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MSC-04422

SPACE SHUTTLE
AUXILIARY PROPULSION SYSTEM
DESIGN STUDY

PROGRESS REPORT NUMBER 1

REPORTING PERIOD 1 JULY TO 1 AUG 1971

CONTRACT No. NAS 9-12013

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PREFACE

This is the first of ten monthly progress reports on the program titled, "Space Shuttle Auxiliary Propulsion System Design Study" This study is being performed for the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas, under Contract No. NAS 9-12013. This report covers the period from 1 July 1971 to 1 August 1971.

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1. INTRODUCTION

This is the first of ten planned progress reports summarizing the status and results of McDonnell Douglas Astronautics Company-East (MDAC-EAST) effort under NASA Contract NAS 9-12013. This contract titled, "Space Shuttle Auxiliary Propulsion System Design Study," is under the technical direction of the National Aeronautics and Space Administration, Manned Spacecraft Center (MSC), Houston, Texas. The objectives of this study program are: first, to develop design and programmatic data, for competitive Space Shuttle reaction control systems (RCS) and integrated RCS/orbit maneuvering systems (OMS) concepts, in sufficient detail that a selection can be made between concepts; and, second, for the selected concept, to define system and component performance over the full range of system operation.

To attain these objectives, a five phase program, conducted in three distinct steps is outlined. The first step, Phase A, is the definition of RCS and OMS requirements Results from this phase define the number, location, and thrust level of the RCS thrusters and orbit maneuver engines, based on vehicle acceleration requirements, failure criteria, and abort requirements. APS total impulse requirements, thrust vector control requirements, and component environment will also be determined from mission time lines and vehicle configurations.

The next step (Phases B, C and D) is to define fully the competing auxiliary propulsion system providing three candidate RCS concepts delineated in

Reference (a). System optimizations are conducted to establish preliminary RCS operating points and sensitivity of the RCS to design requirements and component performance. Once this preliminary operating point is established the many possible RCS control concepts are compared and reduced to a few high value approaches considering benefits of control in terms of system weight, versus increased control complexity and cost. For the high value concepts, system design, transient, and operating analyses will be conducted and development programs will be formulated. Phase B will provide the data required to compare performance factors, operational factors, development risk, and cost, for the three candidate systems with their selected control options.

In Phase C, RCS/OMS integration options, ranging from a fully integrated system to a system in which only propellant storage is integrated, are evaluated to determine the proper compromise between performance and operating requirements, and between system/vehicle development risk and cost Using the same general approach as in Phase B, control and design options for the RCS/OMS are evaluated at different levels of integration and the most promising concepts for more detailed analysis will be selected on the basis of performance advantages versus complexity and development risk.

In Phase D, the two special system approaches, which eliminate requirements for turbopumps and/or heat exchangers, are evaluated and optimum design points determined, and system sensitivites developed The results of this phase will constitute an evaluation of the overall viability of the systems, as determined by a comparison with the systems of Phase B.

The final step of the design study (Phase E) is to evaluate further the system selected from Phases B, C or D by conducting a detailed dynamic performance analysis. Operation of the selected system over a complete range of nominal and off-nominal conditions will be evaluated, including simulation of individual and combined malfunctions. Based on these data, the system design point, and the system schematic and its performance will be thoroughly assessed for adequacy or recommended design alterations.

2. STATUS OF THE PROGRAM

The APS design study was initiated 1 July 1971. The first two weeks of the program were devoted to preparation of the Program Plan and to definition of requirements for the APS. The Program Plan (Reference (b)) was released 15 July. An informal review was held at MSC on 19 July to delineate system requirements derived from evaluation of the baseline booster and orbiter (Reference (c)). The resulting requirements show that the weight penalty associated with use of common RCS hardware for the booster and orbiter is negligible (See paragraph 3.1 below.) For this reason all RCS effort during the next two months of the study will be devoted exclusively to the orbiter stage. The planned booster effort will be directed towards evaluation of the APS for a small orbiter of the general class considered for nonreusable booster systems.

The remaining engineering effort on the program has been directed towards establishing baseline RCS and OMS designs for system trade studies and controls evaluation.

The program is progressing essentially on schedule; however, there have been minor delays at both MDAC-East and at the principal subcontractor, Aerojet Liquid Rocket Co (ALRC), in reaching the planned staffing levels. These delays are not expected to result in any slippage of significant program milestones. Figure 1 shows the effort scheduled and completed to date and Figure 2 provides a comparison of actual versus forecast MDAC-East manhour expenditures on the study.

3. SUMMARY OF EFFORT BY TASK

3.1 TASK 1 - Phase A: Requirements Definition - Complete

The objective of this task was to develop, for the baseline orbiter and booster, all requirements necessary for APS design and to compare the effect of using common RCS hardware for the two stages.

For the RCS, the requirements of principal interest are engine thrust, number of engines, total system thrust, total impulse and total impulse expenditure histories. The approach taken to define these requirements and to assess the impact to using common hardware for both the booster and the orbiter was as follows:

Using the baseline vehicle configurations, the number of RCS engines, and their thrust level was varied to satisfy the vehicle control and maneuvering acceleration requirements Then, using typical minimum impulse bit data as a function of thrust level, the total impulse expenditures were determined for the three missions defined in Reference (c) Booster and orbiter RCS weights were then determined as a function of thrust level and the penalties incurred by using common engines for the two stages were determined for typical RCS design conditions.

Three baseline missions are defined for this study program These are (1) an easterly launch mission, which is intended primarily for delivering and retrieving payloads in a 100 nautical mile circular orbit; (2) a south polar mission, which consists of launching the orbiter into an injection orbit of 50 x 100 nautical miles and circularizing at apogee utilizing the orbital maneuvering propulsion system; and (3) a resupply mission consisting of providing logistic support for a space station/space base in a 270 nautical mile orbit. The reaction control system impulse expenditure for these three missions was determined for varying engine thrust levels. These results are shown in Figure 3 which shows the total RCS impulse and the attitude control portion of that impulse for the three missions. The total RCS impulse includes the maneuvering velocity changes delineated in Figure 4 which are either not in the minus X direction (forward) or are less than 20 feet per second. For illustrative purposes, the RCS total impulse has been broken down into individual requirements for two thrust levels in Figure 5. Of principal significance in Figure 5 are the fine attitude hold and stationkeeping requirements. At 2,000 lbs thrust, these constitute an appreciable total impulse requirement but at 1,000 lbs thrust they are negligible. Other requirements are essentially unchanged by thrust level.

The total impulse requirements defined in Figure 3, together with the engine thrust level and the required number of engines, allow definition of total RCS weight. This was developed for the typical RCS design conditions shown in Figure 6. Also shown in Figure 6 are the partial derivatives or sensitivities identifying the impact of RCS system weight on payload. These sensitivities allow a comparison of exchanges between booster and orbiter RCS weight Using the data of Figures 3 and 5, total RCS weights were developed for both the orbiter and booster and are shown in Figure 7B. As shown, the orbiter RCS weight minimizes at approximately

1,000 lbs thrust while the booster RCS weight minimizes at a thrust level in excess of 2,000 lbs. Using RCS weights at these optimum points as a reference, the effect of varying thrust level, in terms of incremental payload weight, was evaluated and the results are shown in Figure 7A. The reference weight in this figure is that for stage optimized thrust levels, i.e., the orbiter RCS weight at 1,000 lbs thrust and the booster RCS weight at 2,500 lbs thrust. The lower curve of Figure 7A shows the payload weight change associated with the RCS inert or hardware weight only. The upper curves of Figure 7A include the effect of total impulse changes. Both curves show that payload weight is maximized at a thrust level of approximately 1,000 lbs. The two failure conditions shown in Figure 7A reflect a difference in the criteria used for system design. In the fail safe design, the systems are designed to provide design acceleration requirements (see Figures 8 and 9) under normal operating conditions and a safe acceleration after one and after two engine failures. In the second case, the system is designed to provide the "design" acceleration after one engine failure and the safe acceleration level after two failures. As shown, a change in the criteria would have little effect on the thrust level selected. From these data, a thrust level of 1,150 lbs was selected as the recommended design point for the system study. A slightly lower thrust level would provide a small increase in payload capability but would require several additional engines on the booster. At 1,150 lbs thrust, 33 RCS engines are required on the orbiter and 24 are required on the booster. These selections nominally provide a fail safe-fail safe design

Associated with the difference between payload sensitivity to total RCS weight and the sensitivity to only inert weight (Figure 7A) are certain assumptions involved in defining the mission total impulse requirements. The most influential of these assumptions were investigated to ascertain if they would affect the thrust level selection. These are shown in Figure 10. As shown, variations in the prethrust maneuver time, in the operating mode during stationkeeping and in the number of attitude control engines firing have essentially no effect on the payload weight-thrust trend. These data provide additional assurance that the thrust level selected for the study will be unaffected by later changes in the design or operating philosophy of the RCS

The other major requirement affecting system design is the total thrust level capability of the RCS. Figure 4 identifies the thrust level used for the various maneuvers of the three reference missions. These, together with the limit cycle and calculated entry requirements, are summarized in Figure 11. As shown, the maximum system thrust requirements occur during reentry resulting from the requirement for a 1.5 deg/sec^2 continuous yaw-roll coordinated maneuver capability. For the orbiter, 5 engines equivalent thrust is required from the system and for the booster 8 engines continuous thrust is required. For design purposes, a conditioner flow or system thrust capability was selected to be 5,750 lbs of thrust for both the orbiter and booster and an extra conditioner would be provided on the booster to satisfy its increased system thrust requirements. This avoids the large orbiter weight penalties that would be associated with use of a conditioner sized for the booster and/or the increased development cost for two conditioners.

Figures 12 and 13 provide a description of the orbiter and booster thruster locations and the number of thruster assemblies used. Figures 14, 15 and

16 show the capability of this design compared to acceleration requirements during three modes of operation (i.e., entry and on-orbit control and orbit maneuvers). For the orbiter, the aft mounted yaw engines are used to provide on-orbit roll control while the wing mounted engines are used to provide entry roll control. Figures 17, 18 and 19 define the impulse expenditure histories for the three reference missions. In these figures, the RCS maneuvers listed in Figure 4 are included in the maneuver impulse requirements.

Of principal interest to the OMS was confirmation of the OMS/RCS velocity allocation defined by Reference (a) as less than or equal to 20 fps for the RCS. Figures 20, 21 and 22 provide definition of the incremental weight savings associated with using the OMS for the three reference missions at different propellant weight penalties per OMS start. For both the easterly and resupply missions, weight is essentially minimized by the defined allocation. However, in the south polar mission no minimum is observed. An alternate approach to confirmation of the desired RCS velocity increment can be taken which eliminates mission considerations. This is illustrated in Figure 23 which shows system specific impulse as a function of velocity increment for the OMS. The most desirable velocity allocation can be determined when the effective specific impulse of the OMS is equal to that of the RCS. This point is shown in Figure 23. At a typical level of RCS specific impulse, the OMS curves cross at approximately 15 to 20 fps dependent on the OMS start loss. Thus, the definition of the velocity allocation at 20 feet per second is valid for study purposes as changes to the mission profile will have little effect.

The second requirement of importance to OMS design is the design thrust requirement. Figure 24 shows the thrust level and velocity requirements for the OMS if it is designed to provide abort assistance in the event of a main engine failure. At the design OMS tank capacity of 2,000 fps, the south polar mission presents the most severe requirement. For this mission, if the OMS is designed to provide abort impulse, a thrust level of 24,000 lbs would be required. Both the easterly and resupply missions have much reduced thrust requirements for abort Two approaches are possible in the study. These are (1) to design the OMS for abort capability, in which case the 24,000 lbs of system thrust would be a firm requirement and system designs would tailored about that point or (2) to allow the OMS thrust to vary and determine the thrust level that provides the most desirable integration between the OMS and RCS. For study purposes, this latter approach was selected and while systems capable of 24,000 lbs of thrust will be investigated, they will not be treated exclusively.

Figure 25 provides a summary of both RCS and OMS design requirements to be used for system trade studies and analyses In the case of the OMS, the system will be designed as a minimum for on-orbit operations and system/engine thrust level effects will be determined as part of the study output.

3.2 Task 2 - Phase B: Candidate RCS Concept Comparisons

3.2.1 Task 2.1 - Review Component Models - 30% Complete

The purpose of this task is to update all component models over the range of conditions applicable to both separate RCS and to integrated RCS/OMS. The Aerojet Liquid Rocket Co. (ALRC) is a primary contributor to this effort. Analytical models of turbopump weight and thruster weight and performance developed under NAS8-26248 are currently being reviewed and updated by ALRC. Inputs as to the adequacy and/or necessary model refinements are scheduled for mid-August and, at that time, all revisions will be incorporated into the RCS design and sizing computer program.

MDAC-East effort under this task has been devoted principally to revision of vent line and heat exchanger models used for system design and sizing. The weight model for the conditioner vent system was modified to simulate non-propulsive vehicle side vents. System analyses showed the weight of propulsive vents to be especially critical to the parallel flow conditioner assembly. This RCS type requires low turbine vent pressures, thus large vent line diameters to reduce bypass flow requirements to levels competitive with the series flow RCS concepts. With propulsive vents installed in the vehicle empennage, reductions in turbine bypass flow by increased turbine pressure ratio were offset by weight increases in the long vent lines. Also, little impulse benefit was derived from propulsive vents at the current RCS maneuver allocations. Coincident with changes in vent line routing, vent line minimum gauges and compensator/gimbal joint unit weights were adjusted to reflect NAS 9-11012 (Low Pressure APS) study results. Tube-and-shell heat exchanger design points have been generated (See Task 2.5) and curve fits of parametric heat exchanger weight and performance trends about these design points are in work.

3.2.2 Task 2.2 - Develop Component Tolerance Data - 25% Complete

The purpose of this task is to delineate the component tolerance and sensor accuracy data necessary for subsequent control concept screening. A literature search has been initiated to define operating component performance tolerances and sensor accuracies. Although tolerance data has been compiled on almost every RCS component, the literature seldom distinguishes between unit-to-unit (Specification) tolerances, which can be trimmed during system calibration tests, and run-to-run tolerances which cannot be trimmed. To supplement this literature search, Requests for Technical Information (RFTI's) are in work and will be submitted to major component manufacturers, requesting historical data on component tolerances.

3.2.3 Task 2.3 - Perform Vehicle Integration Studies - 30% Complete

The purpose of this task is to develop the configuration and installation data necessary for RCS and RCS/OMS design. APS installation drawings have been prepared for the fully reusable orbiter to define general equipment locations and line lengths. Work is now in process to define vehicle effects associated with relocating the APS hydrogen tank to an aft location.

3.2.4 Task 2.4 - Establish Propellant Tankage and Pressurization Models - 0% Complete

No planned effort during this report period.

3.2 5 Task 2.5 - Conduct Preliminary System Analyses - 15% Complete

The purpose of this task is to establish RCS schematics, preliminary operating conditions, flow balances and weight sensitivities to design requirements. Preliminary system design points were generated for each of the competing RCS concepts. These design points, which are summarized in Figure 26, will form the baseline for control point screening and control concept comparisons. As shown in Figure 26, the two series flow concepts are nearly identical in bypass flow requirements and system performance. A power balance on these systems requires a high, hot side heat exchanger flow rate, and at this flow rate, pump power requirements are satisfied with low pressure ratio turbines. Hence, in the series RCS vent pressures are relatively high. The parallel flow system, on the other hand, requires low flow rate, high pressure ratio turbines in order to efficiently utilize the available thermal energy from the gas generator combustion products. However, as discussed under Task 2.1, increases in turbine pressure ratio (reduced turbine discharge pressure) result in offsetting increases in turbine vent system weight. The minimum system weight occurs at turbine pressure ratios (O_2 and H_2) of approximately 20:1. At this pressure ratio, excess thermal energy is vented overboard and, as shown in Figure 26, the parallel flow system is approximately 500 lbs heavier than the other design approaches. While further reductions in vent system weight could improve the performance of this system, a turbine discharge pressure of 15-20 psia, minimum, is desirable in terms of facility requirements during development testing and for turbopump ground checkout. Thus, for reasons other than weight, higher turbine pressure ratios are undesirable.

Conditioner temperature, pressure and flow rate balances for the three design points are shown in Figures 27 through 29 The remainder of the RCS is identical for all three concepts. A schematic of the complete system, showing the necessary component redundancies, is shown in Figure 30 for the "series-turbine upstream" concept.

The sensitivity of system weight to pertinent design and operating parameters are shown in Figures 31 through 33. While the design points reflect the selection of an off-optimum chamber pressure of 300 psia (Optimums of 400-600 psia) the weight penalty for this selection is small

(150 lbs.), and is equally penalizing for each conditioner concept. This selection affords greater utilization of data from current component technology programs and is likely to be more nearly optimum for system with installed mass flow controllers due to the associated increase in line pressure drop.

Two approaches were used to develop the weight sensitivities: (1) linear sensitivities based on constant accumulator pressure ratios (P_{SWITCH}/P_{MIN} = 1.135 and P_{MAX}/P_{SWITCH} = 2.0) as were determined to be near-optimum from the previous APS definition study (NAS 8-26248), and (2) weight sensitivities based on reoptimization of the accumulators for each change in the design point. The most significant difference in the two approaches is seen in the effect of conditioner response time. The weight penalty associated with increases in response time is appreciably reduced through redesign of the accumulators. The type of optimization performed is illustrated in Figure 34 which shows system weight versus P_{SWITCH}/P_{MIN} (O_2) and P_{SWITCH}/P_{MIN} (H_2) for a fixed number of conditioner cycles at response time of 0.5 seconds and 1.0 seconds. As shown for the slower response system, if P_{SWITCH}/P_{MIN} is too low, weight increases rapidly because volumes must increase to satisfy system mass flow demands during the conditioner start time lag. If the pressure margin is too large, the accumulator volumes are small and high system pressures are necessary to meet conditioner cycle requirements, resulting in increased system weight. These results indicate that increases in response time between design values and developed hardware can be accommodated with low weight penalty by overdesigning switching pressure (P_{SWITCH}/P_{MIN}) or by sacrificing on cycle life requirements. Accumulator volumes for the data of Figure 26 are based on 50 conditioner cycles per mission.

Prerequisite to controls evaluation it is necessary to develop component performance maps for off-design operation. Generalized turbopump characteristics are being developed by ALRC and heat exchanger maps by MDAC-East. Temperature and flow balances for the three point designs were used to obtain heat exchanger design characteristics. These design characteristics are tabulated in Figures 35 and 36 for the oxygen and hydrogen loops, respectively. Heat exchanger performance maps will be generated about these designs to determine the effect of variations in hot and cold gas flowrates, inlet temperatures, overall heat transfer coefficients and friction factors on heat exchanger outlet temperatures and pressures.

3.2.6 Tasks 2.6 through 2.16

No planned effort during this report period.

3.3 Task 3 - Phase C: RCS/OMS Integration Study

3.3.1 Task 3.1 - Define OMS Engine Weight and Performance Model - 20% Complete

The purpose of this task is to establish parametric weight and performance data for a liquid hydrogen/liquid oxygen thrust chamber assembly. This task is being performed by the Aerojet Liquid Rocket Company (ALRC) under subcontract to MDAC-East. Aerojet has completed evaluation of engine performance and definition of assembly weight for variations in thrust level, expansion ratio and chamber pressure. These OMS engines parametric data will be utilized for conducting system design trade-off studies. In addition to the basic parametric thrust chamber data, parametric data are being developed to identify turbopump performance for assemblies exhibiting various head-capacity characteristics. These data will allow investigation and/or tailoring of alternate RCS turbopump designs and will enable definition of the RCS pump head-capacity characteristic most compatible with OMS engine integration. These latter data are in work and will be completed in the next reporting period.

3.3.2 Task 3.2 - Determine Line and Pump Chilldown Losses - 20% Complete

The objective of this task is to define the method or operating mode most desirable for chilldown of the OMS engine pumps and propellant distribution lines. Initial effort under this task has been devoted to development of a computer program for estimation of line chilldown time. To facilitate development of this program, a basic computer program for analyzing line chilldown characteristics has been obtained from MDAC-West and converted for use by MDAC-East facilities. This basic computational procedure will be modified to allow evaluation of OMS start/shutdown losses for simulated mission usage and the computer program will be used to generate parametric data for the OMS study and will also serve to identify propellant heating rates associated with the special RCS concepts under study in Task 4.

