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Final Report

SPACE SHUTTLE AUXILIARY PROPULSION SYSTEM DESIGN STUDY

PHASE C REPORT
OXYGEN - HYDROGEN
RCS/OMS INTEGRATION STUDY

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15 JUNE 1972 REPORT MDC E0523

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OXYGEN - HYDROGEN
RCS/OMS INTEGRATION STUDY

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CONTRACT NO. NAS 9-12013

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ABSTRACT

This report describes one phase of the "Space Shuttle Auxiliary Propulsion System Design Study," Contract NAS 9-12013. The objective of this study was to fully define competing auxiliary propulsion concepts and to compare them on the basis of such selection criteria as weight, reliability, and technology requirements. Propulsion systems using both cryogenic oxygen/hydrogen, and earth storable propellants were considered. The main thrust of the cryogenic effort (Phase B) was focused on detailed design and operating analyses for gaseous, oxygen/hydrogen, Reaction Control Systems (RCS). Phase C complemented this effort by evaluating the potential of integration between the RCS and the Orbit Maneuvering System (OMS). Integration options ranged from a fully integrated system to a separate system in which only propellant storage is common.

In Phase C,numerous methods of implementing the various levels of integration were evaluated. Preferred methods were selected and design points were developed for two fully integrated systems, one partially integration system, and one separate system. In the fully integrated systems, the RCS and OMS share common turbomachinery. Mixture ratio differences between the RCS and OMS are resolved in one of the integrated systems by using two oxygen and one hydrogen pump for the OMS, and in the other integrated system by utilizing bilevel operating pumps. The partially integrated case also uses bilevel pumps, but individual units are provided for the RCS and OMS. OMS single burn impulse requirements are achieved in the integrated systems by the addition of a small, separate conditioning assembly designed to condition only the RCS accumulator makeup gas. In the separate RCS/OMS, with only common propellant storage, a new staged combustion cycle OMS engine was selected.

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1. INTRODUCTION

To provide the technology base necessary for design of the Space Shuttle, NASA has sponsored a number of technology programs related to Auxiliary Propulsion Systems (APS). Among such programs has been a series of design studies intended to provide the system design data necessary for selection of preferred system concepts, and to delineate requirements for complementing component design and test programs. The first of these system study programs considered a broad spectrum of system concepts, but because of high vehicle impulse requirements coupled with safety, reuse, and logistics considerations, only cryogenic oxygen and hydrogen were considered as a propellant combination. Additionally, unknowns in thruster pulse mode ignition and concern over the distribution of cryogenic liquids served to eliminate liquid - liquid feed systems from the list of candidate concepts. Therefore, only systems which delivered propellants to the thrusters in a gaseous state were considered for the Reaction Control System (RCS). The results of these initial studies, reported in References A through D, indicated that among the many options for design of a gaseous oxygen/hydrogen system, an approach using heat exchangers to thermally condition the propellants and turbopumps to provide system operating pressure would best satisfy requirements for a fully reusable Space Shuttle. These studies focused attention on this general system type, but did not examine in depth several viable approaches for turbopump system design and control. To fill this need,NASA contracted with McDonnell Douglas Astronautics Company-East (MDAC-E) in July 1971 for additional study of Space Shuttle Auxiliary Propulsion Systems. This contract (NAS 9-12013) titled "Space Shuttle Auxiliary Propulsion System Design Study" was under the technical direction of Mr. Darrell Kendrick, Propulsion and Power Division, Manned Spacecraft Center, Houston, Texas.

As originally defined, this design study was a five phase program considering only oxygen and hydrogen propellants. Reference E provides an executive summary of program results, and Reference F describes in detail the program plan for each of the five program phases listed below:

1. Phase A-Requirements Definition
2. Phase B-Candidate RCS Concept Comparisons
3. Phase C-RCS/OMS Integration
4. Phase D-Special RCS Studies
5. Phase E-System Dynamic Performance Analysis

Phase A defined all design and operating requirements for the APS. The results of this phase (which are documented in Reference G) showed that requirements for the booster and orbiter stages were sufficiently similar to allow concentration of all design effort on the orbiter stage as the results obtained would be applicable to fly-back-type booster stages. In Phase B, detailed design and control analyses for the three most attractive gaseous oxygen/hydrogen RCS concepts were conducted. Reference H documents Phase B results. Phase C, the subject of this report, was aimed at defining the potential for integration of the RCS with the Orbit Maneuvering System (OMS). As defined by the original contract, only oxygen and hydrogen were considered in this phase. However, vehicle studies which were concurrent with this design effort showed that smaller Shuttle orbiters with external, expendable main engine tankage would provide a more cost effective vehicle approach. This change in vehicle design resulted in a significant reduction in APS requirements. This, coupled with a companion Shuttle program decision to allow scheduled system refurbishment, allowed consideration of systems using earth storable propellants for auxiliary propulsion. Thus, in November 1971, NASA issued a contract change order that extended the scope of Phase C to include earth storable monopropellant and bipropellant systems and redirected Phase E to provide final performance analyses on storable propellant systems. This report documents Phase C effort on oxygen/hydrogen systems while Reference I reports the results of both Phase C and E effort on earth storable propellant systems. In addition to the principal contract effort in Phases B and C, the study included an exploratory effort (Phase D) to evaluate two alternatives to gaseous oxygen/hydrogen RCS using turbopumps. Reference J documents the results of the Phase D studies.

In Phase C, RCS/OMS integration options, ranging from a fully integrated system to a separate system in which only the propellant storage is integrated, were evaluated to determine the proper compromise between performance and complexity. Various system implementation options were evaluated to resolve RCS/OMS mixture ratio differences and RCS constraints on OMS burn time. Four RCS/OMS candidate configurations were selected from the integration options for evaluation of system sensitivity to design requirements and for comparison of controls. These selected configurations were two fully integrated systems, one partially integrated system, and a separate system utilizing staged combustion engines.

The report documents the work performed in Phase C and serves as a final definition and summary of the Phase C oxygen/hydrogen effort. Included in the report are:

(1) Study approach

(2) System requirements and constraints for both the RCS and OMS

(3) Integration options and selection criteria

(4) System definition and comparison, including component performance for the OMS engines, feed system, turbopump and RCS; RCS/OMS system schematics; preliminary system comparison; and candidate system selection and evaluation.

2. STUDY APPROACH

The APS design study was divided into five phases. In the first, Phase A, orbiter RCS/OMS and booster RCS vehicle/mission requirements were defined, including number, location, and thrust level of the RCS thrusters and OMS engines; total impulse requirements; thrust vector control requirements; and component environments. Based on these results, Phases B, C, and D were then conducted concurrently. In Phase B, three candidate RCS concepts (series flow-turbine upstream, series flow-heat exchanger upstream, and parallel flow-separate gas generators) were defined and compared in relation to performance and operational factors. System optimizations were conducted to establish preliminary RCS operating points, sensitivity to design requirements, and component performance. The many possible RCS control concepts were then compared and reduced to a few high-value approaches for which system design, transient, and operating analyses were conducted. In Phase D, two special RCS approaches were evaluated, while Phase E provided a final system performance analysis.

Phase C of the APS study involved design and analysis necessary to establish an optimum integrated liquid OMS and gaseous RCS. RCS/OMS integration options were evaluated to determine the proper compromise between performance and operating requirements. Control and design options for the RCS/OMS were evaluated at different levels of integration and the most promising concepts were selected for more detailed analysis. Also considered were alternate approaches which reduced the degree of RCS/OMS integration ranging from fully integrated to a separate system with integrated propellant tankage only. Component design, operational analysis, complexity evaluation, and component interaction were studied to determine the proper compromise between major performance and operating requirements. The results and information generated concurrently in Phase B were utilized to the maximum extent possible in this phase. Factors considered in determining an optimum system included a minimum need for new technology, simplicity, reliability, flexibility to changes in mission requirements, maintainability, weight, volume, and performance. While all aspects of the system were considered, major emphasis was placed on design and performance limits of the propellant distribution components (feedlines, pumps, and turbines) and on the engines.

3. VEHICLE AND SYSTEM REQUIREMENTS AND CONSTRAINTS

Space Shuttle vehicle configurations and vehicle/mission requirements are defined in the "Space Shuttle Vehicle Description and Requirements Document (SSVDRD)" dated 1 July 1971. Attitude control and maneuvering capability requirements for both booster and orbiter elements of the Phase B Space Shuttle vehicle are included in the SSVDRD. Three baseline missions are defined for this study program: (1) an easterly launch mission, intended primarily for delivering and retrieving payloads in a 100 nautical mile circular orbit, (2) a south polar mission in which the orbiter is launched into an injection orbit of 50 by 100 nautical miles (nmi) and circularized at apogee using the orbital maneuvering propulsion system, and (3) a resupply mission to provide logistic support for a space station/space base in a 270-nmi orbit. The easterly launch mission is designated the design mission, while the south polar and resupply missions are designated reference missions. General vehicle dimensions, RCS thruster locations, and equipment locations are shown in Reference (G).

General requirements of the SSVDRD applied to RCS/OMS design include minimal maintenance with ease of removal and replacement, a minimum service life of 100 mission cycles over a 10-year period with cost effective refurbishment, and 7 days of self-sustaining lifetime for each mission duration. SSVDRD failure criteria required that fail-safe conditions be achieved after the failure of any two critical components except for OMS operation in an abort mode. In this case, the OMS shall be designed for fail-safe operation after a single failure since the main engine failure constitutes the first system failure.

For the RCS, the requirements of principal interest were thrust, number of thrusters, total system thrust, total impulse, total impulse expenditure histories, and RCS hardware commonality for both the booster and orbiter. Of primary interest to the OMS design was definition of the optimum RCS/OMS velocity allocation. The SSVDRD specified that the OMS perform all -X translational maneuvers equal to, or greater than, 20 feet per second (fps) of vehicle velocity increment. Translational maneuvers less than 20 fps in the -X axis and in all other axes will be performed by the RCS. Other requirements of importance to OMS design were engine thrust and number of engines.

3.1 <u>RCS Requirements Definition</u> - Reference (K) specified that the RCS configuration used for integration with the OMS be of the parallel flow type with separate gas generators for both the turbopump and the heat exchanger on both the hydrogen and oxygen sides of the system. Phase A studies defined the RCS requirements and assessed the impact of using common hardware for the two stages of the baseline vehicle, while Phase B studies determined the optimum parallel flow RCS as required for the integration phase of the study to proceed. The number of RCS thrusters and thrust level were varied to satisfy the vehicle control and maneuvering acceleration requirements. Total impulse expenditures were determined for the three missions using typical minimum impulse bit data as a function of thrust level. RCS weights were then determined as a function of thrust level for both stages, and the penalties incurred by using common thrusters for the two stages evaluated. From this effort, a common booster and orbiter RCS thrust level of 1150 lbf was selected as the design point for the system study. A slightly lower thrust level would provide a small increase in payload capability but would require several additional thrusters on the booster. At a thrust level of 1150 lbf, 33 RCS thrusters are required on the orbiter and 24 on the booster.

The other major RCS requirement affecting system integration is the maximum system thrust demanded from the RCS. Maximum RCS thrust requirements were found to occur during reentry because of the requirement for a 1.5 deg/sec^2 continuous yaw-roll coordinated maneuver capability. This requirement dictated a system thrust equivalent to the operation of five thrusters on the orbiter, while for the booster, eight thrusters were required. For design purposes, a common conditioner with a flow rate or system thrust capability of 5750 lb was selected for both the orbiter and booster. An extra conditioner would be provided on the booster to satisfy its increased system thrust requirements. This avoided the large orbiter weight penalties that would be associated with using a conditioner sized for the booster and/or the increased development cost for two differently sized conditioners.

3.2 OMS Requirements Definition - Reference (K) defined 20 fps to be the crossover point at which the OMS, rather than RCS, should be used for -X translational maneuvers. Utilizing this value, the OMS mission requirements, number of burns, and velocity increments were defined for each of the three mission timelines. Then the incremental RCS/OMS weight savings, associated with using the OMS for maneuvers was determined. A liquid propellant orbital maneuvering engine operating at 8000 lbf thrust, a chamber pressure - 800 lbf/in.^{2} and mixture ratio of 6 was assumed in this analysis. OMS system specific impulse was 449 sec compared with 387 sec for the RCS system. OMS weight penalties included three engines, feedlines, and start losses. Engine start losses were parametrically varied from 50 to 150 lbm of propellant per start. Results are presented in Figures 3-1, 3-2 and 3-3 for the easterly, south polar, and resupply missions, respectively. Incremental weight savings are shown as a function of velocity allocated to the OMS. Initially the system weight decreases sharply due to higher OMS performance. This decrease in weight occurs for large mission maneuvers such as ascent, circularization, phasing, and deorbit burns. After these major maneuvers, the OMS burns provide a lower ΔV, resulting in small system weight savings because of increased OMS start losses in relation to the propellant expended during the small maneuver burns. The figures indicate that dependent on the start losses, the OMS should be used for essentially all -X ΔV changes.

An alternate analysis approach which eliminates mission considerations was also used to better quantify the optimal OMS velocity increment. With this approach the crossover point between RCS and OMS usage is determined to be that point at which the effective specific impulse of the OMS equals that of the RCS. This is illustrated in Figure 3-4, which shows system specific impulse as a function of OMS curves cross at approximately 15 to 20 fps (depending on OMS propellant start loss). This result confirms the Reference (K) velocity allocation as being valid for study purposes and is independent of mission timelines.

The orbital maneuvering system mission requirements, based on the optimum velocity split of 20 fps, are shown in Figure 3-5. Shown are on-orbit and once-around abort requirements for the three missions. The south polar reference mission requires an on-orbit ΔV of 1420 fps, of which 900 fps is for boost augmentation, while the resupply reference mission requires an on-orbit ΔV of 1126 fps. The south polar mission presents the most severe requirement in both on-orbit and abort impulse requirements. The easterly and resupply missions present considerably reduced demands. These requirements represent only the three reference missions and more severe requirements can be anticipated for the Shuttle. In anticipation of these needs 2000 fps has been established as the OMS design requirement and this dictates OMS tank capacity.

To provide abort assistance in the event of a main engine failure during ascent it is desirable that the OMS design thrust satisfy the once-around abort requirements. Figure 3-6 shows the associated OMS thrust and velocity requirements. The south polar mission imposes the most severe requirement on OMS thrust level; i.e., a thrust level of 24,000 lb is required at the OMS design tank capability of 2000 fps. This represents the highest thrust level requirement anticipated for the OMS.

WEIGHT SENSITIVITY TO RCS/OMS VELOCITY ALLOCATION

o EASTERLY LAUNCH
o DELIVERY/RETRIEVAL OF OOS

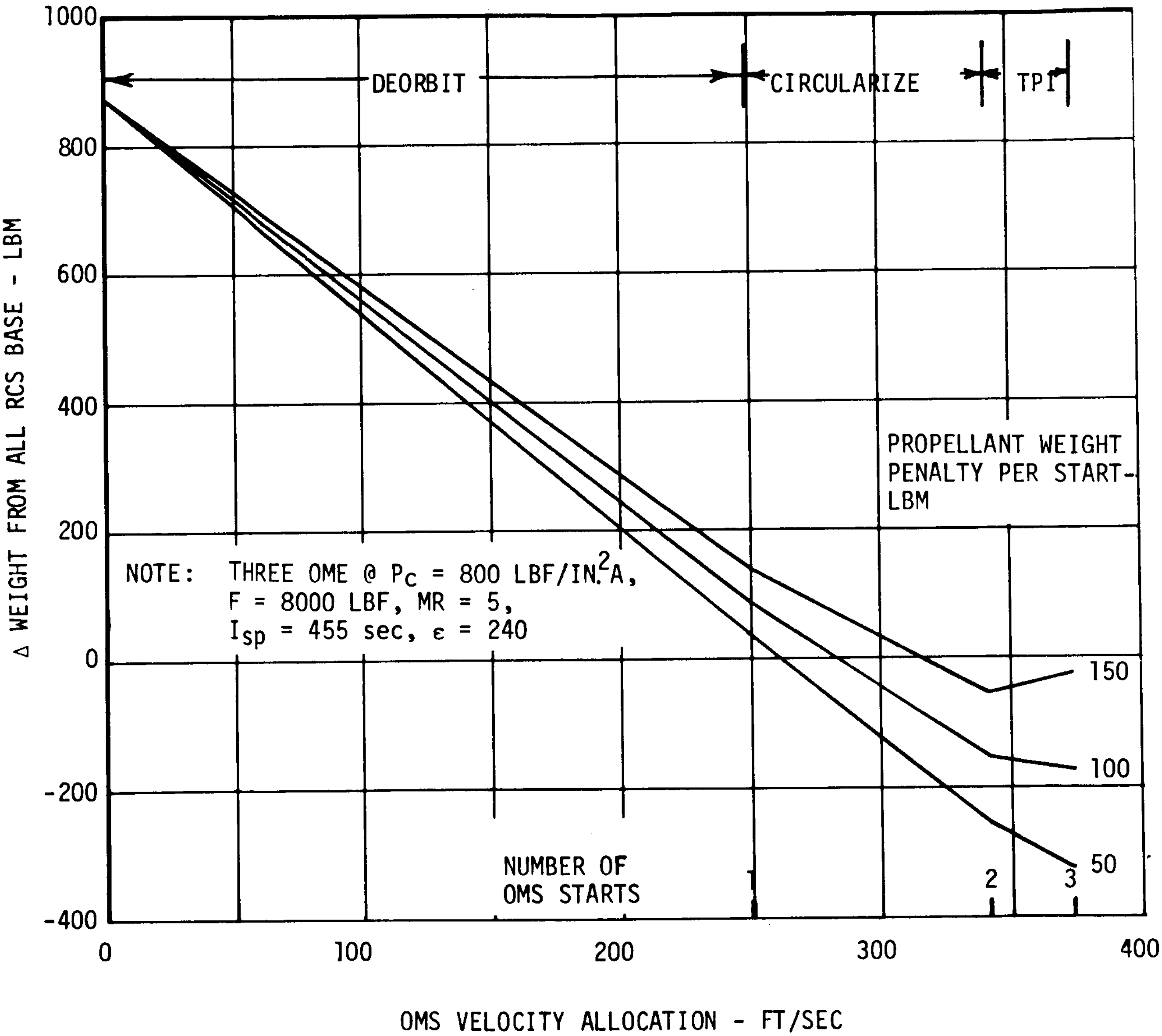


FIGURE 3-1

WEIGHT SENSITIVITY TO RCS/OMS VELOCITY ALLOCATION

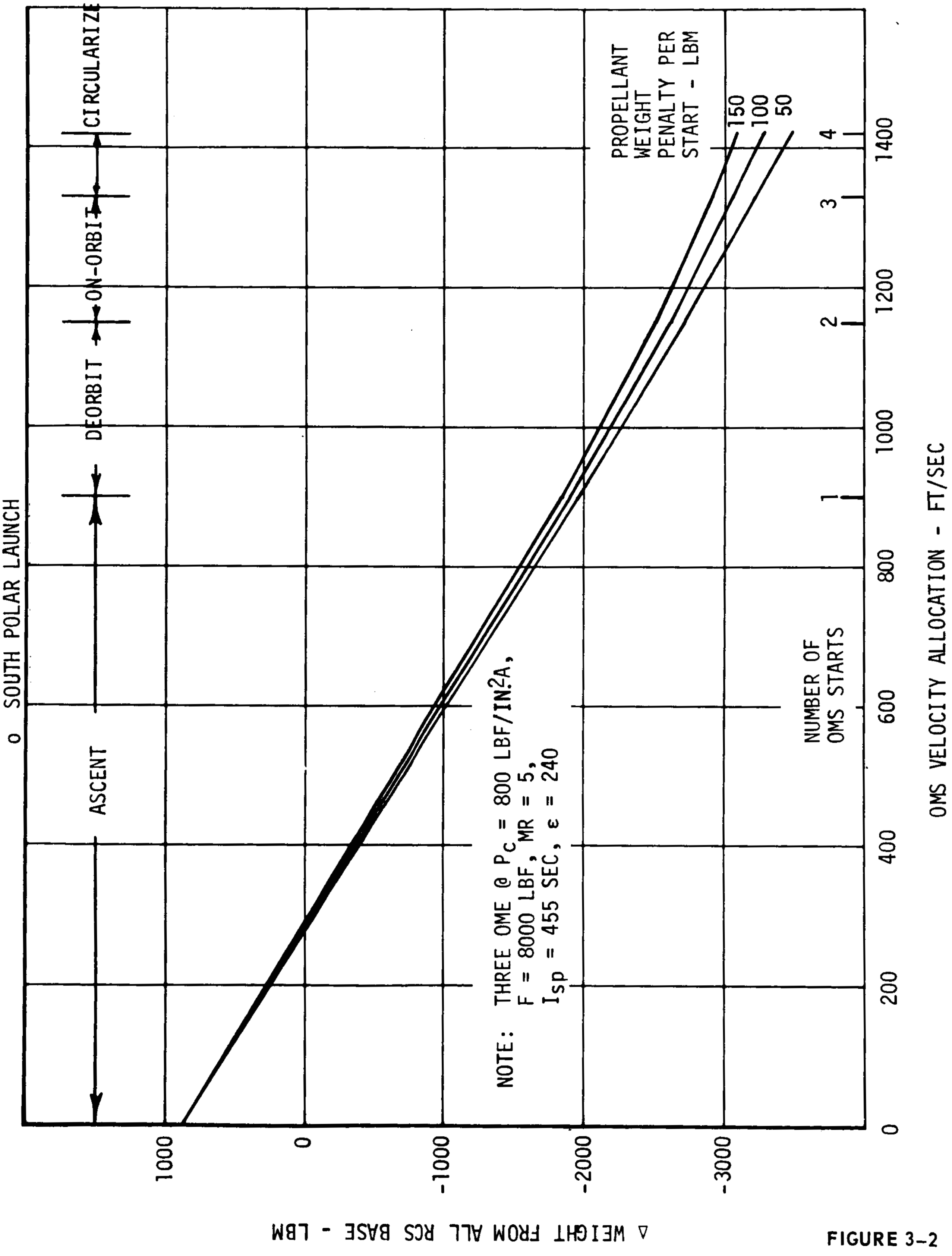


FIGURE 3-2

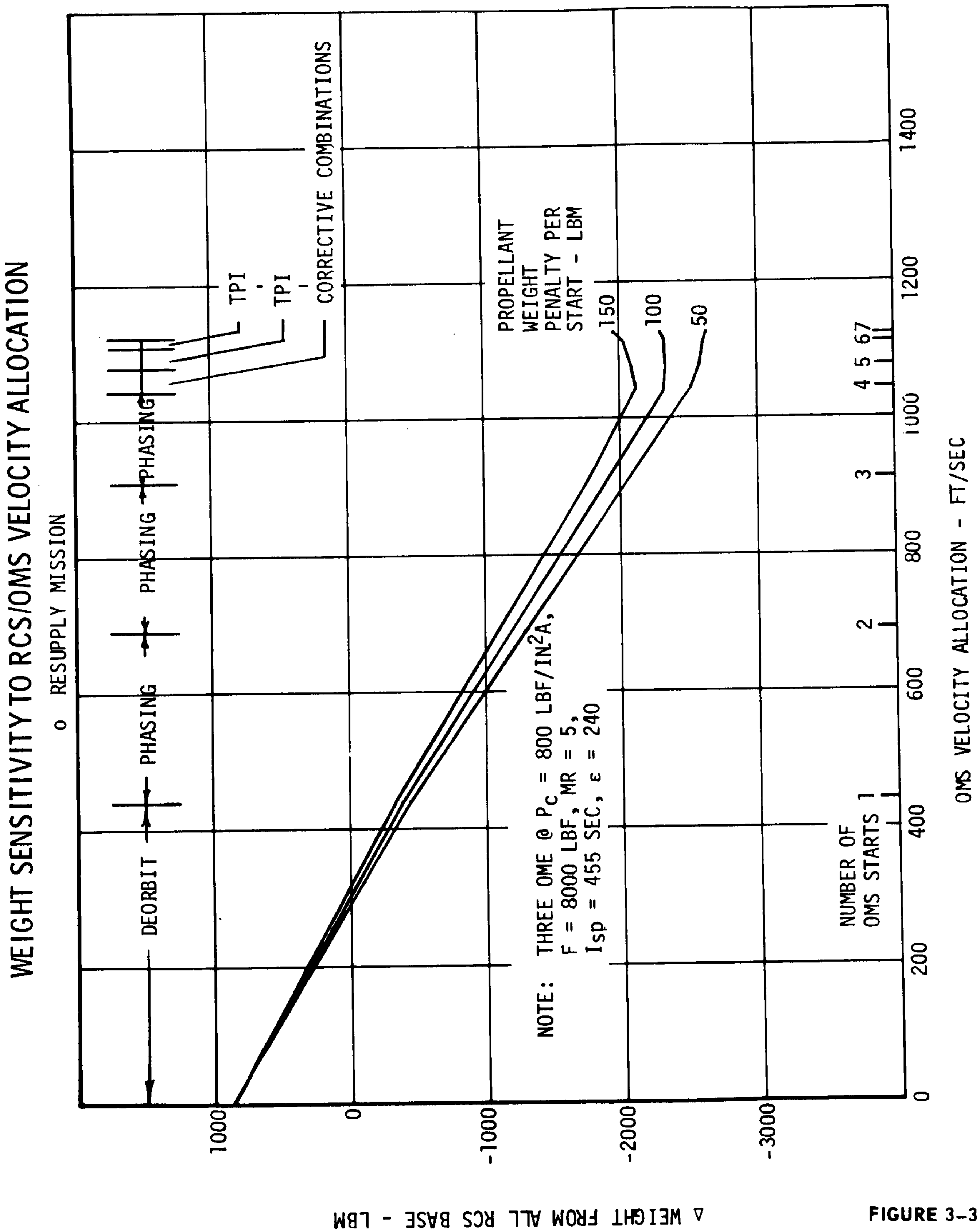

WEIGHT SENSITIVITY TO RCS/OMS VELOCITY ALLOCATION
o RESUPPLY MISSION
DEORBIT
PHASING
PHASING
PHASING
PHASING
TPI
TPI
CORRECTIVE COMBINATIONS
PROPELLANT WEIGHT PENALTY PER START - LBM
150
100
50
NOTE: THREE OME @ P_C = 800 LBF/IN^{2}A,
F = 8000 LBF, MR = 5,
I_{sp} = 455 SEC, ε = 240
NUMBER OF OMS STARTS
1
2
3
4 5 6 7
0
200
400
600
800
1000
1200
1400
OMS VELOCITY ALLOCATION - FT/SEC
1000
0
-1000
-2000
-3000
Δ WEIGHT FROM ALL RCS BASE - LBM

FIGURE 3-3

BREAK POINT - RCS VS OMS

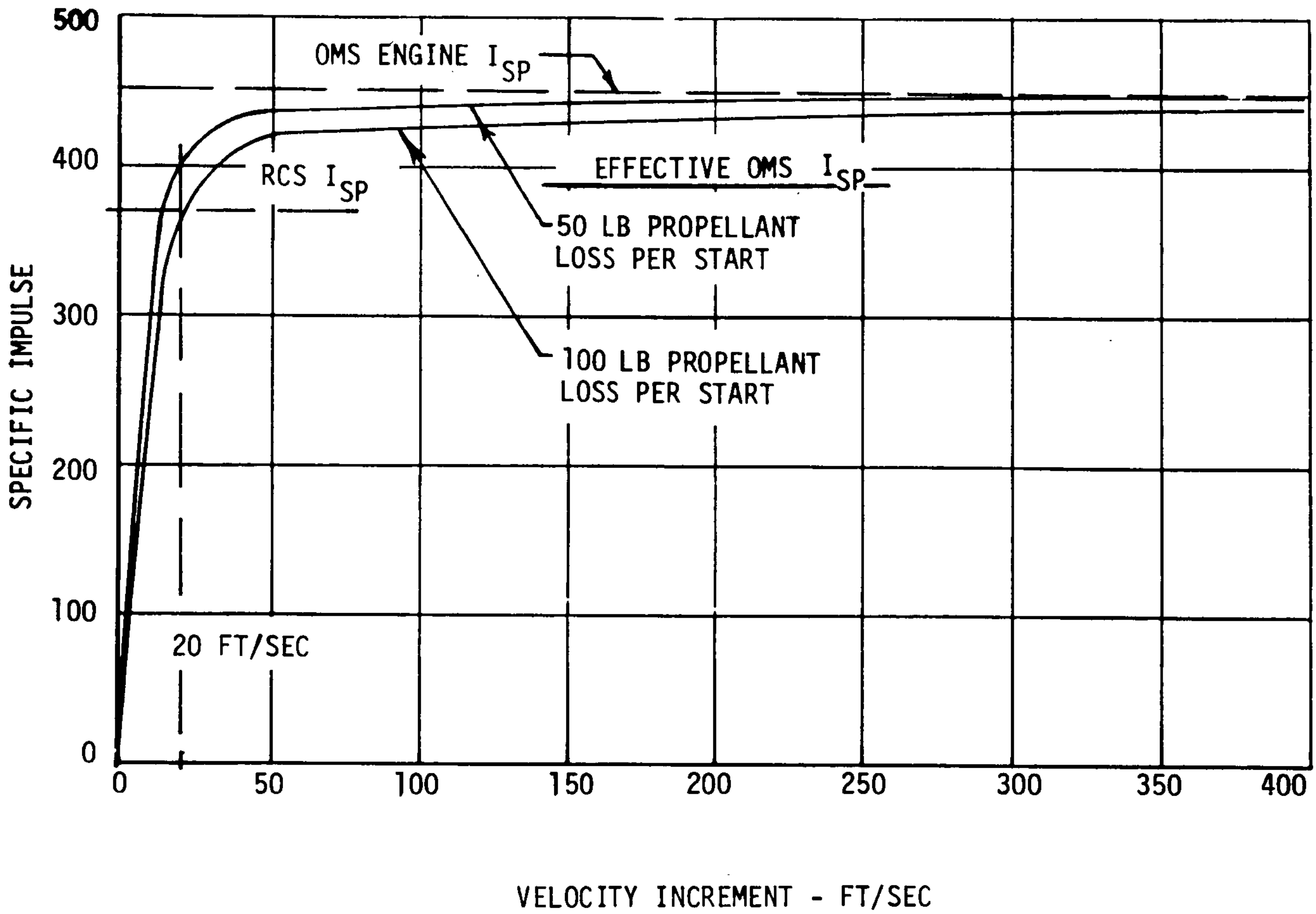


FIGURE 3-4

OMS MISSION REQUIREMENTS

DESIGN-EASTERLY LAUNCH 65,000 LB PAYLOAD (REQ'D) 100 N MI 7 DAYS		REFERENCE - SOUTH POLAR 40,000 LB PAYLOAD (MIN.) 100 N MI 7 DAYS		REFERENCE - RESUPPLY 25,000 LB PAYLOAD (MIN.) 270 N MI 7 DAYS	
FUNCTION	ΔV FT/SEC	FUNCTION	ΔV FT/SEC	FUNCTION	ΔV FT/SEC
CIRCULARIZATION	91	OMS BOOST AUGMENTATION	900	PHASING BURN	133
TERMINAL PHASE INITIATION	32	CIRCULARIZATION	90	PHASING BURN	248
DEORBIT BURN	250	ON ORBIT	180	PHASING BURN	224
		DEORBIT BURN	250	POSIGRADE MANEUVER	33
				TERMINAL PHASE	22
				TERMINAL PHASE	26
				DEORBIT BURN	440
TOTAL	373	TOTAL	1420	TOTAL	1126
ONCE-AROUND ABORT REQUIREMENT	800[1]	ONCE-AROUND ABORT REQUIREMENT	2000[1,2]	ONCE-AROUND ABORT REQUIREMENT	800[1]

1. ABORT REQUIREMENTS FOR OMS THRUST = 24,000 LBF
2. INCLUDES 900 FPS OMS BOOST AUGMENTATION

FIGURE 3–5

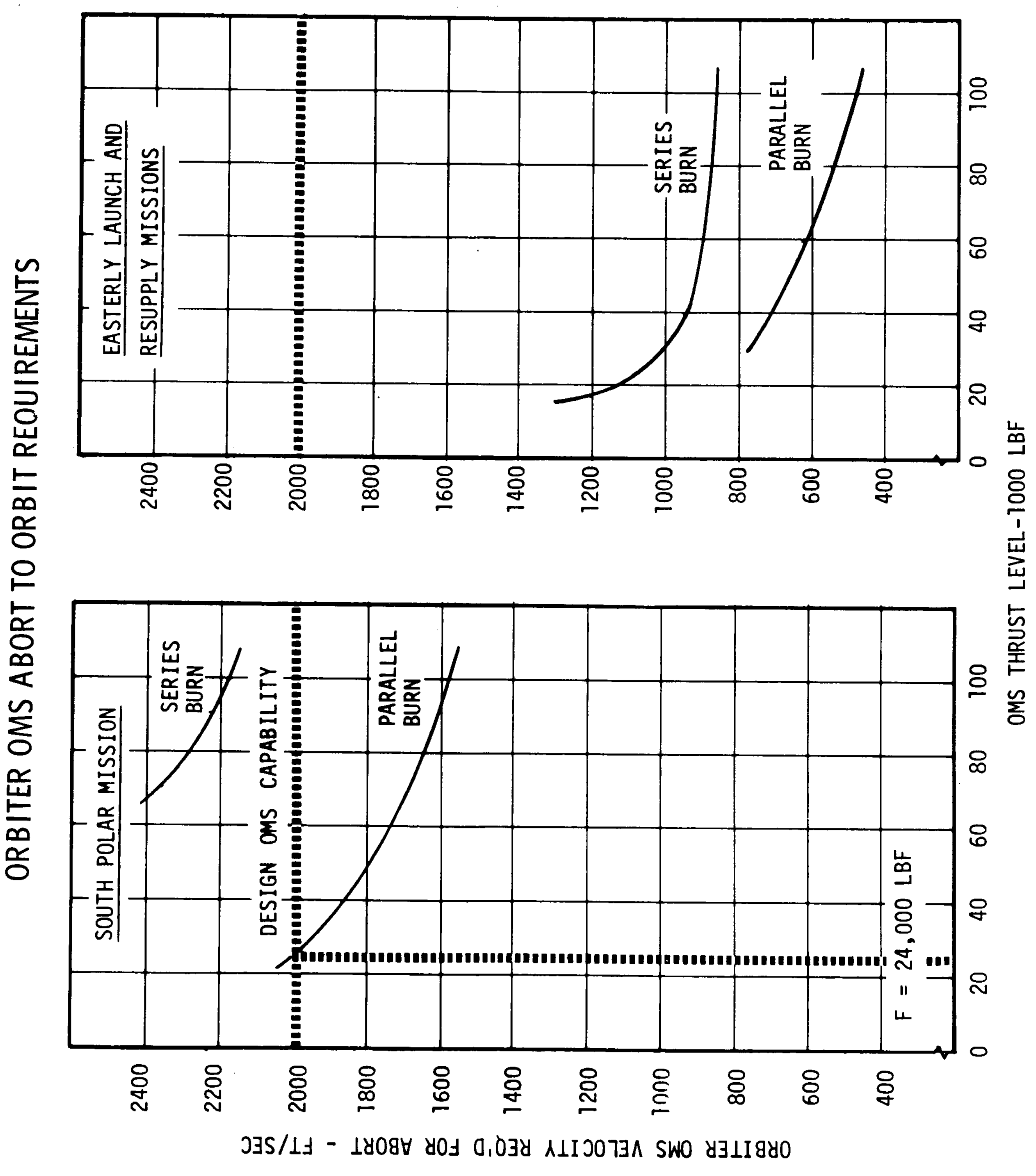

ORBITER OMS ABORT TO ORBIT REQUIREMENTS
EASTERLY LAUNCH AND
RESUPPLY MISSIONS
SERIES
BURN
PARALLEL
BURN
SOUTH POLAR MISSION
SERIES
BURN
DESIGN OMS CAPABILITY
PARALLEL
BURN
F = 24,000 LBF
0
20
40
60
80
100
OMS THRUST LEVEL-1000 LBF
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
ORBITER OMS VELOCITY REQ'D FOR ABORT - FT/SEC

FIGURE 3-6

However, rather than design the OMS for the abort capability, in which case 24,000 lbf system thrust would be a firm study requirement, the OMS thrust was allowed to vary in order to determine the thrust level which provided the most desirable integration between the OMS and RCS. The rationale for this approach was that, if lower thrust offered definite advantages, other ways of providing abort assistance were possible, e.g., higher thrust main engines, or vehicle configurations using three main engines. A thrust level of 6000 lbf (one engine firing) was selected as the lowest value to be investigated, as above this value velocity losses associated with low thrust to weight ratio maneuvers can be neglected.

