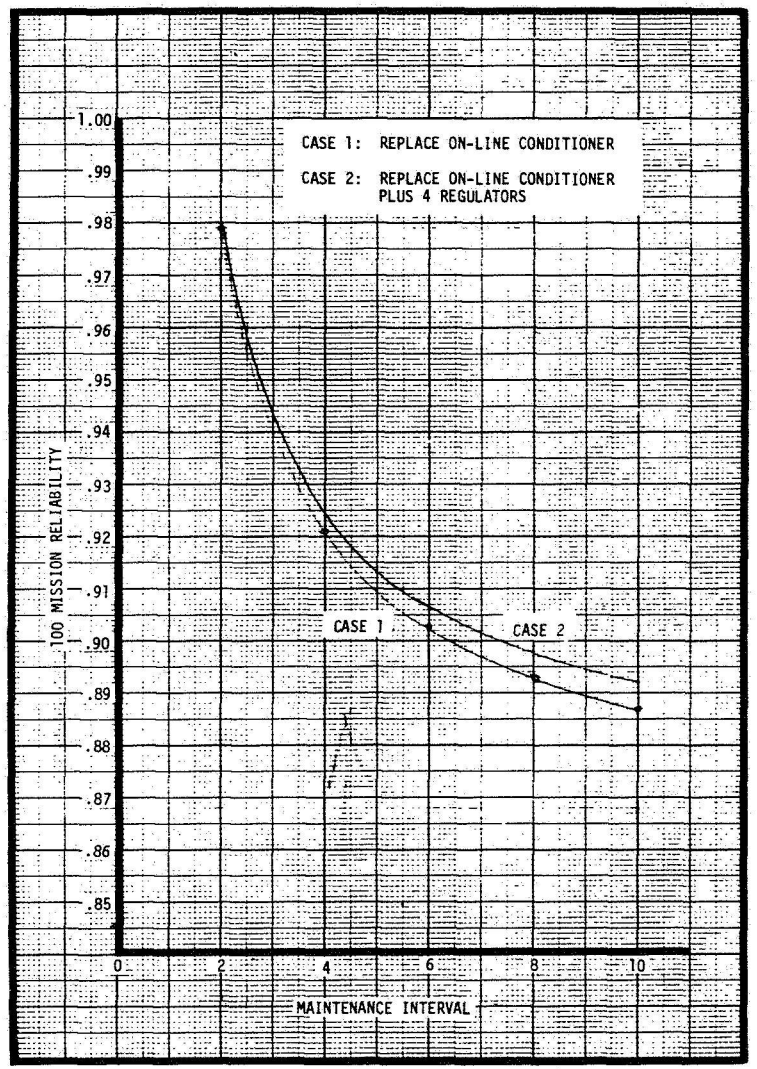


Figure 3-9. Effect on Orbiter Reliability of Replacing Additional Components

4. CRITICAL TECHNOLOGY SUMMARY REQUIREMENTS

The critical technology areas are summarized here as they pertain to the basic selected cycle.

4.1 PHASE ACQUISITION

The best available liquid acquisition technique appears to be surface tension screens. Theoretical considerations show that a 200 x 1400 mesh screen placed strategically in the storage tanks will provide required heads to maintain liquid flow to the pumps under all adverse acceleration requirements. Problem areas are seen in: (1) determination of inert gas effects (from pressurization), (2) maintaining compatibility with the pressurization technique, (3) obtaining screen wetting and providing a foolproof means of checkout, inspection and certification, and (4) providing the internal tank thermodynamic control necessary to maintain NPSP across the screen under the highest liquid drawoff conditions.

A second acquisition technique which appears worthy of continued evaluation involves the use of internal tank momentum exchange, wherein a small amount of the liquid is recirculated inside the tank and sprayed internally to drive the remaining liquid to the point of acquisition in the tank.

The sizing of the tanks and the expected interplay between the acquisition and pressurization techniques point out the need for an early well-designed experiment of sufficient size to simulate the maximum expected negative head.

4.2 PRESSURIZATION

Both internal tank-stored helium and autogenous pressurization techniques are considered: He for low ΔV systems in both O_2 and H_2, and autogenous pressurization in H_2 for high ΔV systems. With respect to the use of helium there may be adverse interaction with the acquisition concept. There may also be a need for internal passive heat exchange to obtain best performance of the helium pressurization.

Autogenous pressurization suffers from the possibility of ultimate loss of head, thus necessitating a need for internal NPSH thermodynamic control. Such control should be self-regulating.

The selected concepts should be evaluated in conjunction with the acquisition techniques.