3.3.3 Task 3.3 - Define and Compare RCS/OMS Integration Options - 20% Complete

The objective of this task is to define the RCS/OMS design options, develop system schematics, identify system design points and determine methods of providing control for operation. The RCS/OMS design options have been defined and are shown in Figures 37 and 38 for the fully integrated and partially integrated systems, respectively. For the fully integrated systems, the starting point for RCS/OMS studies will use a fixed operating point, parallel flow RCS concept. When integrated with this system, the design flows for the OMS are as shown in Figure 39. Under these conditions, the OMS mixture ratio (3.12) is that provided by the RCS pumps without modification. This low mixture ratio, of course, results in low OMS performance. The studies will proceed from this baseline point adapting the system design point and concept to improve OMS performance, increase OMS thrust level and provide the required OMS single burn impulse. Figure 37 identifies the design options to be considered. Five options for tailoring of the OMS mixture ratio are defined. These will be investigated in combination with the single burn impulse extension options shown. For example, each mixture ratio control option will consider various methods of resupplying the accumulators such as bleeding the required flow from the pump discharge through the heat exchanger and heating by use of a bi-level gas generator operating at the low flow condition. As a prerequisite to these studies, heat exchanger operation at off design conditions is being investigated as part of the RCS component effort under Task 2.5. Subsequent effort under this task will include evaluation of the RCS/OMS integration options shown in Figures 37 and 38. At each point, variation of system design and system thrust will be investigated to establish the design point which best satisfies all criteria.

3.3.4 Tasks 3.4 through 3.11 - No Effort Scheduled

3.4 Task 4 - Phase D: Special RCS Studies

3.4.1 Task 4.1 - Conduct Propellant Storage, Acquisition and Pressurization Analyses - 30% Complete

The purpose of this task is to evaluate and compare high pressure propellant storage, acquisition, and pressurization design alternatives for use in study of the special RCS concepts defined by Reference (a). The effort performed during the current reporting period has consisted of definition of propellant tank capacities required as a function of tank resupply rate and definition of tankage and pressurization system weight data for use in subsequent trade studies. In both of the special systems, one of the principal trade-offs to be made is the trade-off between propellant tank capacity and resupply (pump) requirements. In the baseline RCS case, the total RCS requirement is approximately 2.25 million lb-sec. If only a single tank were used in the special systems, this would be the required capacity and would represent a severe penalty to the special systems, which operate at relatively high tank pressures. The tank capacity required can be reduced, however, if it is refilled during the mission from the OMS tank. For example, the total impulse requirement of the propellant tank can be reduced to 650,000 lb-sec. by refilling the APS tank during -X OMS maneuvers. In this event, the APS tank is sized by the largest usage between OMS burns and would have sufficient capacity to supply the entry requirements without replenishment during entry. The storage requirements can be further reduced by using low flow-high head rise transfer pumps in conjunction with an OMS propellant acquisition device. In this case, the RCS tank capacity need only be that required to satisfy the largest single RCS impulse demand (157,000 lb-sec.). By using the storage tanks as liquid accumulators, the equivalent pump flow requirements can be reduced from the total system thrust level of 4600 lbs. to a flow rate equivalent to only 250 lbs. thrust. Selection of the storage tank capacity and pump flow rate will depend on later trade studies of pump weights and power requirements vs tank and pressurization weights. Figure 40 presents the storage tank requirements as a function of the replenishment rate available during the mission.

As part of this task, the weight of regulated helium pressurization assemblies were evaluated for subsequent trade studies and the results are shown in Figure 41. As shown, the pressurization weight penalties for the hydrogen tank are very large and in later effort consideration will be given to both blowdown and autogenous pressurization of the hydrogen tankage.

3.4.2 Task 4.2 - Define Component Models - 40% Complete

The objective of this task is to develop analytical models of the components unique to the special RCS concepts. The component models developed under Task 2.1 have been reviewed and extended as required for the special systems. Specifically, tankage weight characteristics have been developed at higher tank pressures and parametric data have been compiled on pump and motor weights together with their power supplies. The revised/extended tankage weights at high pressure are shown in Figure 42. The large hydrogen tank weight penalties shown can be expected to strongly influence tank pressure level and system mixture ratio trade studies. Pump and motor weights are relatively low but the power weight penalty associated with fuel cells (DC motors) and with fuel cells and inverters (AC motors) are quite large. These trends will tend to optimize the system at low power levels and their magnitude indicate that alternate power sources such as alternators operating from the APU and cold hydrogen or helium driven turbines should be considered. Future effort under this task will be to identify additional component weights as required, e.g., bellows tankage weight and cold turbine performance and weight. Component design data in addition to weight will also be provided at and around the desired operating points as part of this task.

3.4.3 Tasks 4.3 through 4.5 - No Effort Scheduled

4. PLANNED ACTIVITY

The activity of principal significance in the next period will be associated with system trade and design studies. In the case of the RCS the remaining design sensitivities will be developed and system operating sensitivities to conditioner tolerances will be developed. Also component tolerance summaries will be prepared and control trades will be initiated. In the case of the OMS, the necessary trades to develop designs for the schematics defined will be initiated. Special RCS design studies will continue on the gas-gas system without a turbo-pump and will be initiated on the liquid-liquid system when the supply line thermal model is completed.

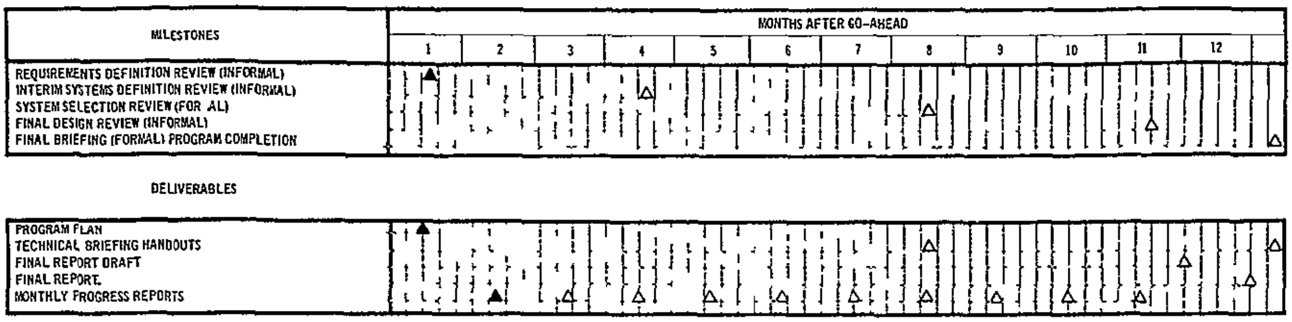
5. REFERENCES

(a) "Space Shuttle Auxiliary Propulsion System Design Study", Request for Proposal No. MSC-BC421-M68-1-10P, April 23, 1971.

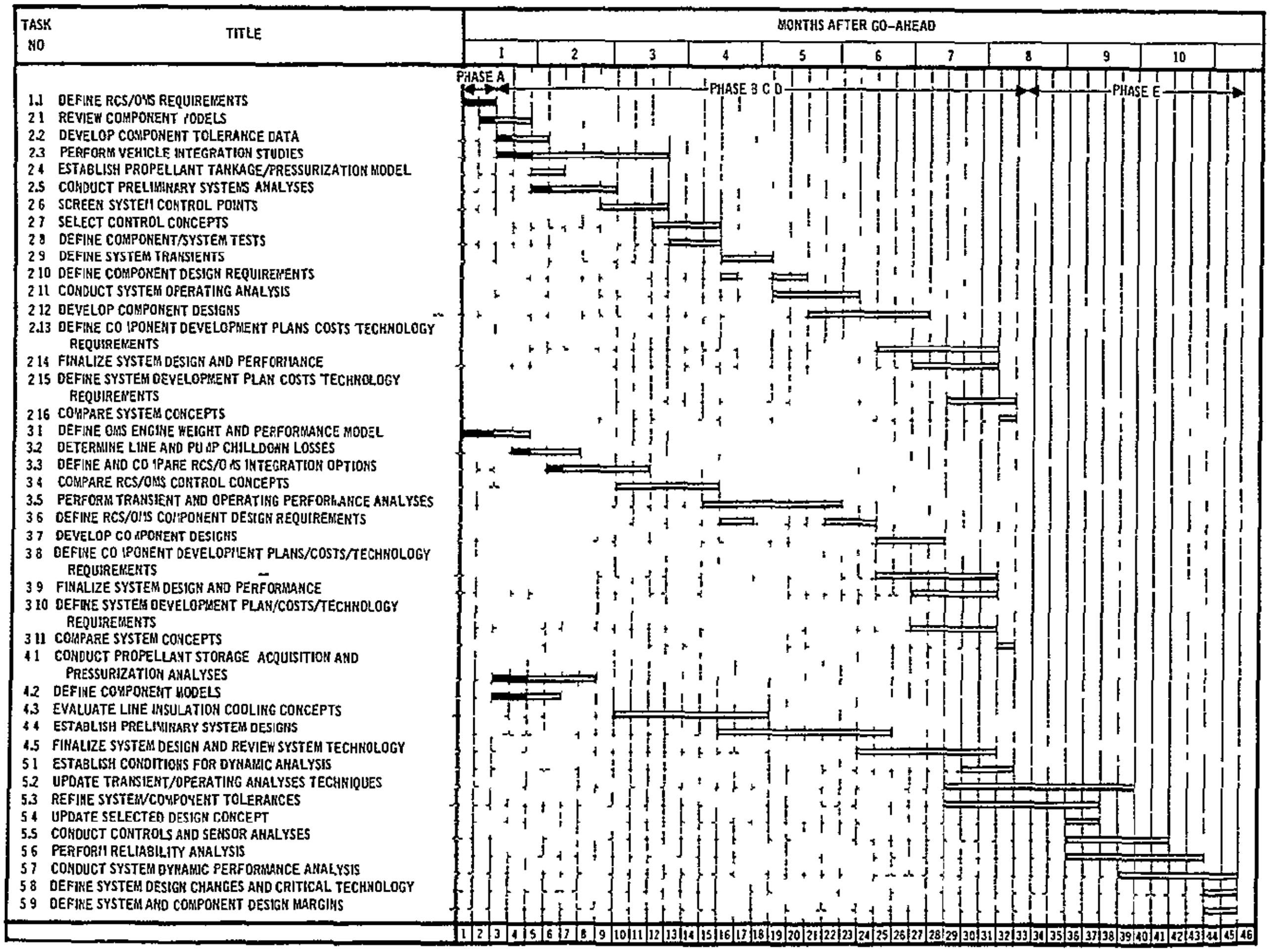
(b) MDC E0346, "Space Shuttle Auxiliary Propulsion System Design Study", Program Plan, dated 15 July 1971.

(c) "Space Shuttle Vehicle Description and Requirements Document", MSC Propulsion and Power Division, dated 1 July 1971.

Master Schedule



Task Schedule



PROGRAM SCHEDULE

FIGURE 1

MANPOWER EXPENDITURE
CONTRACT NAS9-12013

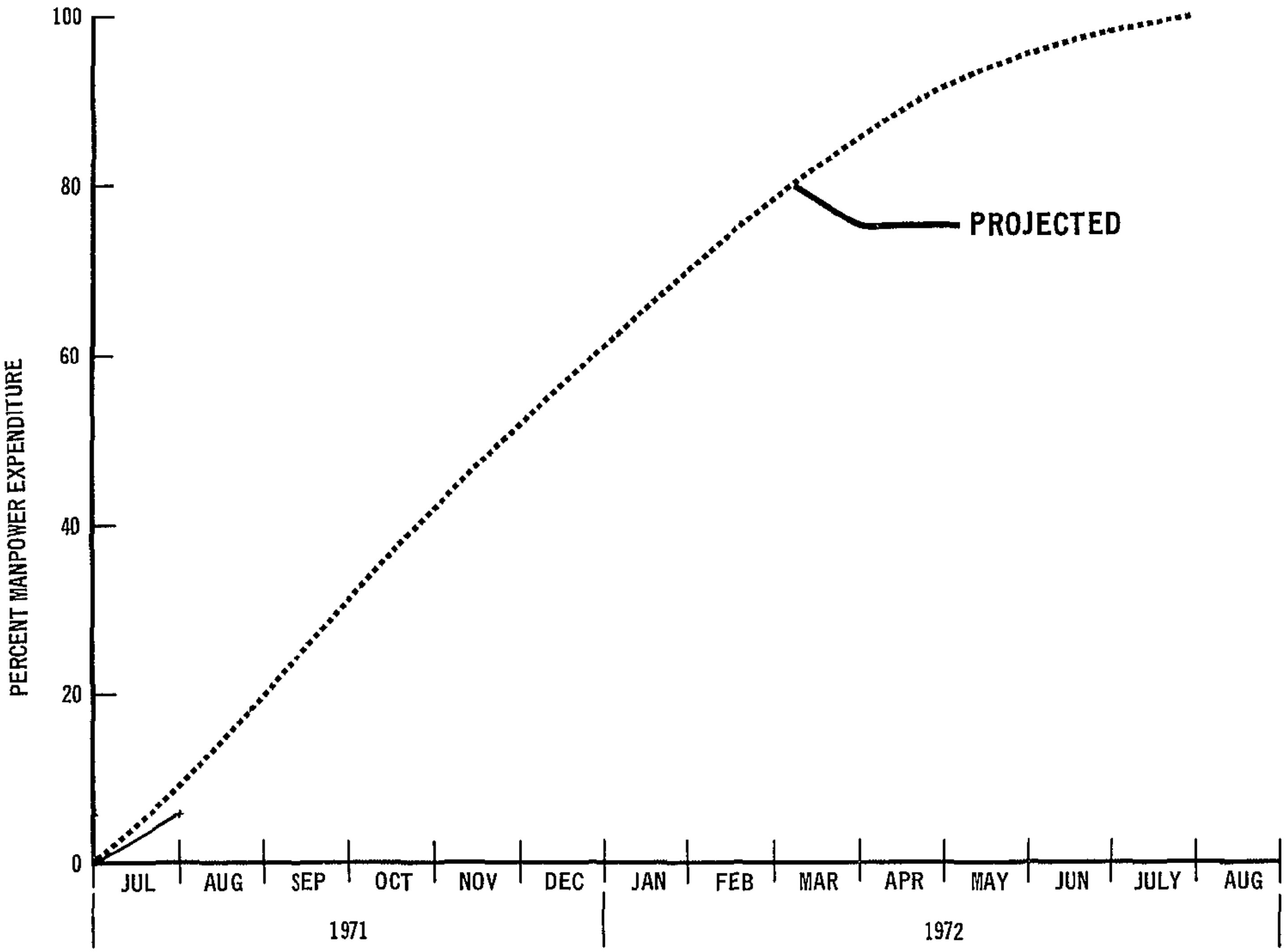


FIGURE 2

RCS MISSION TOTAL IMPULSE REQUIREMENTS

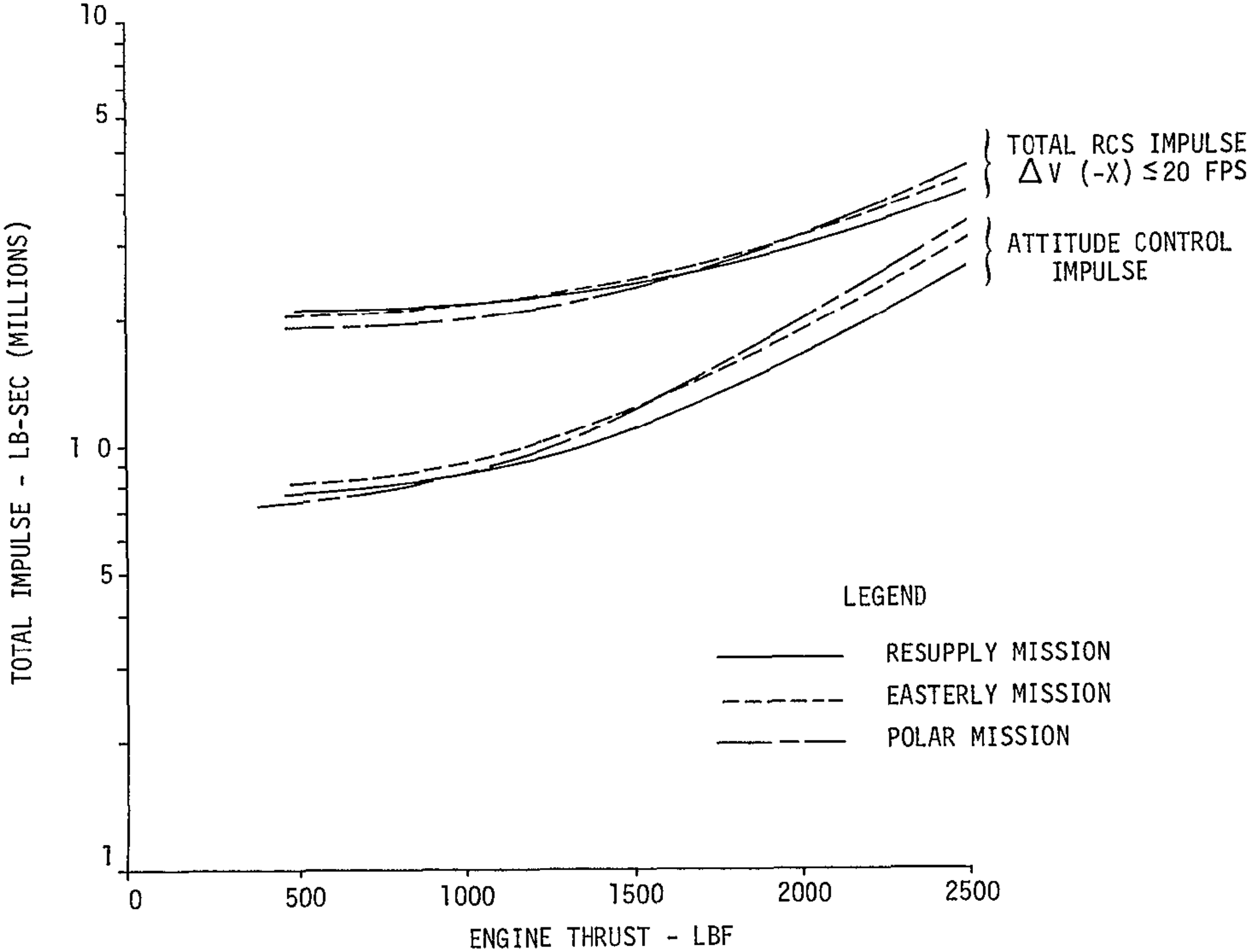


FIGURE 3

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RCS MANEUVER REOUIREMENTS

MISSION	MANEUVER	NO BURNS	ΔV (FPS)	THRUST (LBS)	BURN TIME (SEC)
RESUPPLY	COELLIPTIC BURN	1	18	4600	36
	BRAKING-1	4	45	4600	90
	DOCKING-1	PULSE	10	--	20
	SEPARATION-1	1	10	4600	20
	BRAKING-2	4	54	4600	107
	DOCKING-2	PULSE	10	--	20
	SEPARATION-2	1	10	4600	20
	TOTAL	11	157		
EASTERLY	SPACING BURN-1	1	10	3450	29
	SPACING BURN-2	1	10	3450	29
	ORBIT MAINTENANCE	12	54	4600	116
	BRAKING	4	44	4600	95
	DOCKING	PULSE	10		
	TOTAL	18	128		
SOUTH POLAR	PAYLOAD DEPLOYMENT	2	21	3450	55
	ORBIT MAINTENANCE	12	54	4600	106
	ON-ORBIT ACTIVITIES	5	55	4600	108
	TOTAL	19	130		