Three OMS engines are required to meet the Shuttle fail-safe/fail-safe operating requirement but the number can be reduced to two by utilizing the -X RCS thrusters as OMS backup. Both methods were evaluated to determine the effect on system design and weight.

A summary of both RCS and OMS design requirements is provided in Figure 3-7.

RCS/OMS DESIGN REQUIREMENTS

		ORBITER	BOOSTER
RCS	NUMBER OF THRUSTERS	33	24
	THRUSTER THURST (LB)	1,150	1,150
	NUMBER OF CONDITIONERS	3	4
	SYSTEM THRUST (LB)	5,750	9,200
	TOTAL IMPULSE (LB-SEC)		500,000
	RESUPPLY	2.23×10^6	---
	EASTERLY LAUNCH	2.23×10^6	---
	SOUTH POLAR	2.15×10^6	---
		DESIGNED FOR ON ORBIT	DESIGNED FOR ABORT
OMS	NUMBER OF ENGINES	3	3
	ENGINE THRUST (LB)	TBD*	12,000
	SYSTEM THRUST (LB)	TBD*	24,000
	TOTAL IMPULSE (LB-SEC)		
	RESUPPLY	10.34×10^6	---
	EASTERLY LAUNCH	3.72×10^6	---
	SOUTH POLAR	12.87×10^6	---

* TO BE DETERMINED DURING STUDY FROM RCS/OMS OPTIMIZATION.

FIGURE 3-7

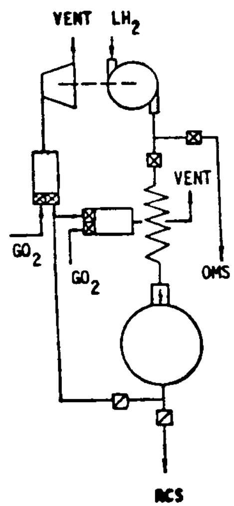
4. INTEGRATION OPTIONS/SELECTION CRITERIA

During the Phase C oxygen/hydrogen portion of the APS study, various degrees of RCS/OMS integration were considered to evaluate relative system complexity, development and operational risks, and other penalties. The concepts evaluated included: (1) a fully integrated system with the RCS and OMS using common turbomachinery, gas generators and heat exchangers; (2) a partially integrated system in which the RCS and OMS had similar but separate turbomachinery; and (3) a separate system in which the OMS engine is separate and independent from the RCS except that both use a common liquid propellant tankage. The fully integrated system is simple schematically because the RCS and OMS use a common propellant feed system. However, operational problems are most pronounced and include mixture ratio differences between the RCS and OMS, RCS accumulator resupply during OMS operation, and controls for proper sequencing of propellants to the OMS. These problem areas are, in general, alleviated or resolved by reducing the degree of integration.

4.1 Fully Integrated System - A general schematic for the fully integrated system concept is presented in Figure 4-1 showing the common hardware usage between the RCS and OMS. Figure 4-1 also lists the design problems associated with integration and the design options investigated as possible solutions.

A primary influence on integration is the different operating mixture ratios required by the RCS and OMS in order to achieve a design goal of minimum weight. The RCS requires a low mixture ratio based on weight optimization and thruster operating temperature considerations. For the OMS, a high mixture ratio provides improved specific impulse and reduces hydrogen tank volume. To adjust for these differences, the design options listed in Figure 4-1 were investigated. The candidate design options are shown schematically in Figure 4-2. In the first option, the system was designed for OMS requirements and the RCS operated at the higher OMS mixture ratio. This results in increased RCS thruster development risk as the RCS thrusters must now operate at higher temperature and cooling becomes more difficult. Designing for RCS requirements and operating at this mixture ratio for the OMS, option 2, degrades OMS performance and increases liquid hydrogen tank weight and volume. The OMS mixture ratio can be increased by operating two oxygen pumps during an OMS burn (option 3) but an additional RCS oxygen pump is required. A similar approach is taken in option 4 except that an additional RCS hydrogen pump is used. In this option, two hydrogen pumps are operated during the RCS functions to reduce the mixture ratio and provide more optimum RCS thruster conditions. The

FULLY INTEGRATED SYSTEM MATRIX



DESIGN QUESTIONS

MIXTURE RATIO

ACCUMULATOR RESUPPLY

OPTIONS INVESTIGATED

MIXTURE RATIO

- OPERATE RCS AT OMS MR
- OPERATE OMS AT RCS MR
- USE 2 RCS O_2 PUMPS FOR OMS
- USE 2 H_2 PUMPS FOR RCS
- OPERATE PUMPS BILEVEL FOR RCS/OMS

ACCUMULATOR RESUPPLY

- USE RCS CONDITIONERS
- ENLARGE ACCUMULATORS
- BILEVEL CONTROL OF RCS CONDITIONERS
- USE A SEPARATE GG/HX

FIGURE 4-1

CANDIDATE FULLY INTEGRATED RCS/OMS OPTIONS

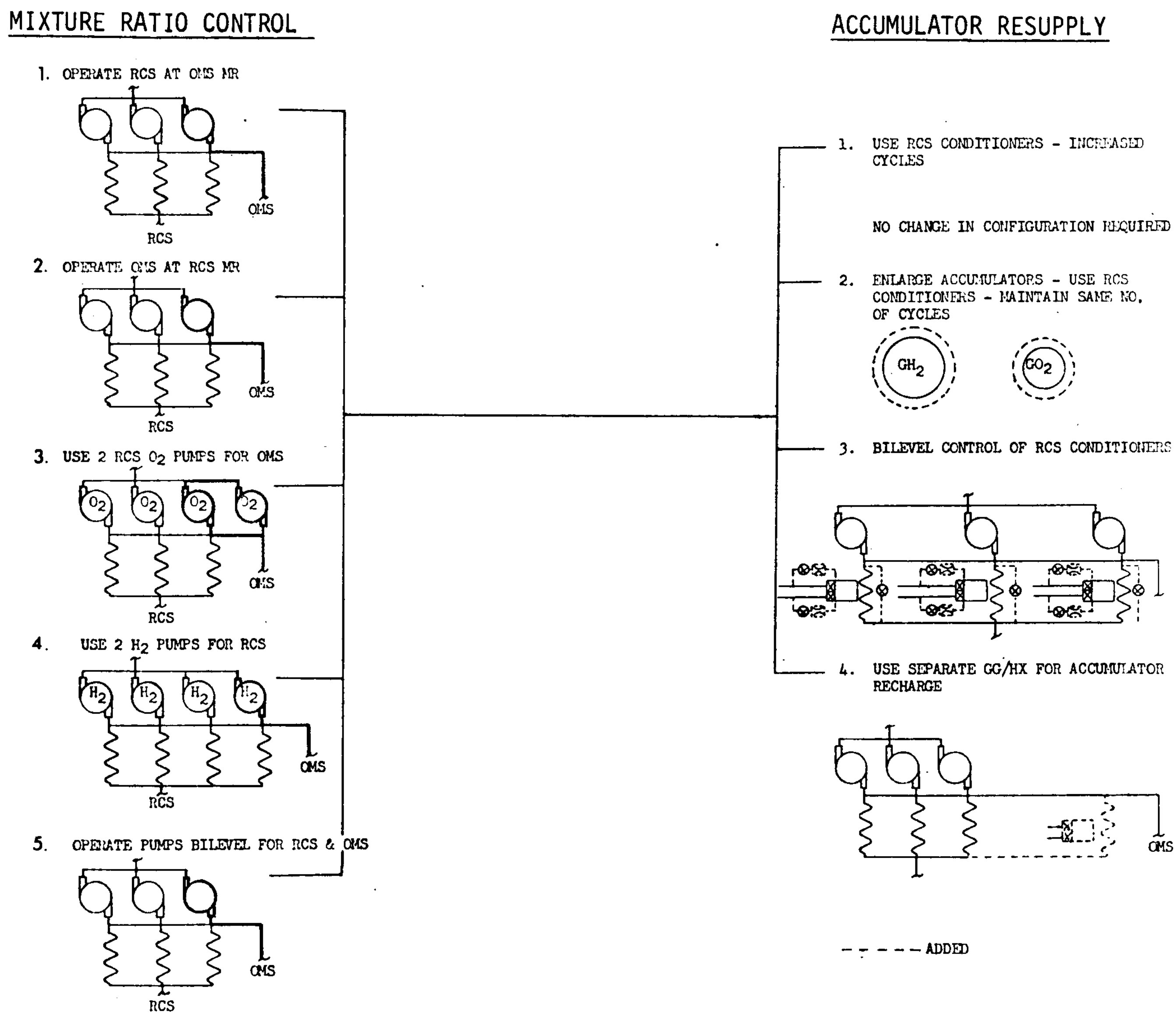


FIGURE 4–2

final option considered bilevel pump operation. This increases turbopump complexity since a broad flow-head range is required but achieves optimum mixture ratio for both the RCS and OMS.

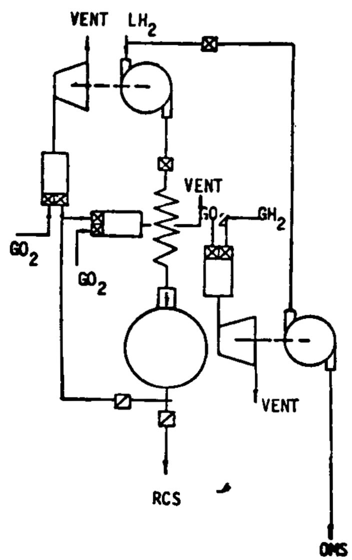
For the integrated RCS/OMS, accumulator makeup propellant is required during OMS operation to maintain RCS accumulator pressure and satisfy the OMS single burn impulse requirements as, without accumulator resupply, the accumulator capacity limits the operating time of the OMS. Accumulator resupply can be accomplished by utilizing the options listed in Figure 4-1 and shown schematically in Figure 4-2. In option 1, periodic accumulator recharge is accomplished by using one of the standby conditioning assemblies operating at full capacity. The disadvantages of this approach include an increased number of accumulator blowdown cycles and the possible need for additional conditioning assemblies to satisfy failure criteria. As an alternate solution, the accumulator could be enlarged to extend burn time, thus maintaining the number of cycles but incurring a weight penalty. Bilevel control of the RCS conditioners to meet both RCS and OMS operation will increase the complexity of heat exchanger controls and affect heat exchanger performance. The last option shown in Figure 4-1 employs a small, separate gas generator/heat exchanger conditioner which requires development of an additional conditioner assembly.

Each of the five options defined for mixture ratio tailoring was investigated in combination with the accumulator resupply options. The resulting system performance is provided in Paragraph 5 where it is compared with results for the partially integrated and separate system concepts described in the following paragraphs.

4.2 Partially Integrated System - The partially integrated system concept schematic is presented in Figure 4-3. Shown also are the associated design problems and possible solutions. Compared with the fully integrated RCS/OMS, the degree of integration has been reduced by the addition of separate OMS turbomachinery.

Use of a separate turbopump to supply the OMS allows both the RCS and OMS to operate at their most desirable mixture ratio. A common turbopump configuration could be utilized for both the RCS and OMS, or the pumps could be different designs. These options are shown schematically in Figure 4-4. For the common pump design case, the turbopumps are designed to provide maximum efficiency during OMS operation and to operate off-design for the RCS. This bilevel operation (i.e., different heads and flows for RCS and OMS) requires gas generator and/or pump output

PARTIALLY INTEGRATED SYSTEM MATRIX



DESIGN QUESTIONS

- o TURBOPUMP CONFIGURATION
- o ACCUMULATOR RESUPPLY

OPTIONS INVESTIGATED

TURBOPUMP CONFIGURATION

- o COMMON TURBOPUMP DESIGN
- o RCS & OMS TURBOPUMP INDEPENDENTLY DESIGNED

ACCUMULATOR RESUPPLY

- o USE RCS CONDITIONERS
- o ENLARGED ACCUMULATORS
- o RECHARGE RCS ACCUMULATORS DURING OMS BURNS BY OMS (SEPARATE GG/HX)

FIGURE 4-3

CANDIDATE PARTIALLY INTEGRATED RCS/OMS CONCEPTS

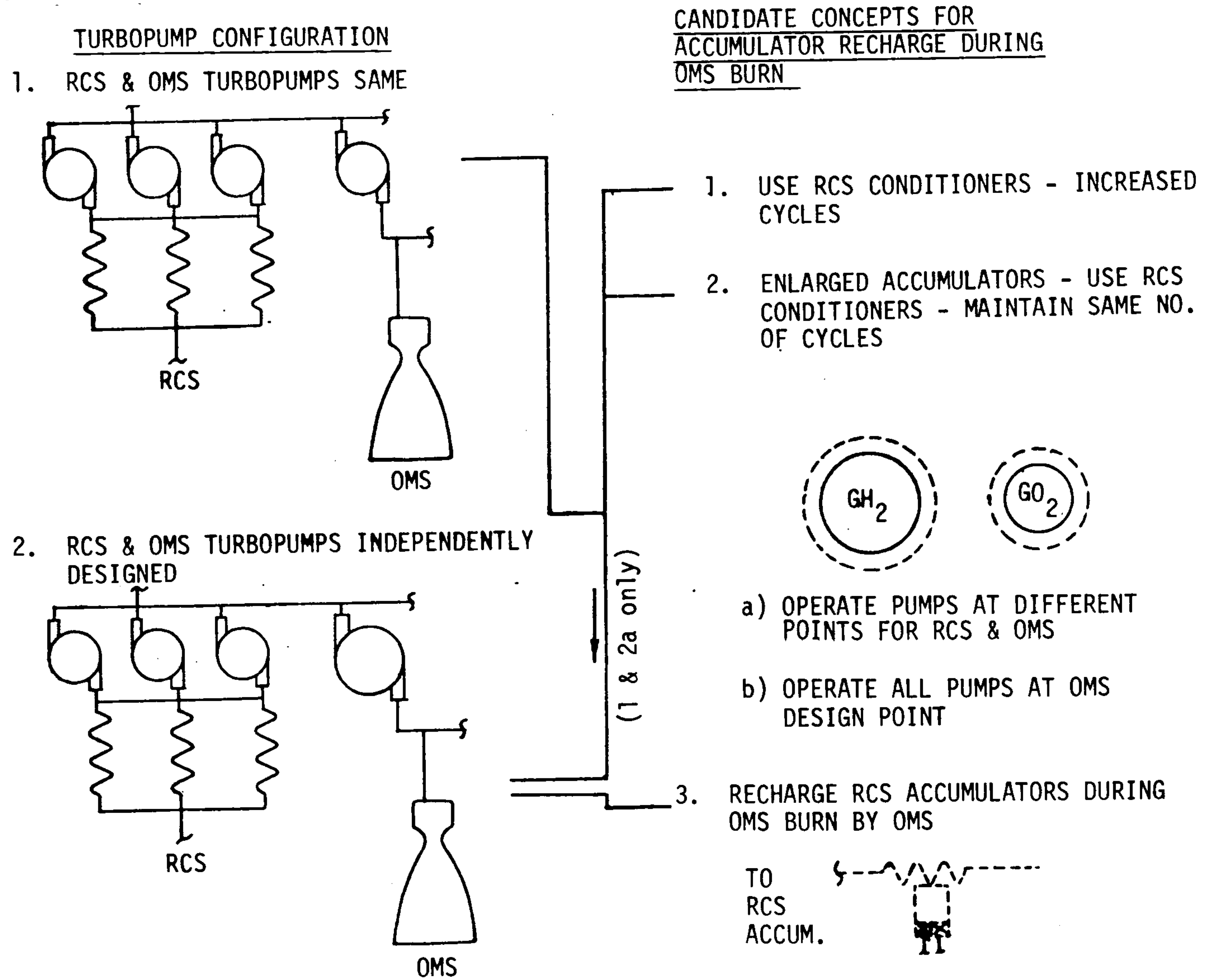


FIGURE 4–4

throttling. Use of independently designed turbopumps will allow operation at maximum efficiency for both RCS and OMS requirements, but will involve greater development costs.

Introduction of separate turbomachinery does not eliminate the limitations on OMS burn time imposed by the RCS accumulator design. Options available to accomplish accumulator resupply during OMS operation are similar to those for the fully integrated case and are shown in Figure 4-4. The bilevel control concept was not included, since it would be identical to the fully integrated system designs discussed previously. As with the fully integrated case, operating the RCS conditioners at full capacity for recharge during OMS burns increases the number of accumulator cycles, increasing accumulator size to maintain the number of cycles results in a weight penalty, and adding a separate conditioning assembly increases development costs.

Each of the turbopump configurations was investigated in combination with the accumulator resupply options and results are presented in paragraph 5.

4.3 Separate Systems - Separating the RCS and OMS completely except for common propellant storage eliminates integration concerns but does require different component designs. The separate RCS/OMS configuration is shown schematically in Figure 4-5 and performance is compared with that of the integrated options in Paragraph 5.

SEPARATE RCS/OMS CONFIGURATION

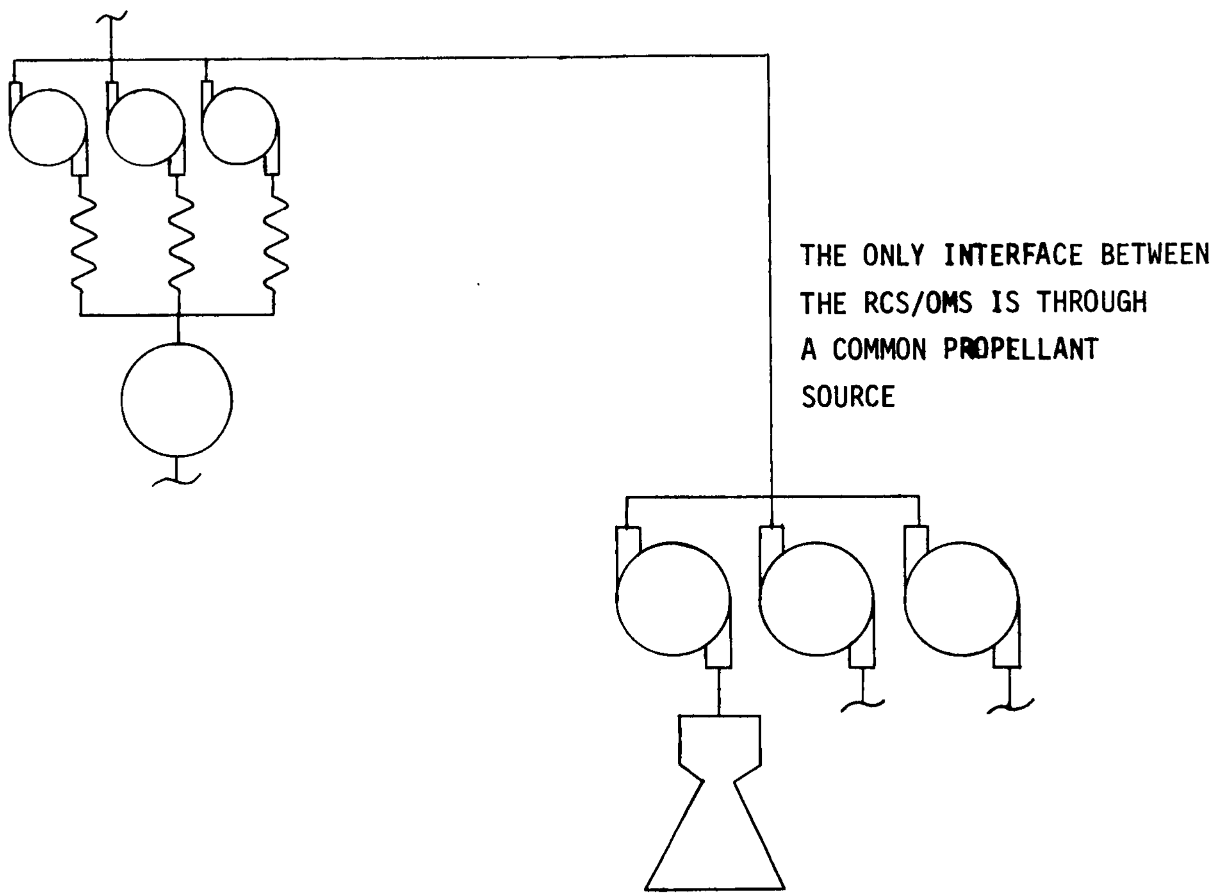


FIGURE 4-5

5. SYSTEM DEFINITION AND COMPARISON

This section defines and compares the various RCS/OMS integration options. First, the individual component characteristics were defined; secondly, system schematics were developed;and finally, design points were identified and control methods evaluated for each schematic. Based on results of this effort, candidate systems were selected for each level of integration and evaluated further to define weight sensitivity to changes in operational parameters.

5.1 Component Performance Characteristics - The most significant OMS components (engine, feedlines, and turbopumps) received the majority of study effort since their design strongly influences OMS performance and weight. These results are described in subsequent paragraphs. Also included is a description of the RCS baseline design which was defined concurrently in Phase B of the study.

5.1.1 Engine - Two liquid OMS engine concepts were considered for the study, one for use with the integrated RCS/OMS concepts, the other for the separate RCS/OMS. For the integrated concepts, an engine assembly design based on the use of gas generator powered turbopumps was used. Performance and weight were defined for the basic thrust chamber assembly (TCA) composed of the thrust chamber, nozzle, propellant valves, and injector, and also for a complete engine including turbopumps. For the separate RCS/OMS, both staged combustion and gas generator cycle engines were considered. In all engines, the chamber and initial portion of the Rao contour nozzle were regeneratively fuel cooled while the nozzle extension was radiatively cooled. Weight and performance of these engines were defined parametrically by the Aerojet Liquid Rocket Company (ALRC) over a wide range of performance and design parameters. Performance was calculated per reference (L) and includes losses due to nozzle kinetics, divergence, boundary layer, and energy release.

Gas generator cycle engine weights, as a function of thrust level, nozzle expansion ratio and chamber pressure, are graphically presented for the thrust chamber assembly in Figure 5-1 and for the complete engine in Figure 5-2. Engine performance sensitivity (vacuum specifc impulse) to mixture ratio, chamber pressure, and expansion ratio are presented in Figures 5-3 and 5-4 for thrust levels of 6000 and 12,000 lbf. Propellant inlet conditions to the engine are 37°R liquid hydrogen and 163°R liquid oxygen while injector pressure drop was assumed to be 20 percent of the chamber pressure.

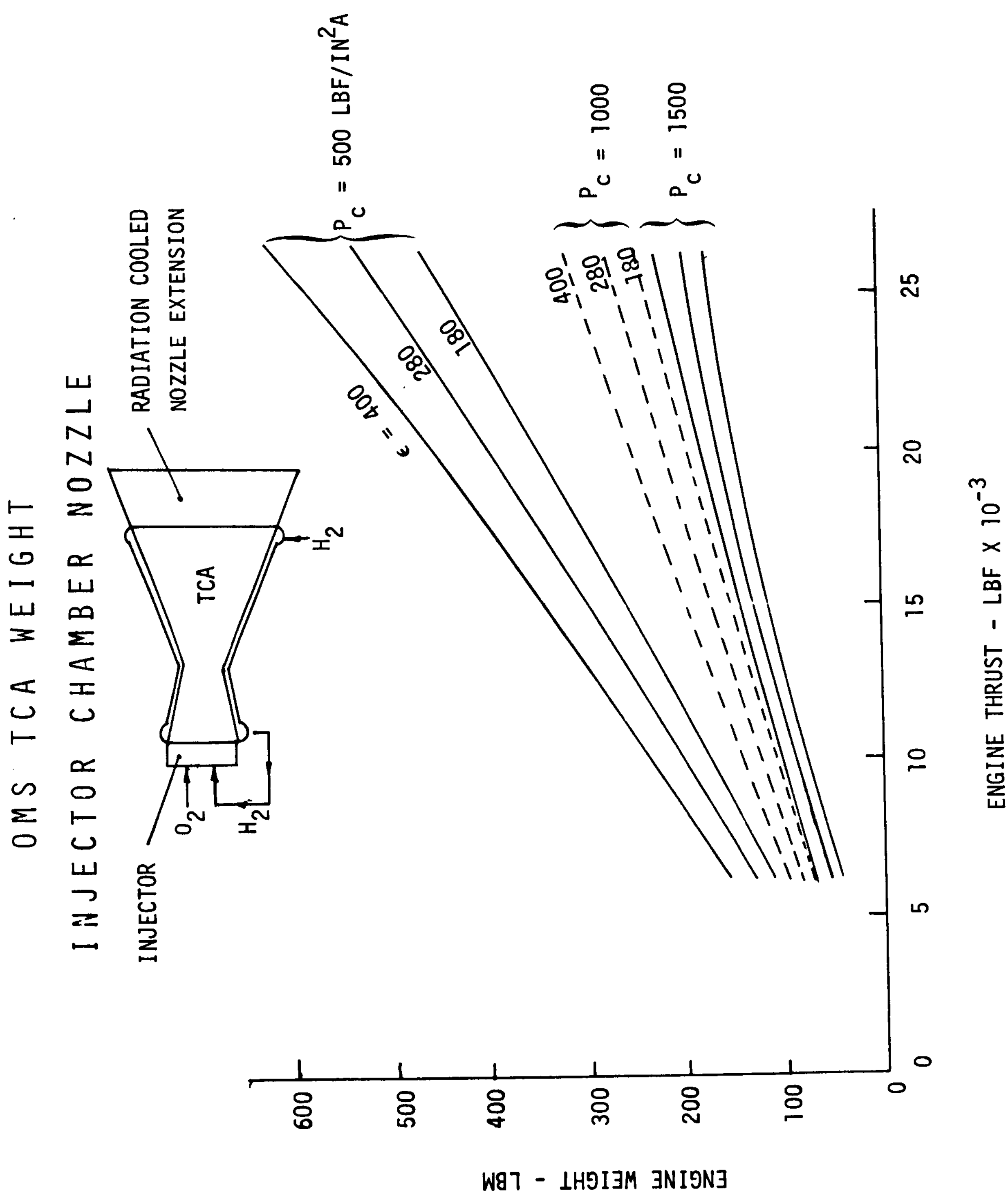

OMS TCA WEIGHT
INJECTOR CHAMBER NOZZLE
RADIATION COOLED
NOZZLE EXTENSION
TCA
H_2
O_2
H_2
INJECTOR
P_c = 500 LBF/IN^{2}A
P_c = 1000
P_c = 1500
ε = 400
280
180
400
280
180
ENGINE THRUST - LBF X 10^{-3}
0
5
10
15
20
25
ENGINE WEIGHT - LBM
0
100
200
300
400
500
600