4.3 TANK INSULATION

Since the storage tanks' insulation techniques are quite dependent upon final mission flexibility requirements, the tank design requirements must await specific tank design studies of much more depth than this study could devote to this subject. It is pertinent at this time, however, to consider the incorporation of thermodynamic vent control of appendage heat leaks. Since the rotating machinery requires thermal management, it is conceivable that thermodynamic vent control could also accomplish the rotating machinery requirements.

With respect to passive insulation, the need for vent design exists if the compartment is not conditioned to prevent moisture entry during ground hold, ascent or descent.

4.4 GAS GENERATORS

There do not appear to be any major problems associated with development of gas generators. Feasibility work is needed to prove the various possible approaches and to verify the life of several design approaches. The turbine power units tend to be relatively small, however. Both power and heat exchanger units can probably be fabricated in identical sets for the two propellants. Experimental work will determine the nature of potential icing and ignition problems. If 3500°R gases are desired, the cooling and life problem may become of sufficient magnitude to warrant fundamental research in this area.

4.5 THRUSTERS

Current NASA contractor approaches appear to be satisfactory to provide concepts which will give adequate performance and cooling. The long-term

life capabilities of the available designs require continued investigation. Off-design mixture ratio variability effects must also be evaluated to determine their effects upon life.

In another area, the limit cycle performance is important as to its effect upon overall APS mixture ratio availability. The effect shows up as a shift in mixture ratio from that of the nominal design.

Reentry heating has currently received no attention. Before the current thruster designs are developed much further, this must be investigated for early definition of problems and assessment of possible solutions.

4.6 TURBOPUMPS

The turbopumps are the heart of the APS design. The preliminary design efforts of this study show that both the oxygen and hydrogen pumps are within current state-of-the-art materials and geometries. It is of interest that these pumps are highly transient in this operation. Up to 50 percent of their operating time is spent in transient run up or run down. Further, they are seldom in thermal equilibrium. As a result, it is anticipated that this transient nature may have a major effect upon bearings and seals. An early program to determine the mechanical design factors necessary to control this transient behavior can prevent later problems.

There is also a premium on rapid start-up capability. Unloaded starts and partial head starts as well as full head starts should be evaluated. On the oxygen pump side minimum inlet head requirements should be evaluated, since they affect the tankage design.

4.7 HEAT EXCHANGERS

The preliminary analyses show that a parallel flow tubular configuration will meet the basic thermal problems. Primary problems may occur in the hot/cold thermal shock area with many cycles on the heat exchangers. This will be particularly true if the 3500°R gas generator, gas heat exchanger is deemed necessary for the cycle. Also, such a heat exchanger may encounter long term durability problems in the oxygen heat exchanger.

The start-up and shutdown response time of the heat exchangers must be determined early, since these response times drive the APS control loop.

Initial programs in this area should provide for fundamental assessment of mechanical integrity in terms of temperature and gas generator mixture ratio variability.

4.8 REGULATORS AND THROTTLE VALVES

The dynamic studies show a need for proportional regulators in the main distribution network, as well as in the gas generator flow loops. Preliminary analysis shows that mass control regulation can eliminate some control requirements.

The gas generators also require throttle trim valves on the oxygen propellant feed side. Shaped pintles in these valves will smooth out the loop control perturbations.

4.9 INSTRUMENTATION

The basic pressure sensors necessary to the APS are currently available. Thermal sensors on the whole are probably adequate for tankage requirements. The active thermal controls in the gas generator and hot component areas require some additional effort.

Propellant quantity gauging in the tankage areas is probably required, perhaps not for PU but for overall mission safety planning.

Complete fault isolation instrumentation techniques are necessary. The areas of interest are:

1) Line components--turbopumps, valves, gas generators, thrusters, regulators, igniters

2) Passive components--tanks, accumulators, lines

3) Detection instrumentation self-fault detection.

(Item number 3 is equally as important as the other two.)

It is recommended that all early development efforts include a task for evaluation and recommendation of fault isolation detection for the particular equipment. All developments should be carried forward with the fault detection techniques being integral with the design.

4.10 DYNAMICS/CONTROL

Because the H_2/O_2 gaseous feed system and the conditioner liquid-gas conversion networks are extremely lively, it is expected that early breadboarding of the fundamental system will serve to isolate potential problems early and afford an evaluation tool for solution. Such a breadboard should emphasize:

1) Pump start-up and shutdown loop
2) Heat exchanger start-up and shutdown loop
3) Pressure switching networks
4) Rapid drawoff
5) Limit cycle drawoff
6. Direct line length and Mach number simulation.