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FIGURE 4

RCS TOTAL IMPULSE BREAKDOWN

o EASTERLY MISSION

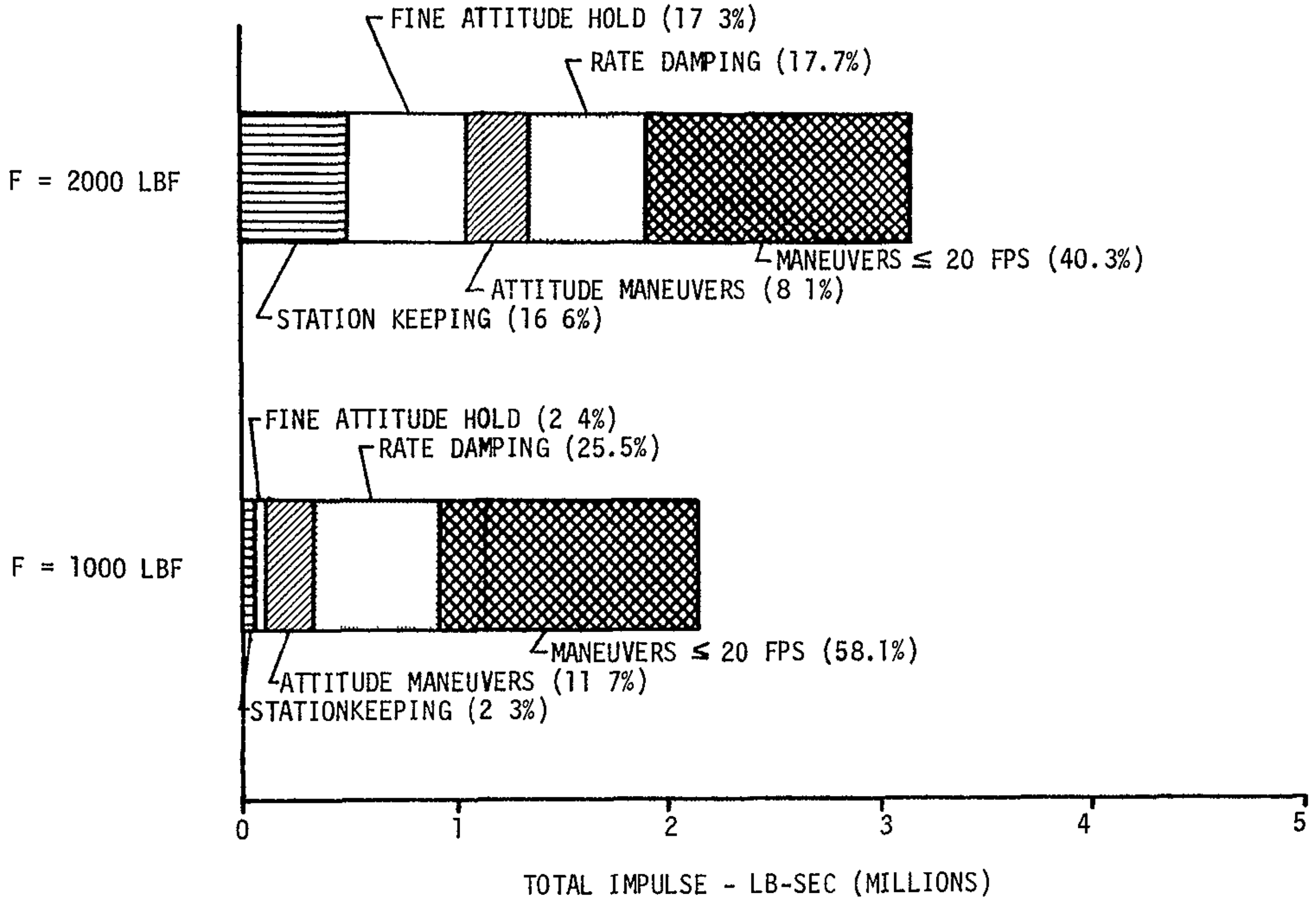

FIGURE 5

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SUMMARY RCS DESCRIPTION

- o RCS DATA USED IN DEVELOPMENT OF PAYLOAD SENSITIVITY TO DESIGN PARAMETERS
- o SERIES GGA FLOW/TURBINE UPSTREAM

BOOSTER		ORBITER	
RCS DESIGN PARAMETER	PAYLOAD SENSITIVITY	RCS DESIGN PARAMETER	PAYLOAD SENSITIVITY
P_C = 500 PSIA		P_C = 500 PSIA	
F = 1150 LBS	$\frac{\partial P}{\partial F}$ = + 16 LB_M/LB_F	F = 1150 LBS	$\frac{\partial P}{\partial F}$ = -1 87 LB_M/LB_F
I_{TOT} = 500,000 LB-SEC		I_{TOT} = 2,210,000 LB-SEC	
$I_{SP_{SYS}}$ = 376 SEC	$\frac{\partial P}{\partial I_{SP}}$ = + 66 LB_M/SEC	$I_{SP_{SYS}}$ = 376/382 SEC	$\frac{\partial P}{\partial I_{SP}}$ = +15 4 LB_M/SEC
ε = 60		ε = 60/120	
O/F = 3 15		O/F = 3 15	
W_{INERT} = 5770	$\frac{\partial P}{\partial W_I}$ = - 16 LB_M/LB_M	W_{INERT} = 9320 LB	$\frac{\partial P}{\partial W_I}$ = -1 0 LB_M/LB_M
$T_{COND} H_2/O_2$ = 200/350°R		$T_{COND} H_2/O_2$ = 200/350°R	
P_{MAX}/P_{SW} = 2 0		P_{MAX}/P_{SW} = 2 0	
P_{SW}/P_{MIN} = 1 135		P_{SW}/P_{MIN} = 1 135	
ΔT_{COND} = 0.5 SEC		ΔT_{COND} = 0 5 SEC	

MCDONNELL DOUGLAS CORPORATION

FIGURE 6

PAYLOAD PENALTY FOR RCS THRUST COMMONALITY

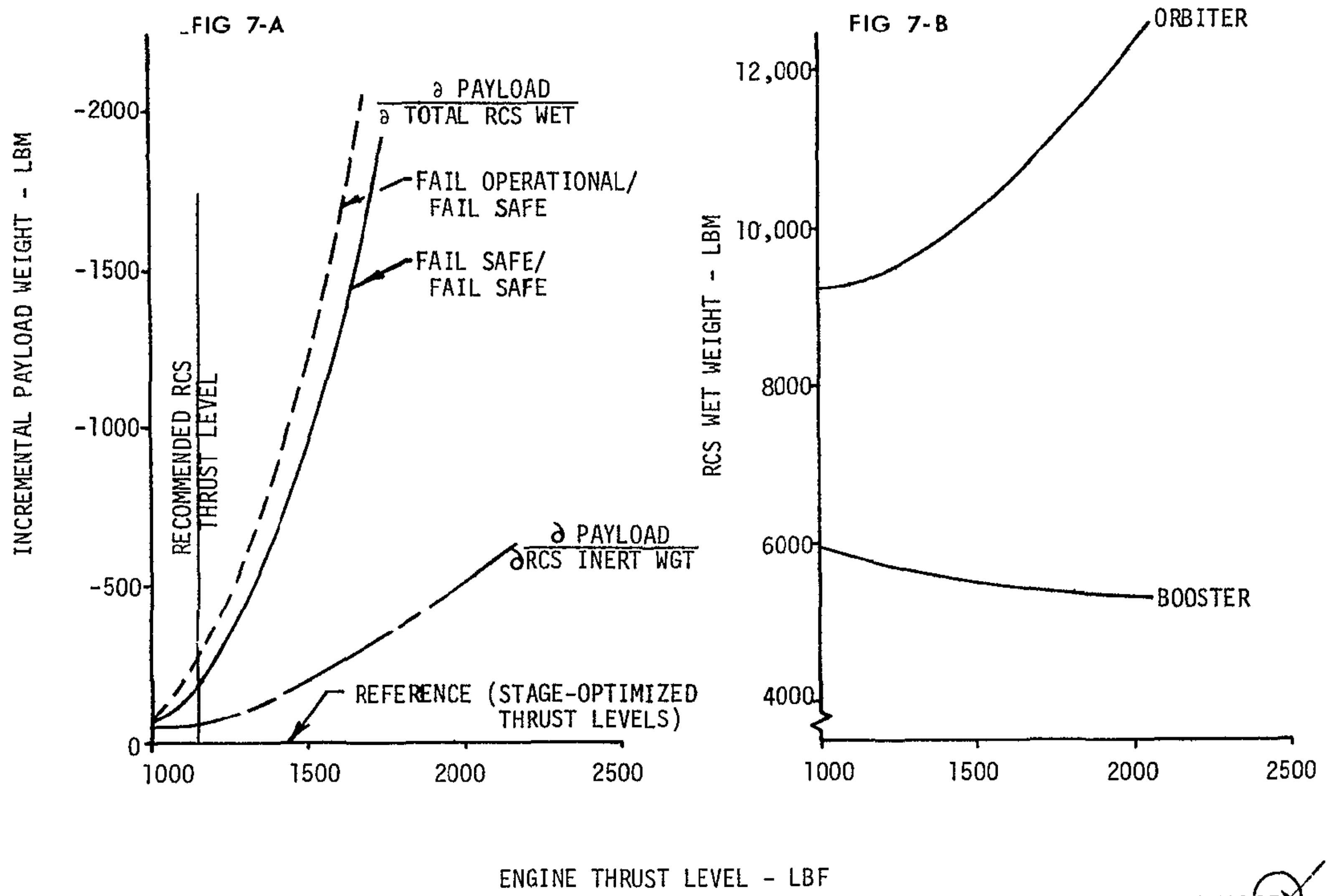

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FIGURE 7

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BOOSTER ACCELERATION REQUIREMENTS

MISSION PHASE		POST-SEPARATION			ORIENTATION			ENTRY[a]			TRANSITION[a]		
		X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
TRANSLATION ACCELERATION FT/SEC^2	SAFE MINIMUM DESIGN	NO REQUIREMENT			NO REQUIREMENT			NO REQUIREMENT			NO REQUIREMENT		
		P	Y	R	P	Y	R	P	Y	R	P	Y	R
ANGULAR ACCELERATION DEG/SEC^2	SAFE MINIMUM	0 12	0 12	0.12	0 12	0 12	0 12	NO REQUIREMENT			NO REQUIREMENT		
	DESIGN	0 30	0 30	0 30	0 30	0 30	0.30						
ATTITUDE LIMITS DEG	FINE	2.00	2 00	2 00	2.00	2 00	2.00	NO REQUIREMENT			NO REQUIREMENT		
	COURSE	N/R	N/R	N/R	N/R	N/R	N/R						

(a) CONTROL PROVIDED BY AERODYNAMIC SURFACES

FIGURE 8

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ORBITER ACCELERATION REQUIREMENTS

MISSION PHASE		ASCENT			ON-ORBIT			ENTRY			TRANSITION		
		-X	+X	±Y,Z	-X(a)	+X	±Y,Z	-X	+X	±Y,Z	-X	+X	±Y,Z
TRANSLATION ACCELERATION FT/SEC^2	SAFE MINIMUM	1.0(OMS)	N/R+		0.6(OMS) 0 2(OMS)	0.0	0 0	N/R+			N/R+		
	DESIGN	1.5(OMS)			1 2(OMS) 0 4(APS)	0.4	0 2						
		P	Y	R	P	Y	R	P	Y	R	P	Y	R
ANGULAR ACCELERATION DEG/SEC^2	SAFE MINIMUM	N/R+		(b)	0 3	0.3	0.3	0 3	0 8	1 0			
	DESIGN				0 5	0 5	0 5	0.5	1 2	1.5	TBD	TBD	TBD
ATTITUDE LIMITS DEG	FINE COURSE	N/R+ N/R+		1 0 N/R+	0 5 20	0.5 20	0.5 20.	1 0 N/R+	2 0 N/R+	2 0 N/R+			

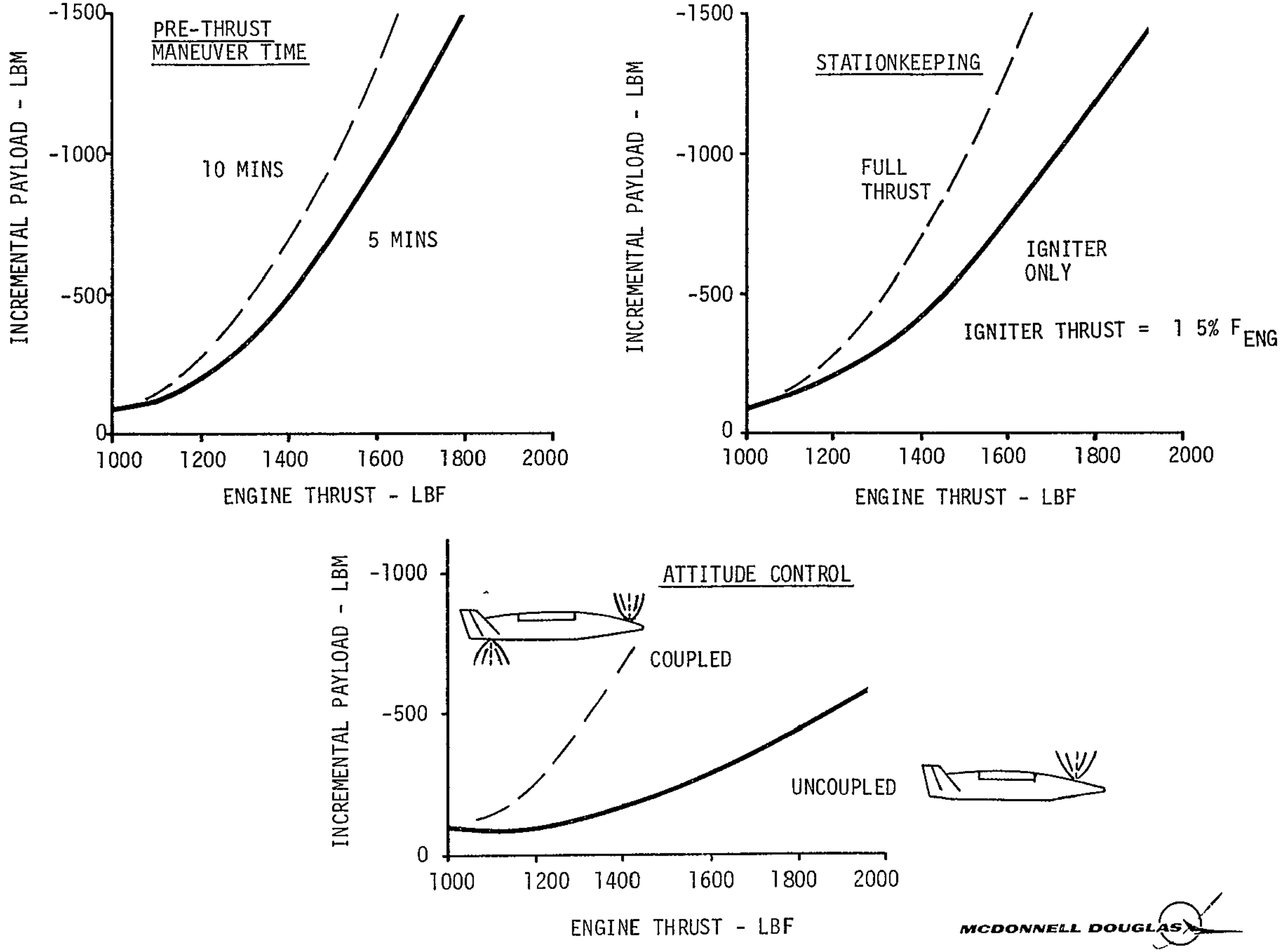
+ NO REQUIREMENT

(a) FAIL SAFE DEORBIT BACKUP SHALL BE PROVIDED BY APS; DEORBIT MANEUVER SHALL NOT EXCEED 5 MINUTES DURATION

(b) ROLL CONTROL TORQUE OF 40,000 FT-LB(MIN) REQUIRED FOR FAILED MAIN ENGINE

FIGURE 9

EFFECT OF ALTERNATE RCS CONTROL MODES ON OPTIMUM THRUST LEVEL



MCDONNELL DOUGLAS CORPORATION

FIGURE 10

SUMMARY OF SYSTEM THRUST REQUIREMENTS

o 1150 LB THRUST ENGINES

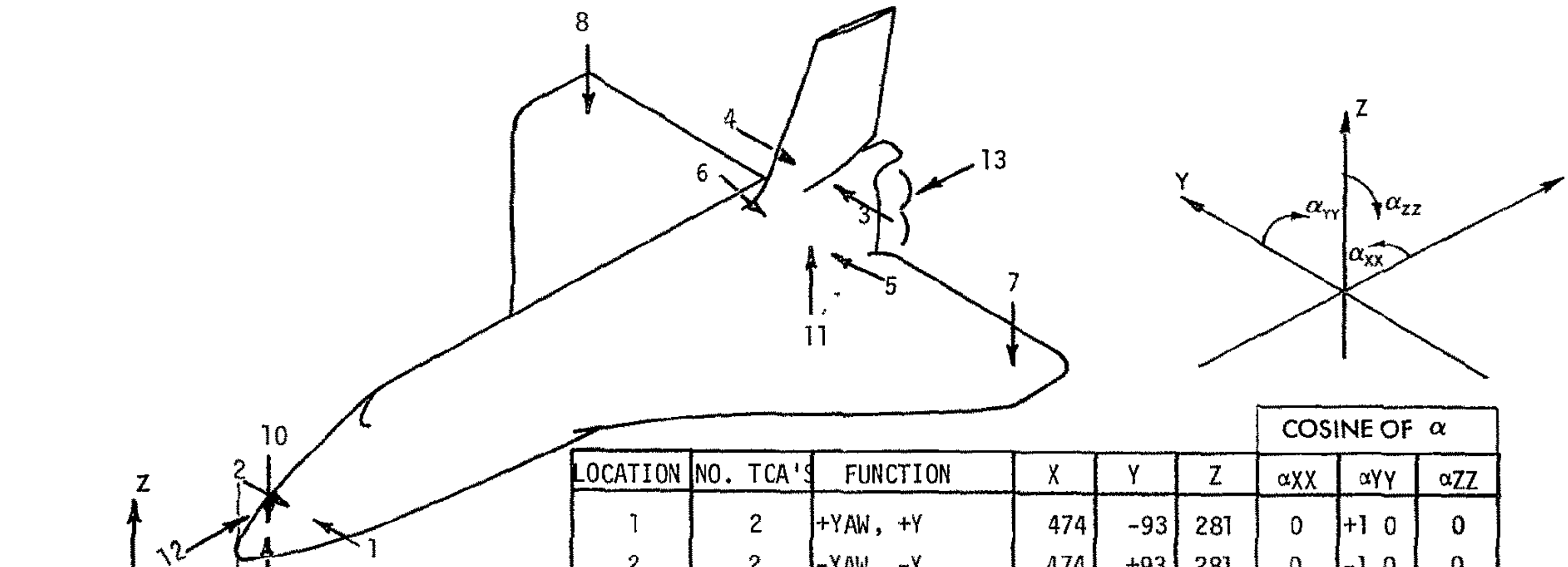
OPERATING CONDITION	SYSTEM THRUST, LB	
	BOOSTER	ORBITER
LIMIT CYCLE	13 - 5 25	15 - 5 97
ORBIT MANEUVERS	+N/R	2300 - 4600
DEORBIT (BACKUP)	+N/R	4600
REENTRY	9200 √	5750 √