FIGURE 5-1

OMS ENGINE WEIGHT

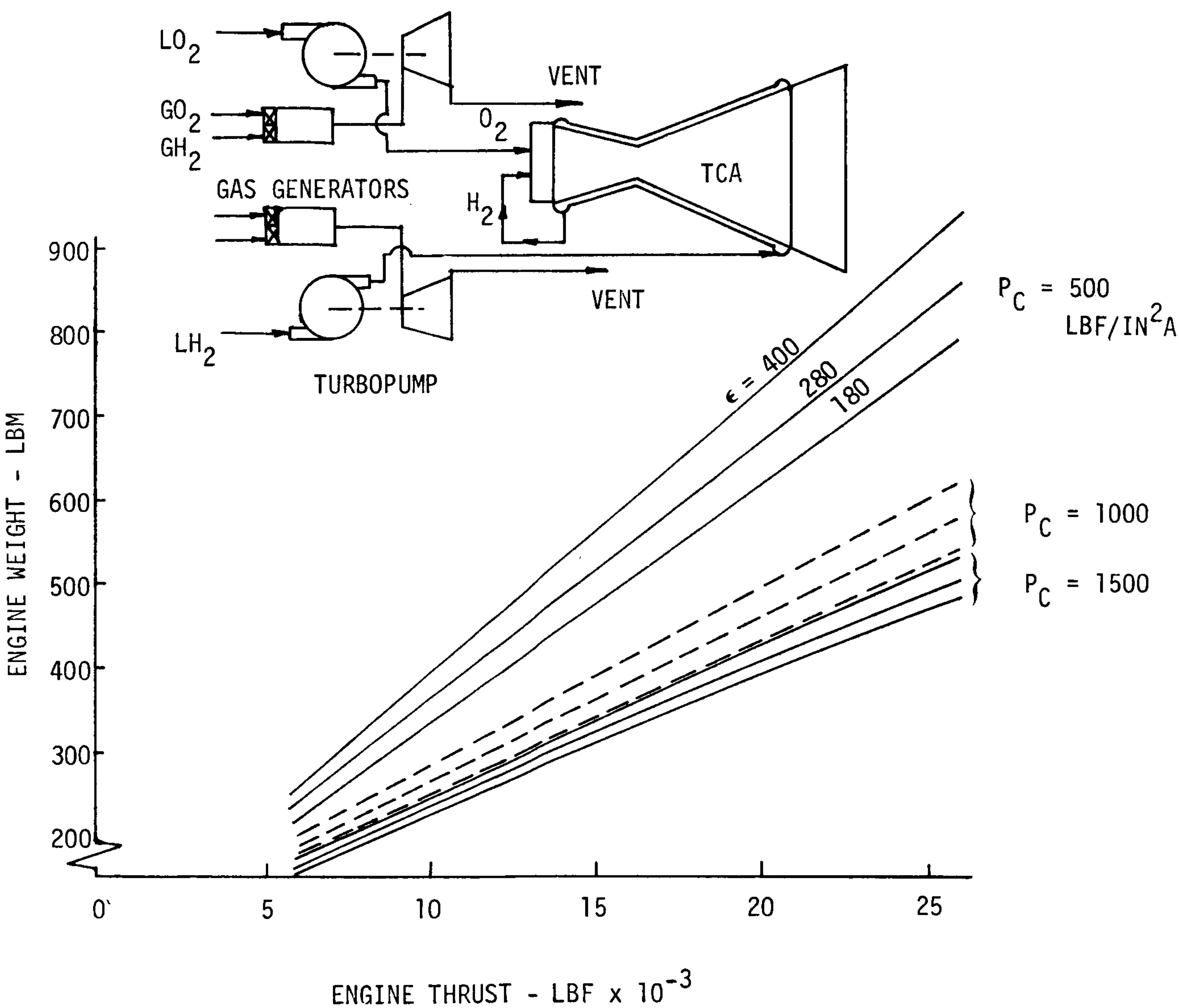


FIGURE 5-2

OMS THRUST CHAMBER PERFORMANCE

F = 6000 LBF
T_{H_2} = 37°R
T_{O_2} = 163°R

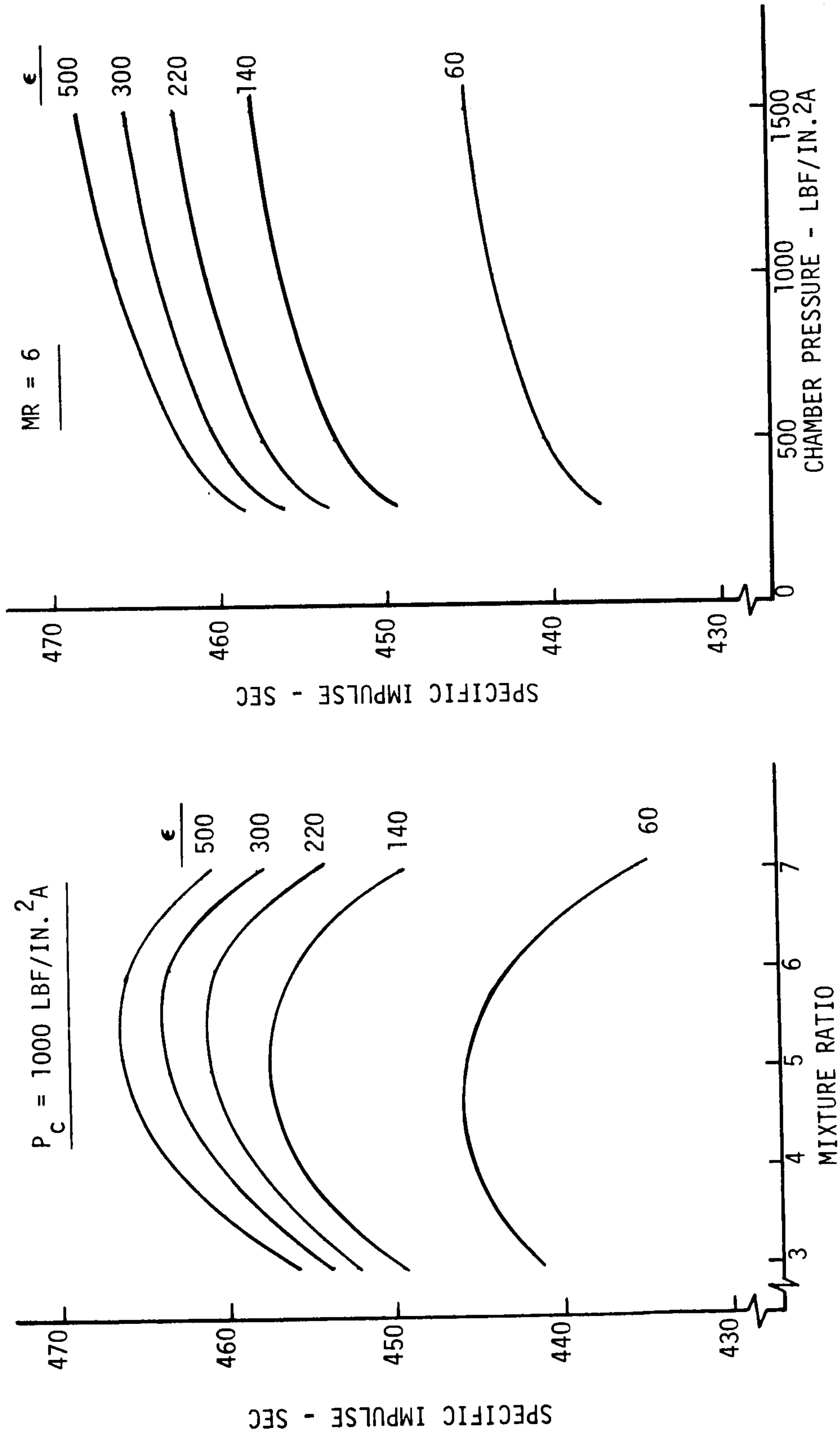


FIGURE 5-3

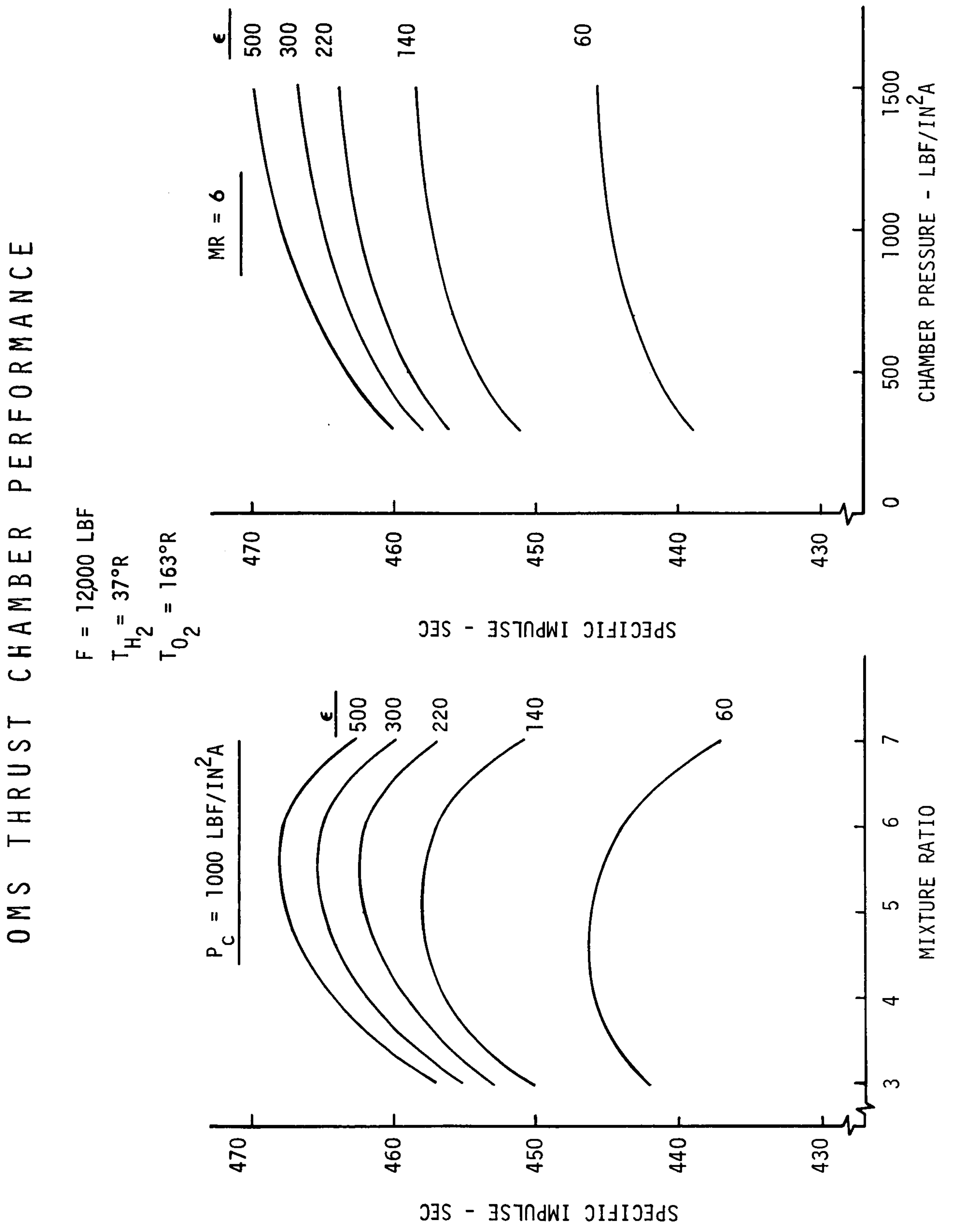

OMS THRUST CHAMBER PERFORMANCE
F = 12,000 LBF
T_{H_2} = 37°R
T_{O_2} = 163°R
MR = 6
ε
500
300
220
140
60
470
460
450
440
430
SPECIFIC IMPULSE - SEC
0
500
1000
1500
CHAMBER PRESSURE - LBF/IN^{2}A
P_c = 1000 LBF/IN^{2}A
ε
500
300
220
140
60
470
460
450
440
430
SPECIFIC IMPULSE - SEC
3
4
5
6
7
MIXTURE RATIO

FIGURE 5-4

The weight and performance of the staged combustion cycle engine is presented in Figure 5-5. Performance was calculated for a design mixture ratio of 6:1, chamber pressures of 100-2500 $lbf/in.^2A$, thrust levels of 8000-50,000 lbf, and expansion ratios of 180 to 500.

5.1.2 Feed Subsystem - The Space Shuttle orbiter configuration used for these studies had the hydrogen tank located forward with the oxygen tank located near the OMS engines at the rear of the vehicle. The liquid propellants are fed via trunk lines from the tanks to the OMS engines. The lines are fabricated of stainless steel and are insulated with multilayer insulation and a stainless steel vacuum jacket. The turbopumps are located near the liquid storage tank outlets for the fully integrated systems and near the OMS thrust chambers or engines for the partially integrated and separate RCS/OMS concepts. Feed system chilldown sequencing varies for the different levels of system integration. For the fully integrated case, the pumps are maintained in a chilled condition by the use of a thermodynamic vent-refrigeration system. Prior to pump startup, the feedlines are filled with liquid propellants at tank pressure. During pump startup, a portion of the propellant is bypassed back into the propellant storage tank to provide proper pump suction pressures for startup. For the partially integrated and separate RCS/OMS, the chilldown propellant is bled through the lines, again at tank pressure, and then through the turbopumps before being vented overboard. Prior to selection of the above sequencing,an analytical model defining liquid cooling/heating and thermal transients within the feedlines was developed to determine optimum feed system configurations and associated propellant losses.

Trade studies conducted on the liquid feedlines included parametric evaluation of feedline chilldown requirements, stainless steel or aluminum lines, parallel or trunk line configurations, and aft or forward pump locations. The lines were sized for one OMS engine firing and the liquid line velocities were limited to 30 fps to minimize surge pressure during shutdown. Line thicknesses were based on stress requirements as defined by maximum surge pressure, a safety factor of 2 and ultimate strength of 64,000, and 100,000 $lbf/in.^2A$ for aluminum and stainless steel respectively. Current fabrication and handling techniques placed a 0.016-inch minimum gage limitation on lines up to 2 inches in diameter for both stainless steel and aluminum. A vacuum jacketed approach was selected to protect the

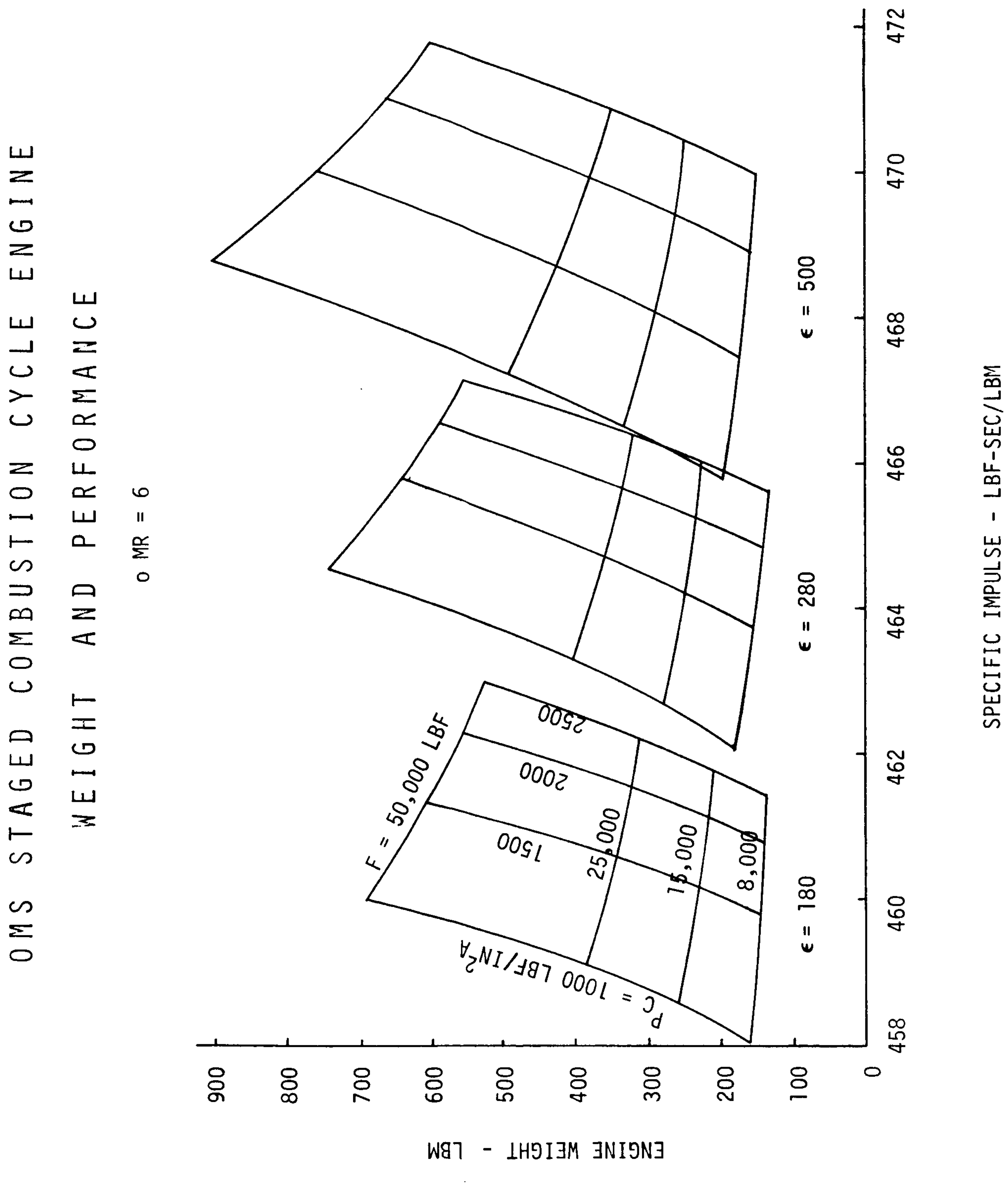

OMS STAGED COMBUSTION CYCLE ENGINE
WEIGHT AND PERFORMANCE
o MR = 6
F = 50,000 LBF
25,000
15,000
8,000
2500
2000
1500
P_C = 1000 LBF/IN^{2}A
ε = 180
ε = 280
ε = 500
ENGINE WEIGHT - LBM
0
100
200
300
400
500
600
700
800
900
SPECIFIC IMPULSE - LBF-SEC/LBM
458
460
462
464
466
468
470
472

FIGURE 5-5

line insulation from water condensation damage during vehicle entry and from normal handling damage. To evaluate line chilldown requirements, a computer model was developed for the approach defined in Reference (M). This model is summarized in Figure 5-6. The model assumes (1) that the flow rate through the line is governed by the vaporized gas velocity, and (2) that the gas exiting the line is at the initial temperature of the line. These assumptions are verified by Reference (M) test data on chilldown time and line temperatures. A typical line temperature history is shown in Figure 5-6. The line is shown to remain at essentially constant temperature until passage of the liquid/vapor interface validating assumptions (1) and (2) above.

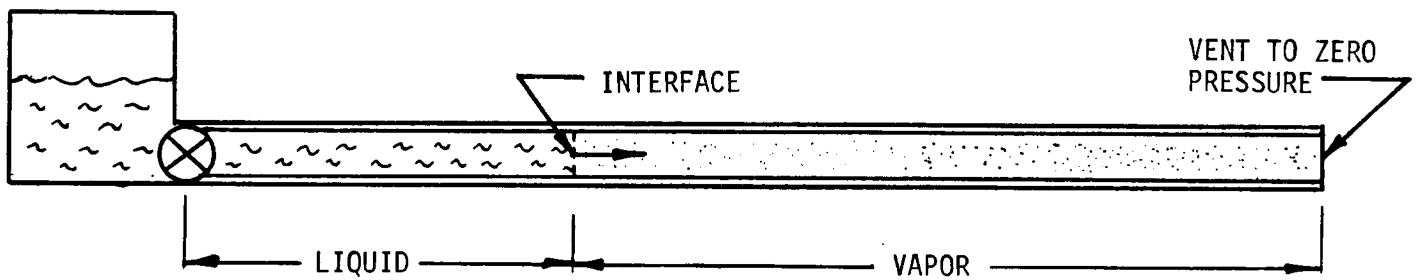
Utilizing the above criteria and model, chilldown propellant requirements were computed for both aluminum and stainless steel and are shown parametrically in Figure 5-7. Flow rates were based on an OMS thrust level of 7000 lbf and a mixture ratio of 3:1. A trunk line configuration was used and various line lengths were investigated. Line thicknesses were varied with diameter to satisfy strength requirements. The time required to achieve chilldown is shown in Figure 5-8. These results show that stainless steel lines, although heavier than aluminum, require less propellant and less time to accomplish chilldown. With the selection of stainless steel as the line material, a weight comparison between trunk and parallel line configurations for both two and three OMS engines was made, as shown in Figure 5-9. A nonoptimum factor of 16 percent was applied to the line weight for joints, fitting, and elbows. Insulation weight for the stainless lines and vacuum jacket was 0.67 lbm per foot of line length and per inch of line diameter. As shown in Figure 5-9, the trunk line concept is superior from a weight standpoint and was used during the study. Both forward and aft pump locations were evaluated in the system weight comparison (discussed in Section 5.3).

Selected feed system physical and performance characteristics are summarized in Figure 5-10.

5.1.3 Turbopump - Turbopumps are required to deliver propellant from low pressure cryogenic storage tanks to the RCS conditioner assembly - gaseous accumulator and/or to the liquid OMS engines. Pump power is provided from the products of a gas generator. Pump power and turbine flow requirements are significantly affected by turbopump design and performance. Therefore, parametric data were developed to identify performance for turbomachinery exhibiting various

LONG LINE THERMAL MODEL

PRESSURIZED CRYOGEN SUPPLY



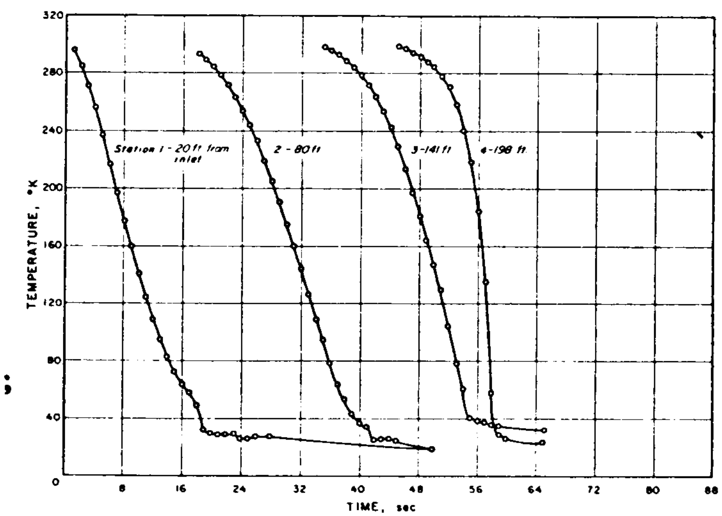
- LINE AT AMBIENT CONDITIONS THROUGHOUT VAPOR SECTION
- ADIABATIC VAPOR FLOW
- MASS FLOW CONTROLLED BY FANNO CHOKED FLOW RELATIONSHIP
- INFINITE HEAT TRANSFER COEFFICIENT AT INTERFACE

$$t_{CHILLDOWN} = \int_0^L \frac{B}{M_i u_s} dx$$

u_s = SONIC VELOCITY; M_i = MACH NUMBER OF GAS AT INTERFACE;

$$B = 1 + \frac{\text{PIPE ENTHALPY CHANGE}}{\text{VAPOR MASS X } (h_{VAPOR} - h_{CRYOGEN})}$$

TYPICAL LINE TEMPERATURE HISTORY*
SUBCOOLED LIQUID HYDROGEN



*NBS REPORT - NASA (SNPO) CONTRACT R-45

FIGURE 5-6

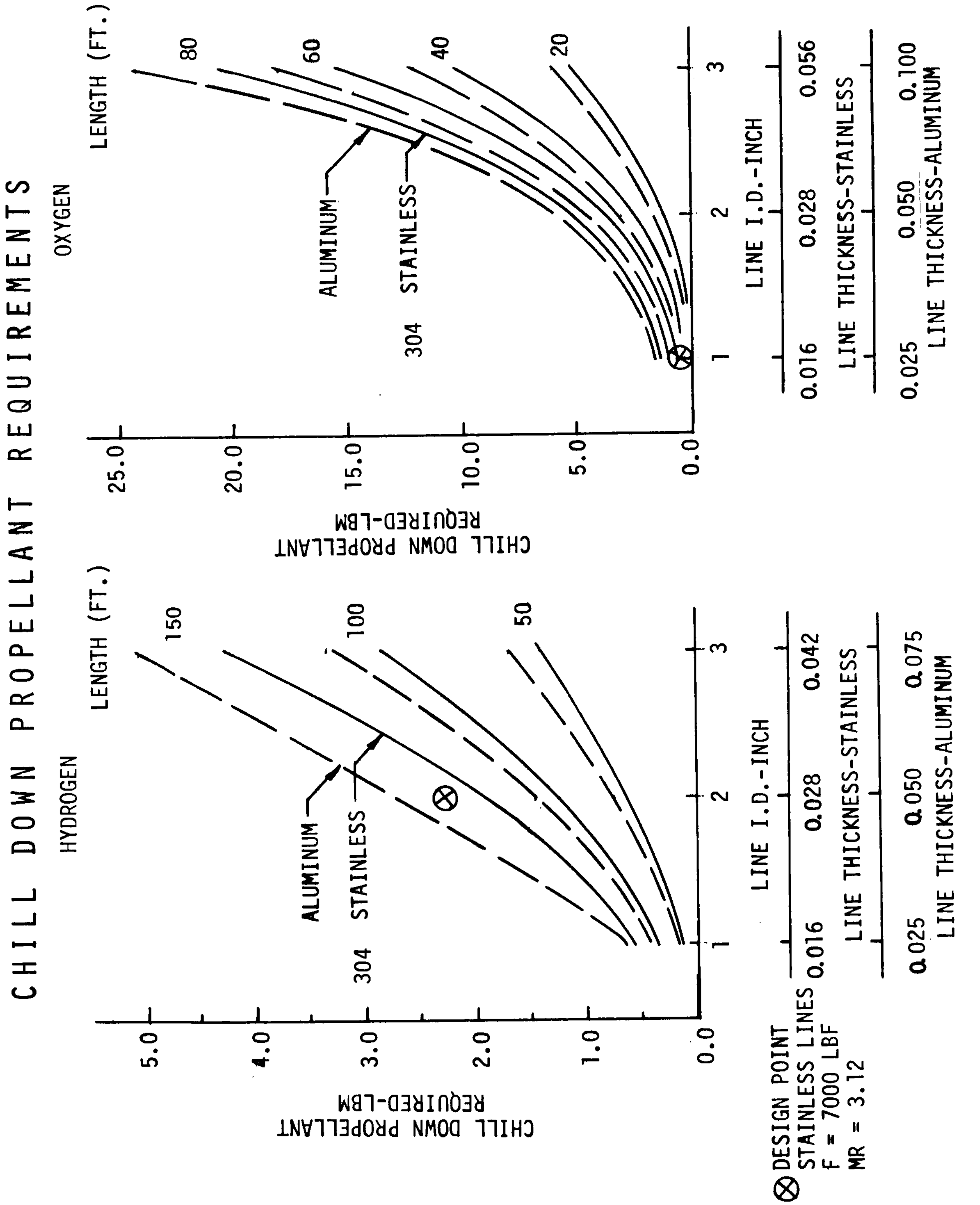

CHILL DOWN PROPELLANT REQUIREMENTS
HYDROGEN
OXYGEN
LENGTH (FT.)
150
100
50
80
60
40
20
ALUMINUM
STAINLESS
304
CHILL DOWN PROPELLANT REQUIRED-LBM
5.0
4.0
3.0
2.0
1.0
0.0
25.0
20.0
15.0
10.0
5.0
0.0
1
2
3
LINE I.D.-INCH
0.016
0.028
0.042
0.056
LINE THICKNESS-STAINLESS
0.025
0.050
0.075
0.100
LINE THICKNESS-ALUMINUM
⊗ DESIGN POINT
STAINLESS LINES
F = 7000 LBF
MR = 3.12

FIGURE 5–7

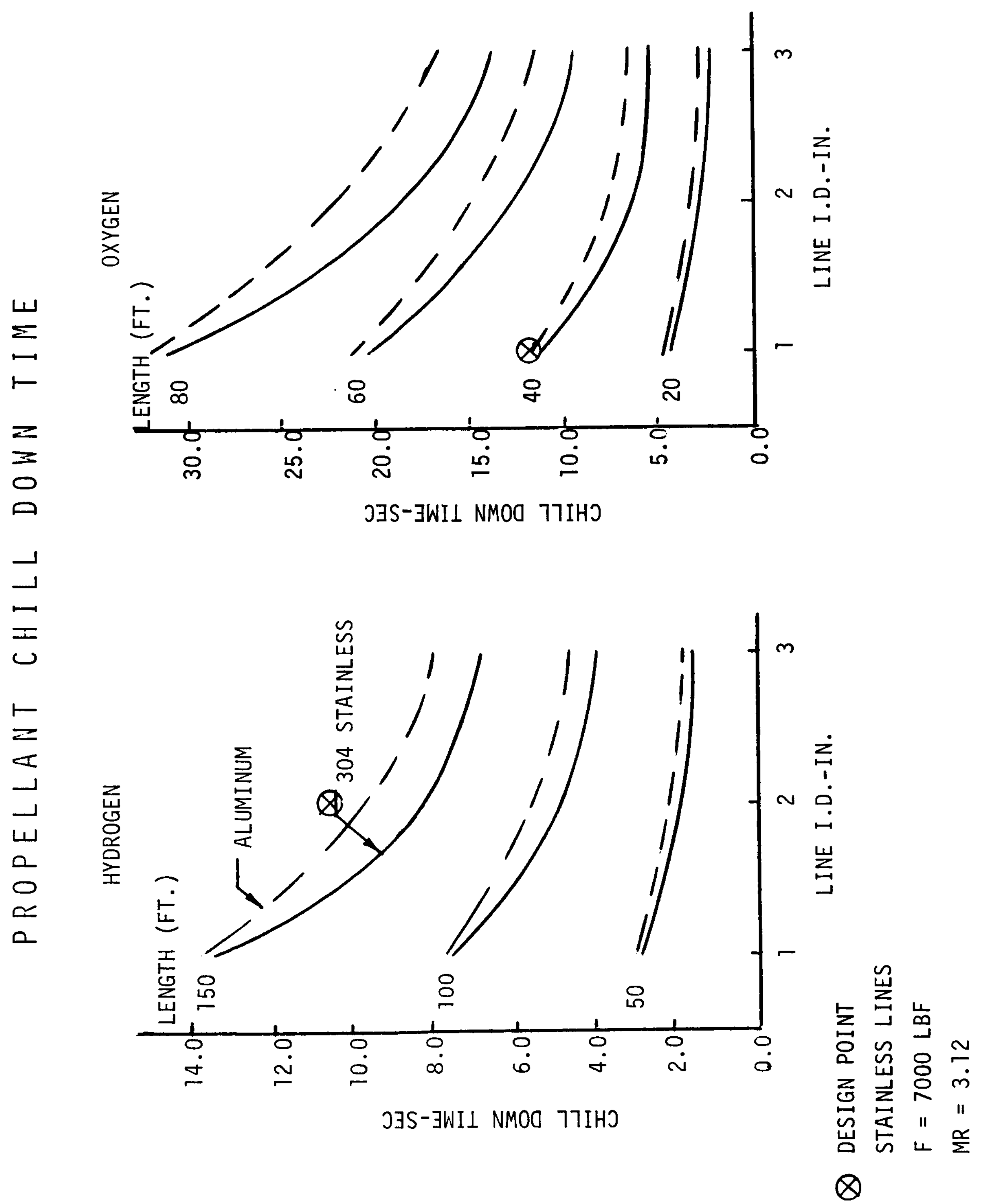

PROPELLANT CHILL DOWN TIME
HYDROGEN
OXYGEN
LENGTH (FT.)
150
100
50
80
60
40
20
ALUMINUM
304 STAINLESS
CHILL DOWN TIME-SEC
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
30.0
25.0
20.0
15.0
10.0
5.0
1
2
3
LINE I.D.-IN.
DESIGN POINT
STAINLESS LINES
F = 7000 LBF
MR = 3.12

FIGURE 5-8

OMS FEEDLINE CONFIGURATIONS AND WEIGHTS

F = 7000 LBF/ENGINE, VACUUM JACKETED LINES

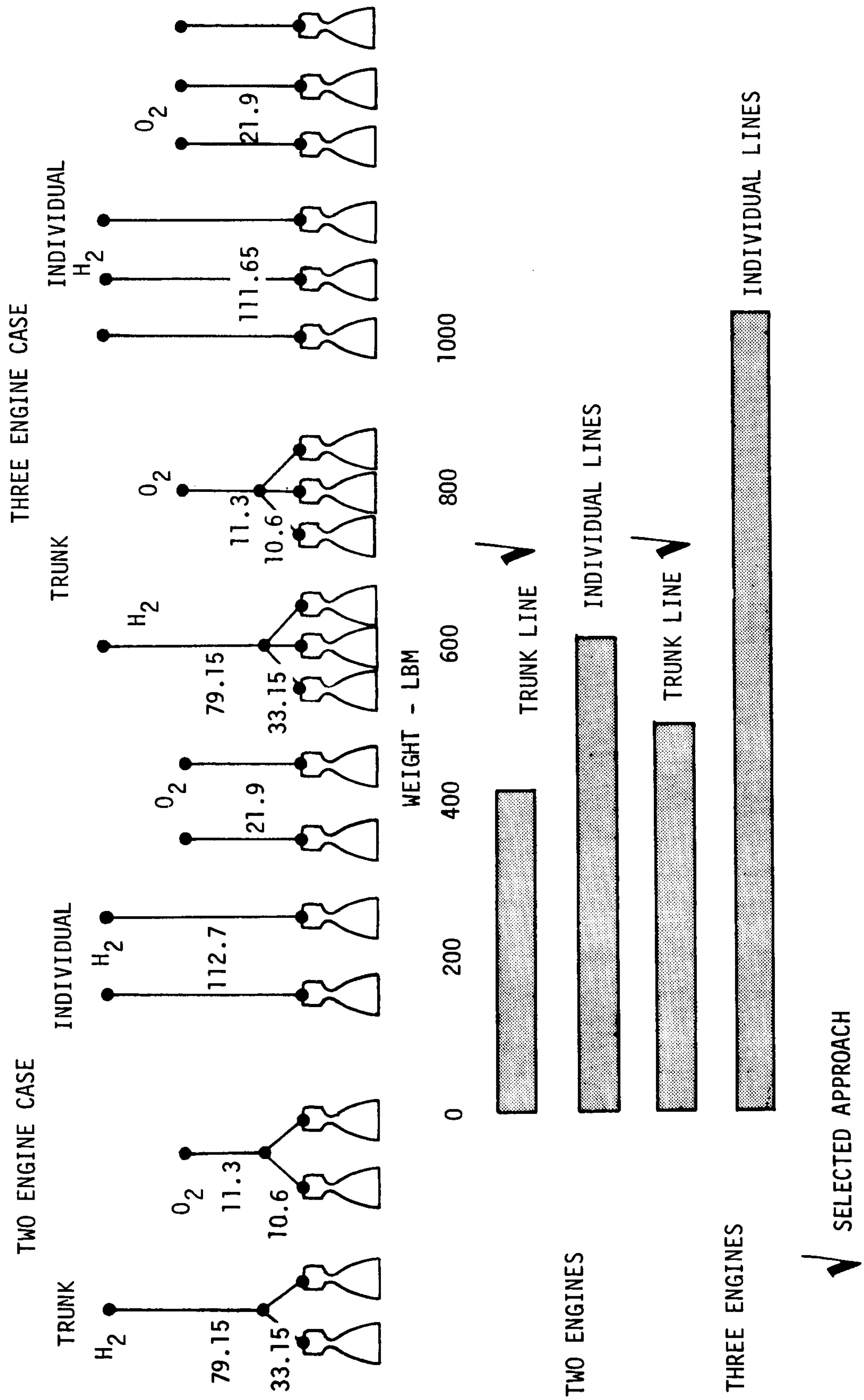


FIGURE 5-9

PROPELLANT FEEDLINE DESIGN CRITERIA

° TRUNK LINE CONFIGURATION

	PUMP LOCATION	
	FORWARD	AFT
NUMBER OF OMS ENGINES FIRING	1	1
LIQUID LINE VELOCITY, FPS	30	30 (H_2), 20 (O_2)
LINE PRESSURE DROP, ΔP, LBF/IN^2	20	40 (H_2), 10 (O_2)
LINE PRESSURE, LBF/IN^2	$1.2\ P_C + \Delta P$	TANK PRESSURE
SURGE PRESSURE, ΔP_S, LBF/IN^2	200 (H_2), 1300 (O_2)	——
LINE MATERIAL	STAINLESS STEEL	STAINLESS STEEL
MATERIAL DESIGN STRENGTH, LBF/IN^2	100,000	100,000
SAFETY FACTOR	2.0	2.0
MINIMUM GAGE * (0 TO 2 IN O.D.), IN.	0.016	0.016
WEIGHT OF FLANGES, ELBOWS, AND BELLOWS	0.16 LBM/LBM (LINE WT)	0.16 LBM/LBM (LINE WT)
WEIGHT OF SS LINER/JACKET	0.67 LBM/FT(L) IN (DIA)	0.67 LBM/FT(L) IN (DIA)

* MINIMUM GAGE BASED ON FABRICATION AND HANDLING LIMITATIONS.