\+ NO REQUIREMENT

√ DESIGN THRUST LEVEL - 1 5°/SEC^2 CONTINUOUS YAW-ROLL COORDINATED MANEUVER

FIGURE 11

ORBITER THRUSTER LOCATIONS

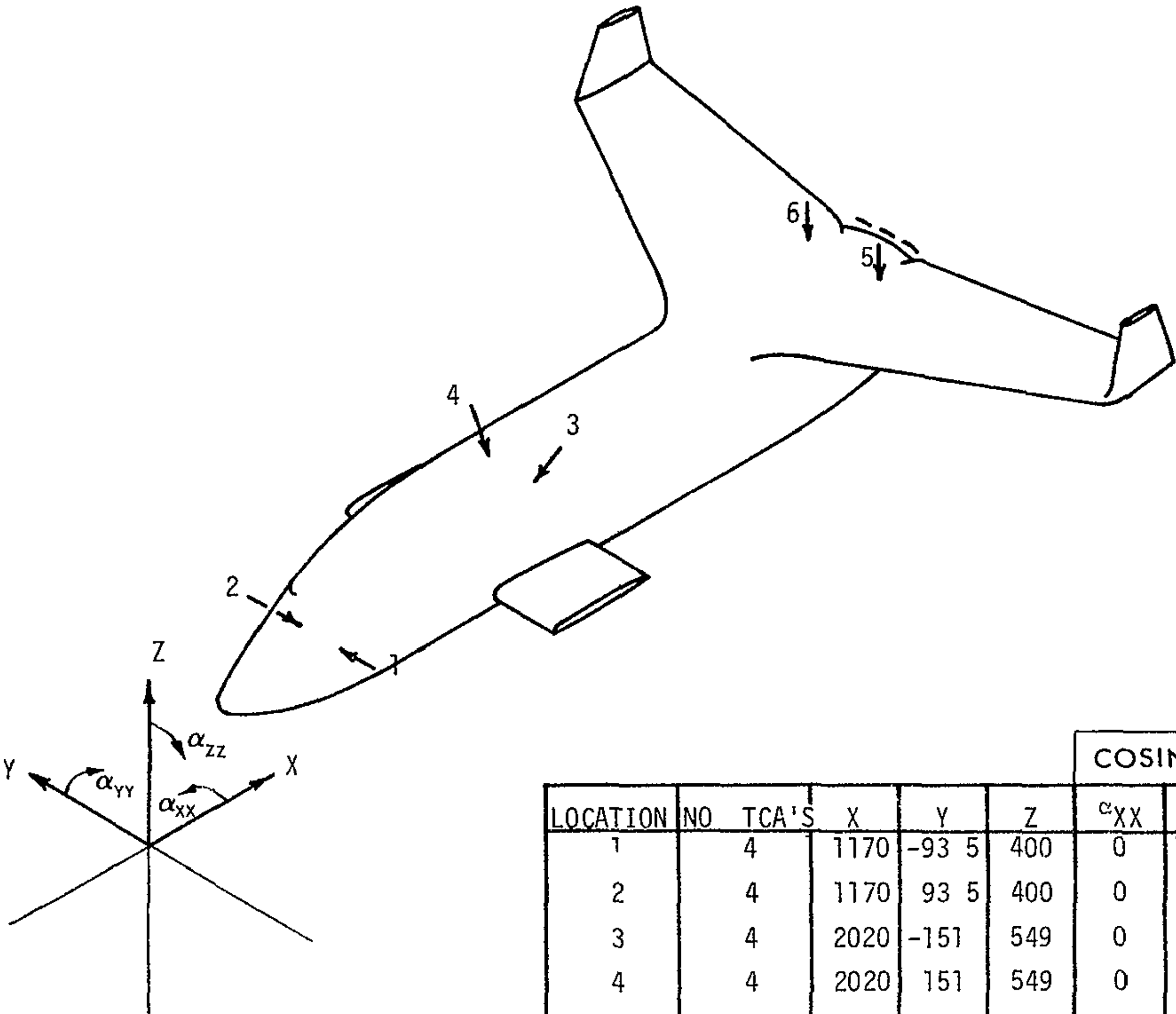


LOCATION	NO. TCA'S	FUNCTION	X	Y	Z	COSINE OF α		
						αXX	αYY	αZZ
1	2	+YAW, +Y	474	-93	281	0	+1 0	0
2	2	-YAW, -Y	474	+93	281	0	-1.0	0
3	2	-YAW, +Y, +ROLL	2029	-106	400	0	+1.0	0
4	2	+YAW, -Y, -ROLL	2029	+106	400	0	-1.0	0
5	2	-YAW, +Y, -ROLL	2029	-142	226	0	+ 985	- 174
6	2	+YAW, -Y, +ROLL	2029	+142	226	0	- 985	- 174
7	3	+PITCH,-Z,-ROLL	1965	-530	235	0	0	-1 0
8	3	+PITCH,-Z,+ROLL	1965	+530	235	0	0	-1 0
9	2	+PITCH, +Z	368	0	175	0	0	+1.0
10	3	-PITCH, -Z	368	0	294	0	0	-1.0
11	2	-PITCH, +Z	1954	0	140	0	0	+1 0
12	4	+X	474	0	307	+1.0	0	0
13	4	-X	2100	0	307	-1.0	0	0

MCDONNELL DOUGLAS CORPORATION

FIGURE 12

BOOSTER THRUSTER LOCATIONS



LOCATION	NO TCA'S	X	Y	Z	COSINE OF α α_{XX}	α_{YY}	α_{ZZ}
1	4	1170	-93 5	400	0	1 0	0
2	4	1170	93 5	400	0	-1 0	0
3	4	2020	-151	549	0	309	- 95
4	4	2020	151	549	0	- 309	- 95
5	4	3833	-200	604	0	0	-1 0
6	4	3833	200	604	0	0	-1 0

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FIGURE 13

ENTRY CONTROL CAPABILITY

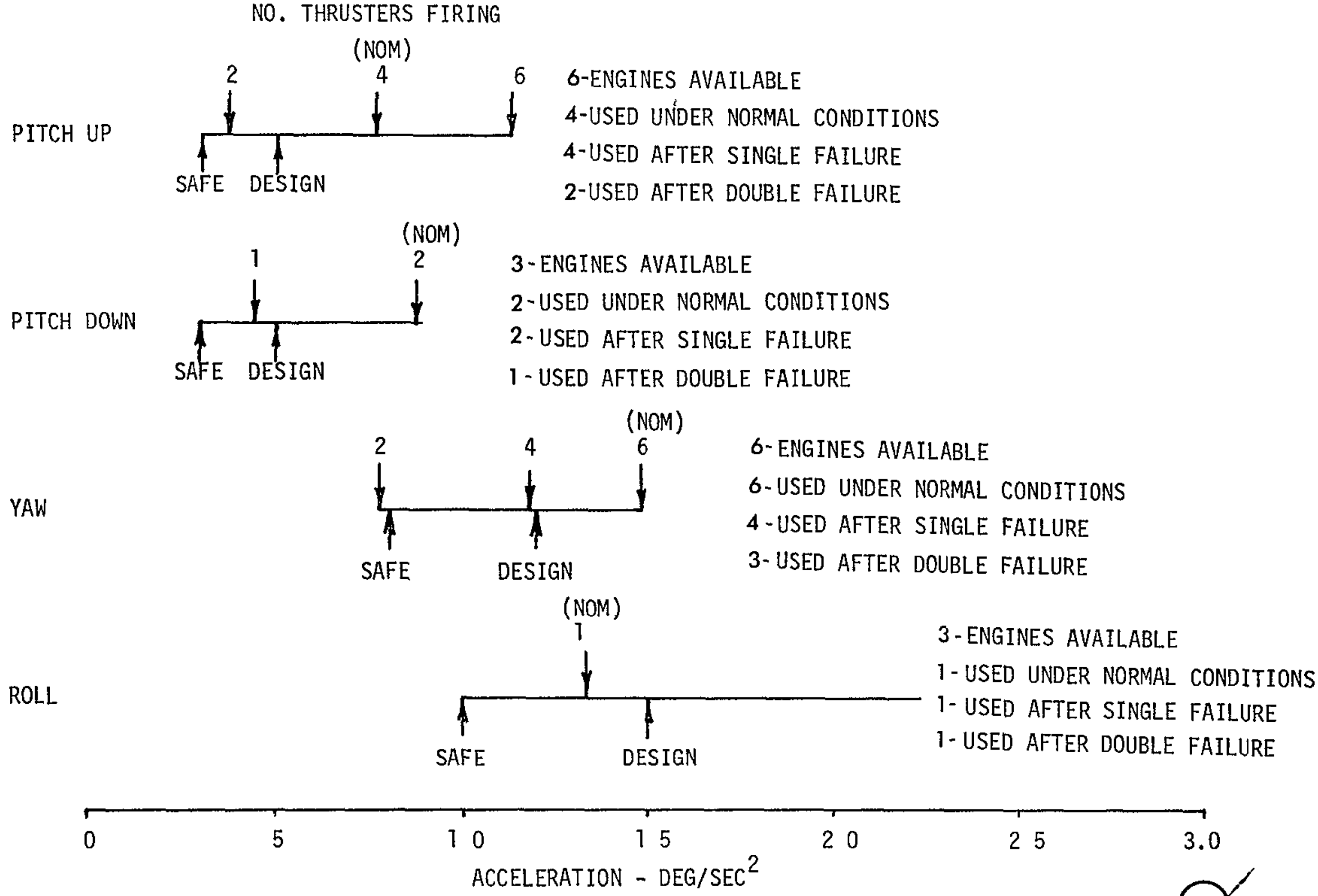

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FIGURE 14

ON ORBIT CONTROL CAPABILITY

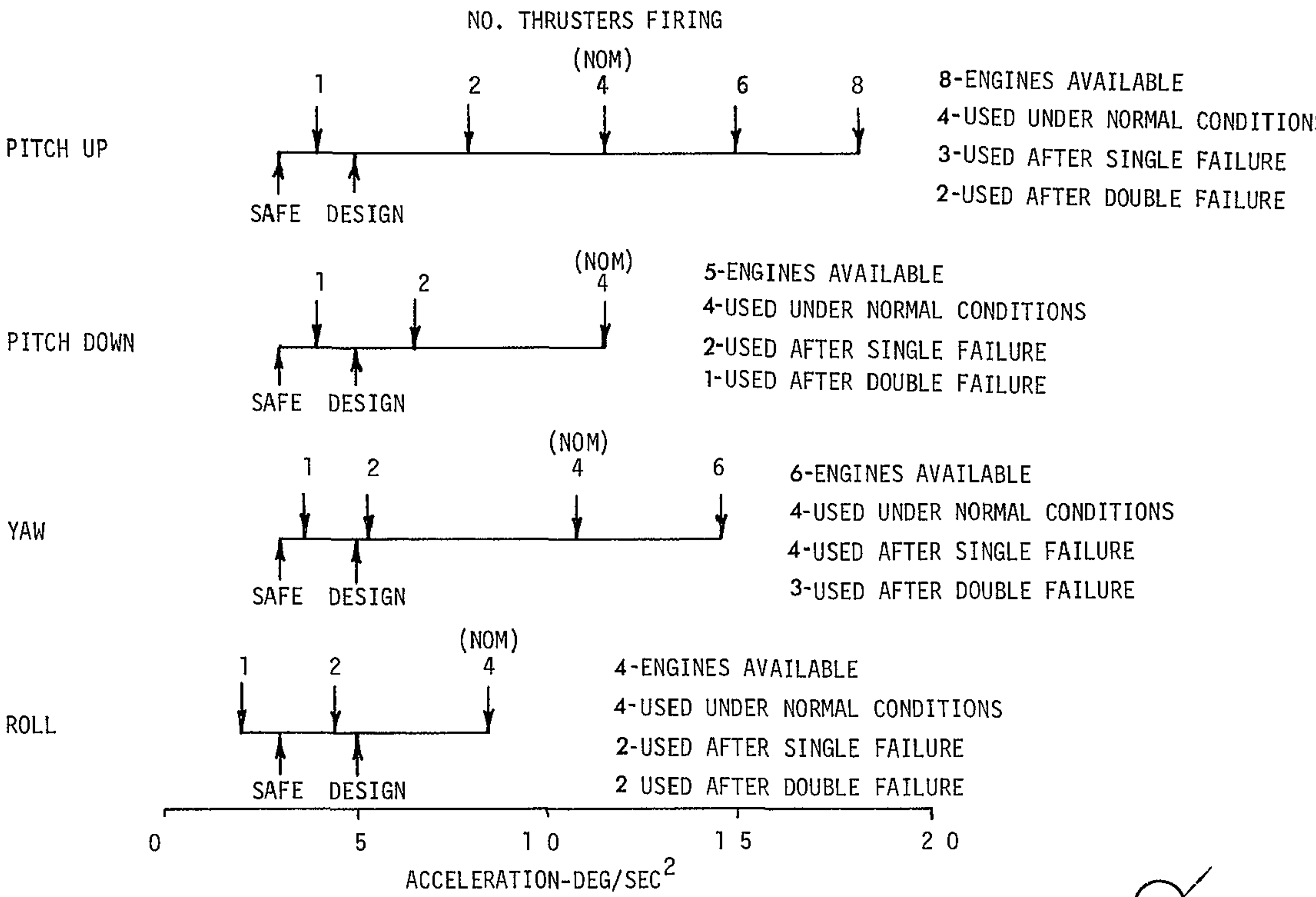

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FIGURE 15

ORBIT MANEUVER CAPABILITY

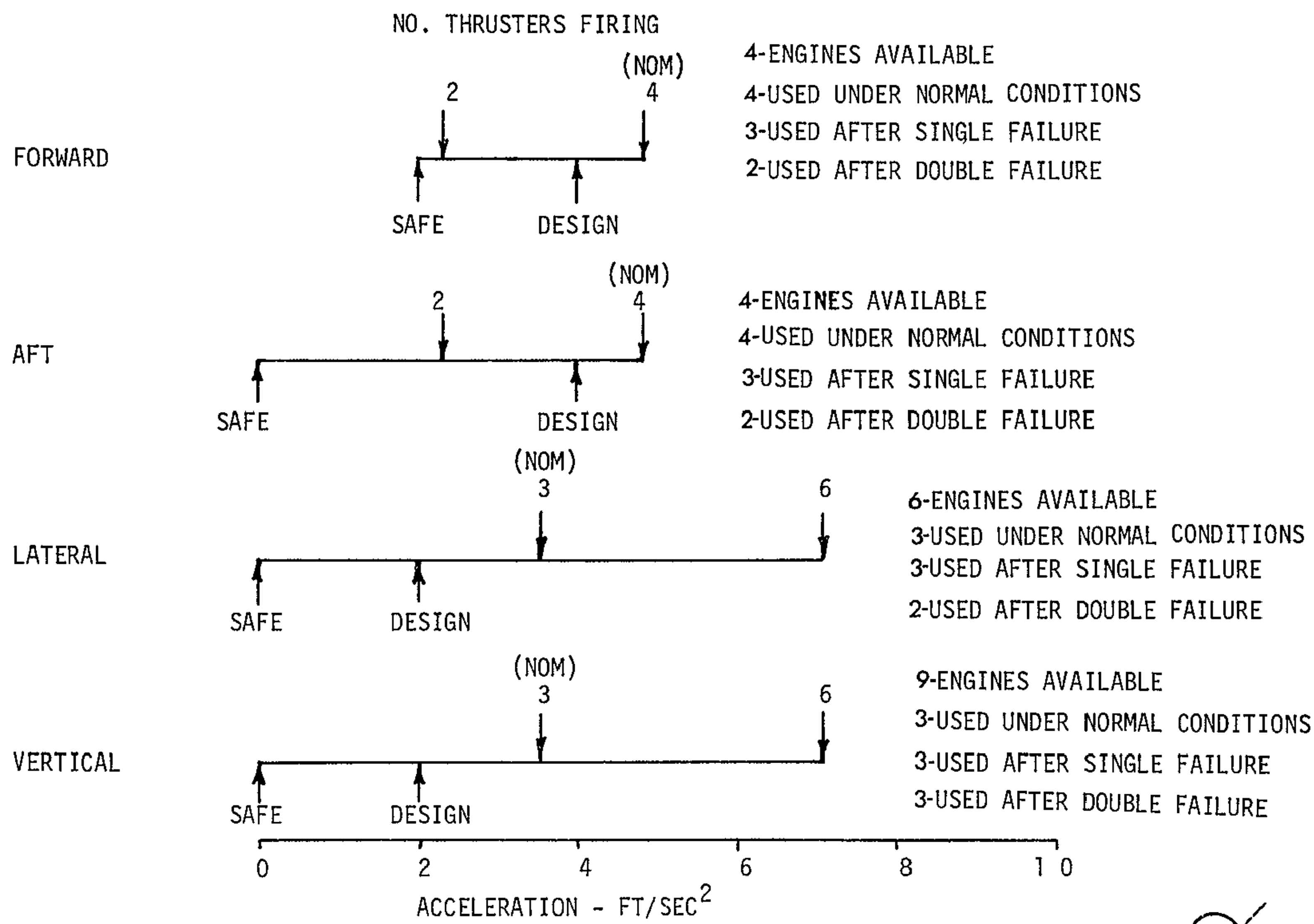

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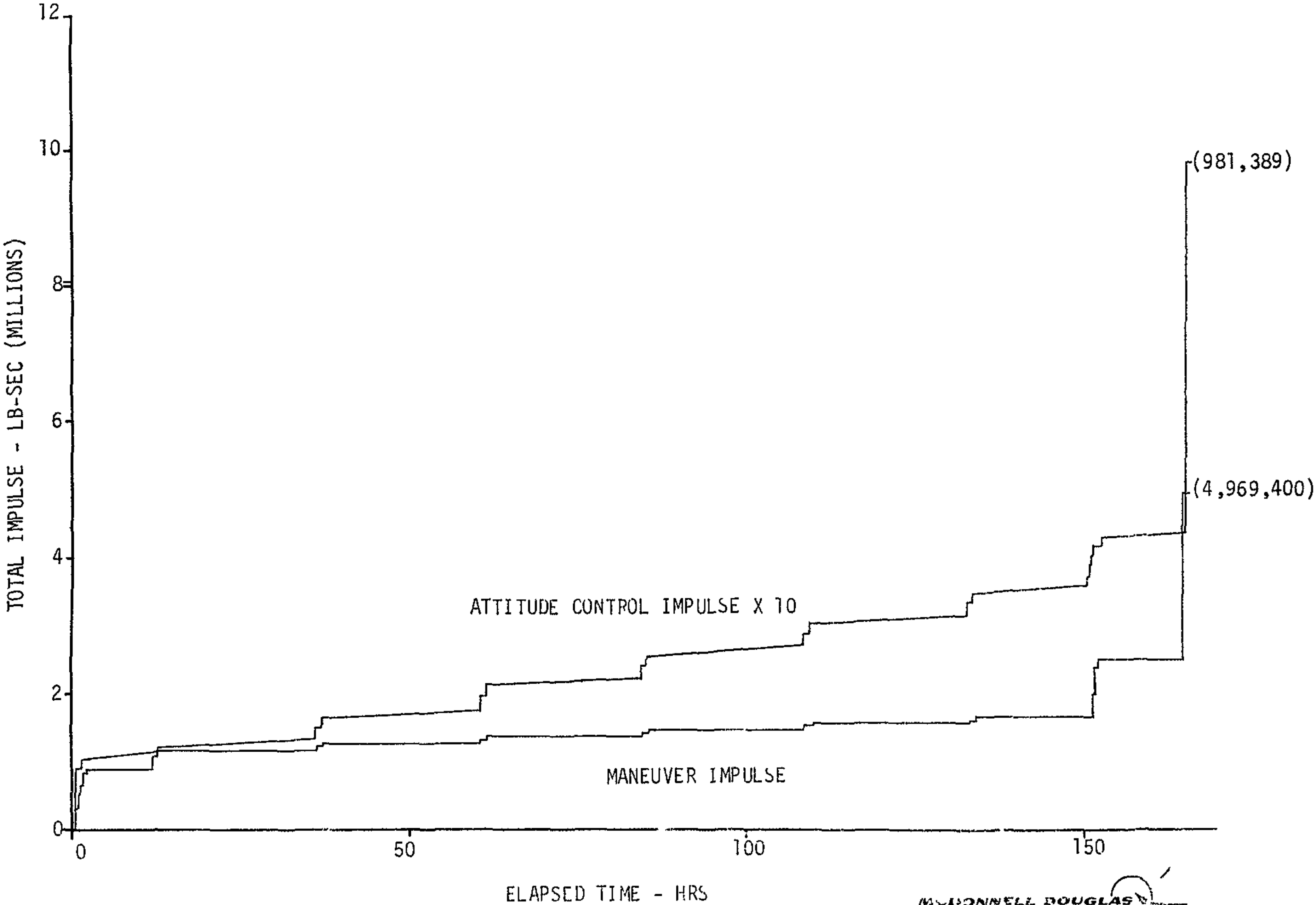
FIGURE 16

EASTERLY MISSION - APS IMPULSE REQUIREMENTS



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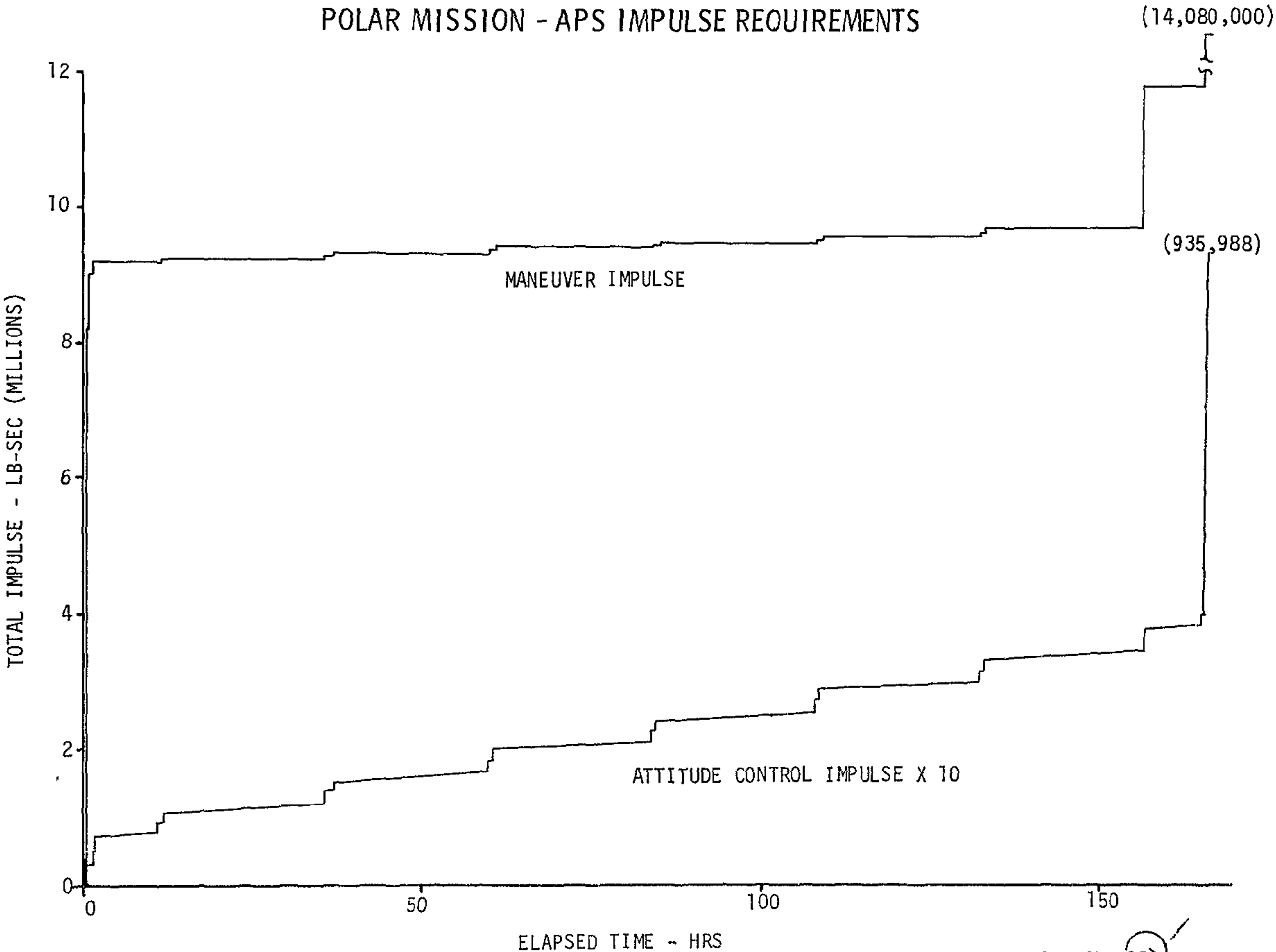
FIGU



MCDONNELL DOUGLAS CORPORATION

FIGURE 18

RESUPPLY MISSION - APS IMPULSE REQUIREMENTS

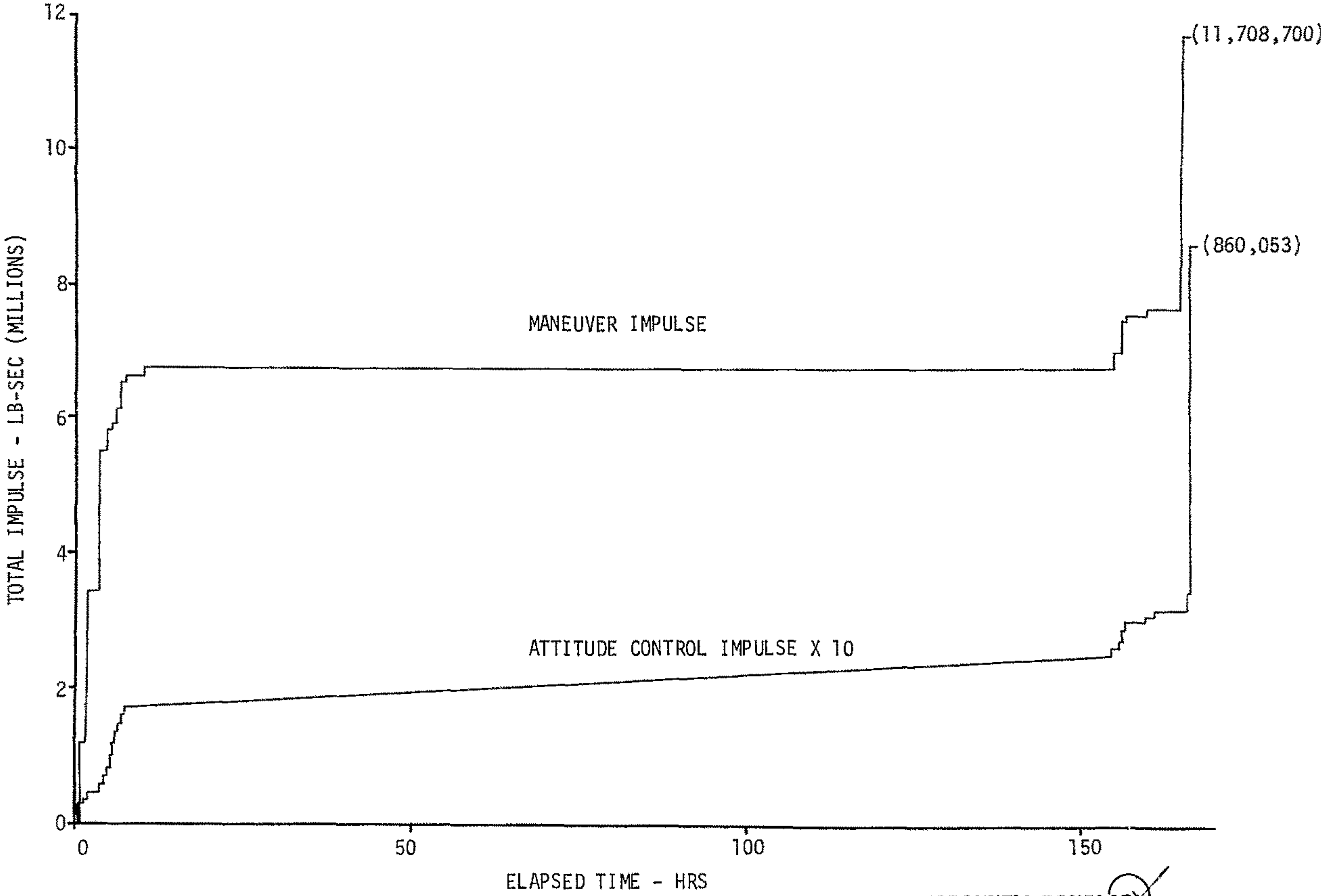


FIGURE 19

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WEIGHT SENSITIVITY TO RCS/OMS VELOCITY ALLOCATION

o EASTERLY LAUNCH
o DELIVERY/RETRIEVAL OF OOS

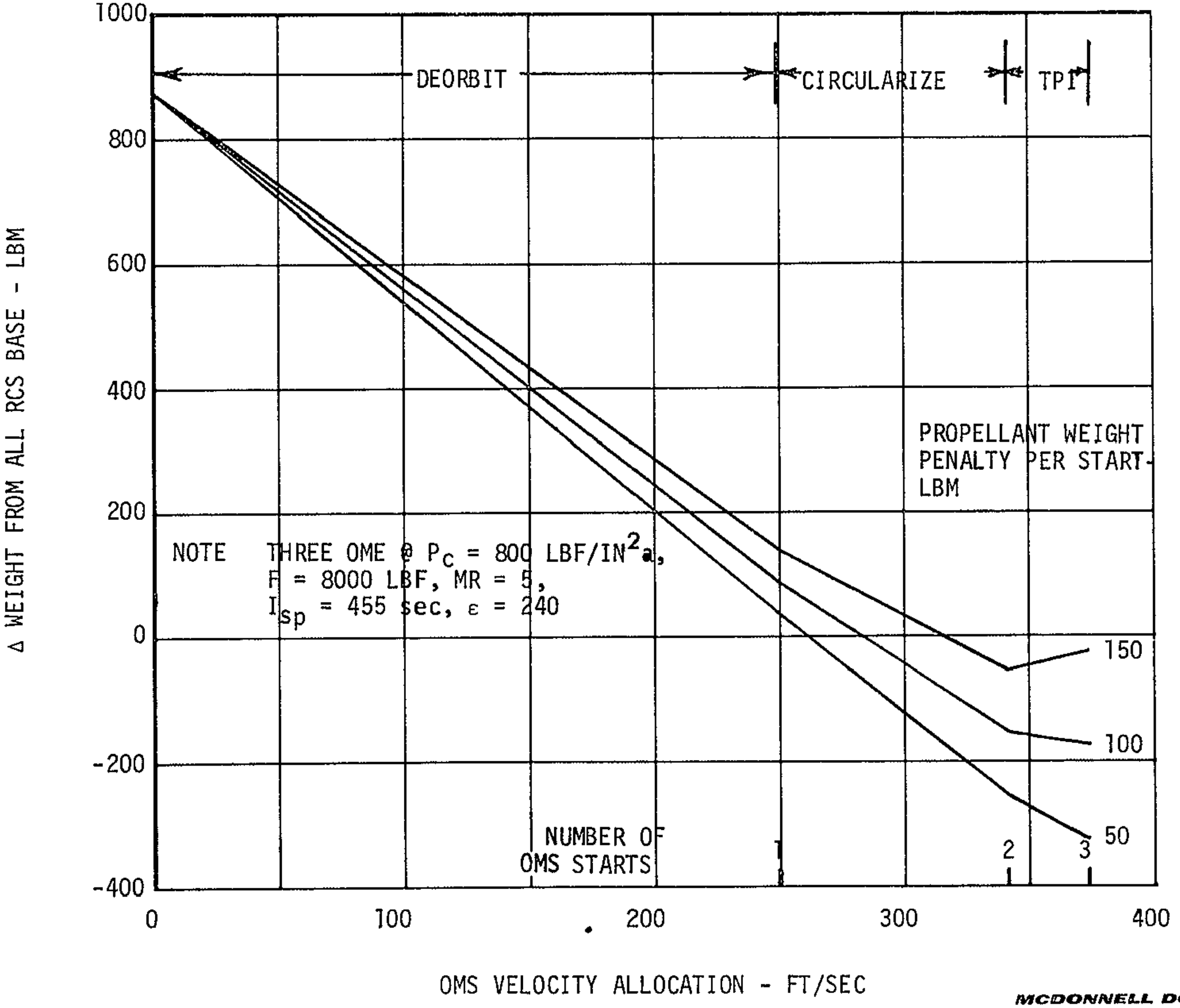

FIGURE 20

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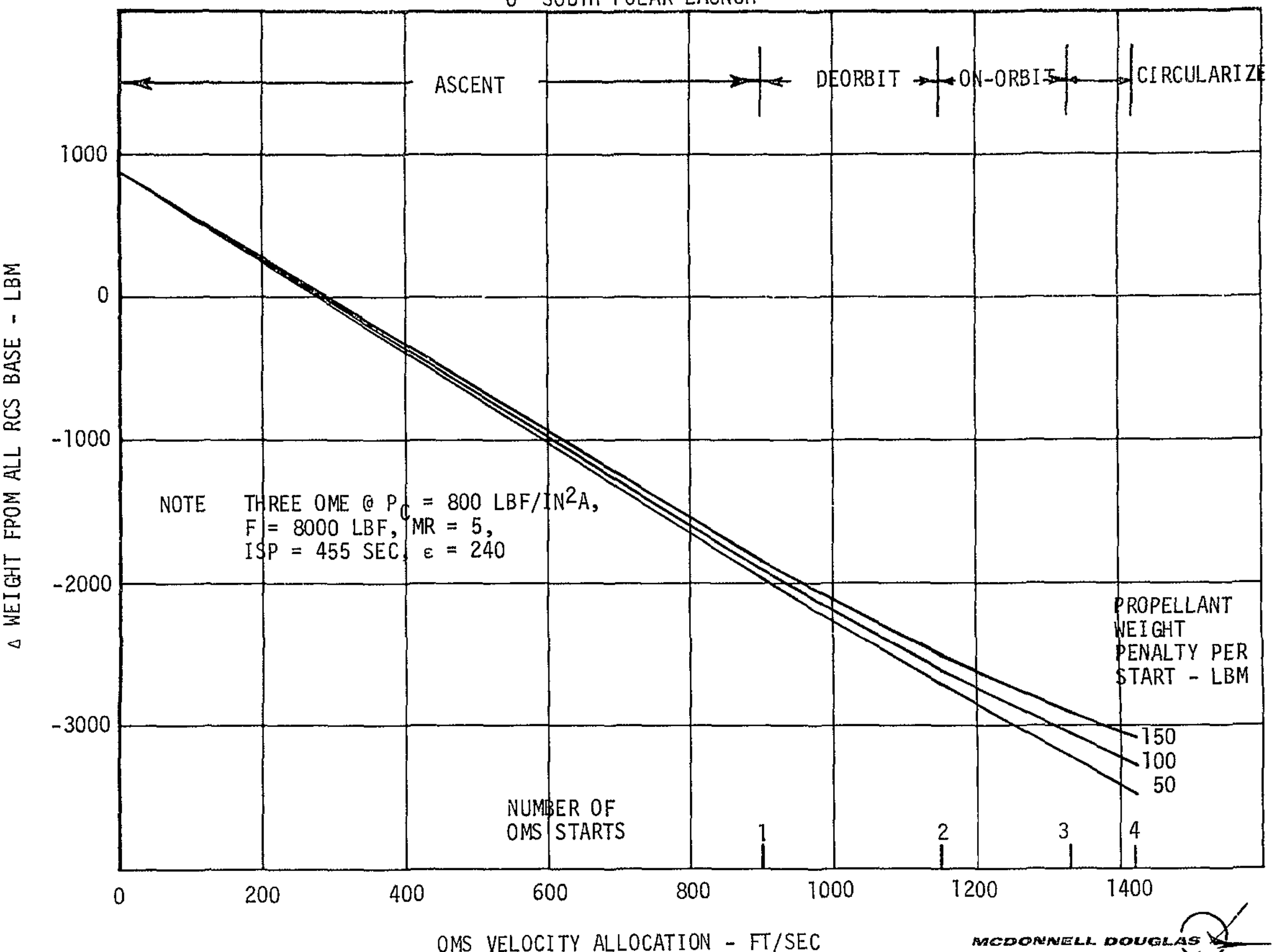
WEIGHT SENSITIVITY TO RCS/OMS VELOCITY ALLOCATION