FIGURE 5–10

head-capacity characteristics. These data allowed tailoring of RCS turbopump designs to provide characteristics most compatible with OMS engine integration.

Predicted pump efficiency characteristics are shown in Figure 5-11 as a function of flow rate and pump specific speed. A specific speed range of 750 to 1250 was selected for the OMS turbopumps. This range represents the most favorable compromise between pump efficiency and complexity as higher efficiency can be attained only by an increase in the number of pump stages. A four-stage pump was selected for the hydrogen side and a two-stage for the oxygen. Suction specific speed was limited to 40,000 maximum based on cavitation considerations and impeller diameter was limited to 2.5 inch minimum based on fabrication considerations. The range of net positive suction pressure was 5-10 $lbf/in.^2$ for liquid hydrogen and 10-15 $lbf/in.^2$ for oxygen. For this design specific speed, predicted pump head/flow, efficiency, power, and torque characteristics were developed by ALRC and are shown in a normalized format in Figure 5-12. The normalized characteristics apply to both the hydrogen and oxygen pumps since their stage specific speeds are in the same range.

Predicted turbine efficiency is presented in Figure 5-13 as a function of stage velocity ratio. The stage isentropic spouting velocity was calculated assuming equal energy split between turbine stages, turbine inlet temperature of 2000°R, and a turbine pressure ratio of 20. Turbine mean blade speed was limited to 1300 fps to provide the desired life characteristics. A three-stage, pressure compounded, axial flow turbine is employed on the hydrogen side, while a two-stage, velocity compounded, axial flow turbine is used for the oxygen side. These turbine design points are indicated on the turbine efficiency curve of Figure 5-13. The complete turbopump assembly design criteria are summarized in Figure 5-14.

Using the normalized pump and turbine efficiency characteristics, pump maps were generated for the various integrated RCS/OMS options. This enabled definition of off-design or bilevel operating characteristics. As an example, hydrogen and oxygen pump performance maps are shown in Figures 5-15 and 5-16 for an integrated RCS/OMS case. The pumps provide an OMS engine thrust of 12,000 lbf and a RCS system thrust of 5750 lbf. The pumps were designed for a maximum efficiency at the OMS operating point, and operate off-design at the RCS flow and pressure requirements. The OMS and RCS operating points are indicated on the figures. For this case, both gas generator and pump discharge control is required to operate at the different heads and flow rates of the RCS and OMS.

PUMP EFFICIENCY CHARACTERISTICS

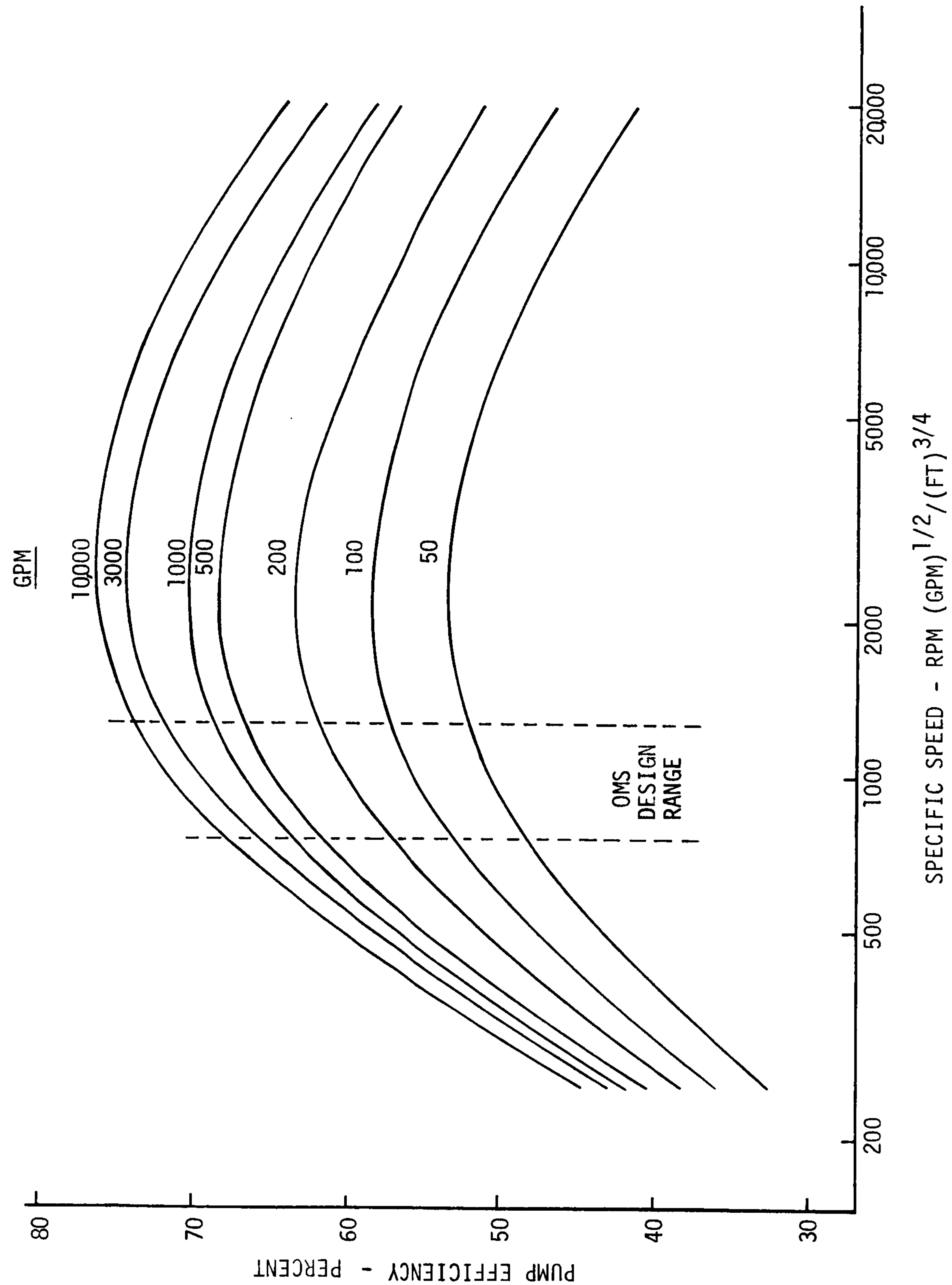


FIGURE 5-11

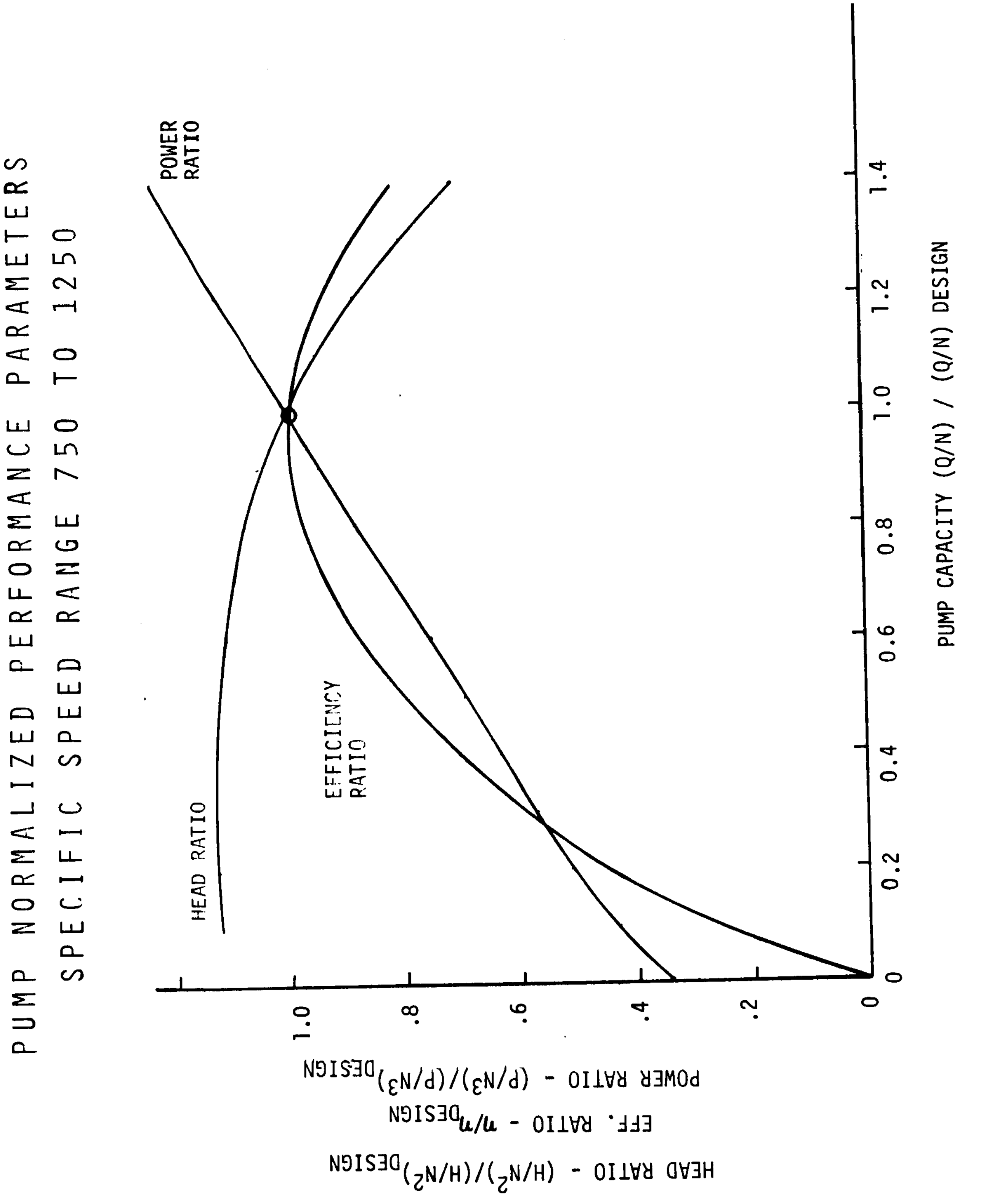

PUMP NORMALIZED PERFORMANCE PARAMETERS
SPECIFIC SPEED RANGE 750 TO 1250
POWER RATIO
EFFICIENCY RATIO
HEAD RATIO
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
PUMP CAPACITY (Q/N) / (Q/N) DESIGN
0
.2
.4
.6
.8
1.0
POWER RATIO - (P/N3)/(P/N3)DESIGN
EFF. RATIO - η/ηDESIGN
HEAD RATIO - (H/N2)/(H/N2)DESIGN

FIGURE 5–12

TURBINE EFFICIENCY CHARACTERISTICS

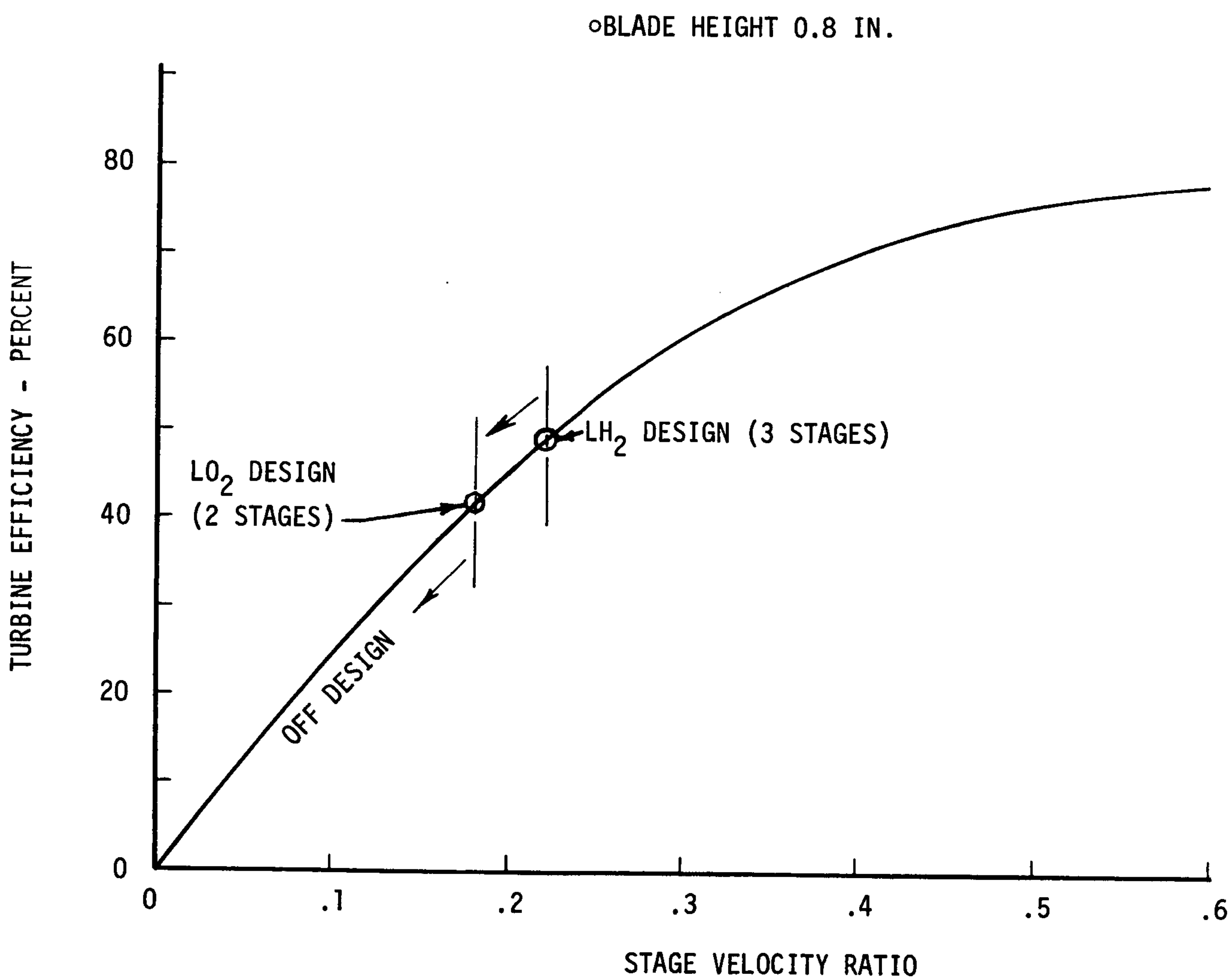


FIGURE 5-13

TURBOPUMP DESIGN PHILOSOPHY

TURBOPUMP CRITERIA

- DESIGN FOR MAXIMUM PERFORMANCE WITHIN MECHANICAL DESIGN CONSTRAINTS
- DESIGN FOR MAXIMUM EFFICIENCY AT OMS OPERATING POINT

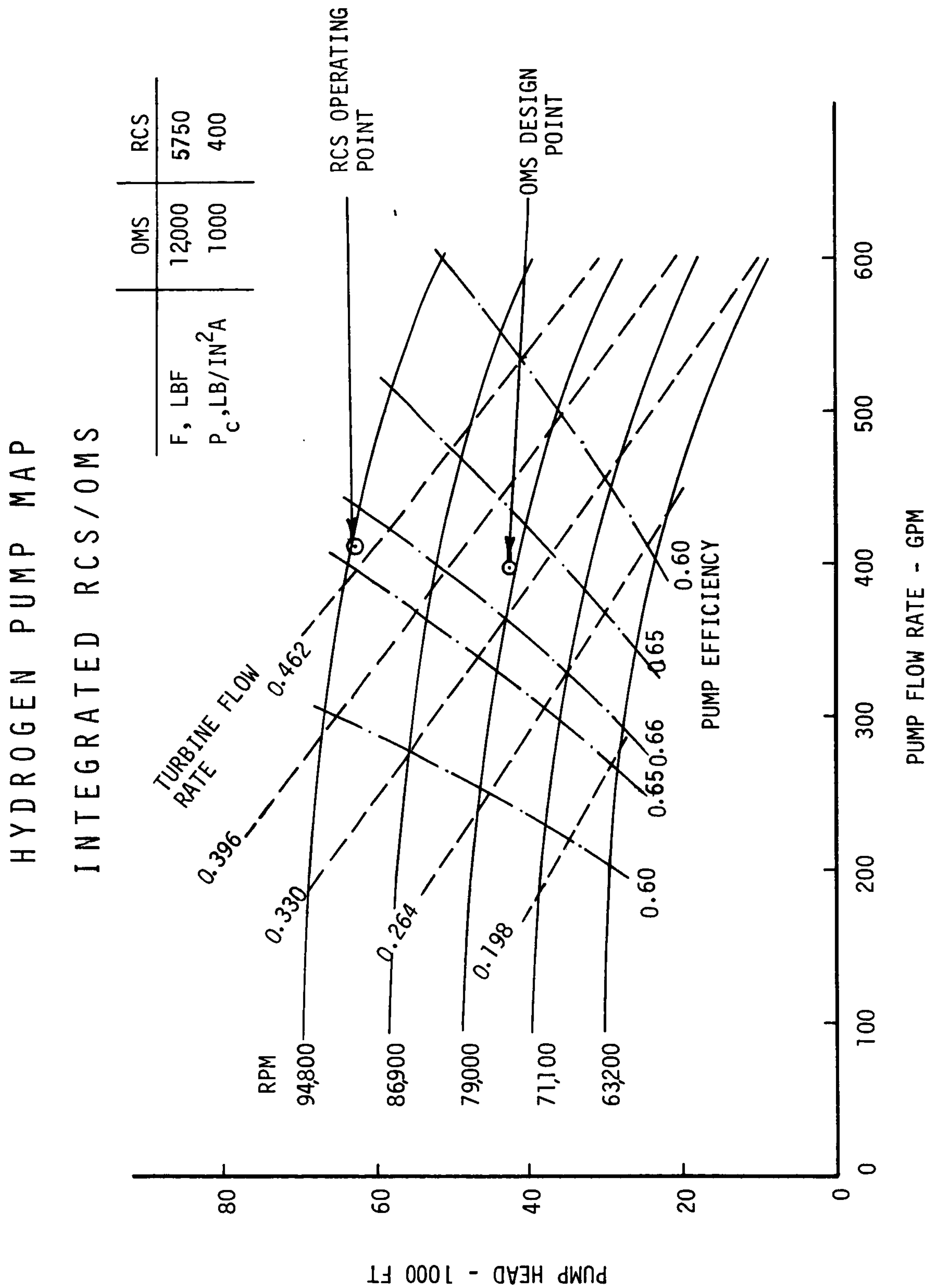
PUMPS

- MAXIMUM NUMBER STAGES, 4 LH_2, 2 LO_2
- NET POSITIVE SUCTION PRESSURE, 6 LBF/IN^2 LH_2, 11 LBF/IN^2 LO_2
- MINIMUM EFFECTIVE NPSH INCLUDES THERMODYNAMIC SUPPRESSION HEAD
- MAXIMUM SUCTION SPECIFIC SPEED, 40,000 RPM
- SPECIFIC SPEED RANGE, 750 to 1250 RPM $(GPM)^{1/2}/(FT)^{3/4}$
- MINIMUM IMPELLER DIAMETER, 2.5 IN.

TURBINES

- MAXIMUM NUMBER STAGES, 3 LH_2, 2 LO_2
- EQUAL ENERGY SPLIT BETWEEN STAGES
- MAXIMUM MEAN BLADE SPEED, 1300 FT/SEC LH_2 AND LO_2
- TURBINE INLET TEMPERATURE, 2000°R
- TURBINE EXIT PRESSURE, 15 LBF/IN^2A

FIGURE 5-14



HYDROGEN PUMP MAP
INTEGRATED RCS/OMS
OMS
RCS
F, LBF
12000
5750
P_c, LB/IN^{2}A
1000
400
RCS OPERATING POINT
OMS DESIGN POINT
TURBINE FLOW RATE
0.462
0.396
0.330
0.264
0.198
RPM
94800
86900
79000
71100
63200
PUMP EFFICIENCY
0.60
0.65
0.66
0.65
0.60
PUMP HEAD - 1000 FT
PUMP FLOW RATE - GPM
0
20
40
60
80
100
200
300
400
500
600

FIGURE 5-15

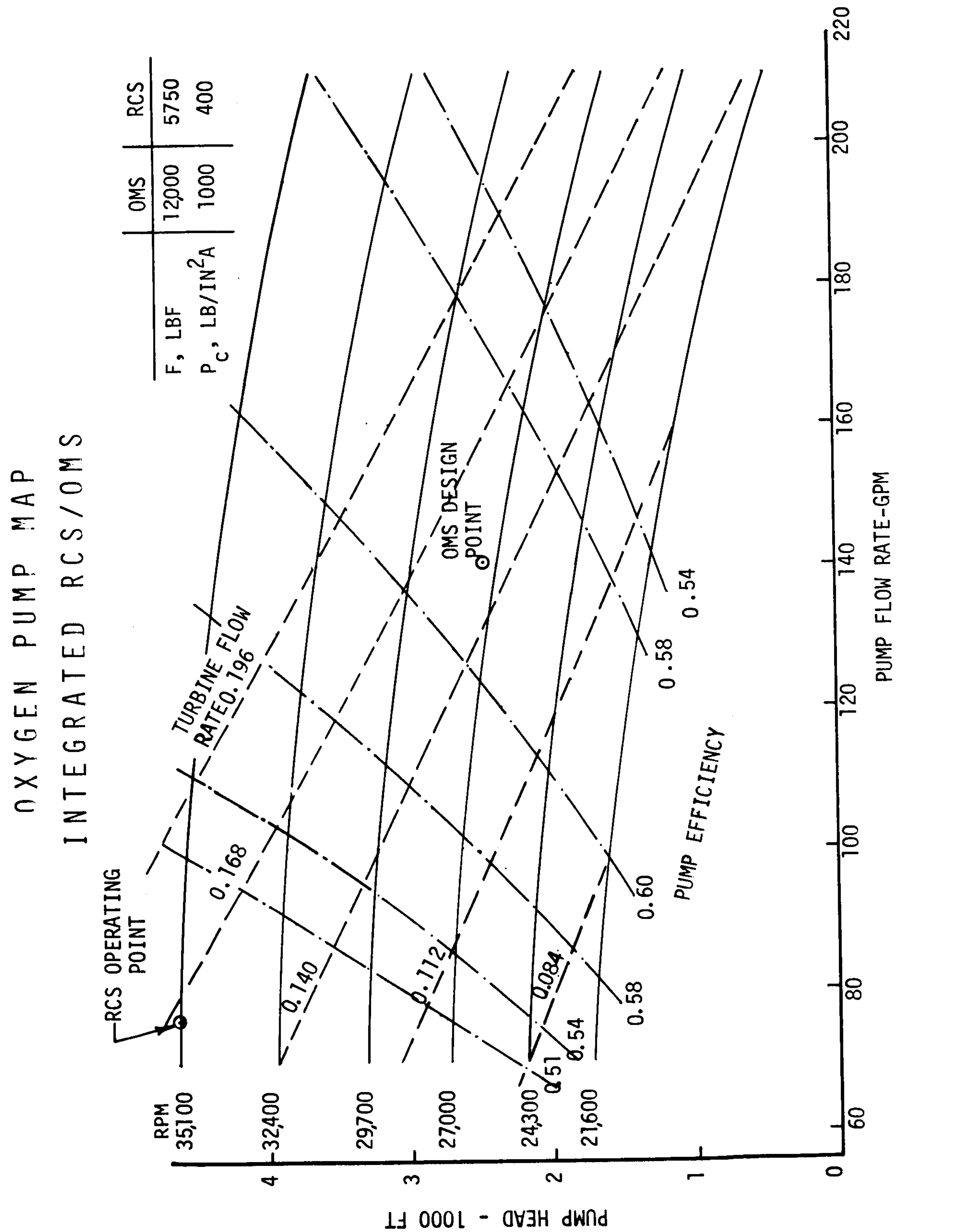

OXYGEN PUMP MAP
INTEGRATED RCS/OMS
OMS
RCS
F, LBF
12000
5750
P_C, LB/IN^{2}A
1000
400
RCS OPERATING POINT
OMS DESIGN POINT
TURBINE FLOW RATE 0.196
0.168
0.140
0.112
0.084
0.51
0.54
0.58
0.60
0.58
0.54
PUMP EFFICIENCY
RPM
35,100
32,400
29,700
27,000
24,300
21,600
PUMP HEAD - 1000 FT
0
1
2
3
4
60
80
100
120
140
160
180
200
220
PUMP FLOW RATE-GPM

FIGURE 5-16

5.1.4 Reaction Control System - This section defines the RCS propulsion system used for the OMS integration study. The RCS concept is shown schematically in Figure 5-17. Turbopumps are used to deliver propellant from low pressure cryogenic storage tanks to a heat exchanger assembly. Energy for the heat exchanger and turbine is provided by separate gas generators. The conditioned propellants are then stored in gas accumulators which decouple the thruster assemblies from the conditioning assemblies. Supply pressure is regulated at the accumulator outlet to provide a constant pressure at the thruster inlets.

RCS component design and performance data are described fully in Reference (K) and, for those components significant to integration studies, a brief summary is provided in the following paragraphs.

The design sensitivity of an integrated RCS/OMS propellant storage tank has been included herein for reference. Sensitivity of propellant tank weight, volume, and cooling requirements, and the sensitivity of pressurant tank weight, volume, and helium requirements to such variables as propellant weight or total impulse, mixture ratio, and NPSP, are shown in Figures 5-18 and 5-19.

The heat exchanger model is a coiled tube and shell design. Heat exchanger weights for this design are shown in Figure 5-20 for varying cold side exit conditions and a fixed hot side temperature drop of 1100°R. Hot side exit temperature is 800°R. Performance of the heat exchanger is discussed as part of the integration concepts comparison, Section 5.4.

The turbopump model provides the capability to evaluate an alternate number of turbine and pump stages using generalized pump efficiency curves and normalized pump characteristics. These data, discussed in Section 5.1.3, allow investigation and tailoring of various turbopump designs and enable definition of off-design or bilevel operating characteristics required for RCS/OMS integration. The modified turbopump model is comprised of separate equations for estimation of (1) turbine and turbine housing weight, (2) power transmission weight, and (3) inducer and pump weights. These are shown parametrically in Figures 5-21 and 5-22.