o SOUTH POLAR LAUNCH

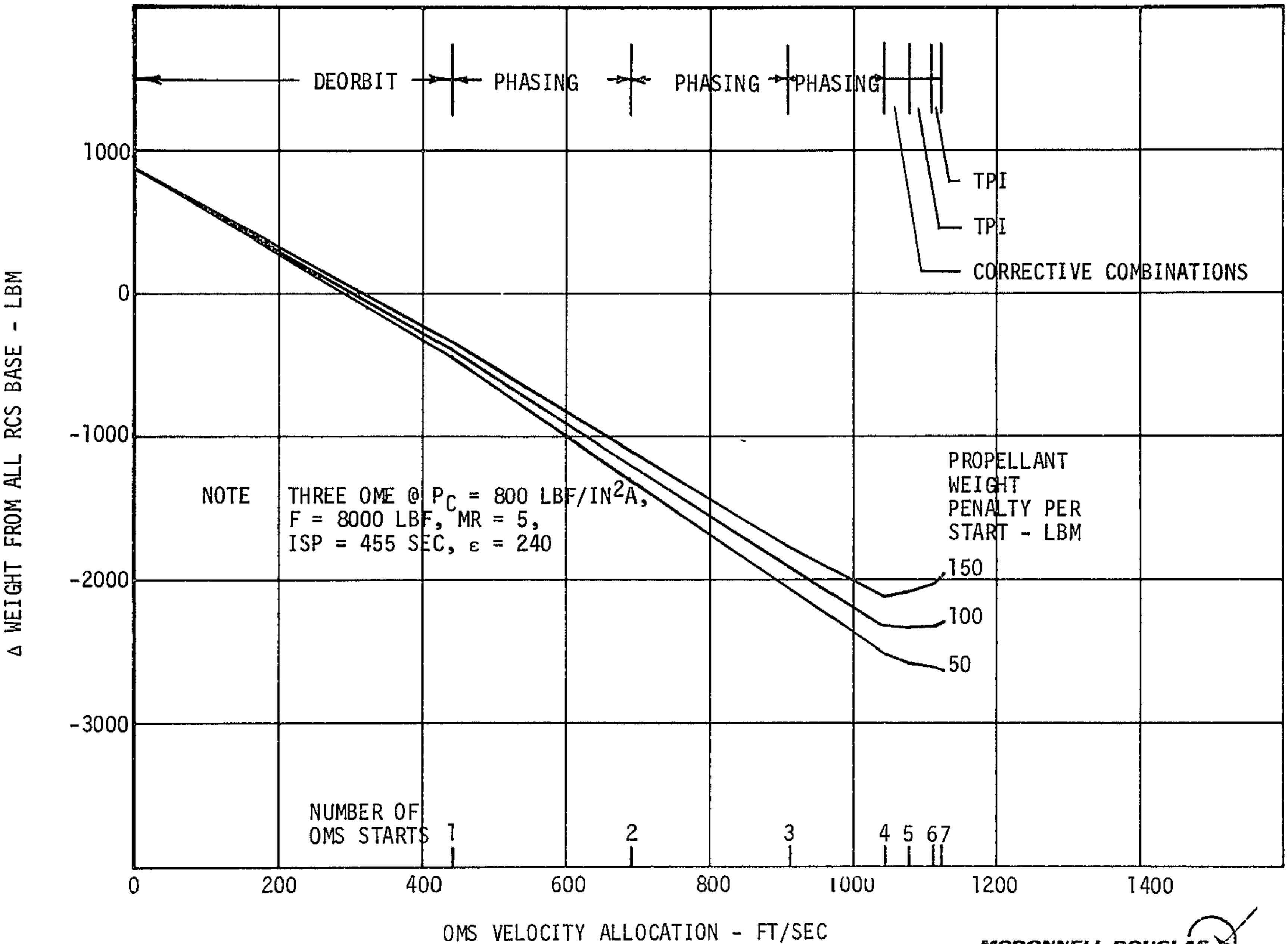


MCDONNELL DOUGLAS CORPORATION

FIGURE 21

WEIGHT SENSITIVITY TO RCS/OMS VELOCITY ALLOCATION

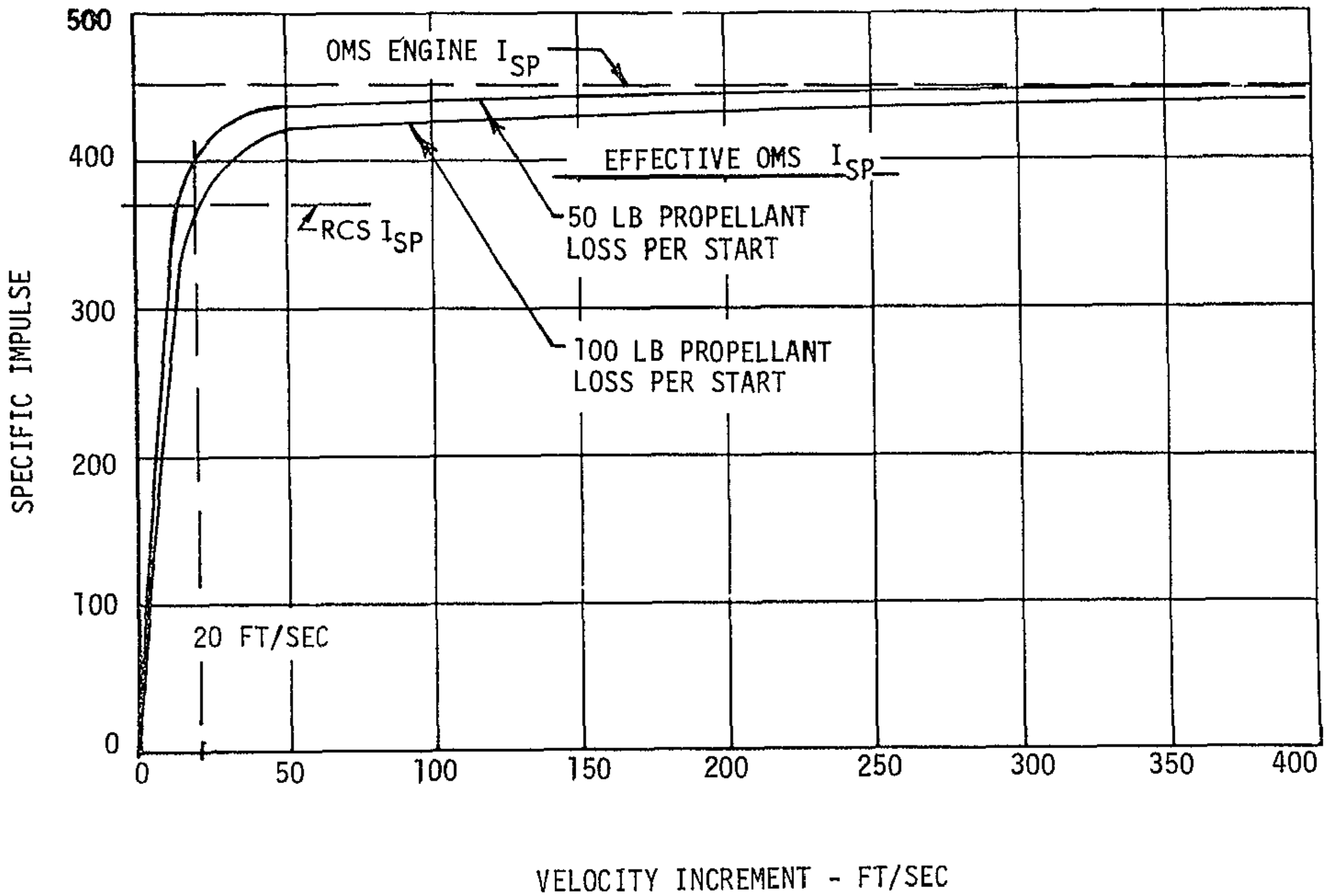
o RESUPPLY MISSION



MCDONNELL DOUGLAS
CORPORATION

FIGURE 22

BREAK EVEN POINT - RCS VS OMS



(44)

FIGURE 23

ORBITER OMS ABORT TO ORBIT REQUIREMENTS

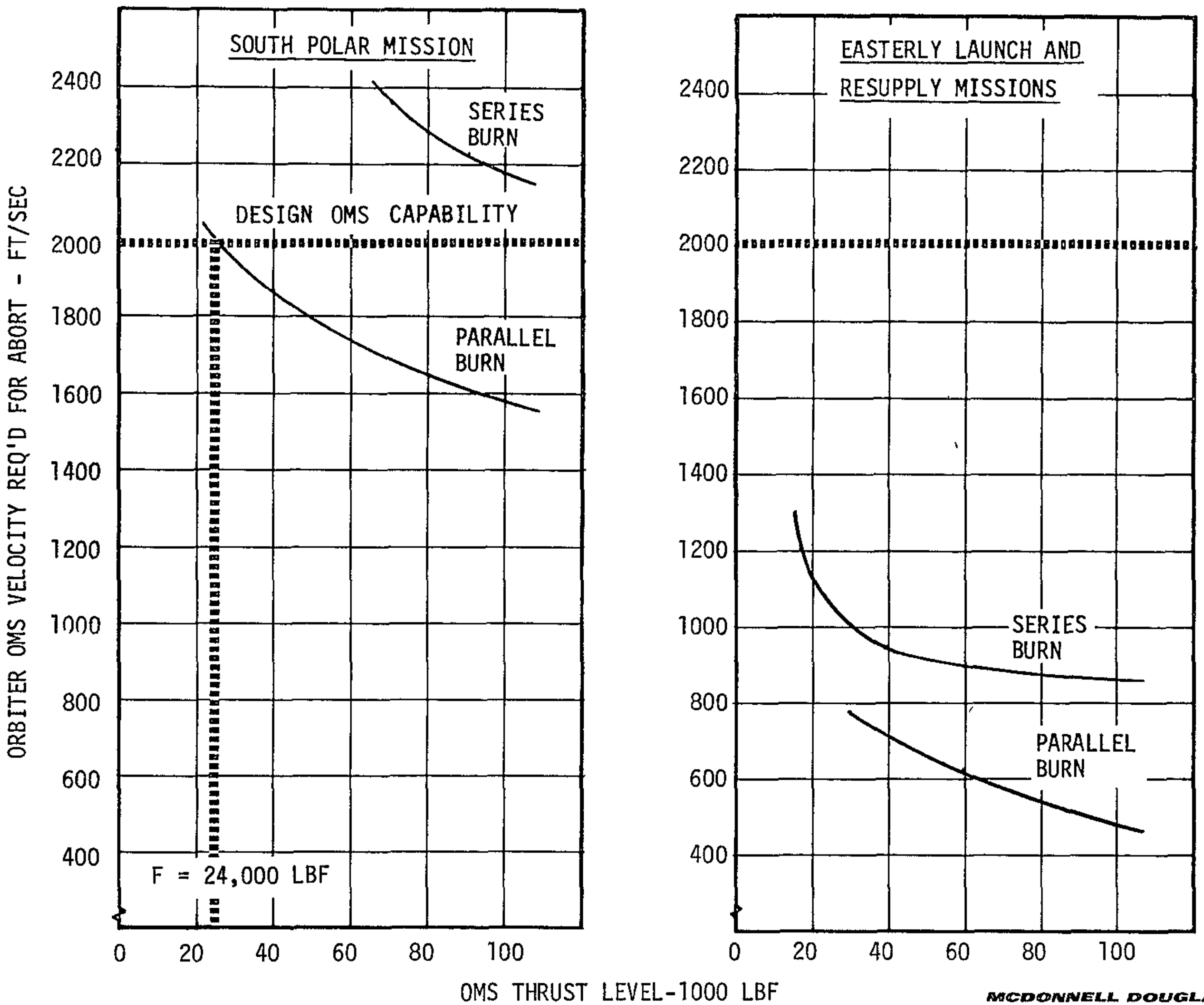


FIGURE 24

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	11,500
	TOTAL IMPULSE (LB-SEC)		500,000
	RESUPPLY	$2\ 23 \times 10^6$	---
	EASTERLY LAUNCH	$2\ 23 \times 10^6$	---
	SOUTH POLAR	$2\ 15 \times 10^6$	---

		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	$10\ 34 \times 10^6$	---
	EASTERLY LAUNCH	3.72×10^6	---
	SOUTH POLAR	12.87×10^6	---

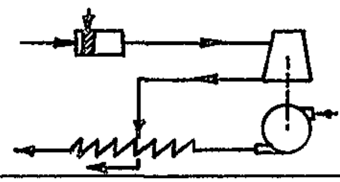
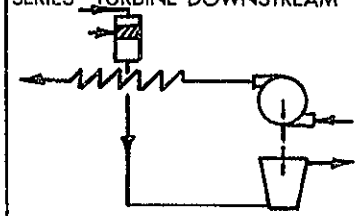
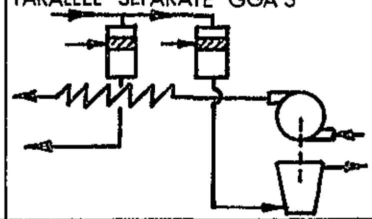
* TO BE DETERMINED DURING STUDY FROM RCS/OMS OPTIMIZATION

FIGURE 25

MCDONNELL DOUGLAS CORPORATION

RCS DESIGN SUMMARY

- o ORBITER
- o TOTAL IMPULSE = 2 23M LB-SEC

	SERIES TURBINE UPSTREAM	SERIES TURBINE DOWNSTREAM	PARALLEL SEPARATE GGA'S
SYSTEM DESIGN PARAMETERS			
THRUSTER MIXTURE RATIO, O/F	4.0	4.0	4.0
EXPANSION RATIO	40:1	40:1	40:1
CHAMBER PRESSURE, PSIA	300	300	300
THRUSTER SPECIFIC IMPULSE, SEC	433	433	433
SYSTEM SPECIFIC IMPULSE, SEC	371	373	356
ACCUMULATOR PRESSURE RATIO (H_2/O_2)			
- P_{SW}/P_{MIN}	1 176/1 172	1.126/1.169	1.134/1.143
- P_{MAX}/P_{SW}	1.994/2 374	1.736/2 359	1.701/2.099
CONDITIONER BYPASS RATIO	.167	.160	.214
TURBINE PRESSURE RATIO	2.70/1.77	6 27/2.30	20/20
SYSTEM THRUST, LB	5750	5750	5750
SYSTEM WEIGHTS (LBS)			
PROPELLANT	6175	6140	6425
TANKAGE	483	479	502
PRESSURIZATION	142	140	152
CONDITIONER ASSEMBLIES	683	665	686
ACCUMULATORS	777	831	856
VENT	113	142	300
INSULATION	155	155	162
LINES, VALVES AND REGULATORS	614	614	615
THRUSTERS	992	992	992
TOTAL WEIGHT	10134	10158	10690

MCDONNELL DOUGLAS CORPORATION

FIGURE 26

CONDITIONER PRESSURE TEMPERATURE AND FLOW BALANCE

SERIES GGA FLOW (TURBINE UPSTREAM)

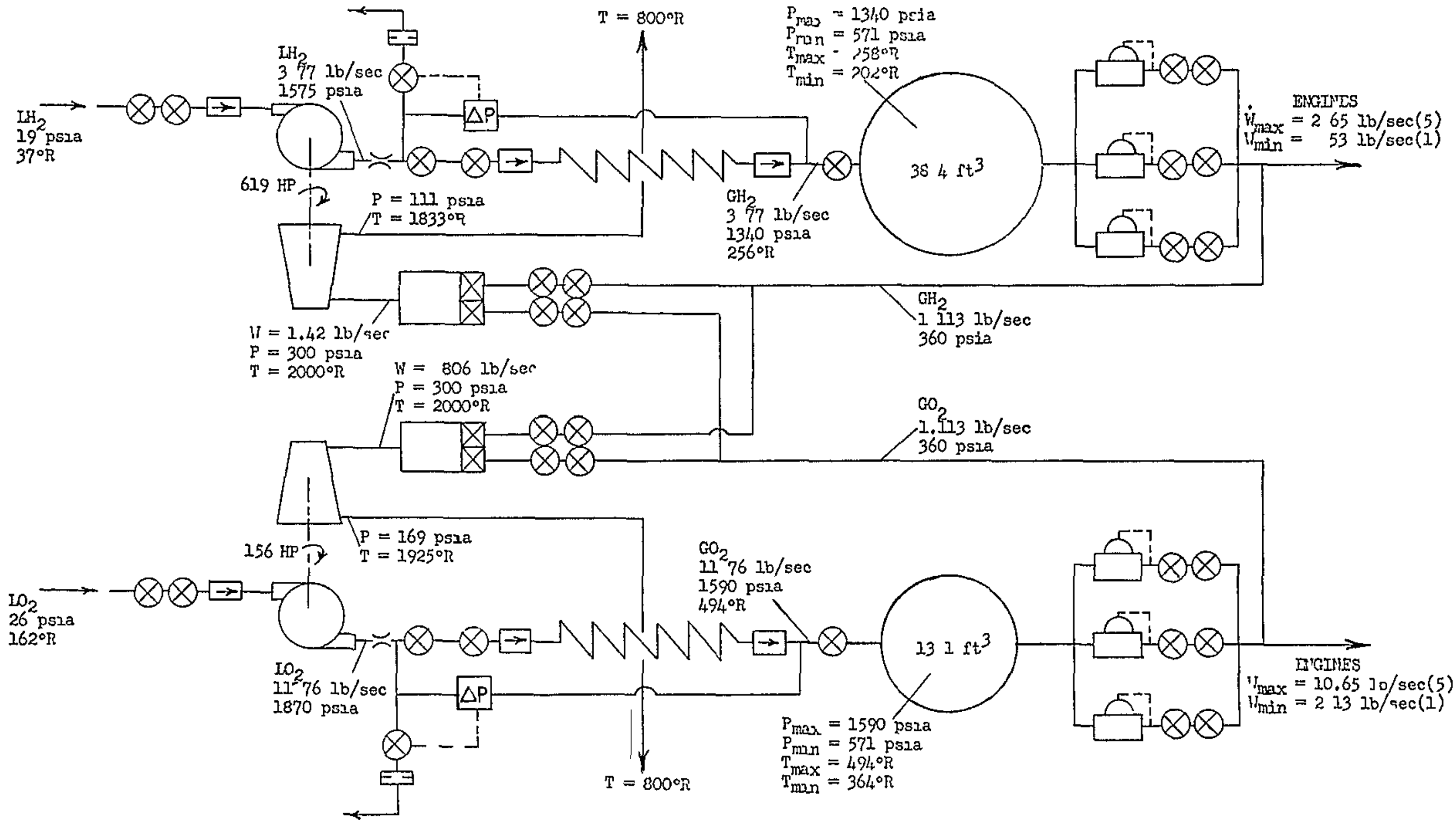


FIGURE (48)

MCDONNELL DOUGLAS CORPORATION

CONDITIONER PRESSURE, TEMPERATURE AND FLOW BALANCE

SERIES GGA FLOW (TURBINE DOWNSTREAM)

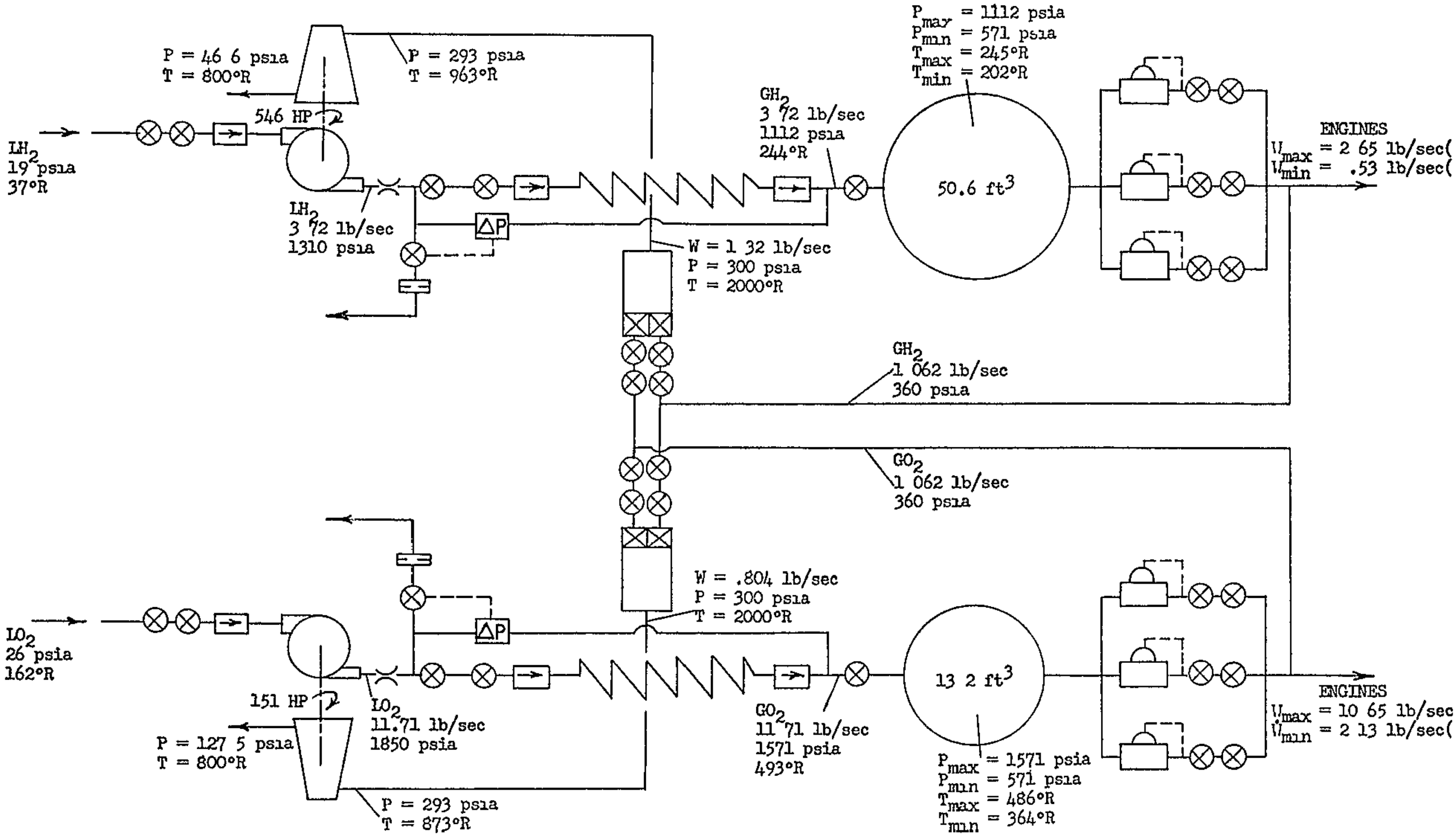
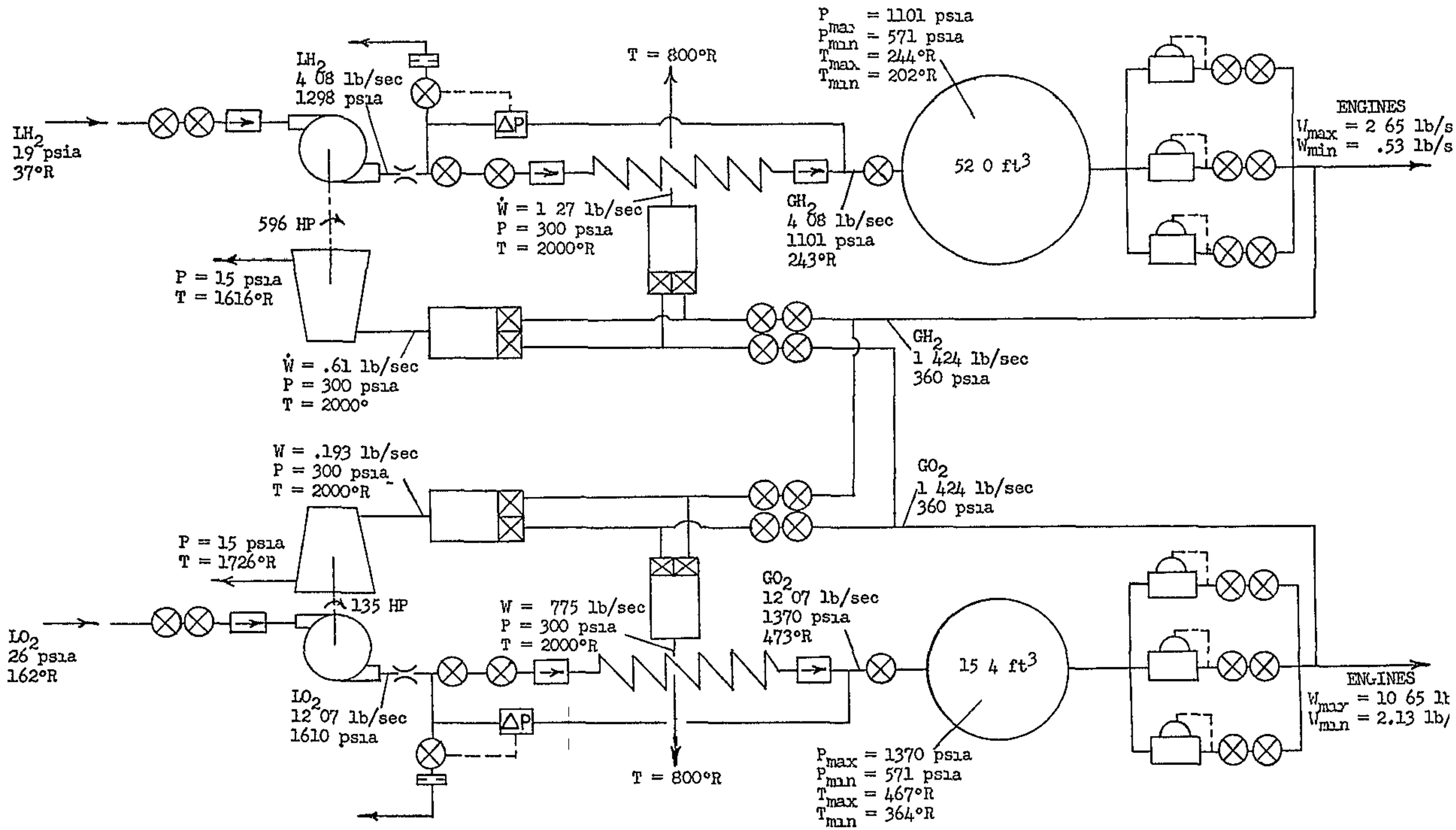