Using data and analysis techniques described in Reference (H), RCS flow balances and weight sensitivities to design requirements were established. An RCS design point, summarized in Figure 5-23, was then determined for the parallel flow concept. The RCS supplies a total impulse of 2.23 million lbf-sec at a

RCS CONCEPT

PARALLEL FLOW

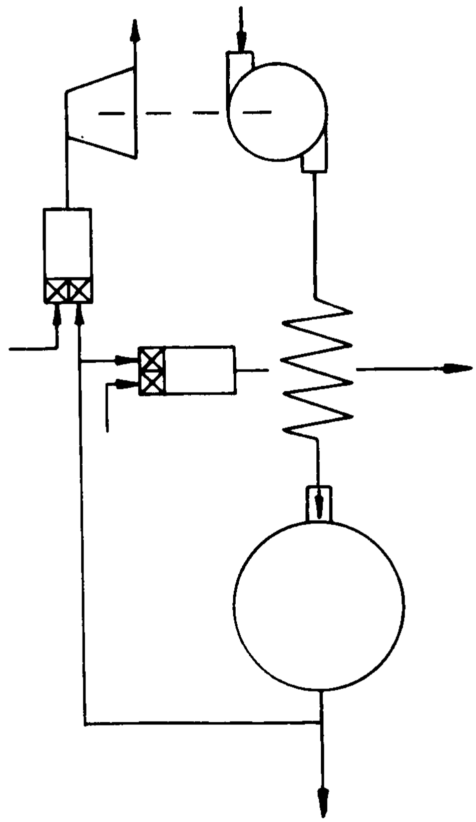


FIGURE 5-17

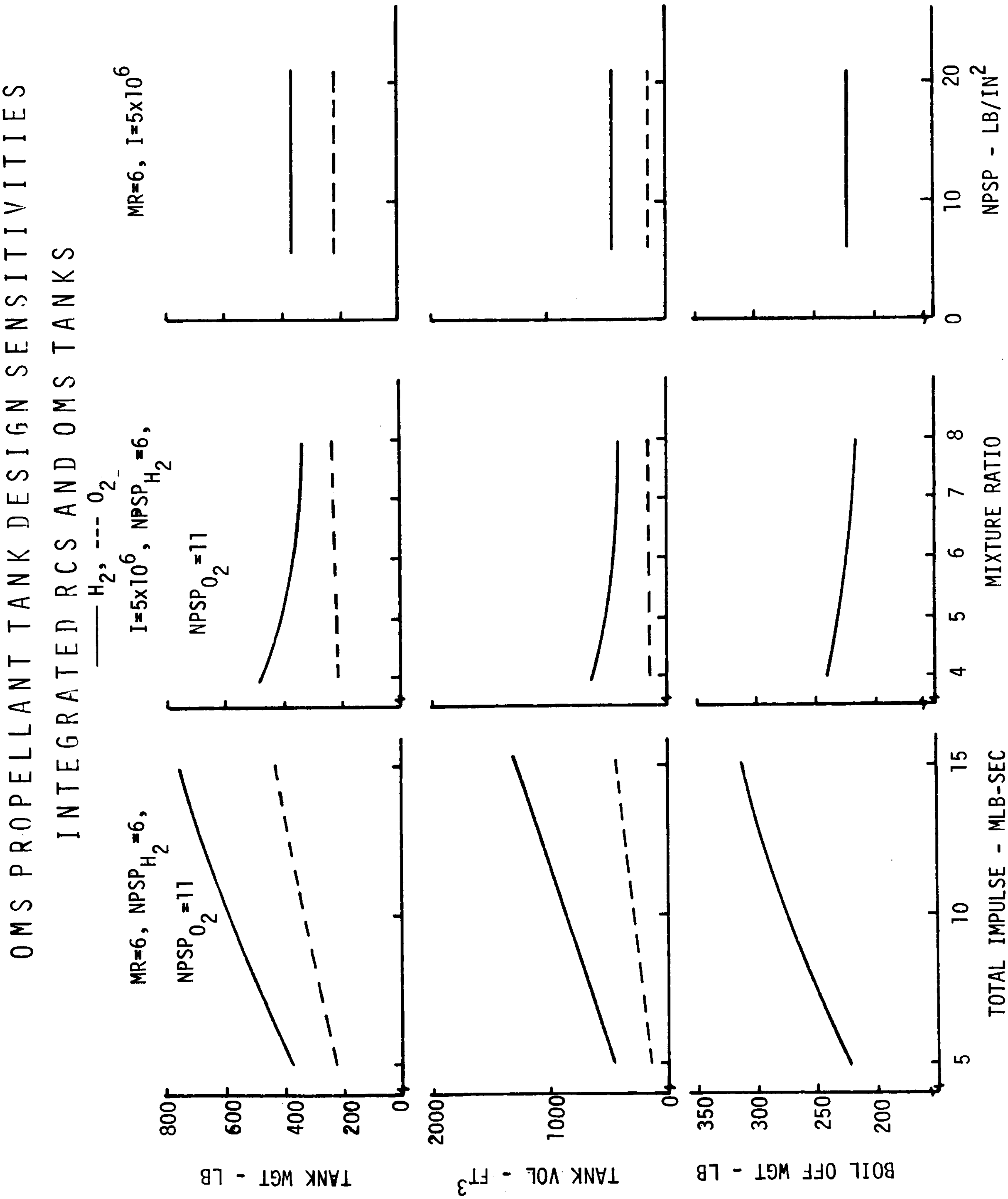

OMS PROPELLANT TANK DESIGN SENSITIVITIES
INTEGRATED RCS AND OMS TANKS
—— H2, --- O2
MR=6, NPSP H2 =6, NPSP O2 =11
I=5x10^6, NPSP H2 =6, NPSP O2 =11
MR=6, I=5x10^6
TANK WGT - LB
800
600
400
200
0
TANK VOL - FT3
2000
1000
0
BOIL OFF WGT - LB
350
300
250
200
TOTAL IMPULSE - MLB-SEC
5
10
15
MIXTURE RATIO
4
5
6
7
8
NPSP - LB/IN2
0
10
20

FIGURE 5-18

OMS PRESSURANT TANK DESIGN SENSITIVITIES
(INTEGRATED RCS AND OMS TANKS)

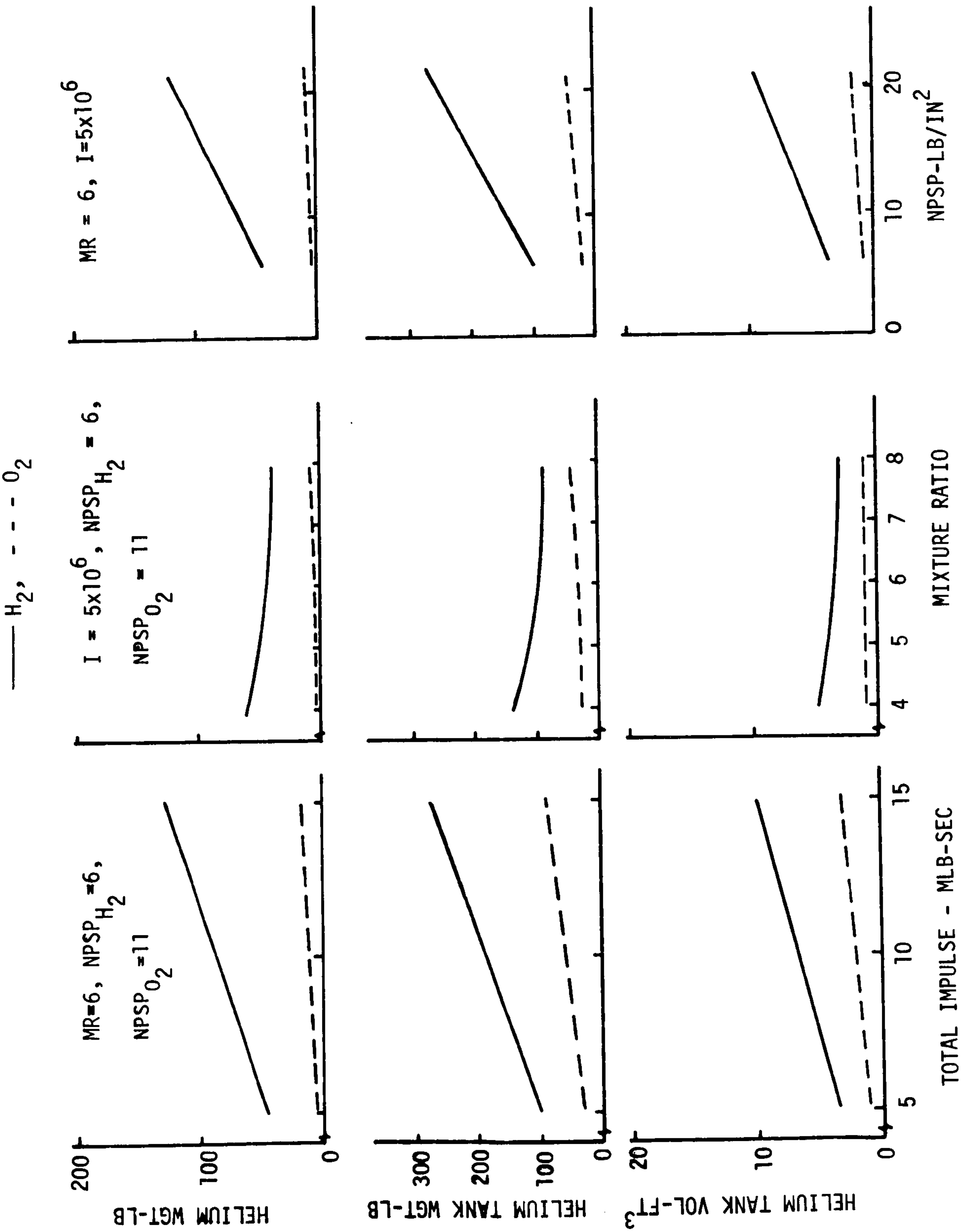
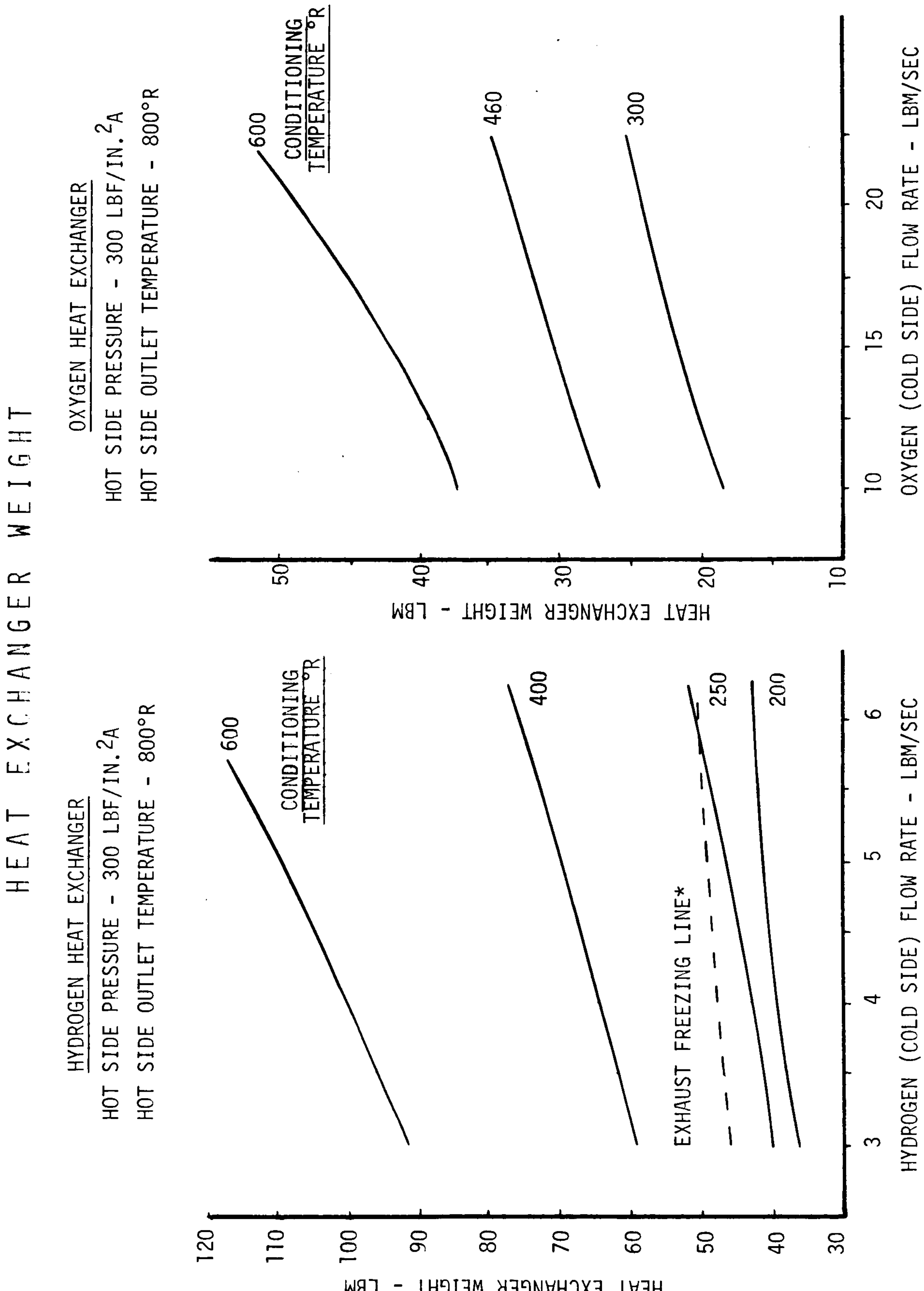


FIGURE 5–19



* BELOW THIS LINE DESIGN TAILORING IS REQUIRED TO AVOID EXHAUST FREEZING

FIGURE 5-20

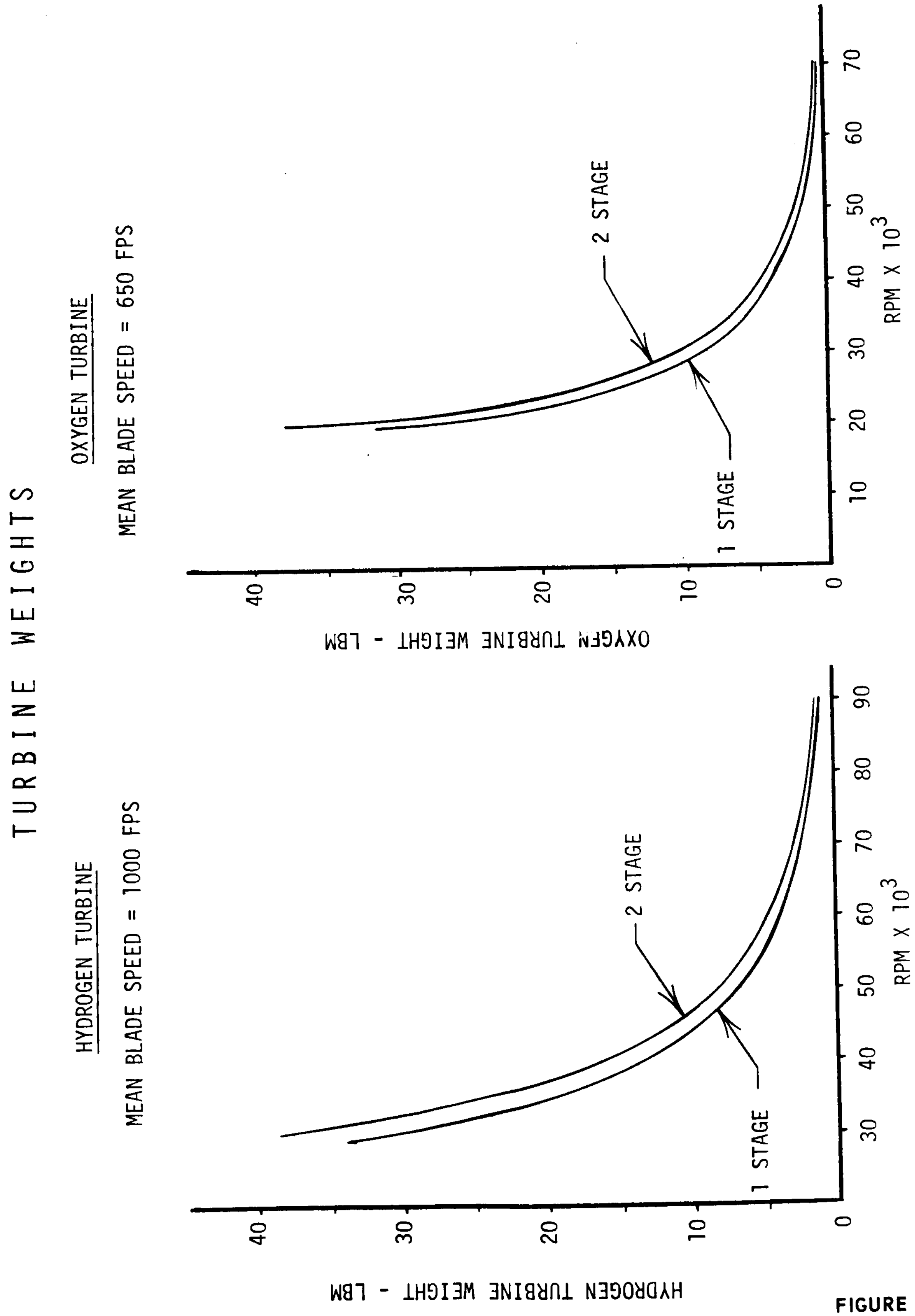

TURBINE WEIGHTS
OXYGEN TURBINE
MEAN BLADE SPEED = 650 FPS
2 STAGE
1 STAGE
OXYGEN TURBINE WEIGHT - LBM
RPM X 10^3
0
10
20
30
40
50
60
70
HYDROGEN TURBINE
MEAN BLADE SPEED = 1000 FPS
2 STAGE
1 STAGE
HYDROGEN TURBINE WEIGHT - LBM
RPM X 10^3
80
90

FIGURE 5-21

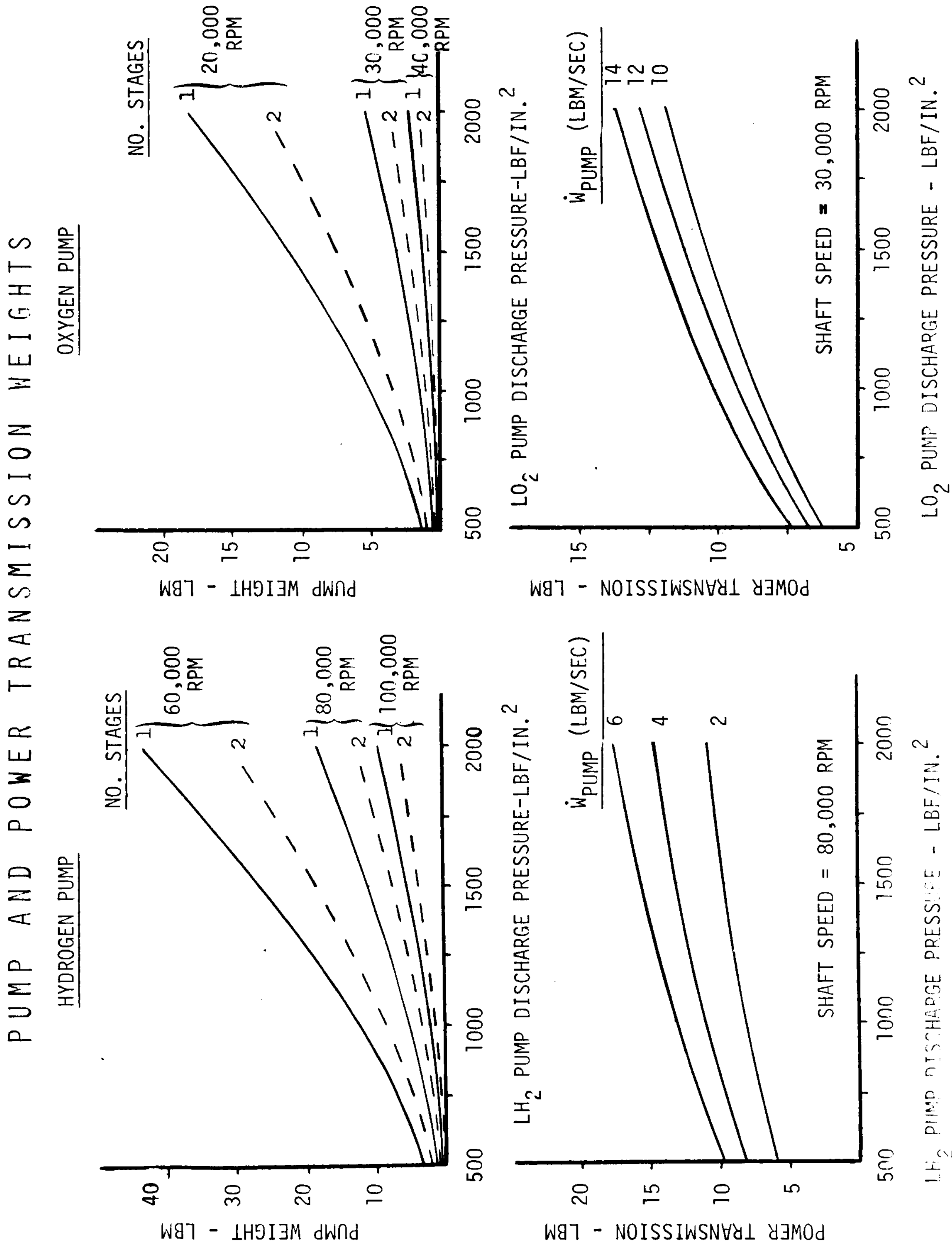

PUMP AND POWER TRANSMISSION WEIGHTS
HYDROGEN PUMP
NO. STAGES
60,000 RPM
80,000 RPM
100,000 RPM
PUMP WEIGHT - LBM
LH2 PUMP DISCHARGE PRESSURE-LBF/IN.2
ẆPUMP (LBM/SEC)
SHAFT SPEED = 80,000 RPM
POWER TRANSMISSION - LBM
LH2 PUMP DISCHARGE PRESSURE - LBF/IN.2
OXYGEN PUMP
NO. STAGES
20,000 RPM
30,000 RPM
40,000 RPM
PUMP WEIGHT - LBM
LO2 PUMP DISCHARGE PRESSURE-LBF/IN.2
ẆPUMP (LBM/SEC)
SHAFT SPEED = 30,000 RPM
POWER TRANSMISSION - LBM
LO2 PUMP DISCHARGE PRESSURE - LBF/IN.2

FIGURE 5-22

system mixture ratio of 2.95 and a system specific impulse of 355 sec. Thruster specific impulse is 433 sec at a mixture ratio of 4.0, 40:1 expansion ratio, and 300 lbf/in^2A chamber pressure. For both the heat exchanger and turbopump gas generators, combustion temperature and pressure are 2000°R and 300 lbf/in^2A. The accumulator volumes shown in Figure 5-23 are based on 50 RCS conditioner cycles per mission.

The parallel flow RCS requires low-flow rate, high-pressure-ratio turbines in order to efficiently utilize the available thermal energy from the gas generator combustion products. However, increases in turbine pressure ratio with resultant decreases in turbine discharge pressure produce offsetting increases in turbine vent system weight. Optimum RCS weight occurs at turbine pressure ratios of about 20:1 for both hydrogen and oxygen. The design turbine discharge pressure of 15 lbf/in^2A is also a desirable minimum in terms of facility requirements during turbopump development testing and/or ground checkout.

Conditioner temperature, pressure, and flow rate balances for the RCS design point are illustrated in Figure 5-24, and the sensitivity of RCS weight to pertinent design and operating parameters is shown in Figure 5-25.

5.2 RCS/OMS System Schematics - System schematics have been developed for the various RCS/OMS integration options and are discussed in Section 4. The candidates considered for the fully and partially integrated systems are listed in Figure 5-26 together with the methods for resolving mixture ratio differences and the methods for extending OMS operating time. Using this index, the applicable conditioner schematic, number of oxygen and hydrogen conditioners required, and applicable OMS schematic can be defined by the numerical code. The conditioner and OMS schematics referenced are shown in Figures 5-27 and 5-28. These schematics reflect the component redundancy required to meet the Shuttle fail-safe/fail-safe reliability criteria. Figure 5-29 presents an example which synthesizes the alternates on these figures into a complete RCS/OMS system.

The separate RCS/OMS configuration consists of the reaction control system discussed in Section 5.1.4, an OMS with staged combustion cycle engines, the propellant feed subsystem, and a common RCS/OMS propellant storage assembly.

5.3 Preliminary System Comparison - A preliminary system comparison was made for all the RCS/OMS system schematics discussed in the previous section. Total system weights and weight sensitivities to key design parameters (chamber pressure and mixture ratio) were developed to determine preliminary design points for each integration option. The weight comparison is based on the following criteria:

PARALLEL GGA FLOW RCS - DESIGN POINT SUMMARY

	FULLY-REUSABLE ORBITER	
SYSTEM		
TOTAL IMPULSE, LBF-SEC	2.23 M	
MIXTURE RATIO	2.95	
SPECIFIC IMPULSE, SEC	355	
THRUSTER		
THRUST LEVEL, LBF	1150	
MIXTURE RATIO	4.0	
CHAMBER PRESSURE, LBF/IN^2	300.	
EXPANSION RATIO	40:1	
SPECIFIC IMPULSE, SEC	433	
GAS GENERATOR	O_2	H_2
COMBUSTION TEMPERATURE, °R	1997	2000
FLOWRATE, LBM/SEC	.227 - TPA .770 - HEX	.605 - TPA 1.27 - HEX
HEAT EXCHANGER		
HOT SIDE INLET TEMP, °R	1997	2000
COLD SIDE EXIT TEMP, °R	476	207
TURBOPUMP ASSEMBLY		
FLOWRATE, LBM/SEC	12.11	4.03
DISCHARGE PRESSURE, LBF/IN^2	1580	1201
SHAFT HORSEPOWER	150	560
ACCUMULATOR		
NO. CYCLES	50.0	50.0
VOLUME, FT^3	15.4	52.0
PRESSURES, LBF/IN^2 - MAX	1370	1101
- SWITCH	654	647
- MIN	571	571
WEIGHT	10,690	

FIGURE 5-23

CONDITIONER PRESSURE, TEMPERATURE AND FLOW BALANCE

PARALLEL GGA FLOW

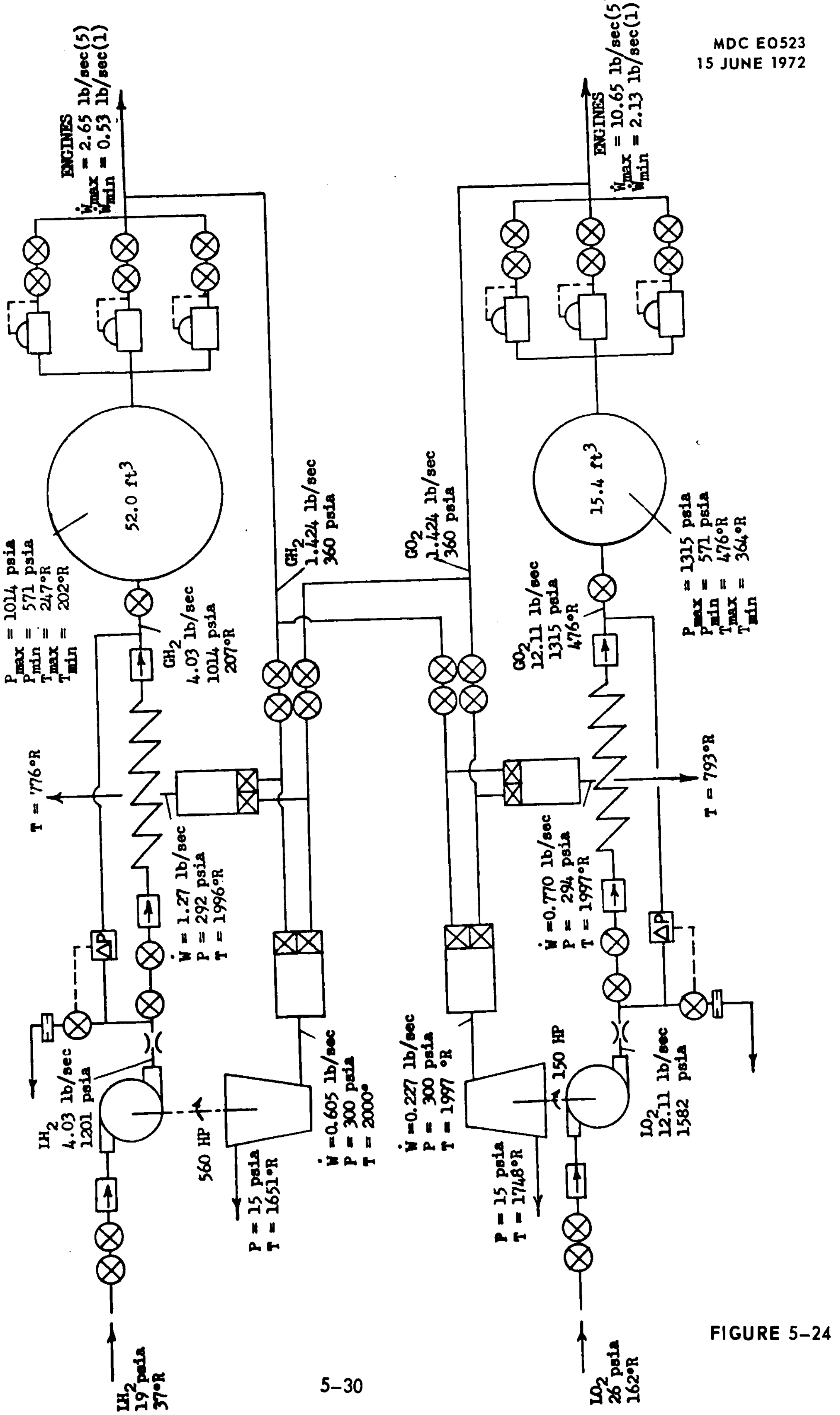


FIGURE 5–24

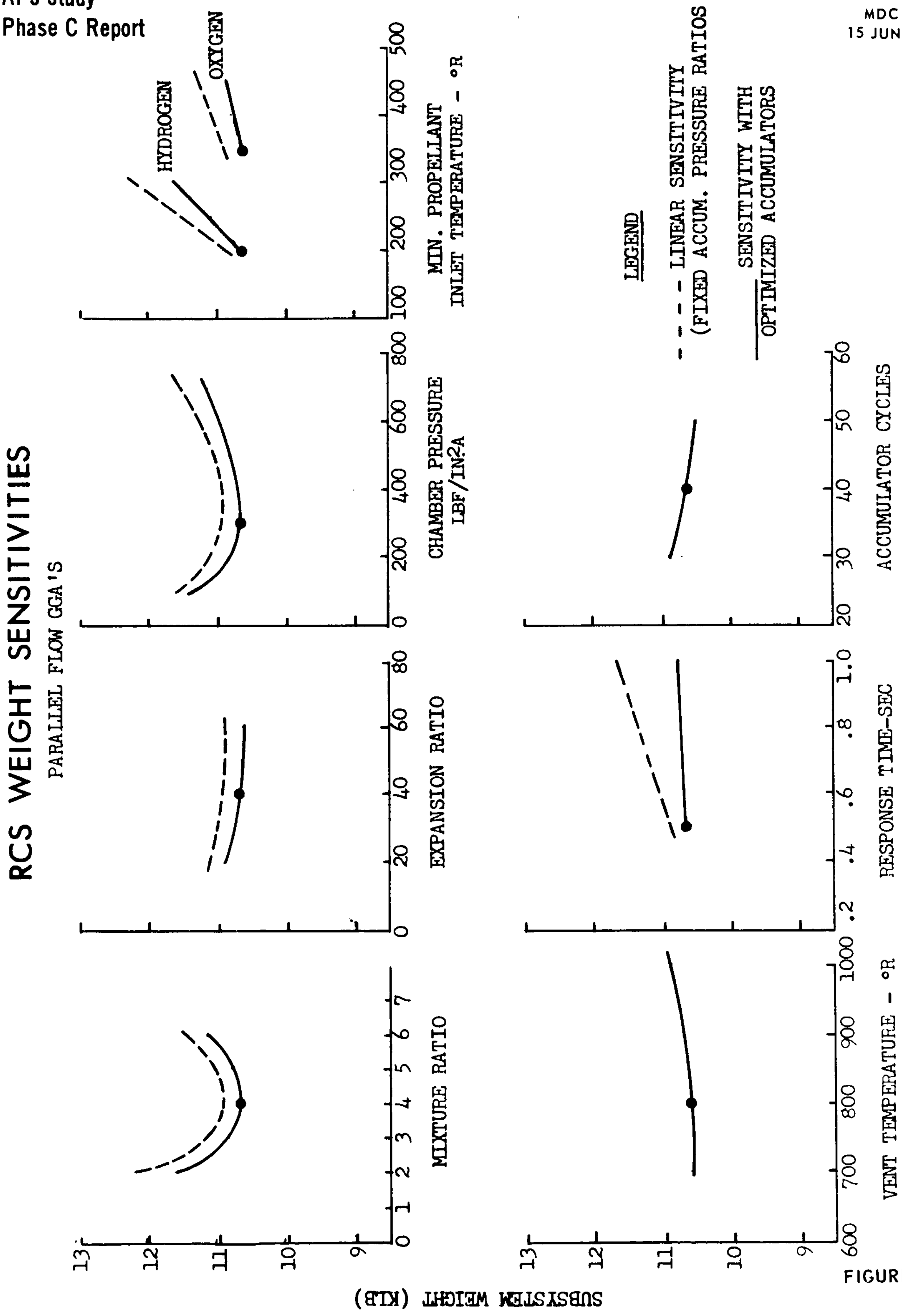

RCS WEIGHT SENSITIVITIES
PARALLEL FLOW GGA'S
SUBSYSTEM WEIGHT (KLB)
MIXTURE RATIO
EXPANSION RATIO
CHAMBER PRESSURE
LBF/IN2A
MIN. PROPELLANT
INLET TEMPERATURE - °R
HYDROGEN
OXYGEN
VENT TEMPERATURE - °R
RESPONSE TIME-SEC
ACCUMULATOR CYCLES
LEGEND
LINEAR SENSITIVITY
(FIXED ACCUM. PRESSURE RATIOS
SENSITIVITY WITH
OPTIMIZED ACCUMULATORS

FIGURE 5-25

SYSTEM CONFIGURATION MATRIX

			CONDITIONER SCHEMATICS	NUMBER OF CONDITIONER O_2	NUMBER OF CONDITIONER H_2	OMS SCHEMATICS
	FULLY INTEGRATED SYSTEMS					
1.	OPERATE RCS AT OMS MR	USE RCS CONDITIONER	2	3	3	A
2.		ENLARGE ACCUMULATOR	2	3	3	A
3.		BILEVEL CONDITIONER CONTROL	3	3	3	A
4.		ADD SMALL CONDITIONER	2	3	3	B
5.	OPERATE OMS AT RCS MR	USE RCS CONDITIONER	2	3	3	A
6.		ENLARGE ACCUMULATOR	2	3	3	A
7.		BILEVEL CONDITIONER CONTROL	3	3	3	A
8.		ADD SMALL CONDITIONER	2	3	3	B
9.	OPERATE 2 O_2 PUMPS FOR OMS	USE RCS CONDITIONER	2	3	3	C
10.		ENLARGE ACCUMULATOR	2	3	3	C
11.		BILEVEL CONDITIONER CONTROL	3	3	3	C
12.		ADD SMALL CONDITIONER	2	3	3	D
13.	OPERATE 2 H_2 PUMPS FOR RCS	USE RCS CONDITIONER	2	3	4	A
14.		ENLARGE ACCUMULATOR	2	3	4	A
15.		BILEVEL CONDITIONER CONTROL	3	3	4	A
16.		ADD SMALL CONDITIONER	2	3	4	B
17.	OPERATE PUMPS BILEVEL	USE RCS CONDITIONER	4	3	3	A
18.		ENLARGE ACCUMULATOR	4	3	3	A
19.		BILEVEL CONDITIONER CONTROL	5	3	3	A
20.		ADD SMALL CONDITIONER	4	3	3	B
	PARTIALLY INTEGRATED SYSTEMS					
1.	DESIGN FOR OMS	USE RCS CONDITIONER	1	3	3	E
2.		ENLARGE ACCUMULATOR	1	3	3	E
3.		RECHARGE BY OMS	1	3	3	E
4.	RCS & OMS INDEPENDENTLY SIZED	USE RCS CONDITIONER	1	3	3	E
5.		ENLARGE ACCUMULATORS	1	3	3	E
6.		RECHARGE BY OMS	1	3	3	F