FIGURE 28

CONDITIONER PRESSURE, TEMPERATURE AND FLOW BALANCE

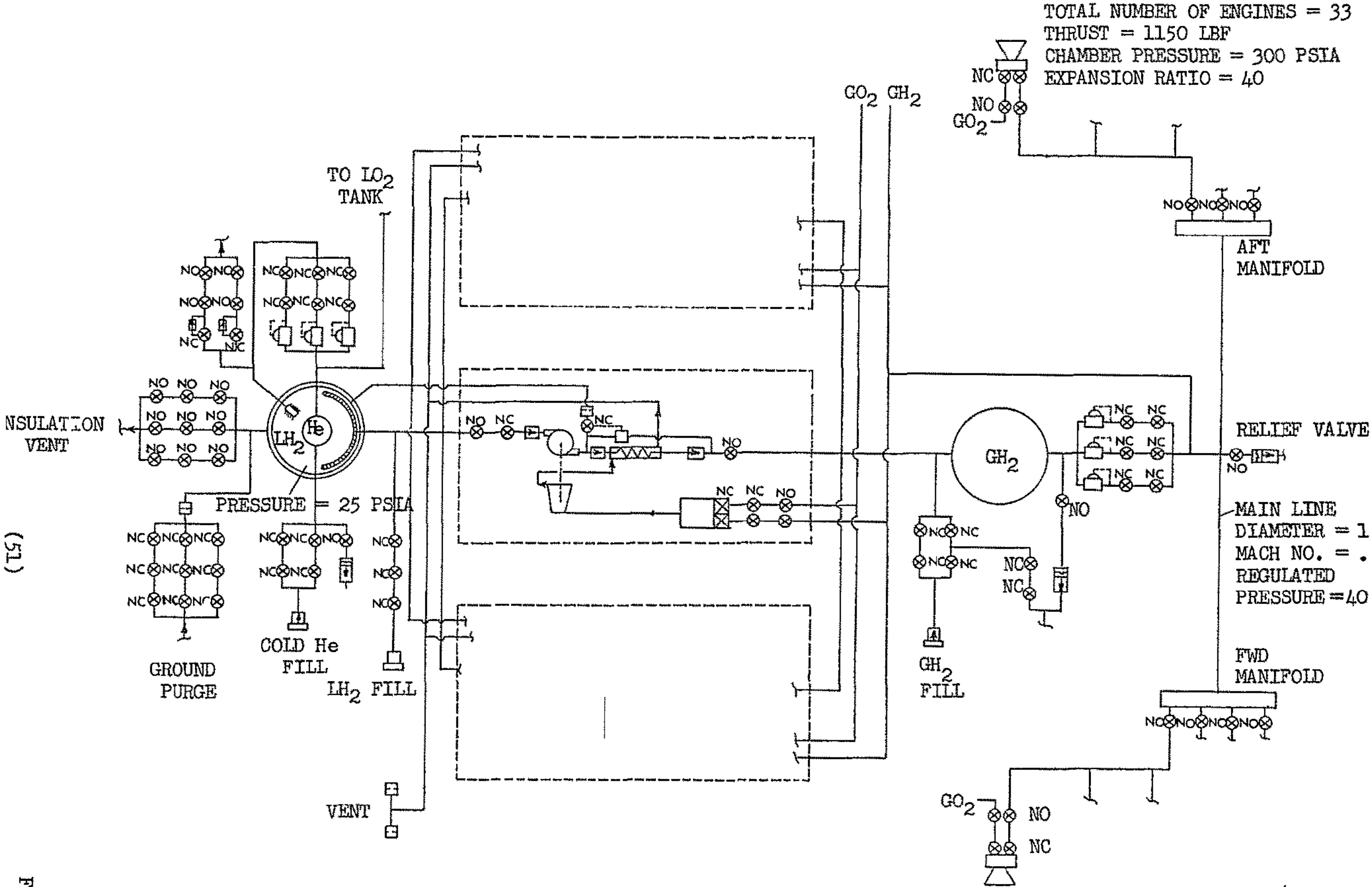
PARALLEL GGA FLOW



MCDONNELL DOUGLAS CORPORATION

FIGURE 29

REACTION CONTROL SYSTEM SCHEMATIC

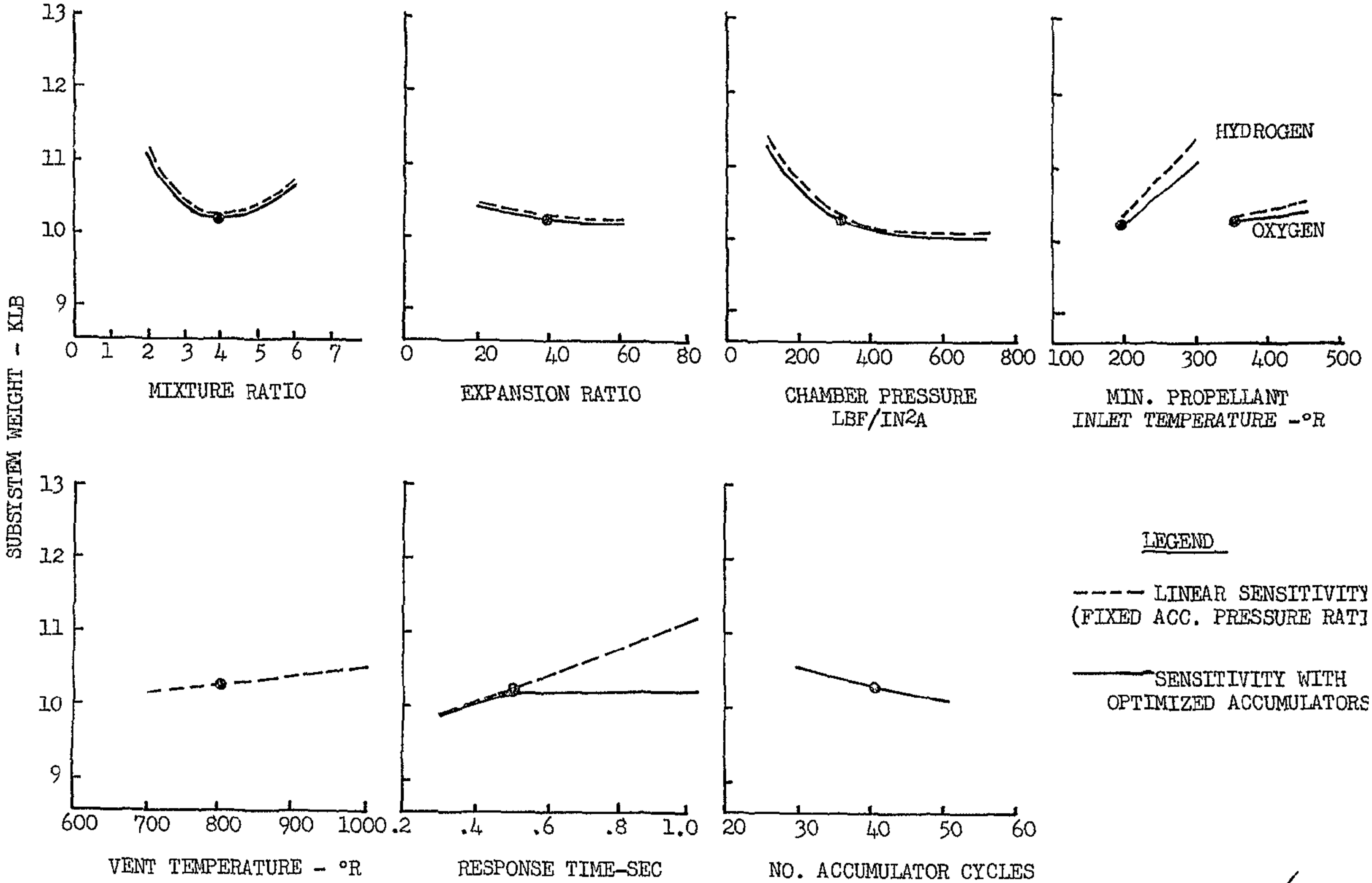


(51)