FIGURE 5-26

RCS/OMS IMPLEMENTATION CONDITIONER CONCEPTS

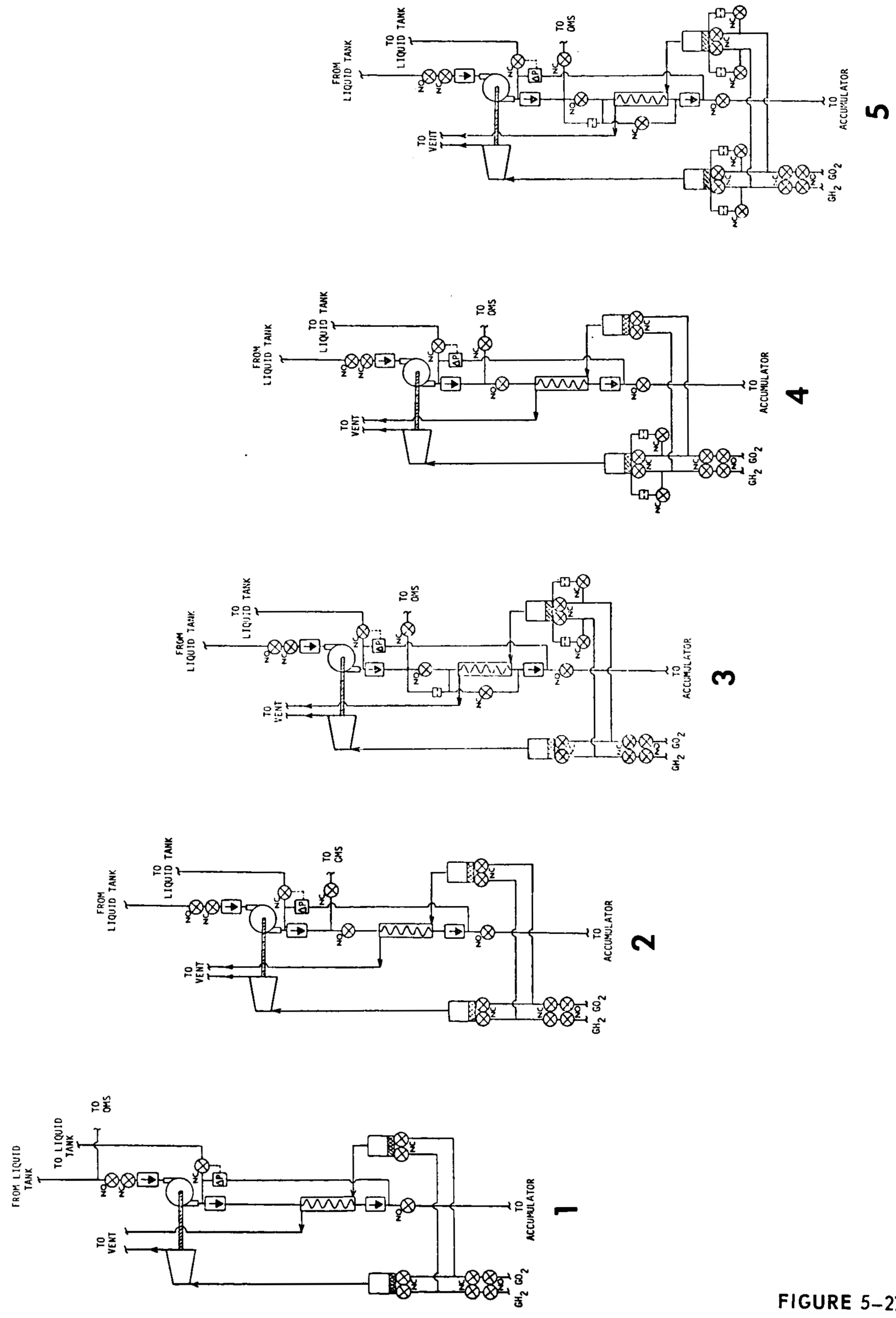


FIGURE 5-27

RCS/OMS IMPLEMENTATION OMS OPTIONS

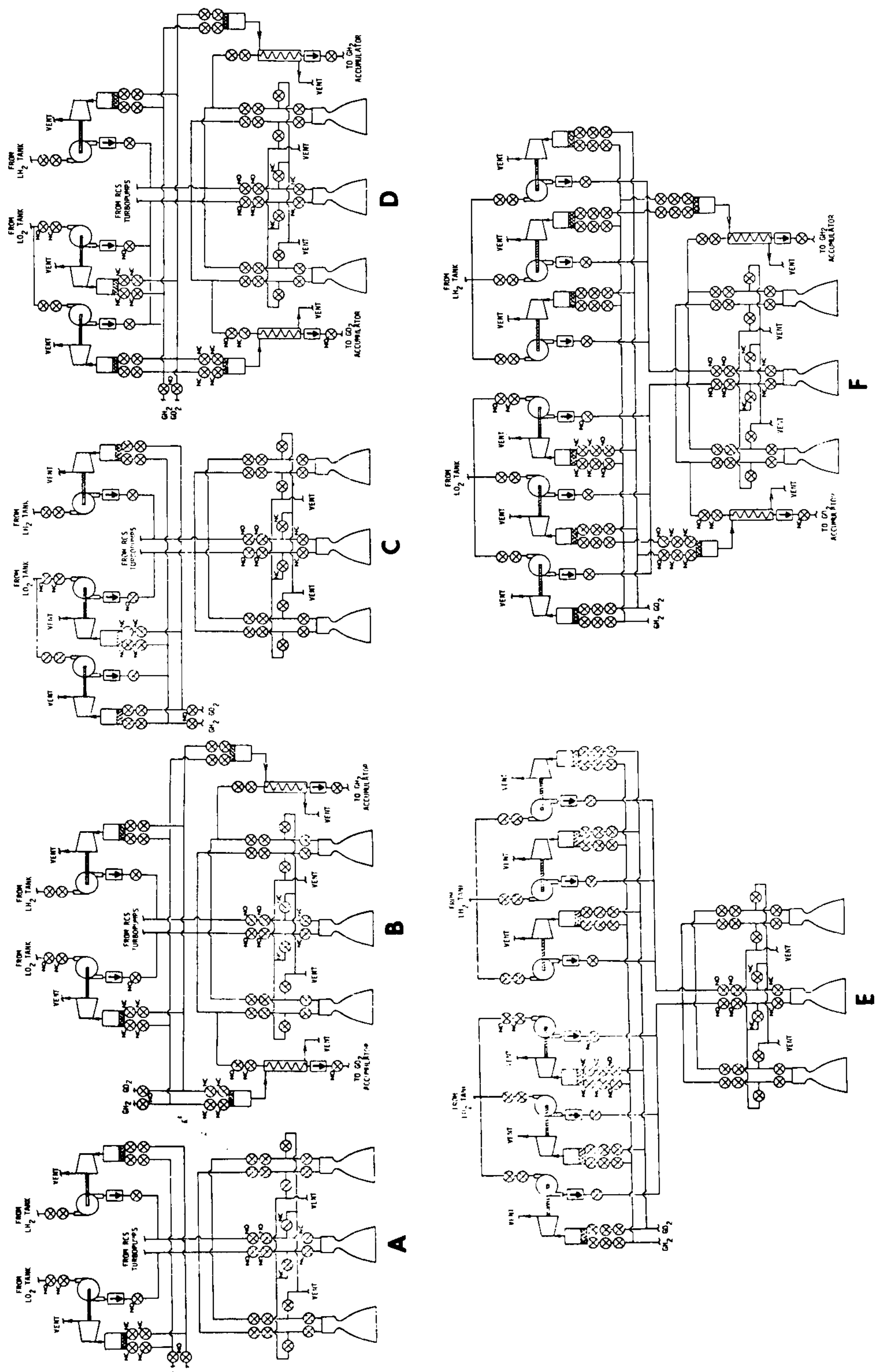
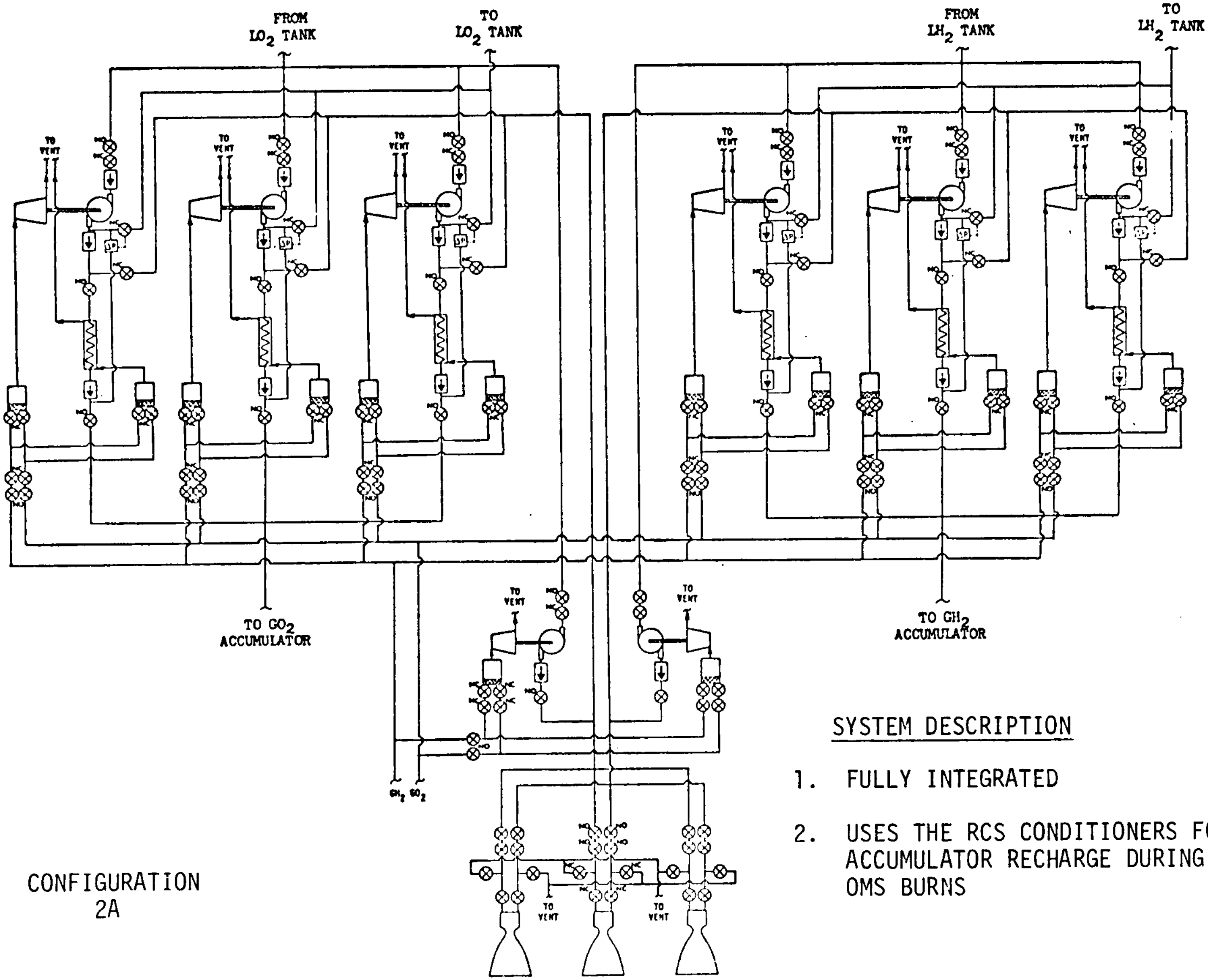


FIGURE 5-28

TYPICAL RCS/OMS SYSTEM IMPLEMENTATION



SYSTEM DESCRIPTION

1. FULLY INTEGRATED
2. USES THE RCS CONDITIONERS FOR ACCUMULATOR RECHARGE DURING OMS BURNS

CONFIGURATION
2A

FIGURE 5-29

integrated RCS/OMS positive expulsion tankage, cold helium pressurization of both propellants, propellant and pressurant tanks sized for an OMS velocity increment of 2000 fps, propellant and pressurant loaded for both the easterly launch design mission (OMS ΔV = 373 fps) and for the fully loaded case (OMS ΔV = 2000 fps). The OMS engines and feed system, turbomachinery, and RCS components used in the comparison were discussed in previous sections herein. The component redundancy required and shown in the schematics was included to allow valid weight comparisons. Results of this analysis are summarized in Figure 5-30 where relative weights for each candidate configuration are given for both OMS velocity increments (373 and 2000 fps). A total of 83 configurations were investigated for the 3 levels of RCS/OMS integration.

For the fully integrated system, system weight was significantly affected by the method employed to resolve the RCS and OMS mixture ratio differences, while the accumulator resupply options had less effect on total weight. Large weight penalties (800 to 1300 lbm) are incurred for operating the OMS at the RCS mixture ratio or conversely. The relationship between the OMS engine mixture ratio (RCS pump mixture ratio) and the RCS thruster and system mixture ratios are shown in Figure 5-31. Using these relationships, the RCS/OMS system weight was calculated as a function of OMS mixture ratio indicating a minimum overall system weight at an OMS mixture ratio of four (see Figure 5-32). For the three remaining mixture ratio options (running two oxygen and one hydrogen pump for the OMS, running one oxygen and two hydrogen pumps for the RCS, or operating the pumps bilevel), both the RCS and OMS operate at or near their optimum mixture ratios and are, thereby, weight competitive. In the bilevel pump concept, the pumps are designed for maximum efficiency at the OMS operating conditions and operate off-design for the RCS. However, the relatively flat efficiency-flow characteristics of the pump design results in high performance for both modes of operation. Significant engine thrust level differences result from the variations in mixture ratio and flow rate. Accordingly, system weight sensitivity to OMS thrust level was evaluated; the results are shown in Figure 5-33 for the easterly mission. As illustrated, the 800 to 1000 lb weight penalty associated with operation at off-design mixture ratios for either the RCS or OMS remains essentially constant over the thrust range of interest. The major difference in system weight for the various options of accumulator gas resupply is about 200 lbm for an OMS ΔV of 373 fps and 750 lbm for 2000 fps. This weight is associated with the option in which the accumulators are enlarged to maintain the same number of conditioner operating cycles. The other resupply options have competitive weight characteristics.

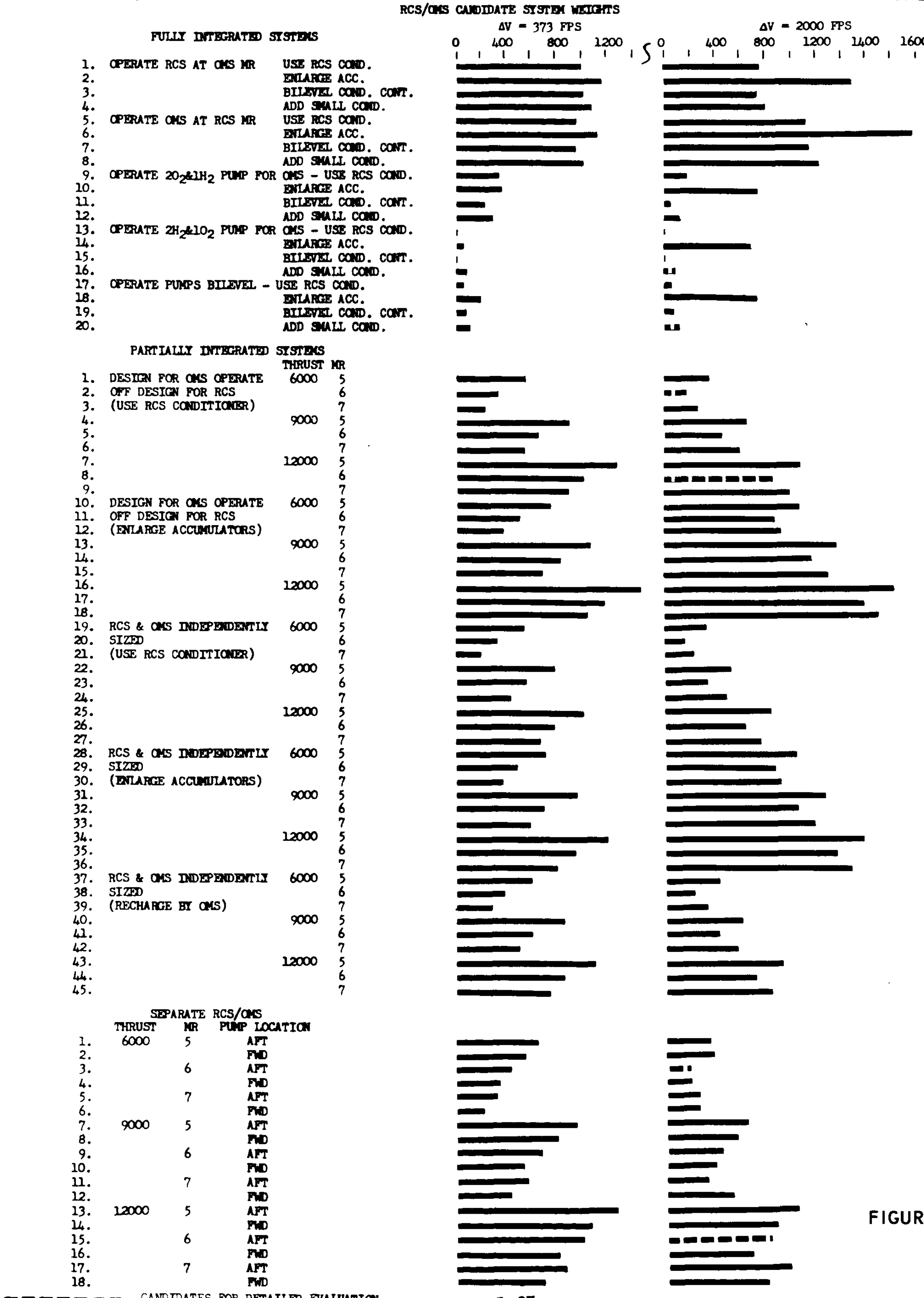

RCS/OMS CANDIDATE SYSTEM WEIGHTS
ΔV = 373 FPS
0 400 800 1200
ΔV = 2000 FPS
0 400 800 1200 1400 1600
FULLY INTEGRATED SYSTEMS
1. OPERATE RCS AT OMS MR USE RCS COND.
2. ENLARGE ACC.
3. BILEVEL COND. CONT.
4. ADD SMALL COND.
5. OPERATE OMS AT RCS MR USE RCS COND.
6. ENLARGE ACC.
7. BILEVEL COND. CONT.
8. ADD SMALL COND.
9. OPERATE 2O2&1H2 PUMP FOR OMS - USE RCS COND.
10. ENLARGE ACC.
11. BILEVEL COND. CONT.
12. ADD SMALL COND.
13. OPERATE 2H2&1O2 PUMP FOR OMS - USE RCS COND.
14. ENLARGE ACC.
15. BILEVEL COND. CONT.
16. ADD SMALL COND.
17. OPERATE PUMPS BILEVEL - USE RCS COND.
18. ENLARGE ACC.
19. BILEVEL COND. CONT.
20. ADD SMALL COND.
PARTIALLY INTEGRATED SYSTEMS
THRUST MR
1. DESIGN FOR OMS OPERATE 6000 5
2. OFF DESIGN FOR RCS 6
3. (USE RCS CONDITIONER) 7
4. 9000 5
5. 6
6. 7
7. 12000 5
8. 6
9. 7
10. DESIGN FOR OMS OPERATE 6000 5
11. OFF DESIGN FOR RCS 6
12. (ENLARGE ACCUMULATORS) 7
13. 9000 5
14. 6
15. 7
16. 12000 5
17. 6
18. 7
19. RCS & OMS INDEPENDENTLY 6000 5
20. SIZED 6
21. (USE RCS CONDITIONER) 7
22. 9000 5
23. 6
24. 7
25. 12000 5
26. 6
27. 7
28. RCS & OMS INDEPENDENTLY 6000 5
29. SIZED 6
30. (ENLARGE ACCUMULATORS) 7
31. 9000 5
32. 6
33. 7
34. 12000 5
35. 6
36. 7
37. RCS & OMS INDEPENDENTLY 6000 5
38. SIZED 6
39. (RECHARGE BY OMS) 7
40. 9000 5
41. 6
42. 7
43. 12000 5
44. 6
45. 7
SEPARATE RCS/OMS
THRUST MR PUMP LOCATION
1. 6000 5 AFT
2. FWD
3. 6 AFT
4. FWD
5. 7 AFT
6. FWD
7. 9000 5 AFT
8. FWD
9. 6 AFT
10. FWD
11. 7 AFT
12. FWD
13. 12000 5 AFT
14. FWD
15. 6 AFT
16. FWD
17. 7 AFT
18. FWD
CANDIDATES FOR DETAILED EVALUATION

FIGURE 5-30

OMS ENGINE MR AS A FUNCTION OF RCS THRUSTER MR

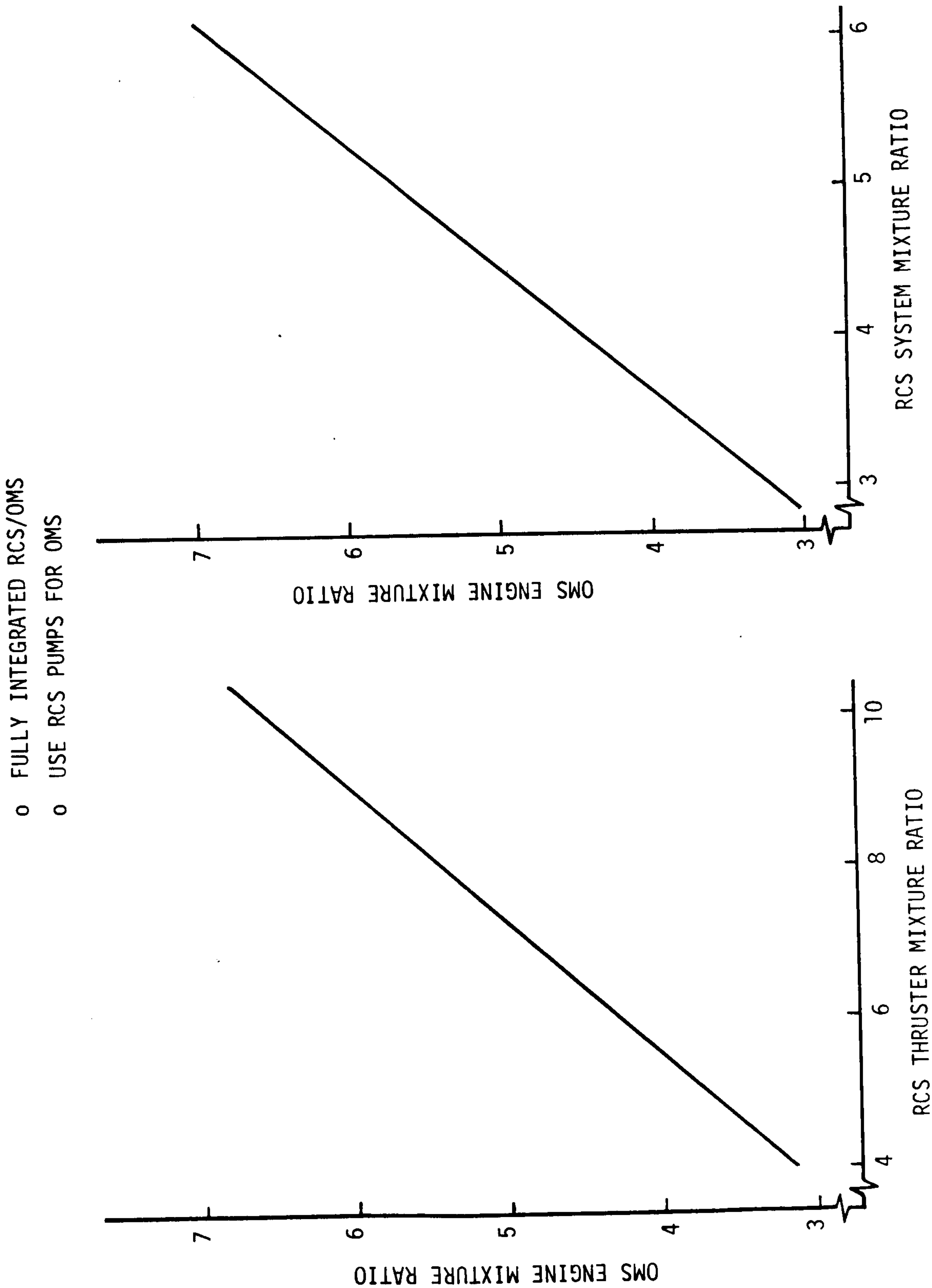


FIGURE 5-31

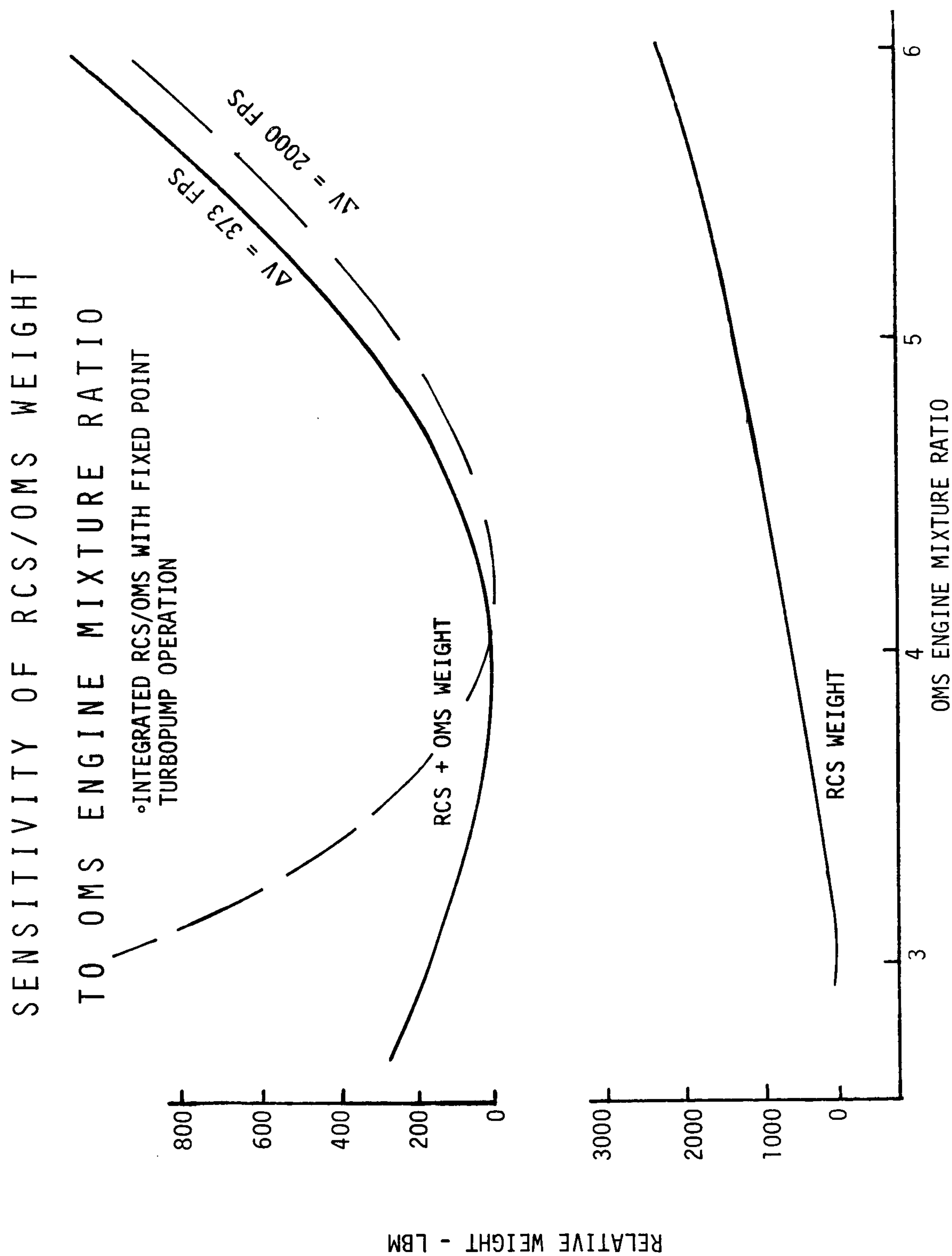

SENSITIVITY OF RCS/OMS WEIGHT
TO OMS ENGINE MIXTURE RATIO
°INTEGRATED RCS/OMS WITH FIXED POINT
TURBOPUMP OPERATION
ΔV = 2000 FPS
ΔV = 373 FPS
RCS + OMS WEIGHT
RCS WEIGHT
800
600
400
200
0
3000
2000
1000
0
RELATIVE WEIGHT - LBM
3
4
5
6
OMS ENGINE MIXTURE RATIO

FIGURE 5-32

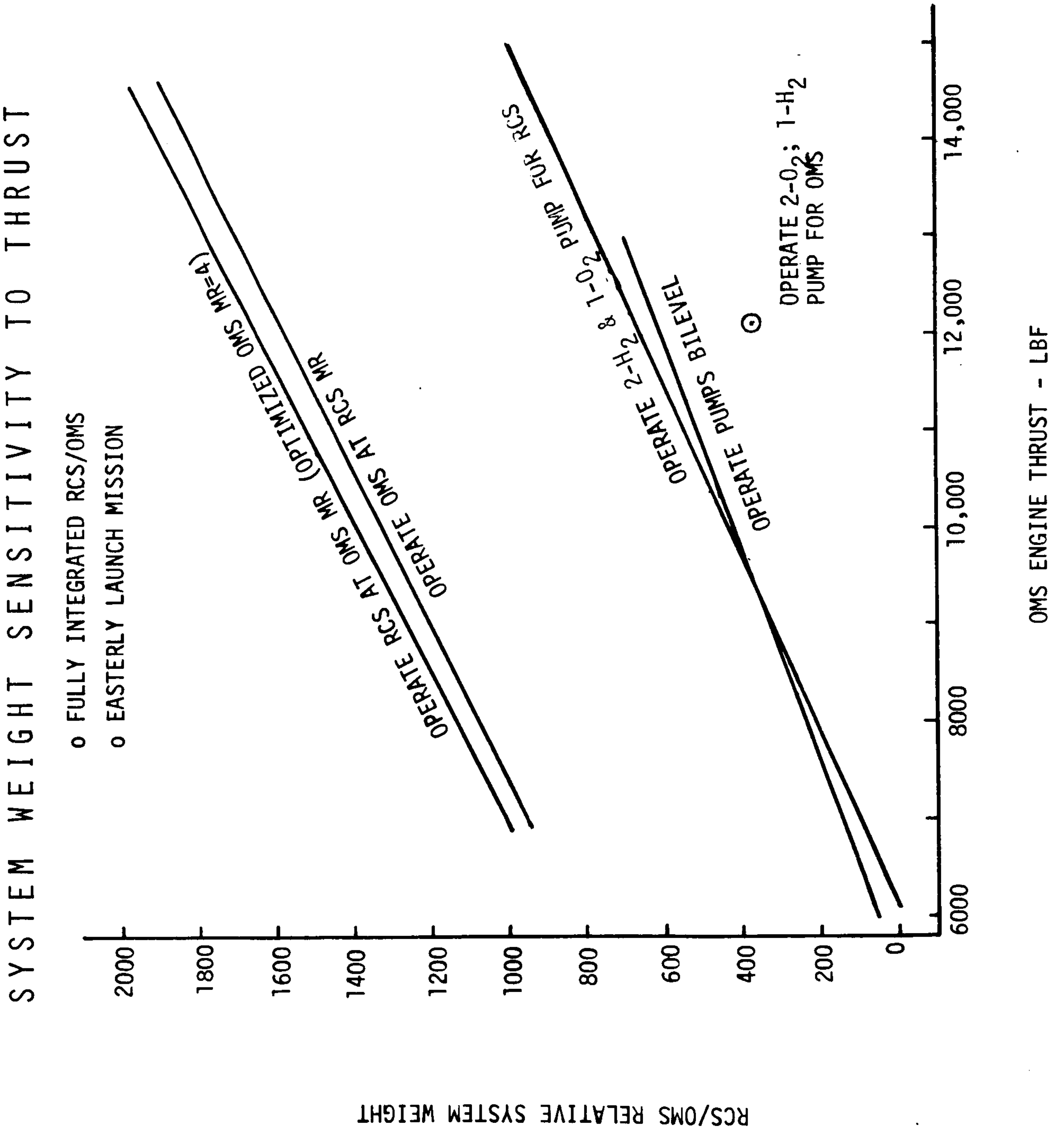

SYSTEM WEIGHT SENSITIVITY TO THRUST
o FULLY INTEGRATED RCS/OMS
o EASTERLY LAUNCH MISSION
OPERATE RCS AT OMS MR (OPTIMIZED OMS MR=4)
OPERATE OMS AT RCS MR
OPERATE 2-H2 & 1-O2 PUMP FOR RCS
OPERATE PUMPS BILEVEL
OPERATE 2-O2; 1-H2 PUMP FOR OMS
RCS/OMS RELATIVE SYSTEM WEIGHT
2000
1800
1600
1400
1200
1000
800
600
400
200
0
6000
8000
10,000
12,000
14,000
OMS ENGINE THRUST - LBF

FIGURE 5-33

Weights for partially integrated systems were determined for various OMS thrust levels and mixture ratios, since at this integration level both the OMS and RCS have their own turbopumps. Thrust levels of 6000, 9000, and 12,000 lbf and mixture ratios of 5, 6, and 7 were evaluated for each turbopump configuration option and accumulator resupply option (see Figure 5-30). The OMS engine chamber pressure was baselined at 1000 lbf/in^2A and a nozzle expansion ratio of 240:1 was used. At a specific thrust level and mixture ratio, use of independently sized RCS and OMS turbopumps resulted in only a small system weight savings compared with operating the same pump configuration in a bilevel mode at two different design points. This is again due to the flat efficiency-flow curves of the pump, allowing good efficiency at both RCS and OMS conditions. Development of independently sized pumps would result in weight savings of 20 to 25 lbm at the 6000 lbf thrust level, 110 to 125 lbm at 9000 lbf, and 220 to 250 lbm at 12,000 lbf. As with the fully integrated systems, the use of enlarged accumulators produces the largest accumulator gas makeup weight penalty. This penalty is impulse dependent and is the same as for the fully integrated system. The weight sensitivity of a partially integrated system to OMS mixture ratio is illustrated in Figure 5-34. In this example, the same turbopump configuration is used for both the RCS and OMS. RCS conditioners are used for accumulator resupply and the OMS thrust level is 9000 lbf. As Figure 5-34 indicates, the system weights are relatively insensitive in the OMS mixture ratio range of 5 to 7, but an optimum does exist at a mixture ratio of 6 for the 2000-fps velocity increment case.

Separate RCS/OMS system weights were evaluated for the same three thrust levels and mixture ratios used above for the partially integrated case. For this initial evaluation of separate systems a gas generator cycle engine was assumed and again, baseline chamber pressure and expansion ratio were 1000 lbf/in^2A and 240:1 respectively. Both forward located OMS pumps and aft located pumps were studied to define optimum component location. As Figure 5-30 shows, the forward pump location is somewhat lighter over essentially the whole range of thrust and mixture ratio values, but long high pressure lines are required and the engine ignition would be inherently more difficult to sequence. System sensitivities to mixture ratio and thrust level may also be seen in Figure 5-30. The separate system weight optimized at an OMS engine mixture ratio of 6 for the 2000 fps velocity increment case.

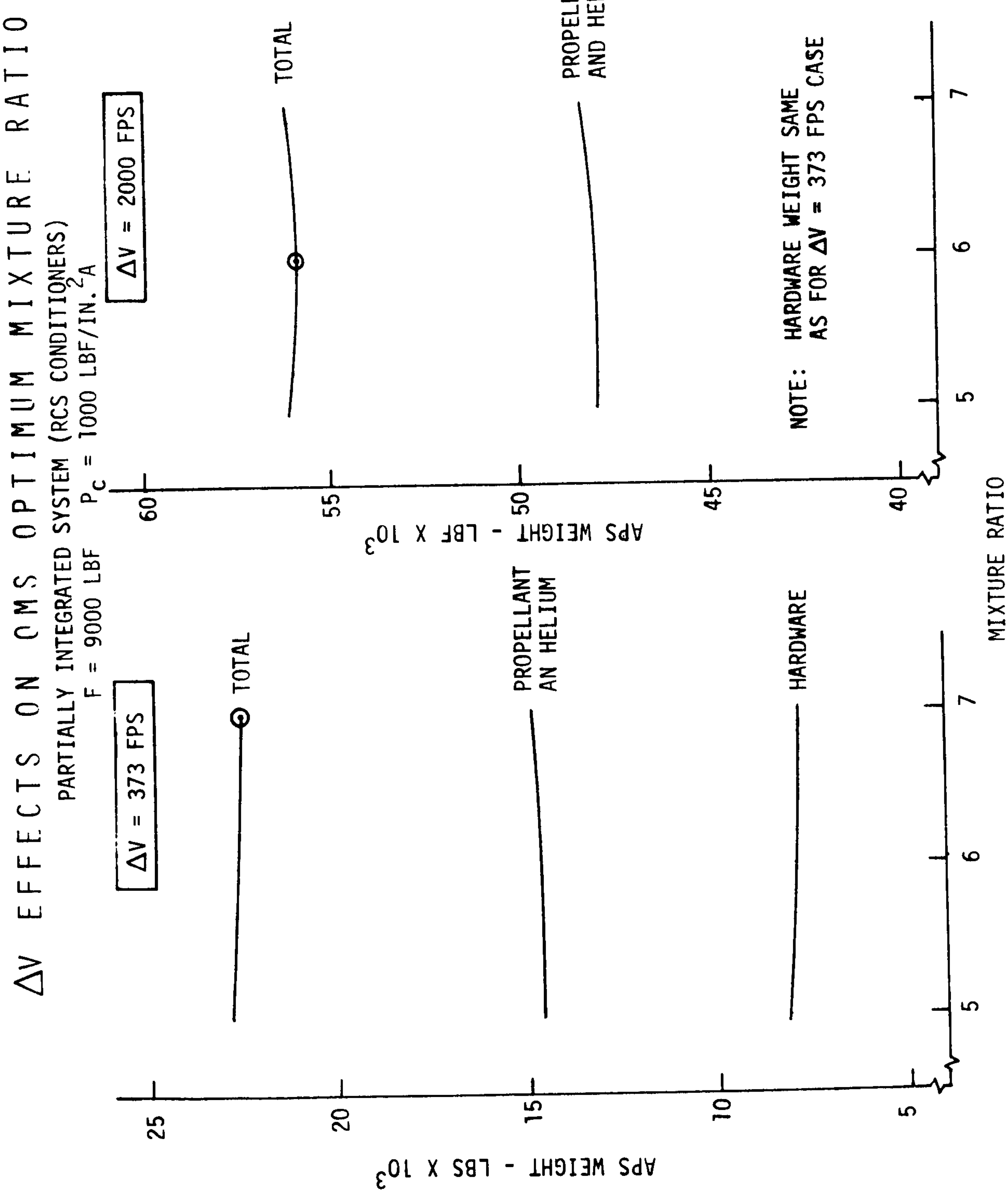

ΔV EFFECTS ON OMS OPTIMUM MIXTURE RATIO
PARTIALLY INTEGRATED SYSTEM (RCS CONDITIONERS)
F = 9000 LBF P_C = 1000 LBF/IN.^{2}A
ΔV = 2000 FPS
TOTAL
PROPELLANT AND HELIUM
NOTE: HARDWARE WEIGHT SAME AS FOR ΔV = 373 FPS CASE
APS WEIGHT - LBF X 10^3
60
55
50
45
40
5
6
7
ΔV = 373 FPS
TOTAL
PROPELLANT AN HELIUM
HARDWARE
APS WEIGHT - LBS X 10^3
25
20
15
10
5
MIXTURE RATIO

FIGURE 5-34

Concern with the ability to properly sequence ignition was the principal factor leading to elimination of OMS engines using forward located pumps. With this decision a comparison was made between a gas generator cycle engine with aft located pumps and a staged combustion cycle engine with pumps incorporated as an integral part of the engine assembly. This comparison showed that the system performance was far superior with the staged combustion engine and the remainder of study effort on separate systems considered this engine type exclusively.

5.4 Candidate System Selection - Four RCS/OMS system configurations were selected from the preliminary screening as candidates for more detailed evaluation. These configurations are indicated in Figure 5-30 and include two fully integrated systems, a partially integrated system, and a separate system. Except for one fully integrated system, in which OMS thrust is dictated by the RCS design, each system was evaluated at OMS thrust levels of 6000 and 12,000 lbf.

The two selected options for resolving fully integrated RCS and OMS mixture ratio differences are: (1) using pumps designed for RCS requirements operate two oxygen pumps and one hydrogen pump for the OMS, and (2) using the pumps in a bilevel mode which provides maximum efficiency for the OMS operation. As indicated previously, these two options are lighter weight when compared with operating the OMS at the RCS mixture ratio or conversely. Systems which use two hydrogen pumps were also competitive at low thrust levels, but exhibited greater weight sensitivity to thrust and consequently were not selected. For the partially integrated configuration, the same turbopump design was chosen for both the RCS and OMS. This pump is also designed for maximum efficiency for the OMS and operates off-design when used in the RCS. Development of independently sized RCS and OMS pumps is not justified by the small weight advantage of this option. As stated in the turbopump section, the bilevel pumps require gas generator and pump output control to operate at the different discharge pressures and flows of the integrated OMS and RCS. For the separate RCS/OMS, the pumps are an integral part of the staged combustion cycle engine.

A separate gas generator and heat exchanger were selected as the recommended method of providing accumulator makeup propellant required for the integrated systems during OMS operation. This selection was based on design and system weight considerations. In the first option, running the standby RCS conditioners at full capacity during an OMS burn increases the number of RCS accumulator cycles (Reference Figure 5-35A). Penalties for both an easterly launch and polar launch missions are indicated. The hydrogen accumulator represents the constraining condition since, at low gas generator mixture ratios, it depletes at a much

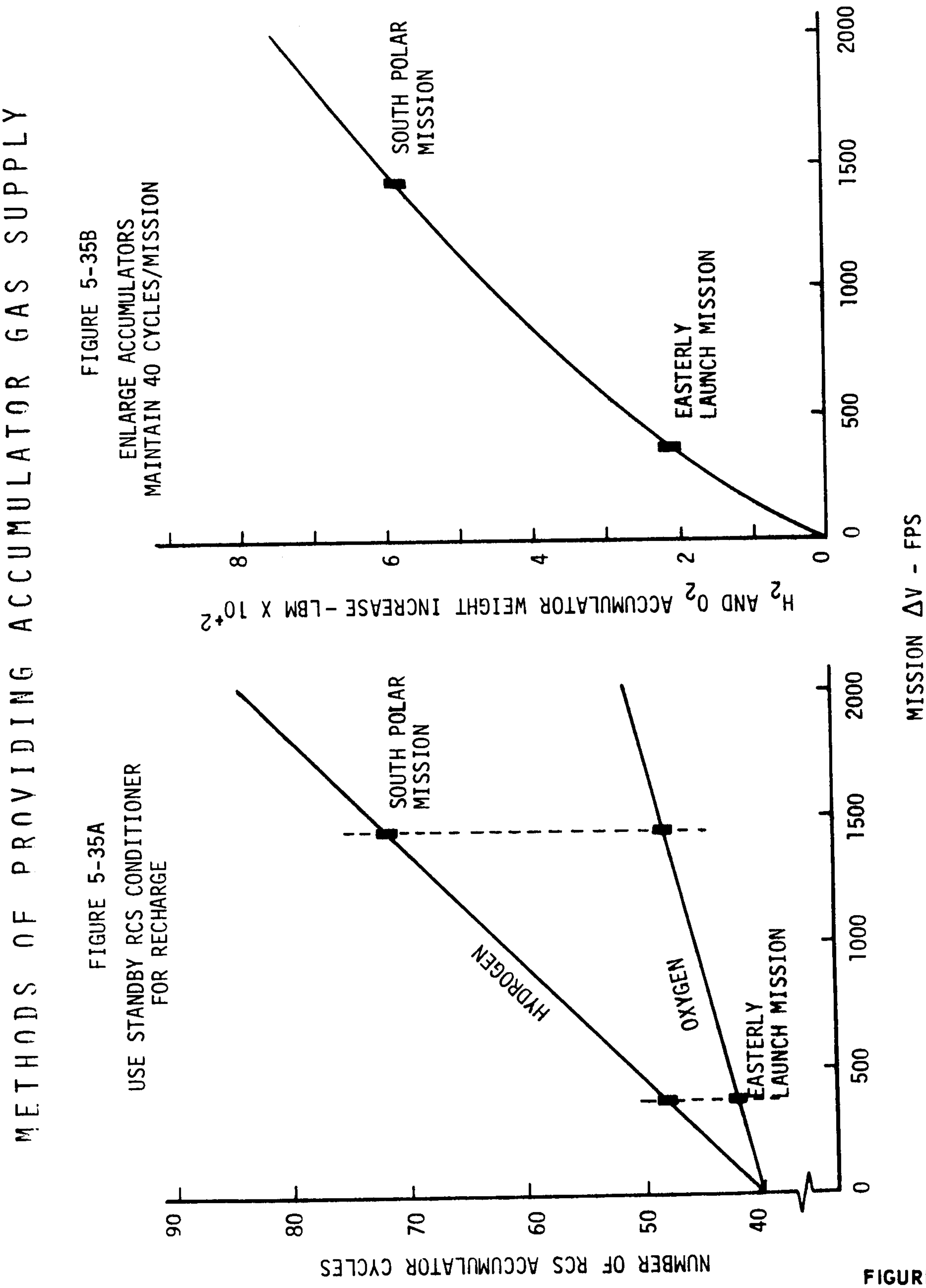

METHODS OF PROVIDING ACCUMULATOR GAS SUPPLY
FIGURE 5-35A
USE STANDBY RCS CONDITIONER FOR RECHARGE
NUMBER OF RCS ACCUMULATOR CYCLES
90
80
70
60
50
40
HYDROGEN
OXYGEN
SOUTH POLAR MISSION
EASTERLY LAUNCH MISSION
0
500
1000
1500
2000
FIGURE 5-35B
ENLARGE ACCUMULATORS
MAINTAIN 40 CYCLES/MISSION
H_2 AND O_2 ACCUMULATOR WEIGHT INCREASE - LBM X 10^{+2}
8
6
4
2
0
SOUTH POLAR MISSION
EASTERLY LAUNCH MISSION
0
500
1000
1500
2000
MISSION ΔV - FPS

FIGURE 5-35

faster rate than the oxygen accumulator. The additional number of hydrogen conditioner cycles per flight is 9 for an easterly launch mission and 45 for a 2000-fps mission. These increases significantly impact component design life and, as such, this approach was eliminated from further consideration. Maintaining the same number of conditioner cycles by enlarging the accumulators and reoptimizing the accumulator pressure ratios results in a weight increase of 150 to 200 lbm for the easterly launch mission. However, the weight increase is 750 lbm for a 2000-fps mission and this was considered to be an excessive penalty. Figure 5-35B presents this weight penalty as a function of mission velocity requirements. The third method of providing accumulator makeup is to bleed a small portion of the pump flow through the heat exchanger for conditioning to the required accumulator inlet temperature. This reduced flow rate necessitates heat exchanger operation at conditions far below design and requires severe throttling of the heat exchanger gas generators. This effect is shown in Figure 5-36 for an OMS thrust level of 12,000 lbf. For both the hydrogen and oxygen sides, gas generator flows required for OMS operation are about 10 percent of the RCS flow rates. In addition, to prevent freezing of H_2O in the hot side flow, bypass of the cold flow around the heat exchanger is required. This off-design performance is shown for the hydrogen and oxygen side heat exchangers in Figures 5-37 and 5-38 respectively. Hot side inlet and outlet temperatures are 2000 and 800°R, respectively, for both hydrogen and oxygen side heat exchangers, while cold side exit conditions are 250°R for hydrogen and 470°R for oxygen. The cold side bypass required is between 70 and 75 percent in the hydrogen side and 40 percent in the oxygen side. The increased control required to bypass the heat exchanger, and deep throttle the gas generator, would result in significantly increased development time and cost, making this option undesirable. Thus, the recommended method of providing accumulator makeup is to use a separate gas generator and heat exchanger which has the same controls as the RCS. This additional heat exchanger and gas generator would be sized to condition only the accumulator makeup gas required for OMS operation. A single unit would be added for each propellant, and backup operation in case of a failure would be provided by one of the standby RCS conditioners.

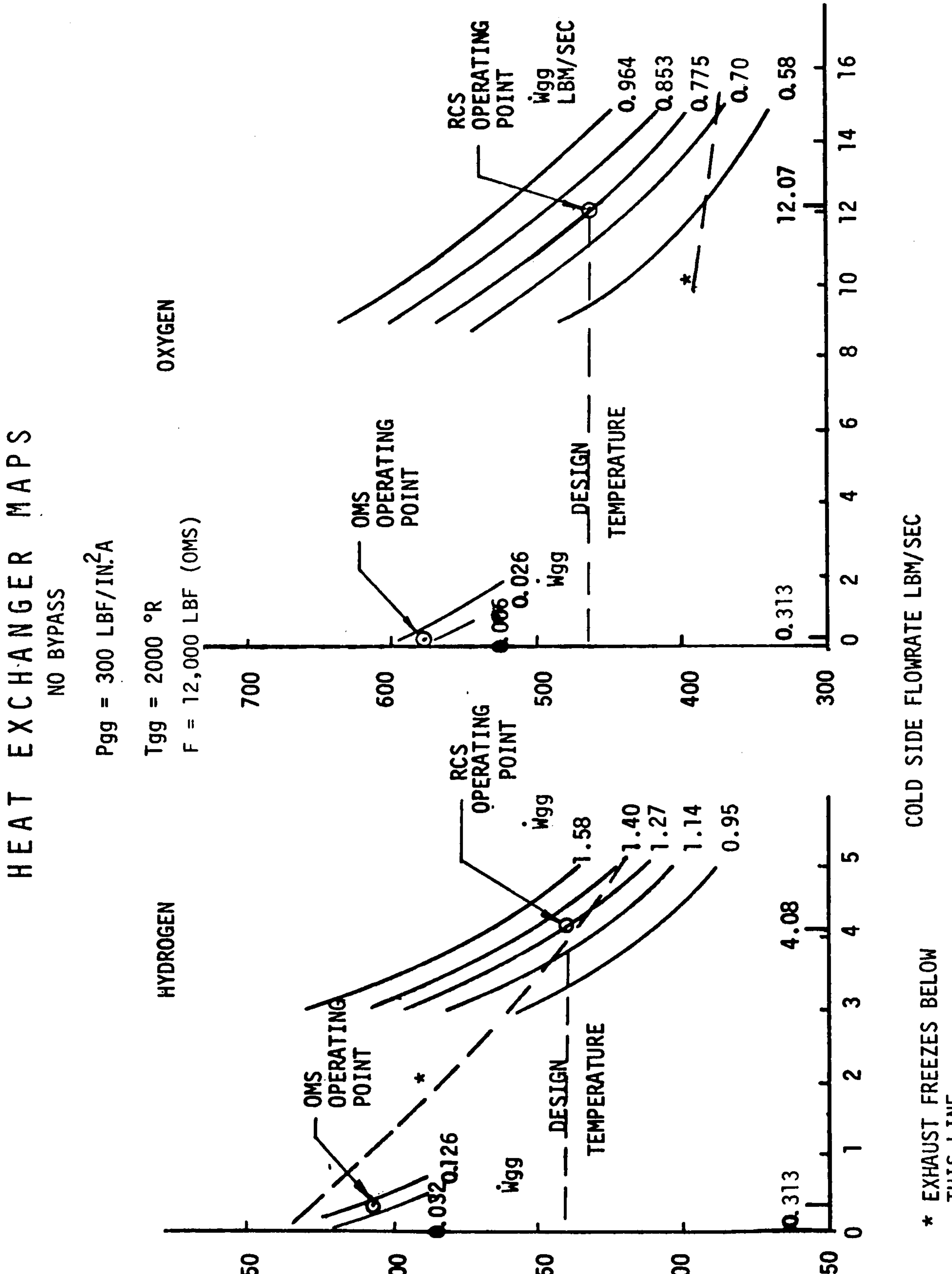

HEAT EXCHANGER MAPS
NO BYPASS
Pgg = 300 LBF/IN.2A
Tgg = 2000 °R
F = 12,000 LBF (OMS)
HYDROGEN
OXYGEN
COLD SIDE EXIT TEMP - °R
COLD SIDE FLOWRATE LBM/SEC
RCS OPERATING POINT
OMS OPERATING POINT
Ẇgg
Ẇgg LBM/SEC
DESIGN TEMPERATURE
1.58
1.40
1.27
1.14
0.95
0.126
0.032
0.313
4.08
0.964
0.853
0.775
0.70
0.58
0.026
0.006
12.07
350
300
250
200
150
700
600
500
400
0
1
2
3
4
5
6
8
10
12
14
16
* EXHAUST FREEZES BELOW THIS LINE

FIGURE 5-36

HYDROGEN APS HEAT EXCHANGER OFF DESIGN PERFORMANCE

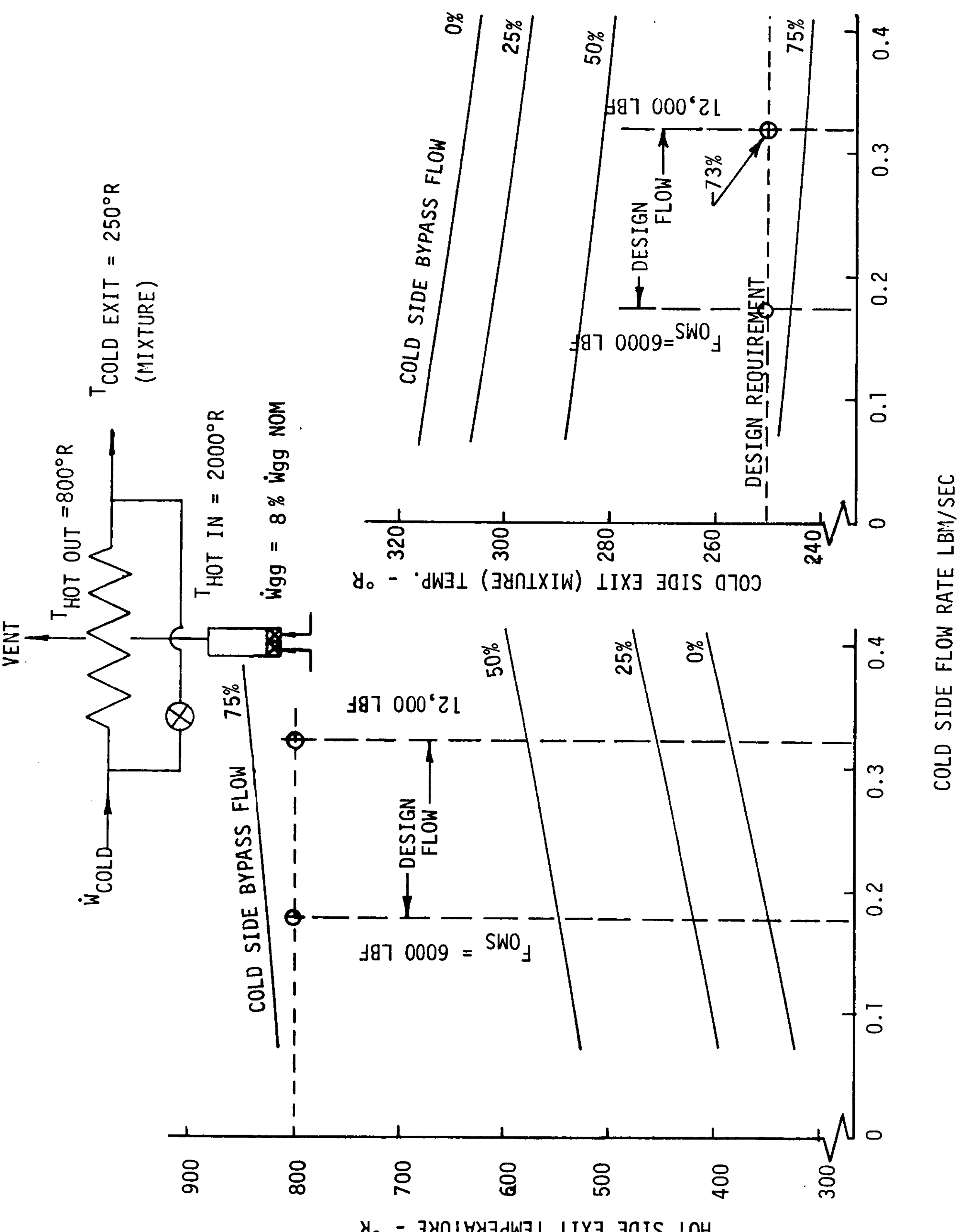


FIGURE 5-37

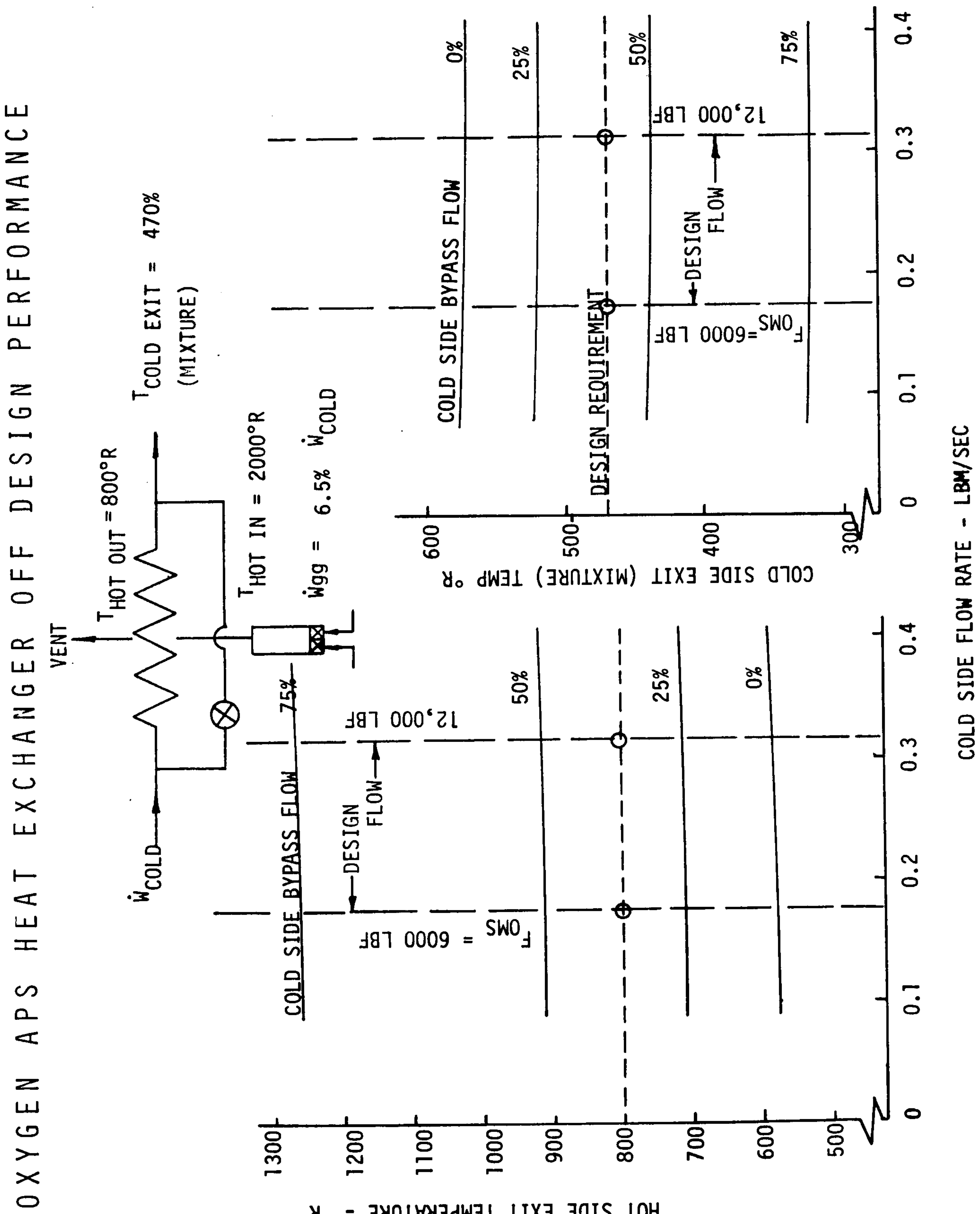

OXYGEN APS HEAT EXCHANGER OFF DESIGN PERFORMANCE
VENT
T HOT OUT = 800°R
T COLD EXIT = 470%
(MIXTURE)
T HOT IN = 2000°R
Ẇgg = 6.5% Ẇ COLD
Ẇ COLD
COLD SIDE BYPASS FLOW
0%
25%
50%
75%
12,000 LBF
F OMS = 6000 LBF
DESIGN FLOW
DESIGN REQUIREMENT
COLD SIDE EXIT (MIXTURE) TEMP °R
600
500
400
300
HOT SIDE EXIT TEMPERATURE - °R
1300
1200
1100
1000
900
800
700
600
500
COLD SIDE FLOW RATE - LBM/SEC
0
0.1
0.2
0.3
0.4

FIGURE 5-38

Alternatives evaluated to provide attitude control during OMS burns were a gimballed OMS or the RCS. Misalignment sources included in the study were vehicle center of gravity uncertainty, OMS thrust vector errors comprised of mechanical/ thrust centerline misalignments and variations during burn, aiming errors, and structural deflection. These sources were combined by the root-sum-squares (RSS) method which then defines the control capability required of the gimballed OMS or by the RCS. For the nongimballed case, the RCS propellant requirements are 45 lbm for the easterly launch mission and 235 lbm for a 2000-fps velocity increment mission. Since the weight penalties were minimal, this simple control approach was selected instead of gimballing the OMS.

Three OMS engines are required to meet the Shuttle fail-safe/fail-safe operating requirements. As an alternative, the number of engines can be reduced to two by utilizing the -X RCS thrusters as OMS backup. For the easterly launch mission, an analysis was conducted to determine the optimum method of performing the deorbit function in the event of an OMS malfunction. The velocity increment required for this burn is 250 fps. Use of the RCS thrusters requires additional propellant loading, due to the lower system specific impulse of the RCS. Assignment of this function to the OMS demands an additional engine and feedlines. Related weight penalties include additional structural support and orbiter weight increases associated with base area growth. The analysis results indicated that using three engines offered lighter weight, so this option was selected as the study baseline.

5.5 Candidate System Evaluation - The four selected RCS/OMS system configurations were evaluated to define weight sensitivity about the design point and to provide a direct comparison around the various levels of integration. Where applicable, both 6000 and 12,000 lbf OMS engine thrust levels were used. Sensitivities were developed for the 2000 fps OMS velocity increment case, and total weights were defined for both 373 and 2000 fps.

In the fully integrated configurations which use two oxygen pumps for the OMS, the RCS baseline configuration, discussed in Section 5.1.4 and summarized in Figure 5-23, was used to define the turbopump design. This results in a near optimum mixture ratio of 6.75 for the OMS when operating two oxygen and one hydrogen pump. Resultant OMS thrust level is 12,550 lbf. Engine chamber pressure and nozzle expansion ratio optimized at 1000 $lbf/in.^2A$ and 500:1, respectively. Operation of this system in the OMS mode is as follows: the gas generators which supply the turbines are operated at the RCS design points and a small portion of the hydrogen and oxygen pump discharge flow is diverted through the small, separate heat exchangers to supply the accumulator makeup propellant.

In the other fully integrated RCS/OMS system (and also in the partially integrated system), the turbopump is operated bilevelly at the different pressures and flow rates required for the RCS and OMS. The turbopumps are designed to provide maximum efficiency for the OMS requirements and operate off-design for the RCS. Optimum mixture ratios for both the OMS and RCS (i.e., 6.0 for the OMS engine and 4.0 for the RCS thrusters) were provided. Pumps were designed to supply both 6000 and 12,000-lbf OMS engine thrust levels. The different operating points of the OMS and RCS require gas generator and pump output control. Accumulator resupply is again provided by bleeding a fraction of the pump discharge through small, separate gas generators/heat exchangers to provide propellant conditioning.

For those integrated systems using bilevel turbopumps, system weight sensitivity was evaluated for changes in OMS engine thrust level, mixture ratio, chamber pressure, and expansion ratio. In addition, system sensitivity to RCS chamber pressure was determined. All other RCS design parameters are either dictated by mission requirements (number of thruster, thrust level, RCS total impulse, etc.) or do not significantly interface with the OMS design (thruster mixture ratio, expansion ratio, etc.). System weights were based on the same criteria used in the preliminary system comparison. The system weight sensitivity to the RCS thruster chamber pressure is presented in Figure 5-39 for both OMS thrust levels and for various OMS engine chamber pressures. These curves indicate that total weight is insensitive to RCS operating pressures in the range of 300 to 500 $lbf/in.^2A$, although minimums do occur at a RCS thruster pressure of 500 $lbf/in.^2A$ for an OMS thrust level of 6000 lbf and 400 $lbf/in.^2A$ for the 12,000 lbf thrust case. Linear system sensitivities to the pertinent OMS design and operating parameters are graphically presented in Figure 5-40 for the 6000-lbf OMS thrust level, and in Figure 5-41 for the 12,000 lbf case. For both the fully and partially integrated cases, the RCS/OMS weights optimized at an OMS engine mixture ratio of 6, chamber pressure of 1000 $lbf/in.^2A$, and an expansion ratio of 500:1.

The separate RCS/OMS system consists of the parallel flow RCS and an OMS which includes staged combustion cycle engines and a feed subsystem. Only propellant tankage is common to the two systems. An optimum mixture ratio of 6:1 was defined in the preliminary screening, and system weight sensitivities were evaluated for

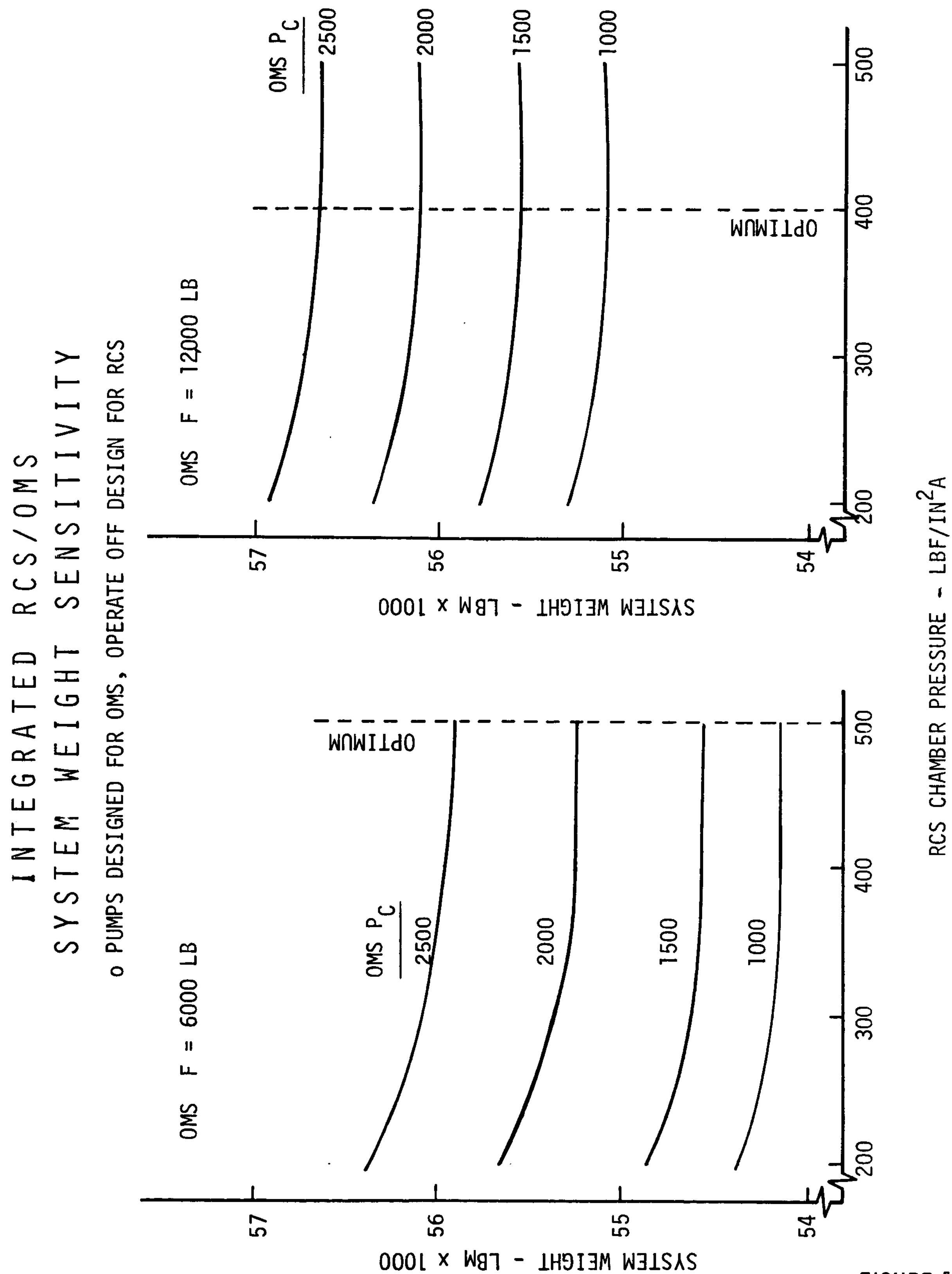

INTEGRATED RCS/OMS
SYSTEM WEIGHT SENSITIVITY
o PUMPS DESIGNED FOR OMS, OPERATE OFF DESIGN FOR RCS
OMS F = 12000 LB
OMS P$_C$
2500
2000
1500
1000
OPTIMUM
57
56
55
54
SYSTEM WEIGHT - LBM x 1000
OMS F = 6000 LB
OMS P$_C$
2500
2000
1500
1000
OPTIMUM
57
56
55
54
SYSTEM WEIGHT - LBM x 1000
200
300
400
500
RCS CHAMBER PRESSURE - LBF/IN^{2}A

FIGURE 5-39

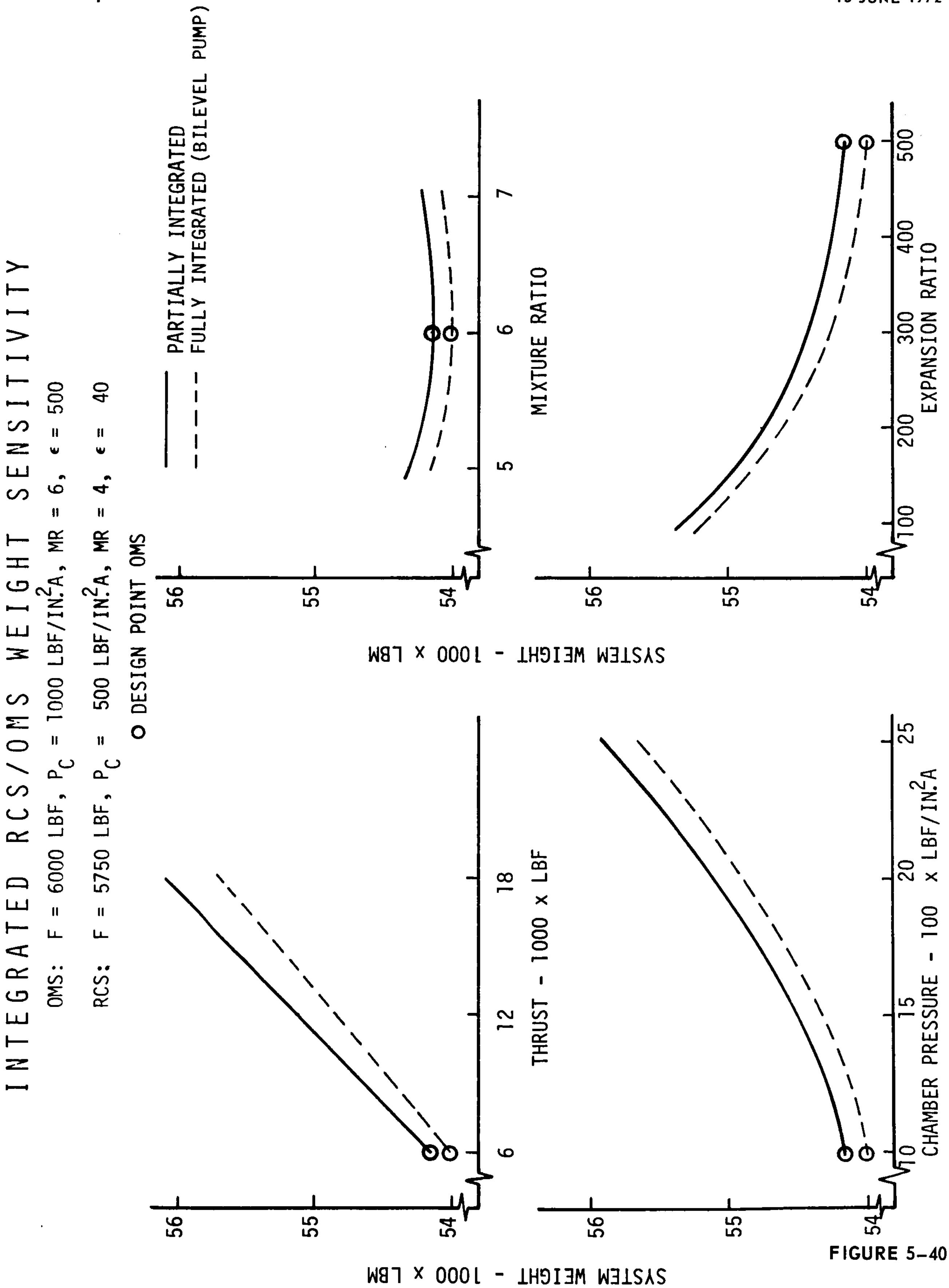

INTEGRATED RCS/OMS WEIGHT SENSITIVITY
OMS: F = 6000 LBF, P_C = 1000 LBF/IN.²A, MR = 6, ϵ = 500
RCS: F = 5750 LBF, P_C = 500 LBF/IN.²A, MR = 4, ϵ = 40
O DESIGN POINT OMS
—— PARTIALLY INTEGRATED
- - - FULLY INTEGRATED (BILEVEL PUMP)
SYSTEM WEIGHT - 1000 x LBM
56
55
54
THRUST - 1000 x LBF
6
12
18
MIXTURE RATIO
5
6
7
CHAMBER PRESSURE - 100 x LBF/IN.²A
10
15
20
25
EXPANSION RATIO
100
200
300
400
500

FIGURE 5-40

INTEGRATED RCS/OMS WEIGHT SENSITIVITY

OMS: F = 12,000 LBF, P_C = 1000 LBF/IN.^{2}A, MR = 6, ϵ = 500

RCS: F = 5,750 LBF, P_C = 400 LBF/IN.^{2}A, MR = 4, ϵ = 40

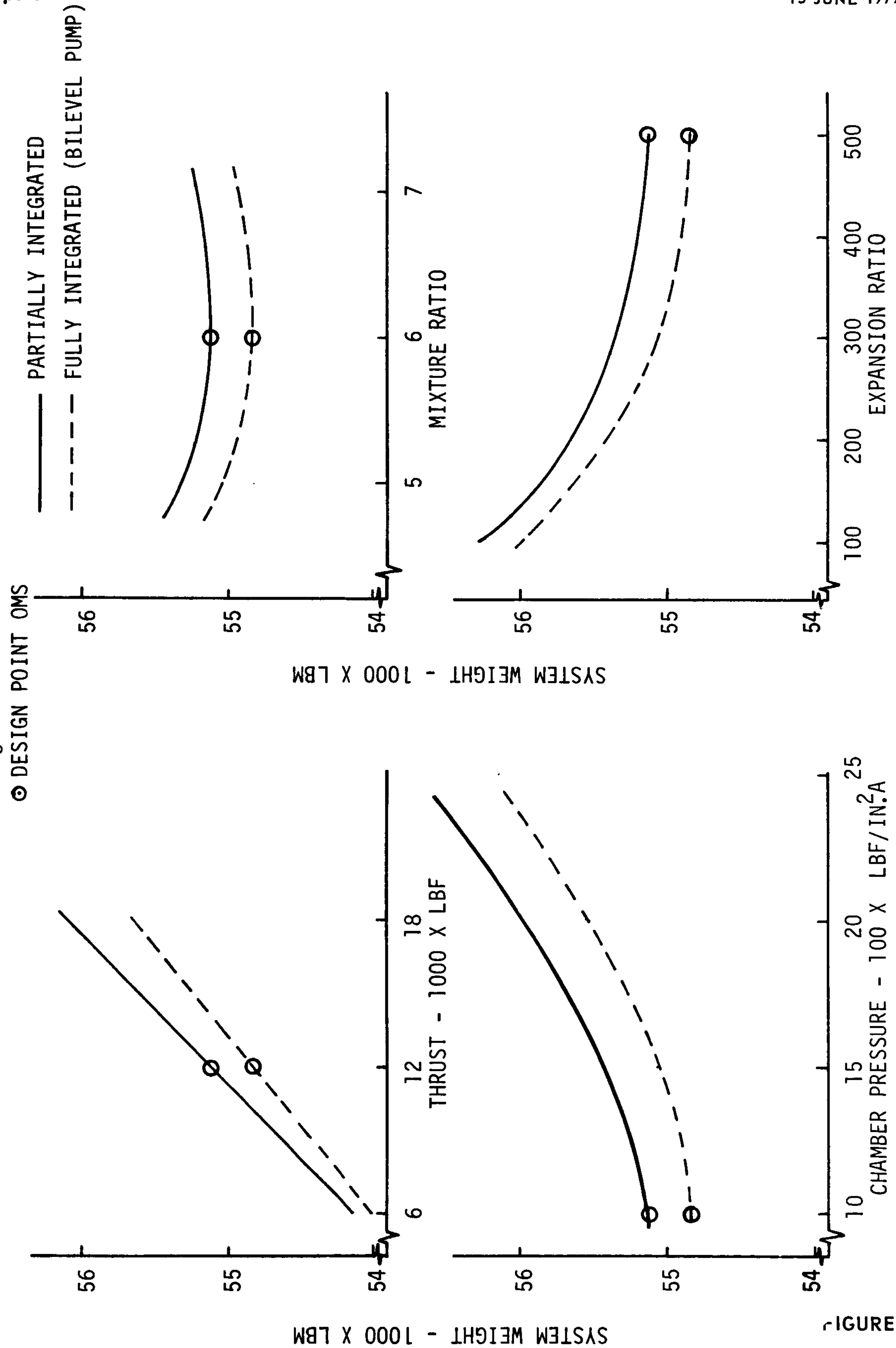


FIGURE 5-41

6000 and 12,000 lbf thrust levels. Weight sensitivity of this separate RCS/OMS design to engine chamber pressure and expansion ratio is displayed in Figures 5-42 and 5-43 for the 6000 and 12,000 lbf thrust level engines. Expansion ratio-nozzle diameter effects on orbiter base area and structure weight are included as OMS weight penalties. An orbiter weight to base area sensitivity of 2.0 lbf/ft^2 was used in the analysis based on Shuttle vehicle studies. As can be seen in the figures, this low sensitivity to base area drives the OMS engine to very high expansion ratios. Higher engine chamber pressures also reduce system weight, and the highest practicable chamber pressures produce minimum weight. Practical design values selected were an expansion ratio of 500:1 and a chamber pressure of 2500 lbf/in^2A.

A summary of both RCS and OMS design parameters is tabulated in Figure 5-44 for each of the four candidate systems. A detailed weight breakdown for these optimum design points is provided in Figure 5-45 for a 2000 fps OMS velocity increment. Weights are listed for propellant, propellant tankage, and pressurization, and for RCS and OMS components. The propellant weight accounts for RCS and OMS usable, vent, boiloff, and residual propellant requirements. Total system weight is also exhibited in the bar graph, Figure 5-46, for both the 373 fps (easterly launch mission) and a 2000 fps mission. At the lower velocity increment and at a specific thrust level, the three levels of integration are weight competitive, but the separate system becomes advantageous at the higher velocity increment.

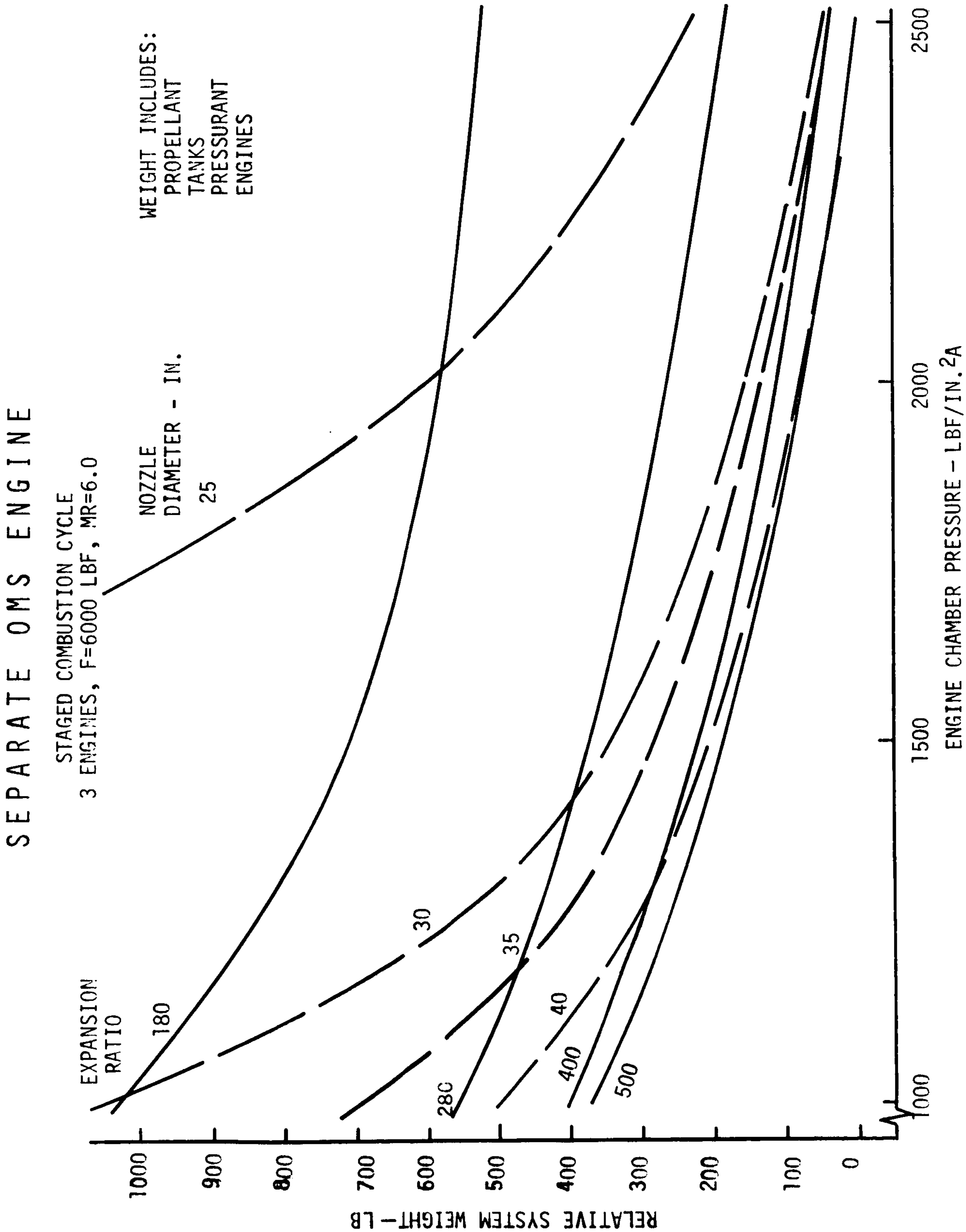

SEPARATE OMS ENGINE
STAGED COMBUSTION CYCLE
3 ENGINES, F=6000 LBF, MR=6.0
WEIGHT INCLUDES:
PROPELLANT
TANKS
PRESSURANT
ENGINES
NOZZLE
DIAMETER - IN.
25
30
35
40
EXPANSION
RATIO
180
280
400
500
RELATIVE SYSTEM WEIGHT-LB
1000
900
800
700
600
500
400
300
200
100
0
1000
1500
2000
2500
ENGINE CHAMBER PRESSURE - LBF/IN.²A

FIGURE 5-42

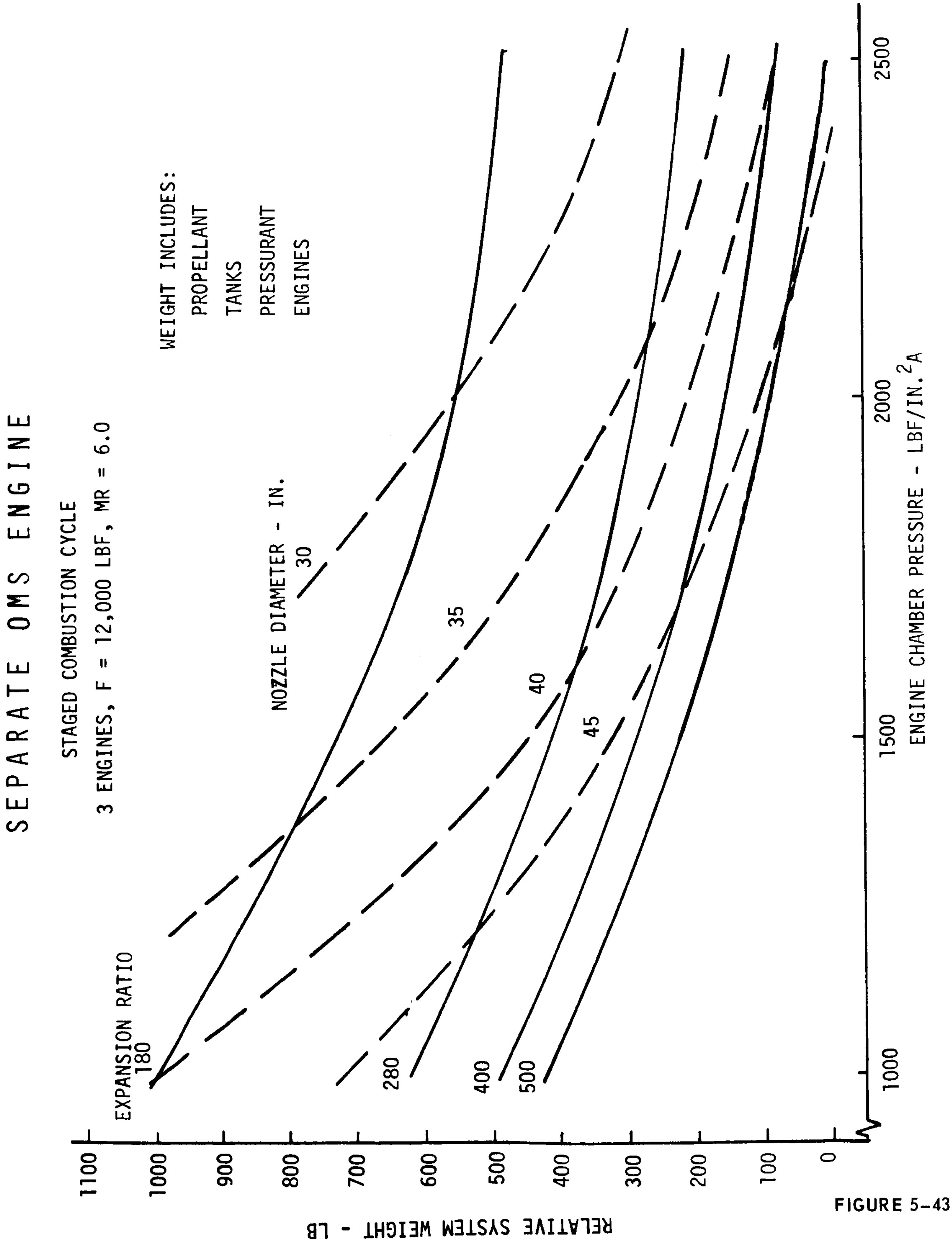

SEPARATE OMS ENGINE
STAGED COMBUSTION CYCLE
3 ENGINES, F = 12,000 LBF, MR = 6.0
WEIGHT INCLUDES:
PROPELLANT
TANKS
PRESSURANT
ENGINES
NOZZLE DIAMETER - IN.
30
35
40
45
EXPANSION RATIO
180
280
400
500
RELATIVE SYSTEM WEIGHT - LB
1100
1000
900
800
700
600
500
400
300
200
100
0
ENGINE CHAMBER PRESSURE - LBF/IN.2A
1000
1500
2000
2500

FIGURE 5-43

RCS/OMS INTEGRATION DESIGN SUMMARY

	FULLY INTEGRATED		PARTIALLY INTEGRATED	SEPARATE
	OPERATE 2-O_2 AND 1-H_2 PUMP FOR OMS	OPERATE PUMPS BILEVEL	DESIGN PUMPS FOR OMS-OPERATE OFF DESIGN FOR RCS	OMS PUMPS LOCATED AFT
RCS				
NUMBER OF THRUSTERS	33	33	33	33
THRUST PER THRUSTER (LBF)	1150	1150	1150	1150
SYSTEM THRUST	5750	5750	5750	5750
THRUSTER MIXTURE RATIO	4	4	4	4
EXPANSION RATIO	40	40	40	40
CHAMBER PRESSURE, LBF/IN.^{2}A	300	400/500	400/500	300
OMS				
NUMBER OF ENGINES	3	3	3	3
THRUST, LBF	12,550	12,000/6000	12,000/6000	12,000
ENGINE MIXTURE RATIO	6.75	6	6	6
EXPANSION RATIO	500	500	500	500
CHAMBER PRESSURE, LBF/IN.^{2}A	1000	1000	1000	2500

FIGURE 5-44

CANDIDATE RCS/OMS COMPONENT WEIGHTS

	FULLY INTEGRATED			PARTIALLY		SEPARATE	
	OPERATE $2\text{-}O_2$ & $1\text{-}H_2$ PUMP	OPERATE PUMPS BILEVEL		DESIGN PUMPS FOR OMS-OPERATE RCS OFF DESIGN		AFT PUMP LOCATION	
OMS THRUST LEVEL, LBF	12,550	6000	12,000	6000	12,000	6000	12,000
PROPELLANT, H_2	7468	8283	8207	8283	8207	7708	7684
PROPELLANT, O_2	41,250	39,113	39,139	39,113	39,139	38,600	38,544
PROPELLANT STORAGE ASSY	1992	2057	2051	2057	2051	2000	2000
PRESSURIZATION SUBASSY	530	550	547	550	547	514	514
RCS WEIGHTS	(3246)	(2999)	(3163)	(2999)	(3163)	(3246)	(3246)
VENT	300	356	320	356	320	300	300
THRUSTERS (33)	992	818	889	818	889	992	992
FEED LINES	271	243	256	243	256	271	271
VALVES AND REGS	344	295	315	295	315	344	344
ACCUMULATORS	855	906	862	906	862	855	855
HEAT EXCHANGER	335	221	210	221	210	335	335
GAS GENERATORS	53	64	62	64	62	53	53
TURBOPUMPS	96	96	249	96	249	96	96
OMS WEIGHTS	(1492)	(999)	(1721)	(1141)	(1994)	(1084)	(1546)
ENGINES (3)	502	330	534	330	534	360	630
LINES (LINE, INS, FILL & CHILL)	886	524	928	524	928	636	828
VALVES	104	92	154	128	216	88	88
GAS GENERATORS	-	21	22	63	67	-	-
TURBOPUMPS	-	32	83	96	249	-	-
TOTAL WEIGHT (LBM)	55,978	54,001	54,828	54,143	55,101	53,152	53,535

FIGURE 5-45

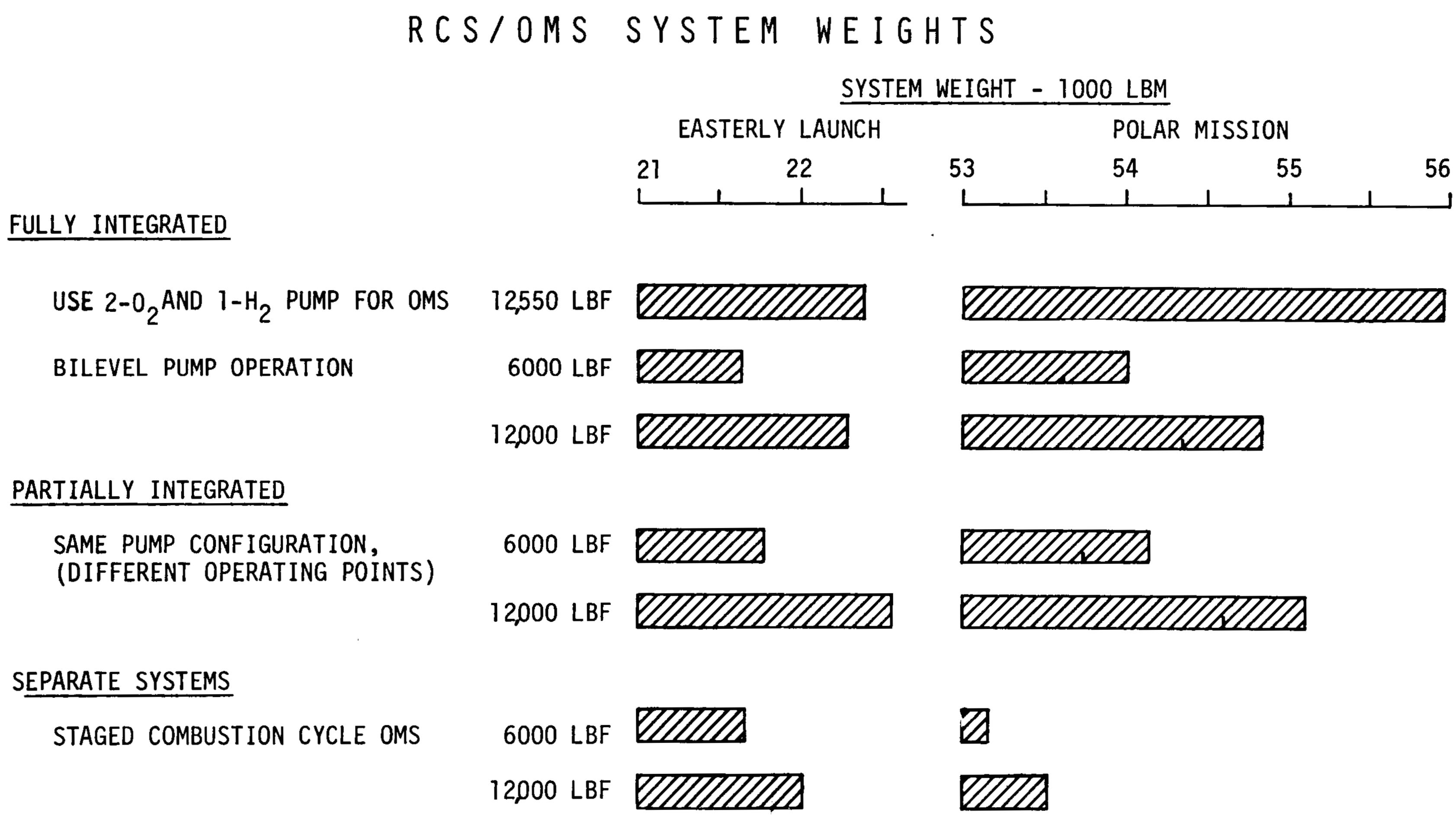

RCS/OMS SYSTEM WEIGHTS
SYSTEM WEIGHT - 1000 LBM
EASTERLY LAUNCH
POLAR MISSION
21
22
53
54
55
56
FULLY INTEGRATED
USE 2-O2 AND 1-H2 PUMP FOR OMS
12,550 LBF
BILEVEL PUMP OPERATION
6000 LBF
12,000 LBF
PARTIALLY INTEGRATED
SAME PUMP CONFIGURATION, (DIFFERENT OPERATING POINTS)
6000 LBF
12,000 LBF
SEPARATE SYSTEMS
STAGED COMBUSTION CYCLE OMS
6000 LBF
12,000 LBF

FIGURE 5-46

6. STUDY CONCLUSIONS

During this portion of the APS design study, all viable oxygen/hydrogen RCS/OMS integration configurations were compared on the basis of weight, relative complexity, technology, and flexibility in meeting mission requirements. The gaseous RCS baseline design is comprised of high pressure turbopumps with parallel flow gas generators for the turbopump and thermal conditioner assemblies. The OMS consists of liquid propellant engines fed by a distribution network from the propellant storage assembly. The degree of integration varied from a fully integrated RCS/OMS with common turbomachinery, gas generators,and heat exchangers to a separate system with common propellant tankage only. The fully integrated system is relatively simple due to hardware commonality; however, associated problems include OMS and RCS mixture ratio differences, RCS accumulator resupply during OMS operation, and controls for propellant sequencing to the OMS engines. By reducing the degree of integration, these problem areas can be resolved or alleviated.

Preliminary screening of candidate configurations at each integration level resulted in selecting four RCS/OMS candidate configurations. Prior to this, performance and design characteristics of the OMS engine, feedlines and turbopumps were developed. Design options to resolve integration concerns were devised and system schematics drawn for each option and integration level. Following this, the preliminary design points were determined for each option. The selected configurations are two fully integrated systems, one partially integrated system, and a separate system. Mixture ratio differences were resolved on the fully integrated system by using either two oxygen and one hydrogen RCS pumps for the OMS operation or by utilizing bilevel operating pumps. The partially integrated case also uses a bilevel pump configuration, since the use of independently designed RCS and OMS pumps could not be justified from a weight savings standpoint. The bilevel turbopumps are designed for the OMS requirements and operate off-design for the RCS. These different operating points require gas generator and pump output control. The recommended option of providing accumulator makeup propellant, required for the integrated systems during OMS operation, is the addition of a small, separate heat exchanger/gas generator sized to condition only the accumulator makeup gas. A single unit for each propellant would be added with the RCS conditioners providing backup operation in case of a failure. This option requires the development of an additional component but is the preferred approach since the alternate options result in an excessive number of conditioner cycles, excessive weight penalties, or increased complexity. In the separate RCS/OMS, a staged combustion cycle OMS engine is recommended.

System weights and sensitivities to design point changes were evaluated for each of the four candidates. A broad range of OMS thrust levels and OMS mission requirements (velocity increment) were used. At the lower velocity requirements of the easterly launch mission, the candidate RCS/OMS systems were all weight competitive. At the higher velocity increment (2000 fps), the separate RCS/OMS system is most attractive.

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