FIGURE 30

RCS WEIGHT SENSITIVITIES

SERIES GGA FLOW TURBINE UPSTREAM

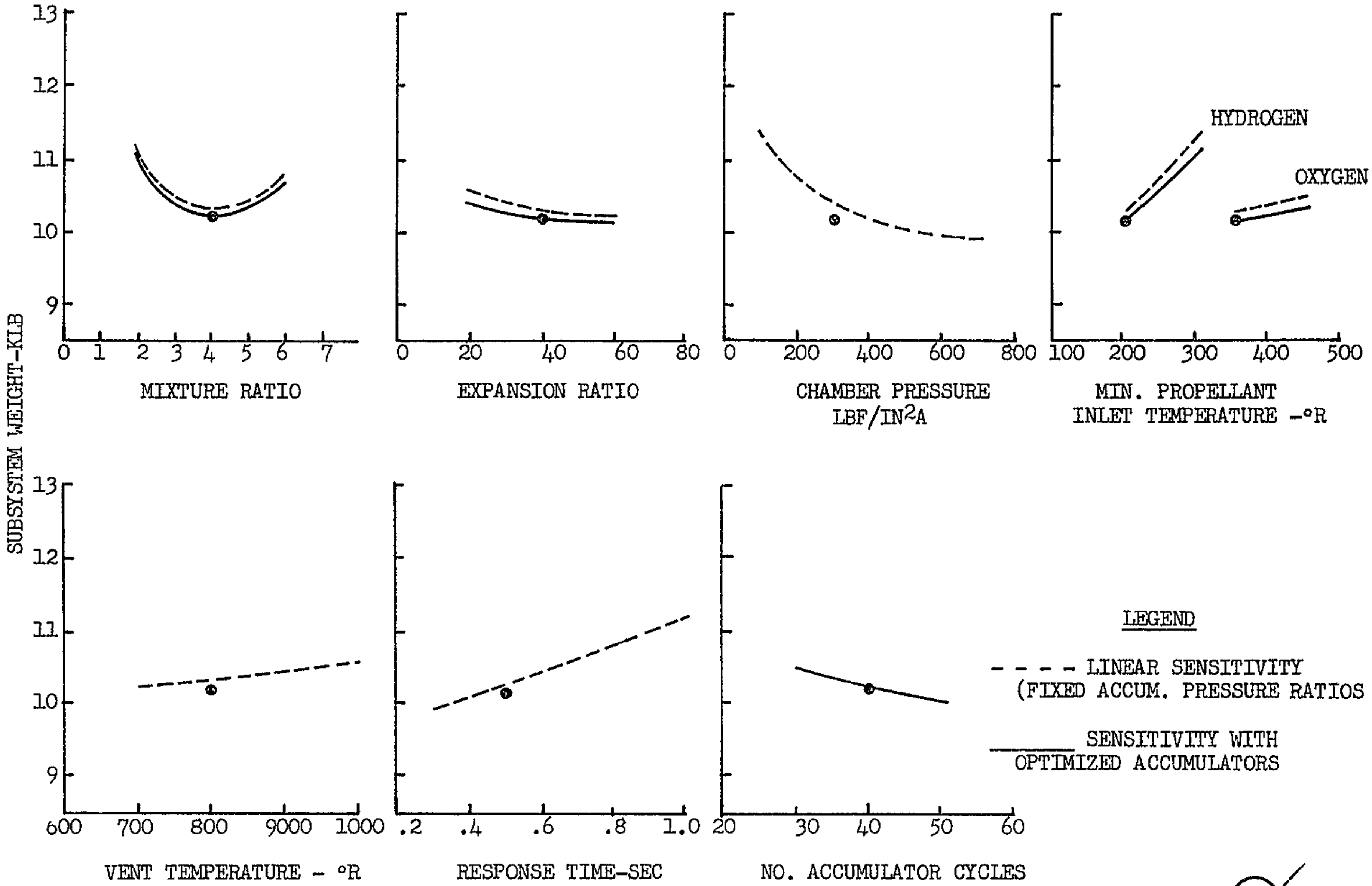


MCDONNELL DOUGLAS CORPORATION

FIGURE 31

RCS WEIGHT SENSITIVITIES

SERIES GGA FLOW TURBINE DOWNSTREAM

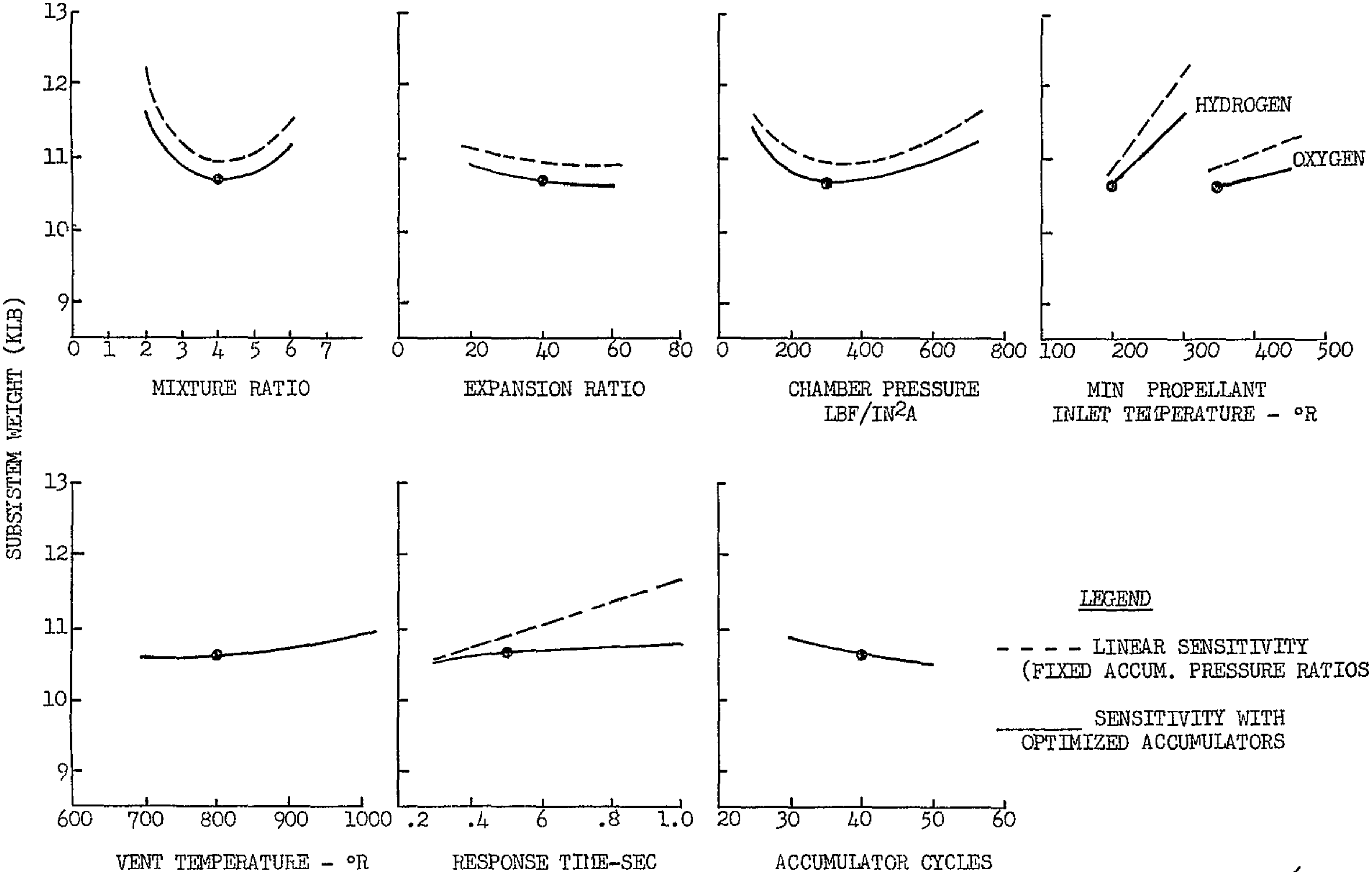


MCDONNELL DOUGLAS CORPORATION

FIGURE 32

RCS WEIGHT SENSITIVITIES

PARALLEL FLOW GGA'S



MCDONNELL DOUGLAS
CORPORATION

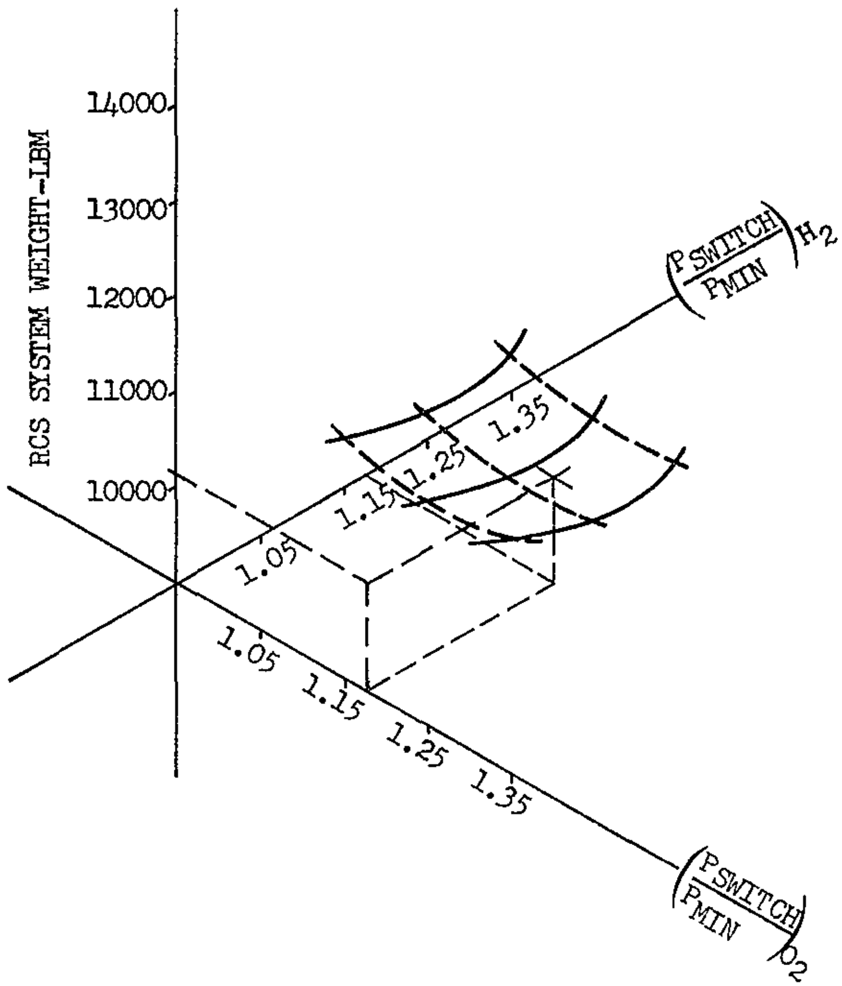
FIGURE 33

ACCUMULATOR OPTIMIZATION

- RESPONSE TIME = 0.5 SEC
- MINIMUM WT = 10155 LBM @

$$\left(\frac{P_{SWITCH}}{P_{MIN}}\right)_{H_2} = 1.173$$

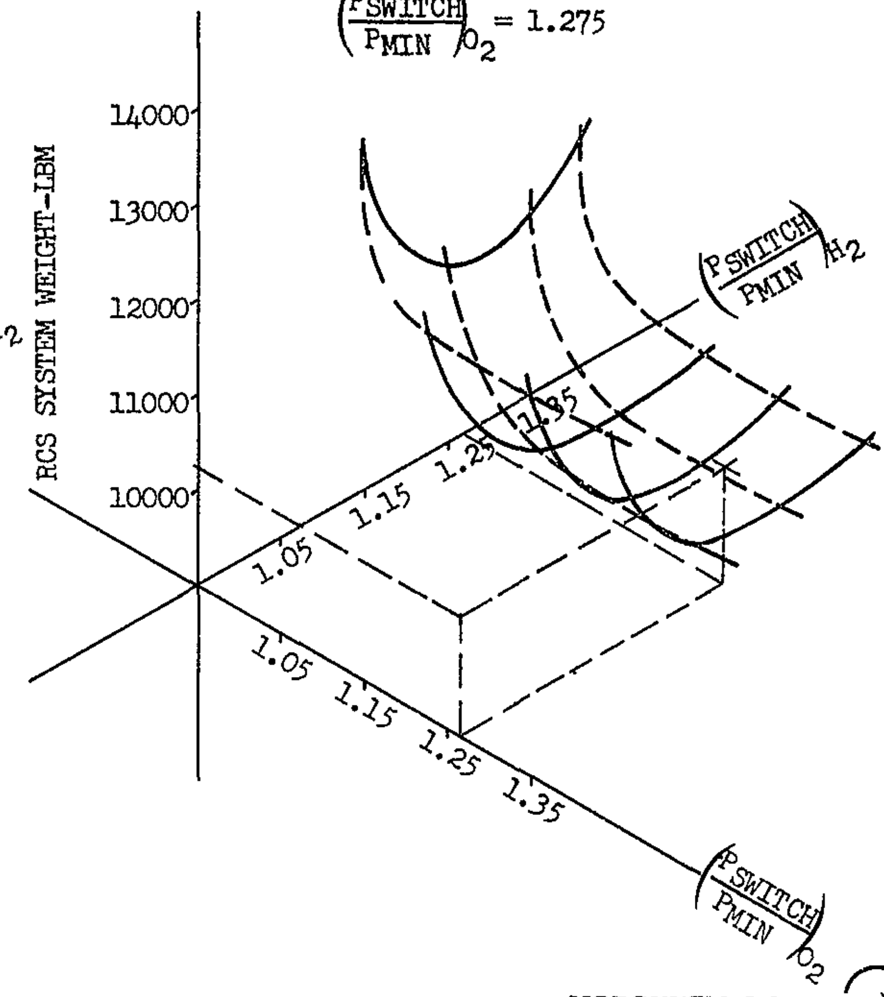
$$\left(\frac{P_{SWITCH}}{P_{MIN}}\right)_{O_2} = 1.175$$



- RESPONSE TIME = 1.0 SEC
- MINIMUM WT = 10235 LBM @

$$\left(\frac{P_{SWITCH}}{P_{MIN}}\right)_{H_2} = 1.254$$

$$\left(\frac{P_{SWITCH}}{P_{MIN}}\right)_{O_2} = 1.275$$



MCDONNELL DOUGLAS CORPORATION

FIGURE 34

2

OXYGEN HEAT EXCHANGER DESIGN

DESIGN PARAMETER	SERIES TURBINE UPSTREAM	SERIES TURBINE DOWNSTREAM	PARALLEL FLOW GGA'S
LOX Inlet Pressure (psia)/Temp.(°R)	1597/179	1578/177	1378/178
Hot Gas Inlet Pressure/Temp.	169/1925	300/2000	300/2000
$\dot{w}$ (lbm/sec) LOX/Hot Gas	11.73/0.806	11.71/.804	11.97/.775
CONFIGURATION (UPSTREAM/DOWNSTREAM)			
No. Concentric Rings	5/5	5/5	5/5
No. Spokes	12	12	12
Tube O.D. (in.)	.250/.250	.250/.250	.250/.250
Tube Wall Thickness (in.)	.016/.016	.016/.016	.016/.016
Radial Gap (in.)	.150	.150	.150
CALCULATED PARAMETER			
Length (in.)	21.3	17.4	19.5
Wt (lbs)	24.2	22.7	24.3
GOX Outlet Pressure/Temp.	1567/497	1552/478	1345/471
Hot Gas Outlet Pressure/Temp.	166/781	298/898	298/831

FIGURE 35

MCDONNELL DOUGLAS CORPORATION

HYDROGEN HEAT EXCHANGER DESIGN

DESIGN PARAMETER	SERIES TURBINE UPSTREAM	SERIES TURBINE DOWNSTREAM	PARALLEL FLOW GGA'S
LH_2 Inlet Pressure (psia)/Temp (°R)	1348/64.5	1118/64.5	1108/64.4
Hot Gas Inlet Pressure/Temp.	111/1833	300/2000	300/2000
$\dot{w}$ (lbm/sec) LH_2/Hot Gas	3.77/1 42	3.75/1.32	4.01/1.27
CONFIGURATION (UPSTREAM/DOWNSTREAM)			
No. Concentric Rings	5/5	5/4	5/4
No Spokes	12	12	12
Tube O.D. (in.)	.3125/ 4325	.3125/.4325	.3125/ 4325
Tube Wall Thickness (in.)	.016/.036	.016/.036	.016/.036
Radial Gap (in.)	.100	.150	.100
CALCULATED PARAMETER			
Length (in.)	19 7	16.7	19.4
Wt (lbs)	31 8	34.2	33.8
GH_2 Outlet Pressure/Temp.	1341/252 6	1112/249 6	1101/246.4
Hot Gas Outlet Pressure/Temp	64 4/808	296/992	289/825

FIGURE 36

MCDONNELL DOUGLAS CORPORATION

FULLY INTEGRATED RCS/OMS MATRIX

PARAMETER		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		CASES																			
MIXTURE RATIO	DESIGN RCS TO OPERATE AT HIGH (OMS) MR	√	√	√	√																
	DESIGN OME TO OPERATE AT LOW RCS MR					√	√	√	√												
	DESIGN FOR RCS REQUIREMENTS, OPERATE 2 O_2 PUMPS FOR OME									√	√	√	√								
	DESIGN FOR OMS REQUIREMENTS, OPERATE 2 H_2 PUMPS FOR RCS													√	√	√	√				
	OPERATE TURBOPUMPS BILEVEL																	√	√	√	√
OMS SINGLE BURN IMP	RECHARGE RCS ACCUMULATORS DURING OME BURN USING STANDBY TURBOPUMP & CONDITIONING ASSY'S	√				√				√				√				√			
	ENLARGE RCS ACCUMULATORS		√				√				√				√				√		
	CHARGE RCS ACCUMULATORS DURING OME BURN USING BILEVEL OR ANALOG CONDITIONER ASSY'S			√				√				√				√				√	
	CHARGE RCS ACCUMULATORS DURING OME BURN USING SEPARATE CONDITIONER ASSEMBLIES				√				√				√				√				√

FIGURE 37

PARTIALLY INTEGRATED RCS/OMS MATRIX

PARAMETER	OPTION	CASES 1	2	3	4	5	6	7	8	9	10	11	12
TURBO PUMP	RCS AND OMS SAME CONFIGURATION	✓	✓	✓	✓	✓	✓	✓	✓	✓			
	RCS AND OMS INDEPENDENTLY SIZED										✓	✓	✓
MIXTURE RATIO	DESIGN PUMP FOR BEP AT RCS REQUIREMENTS, OPERATE TWO O_2 PUMPS FOR OMS	✓	✓	✓	✓								
	OPERATE TURBOPUMPS BILEVEL					✓	✓						
	DESIGN PUMP FOR BEP AT OMS REQUIREMENTS, OPERATE AT OFF DESIGN FOR RCS							✓	✓				
	DESIGN PUMP FOR BEP AT OMS REQUIREMENTS, RCS OPERATES AT OMS DESIGN POINT									✓			
OMS SINGLE BURN IMP	CHARGE RCS ACCUMULATORS DURING OMS BURN UTILIZING SEPARATE CONDITIONER ASS'Y	✓											
	RECHARGE RCS ACCUMULATORS DURING OMS BURN UTILIZING RCS CONDITIONING ASSY'S		✓			✓		✓			✓		
	ENLARGE RCS ACCUMULATORS			✓			✓		✓			✓	
	CHARGE RCS ACCUMULATORS DURING OMS BURN USING BILEVEL OR ANALOG CONDITIONER ASSY'S				✓								
	RECHARGE RCS ACCUMULATORS DURING OMS BURN USING RCS CONDITIONER AT OMS LEVEL. ENLARGED ACCUMULATOR REQ'D TO LIMIT CYCLES FOR RCS									✓			
	RECHARGE OF RCS ACCUMULATORS ACCOMPLISHED BY OMS												✓

FIGURE 38

FULLY INTEGRATED RCS/OMS BASELINE SCHEMATIC

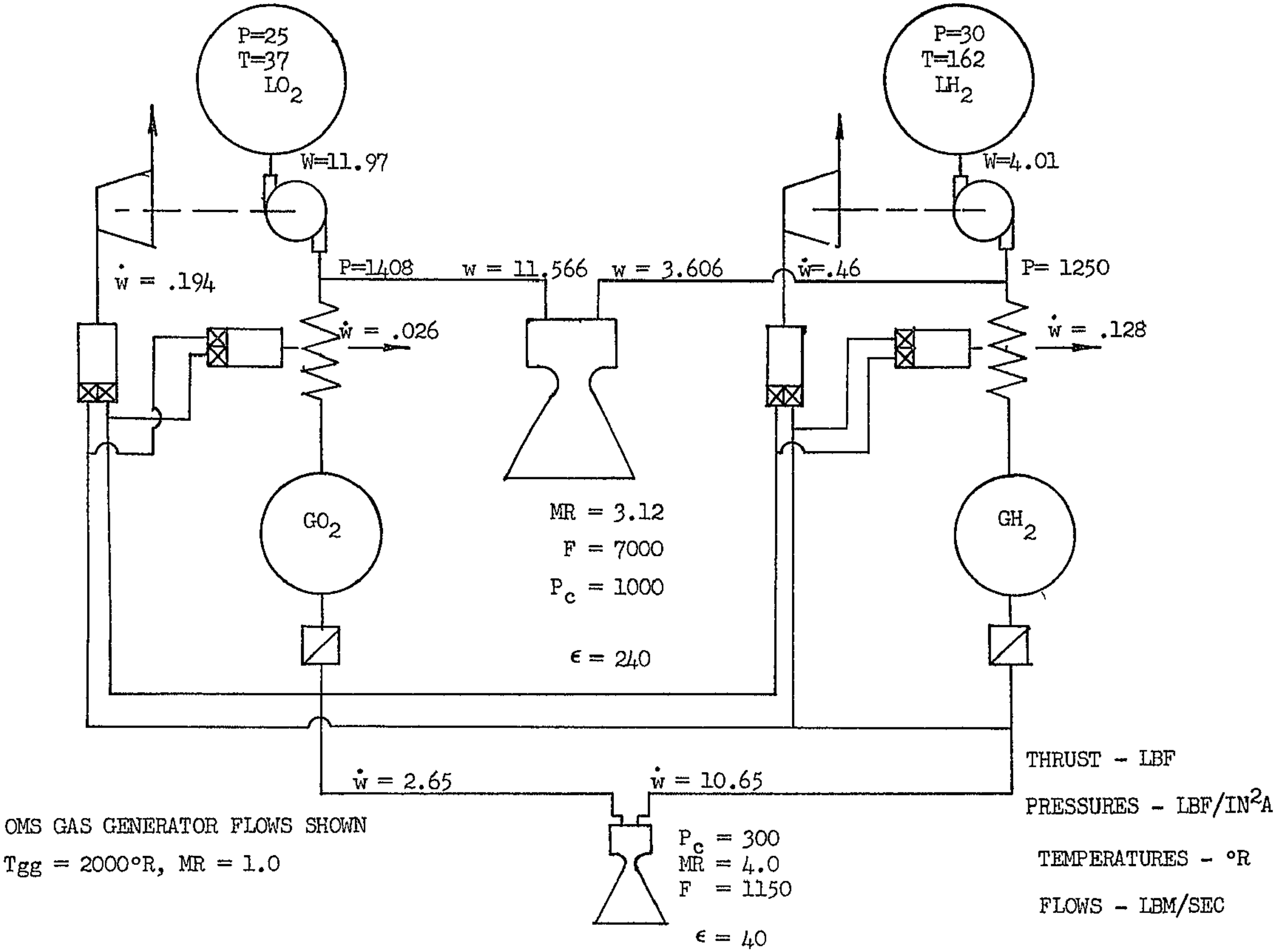


FIGURE 39

HIGH PRESSURE LIQUID PROPELLANT STORAGE REQUIREMENT

TOTAL APS REQUIREMENT	2 23 x 10^6 LB-SEC
ON ORBIT APS USAGE BETWEEN -X MANEUVERS	650,000 LB-SEC
ENTRY APS USAGE	520,000 LB-SEC
MAXIMUM SINGLE APS USAGE	157,000 LB-SEC

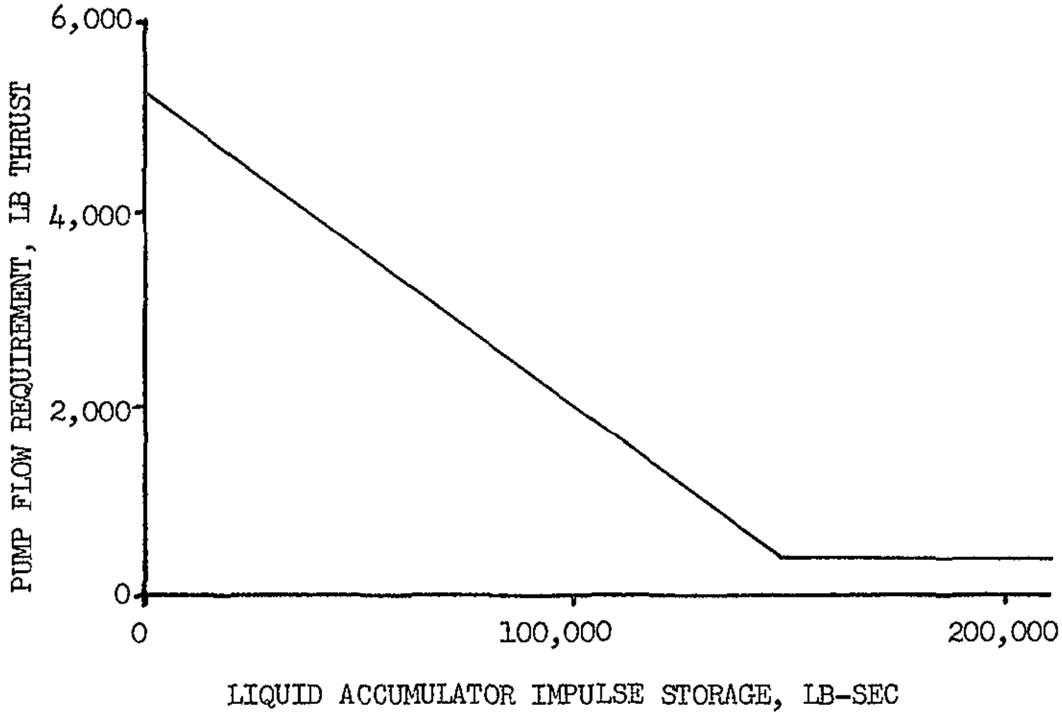


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FIGURE 40

REGULATED HELIUM PRESSURIZATION

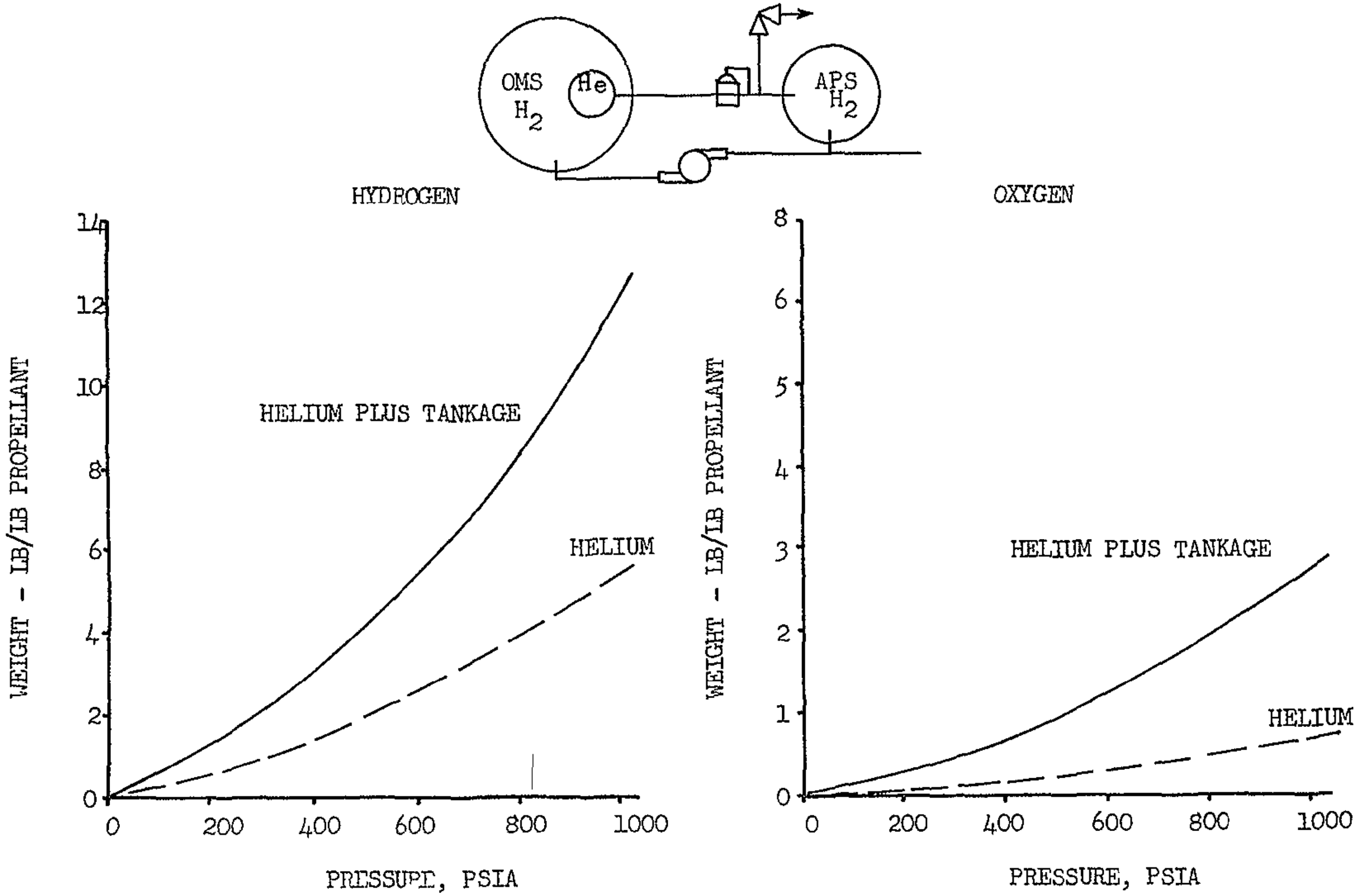

FIGURE 41

PROPELLANT TANKAGE WEIGHTS

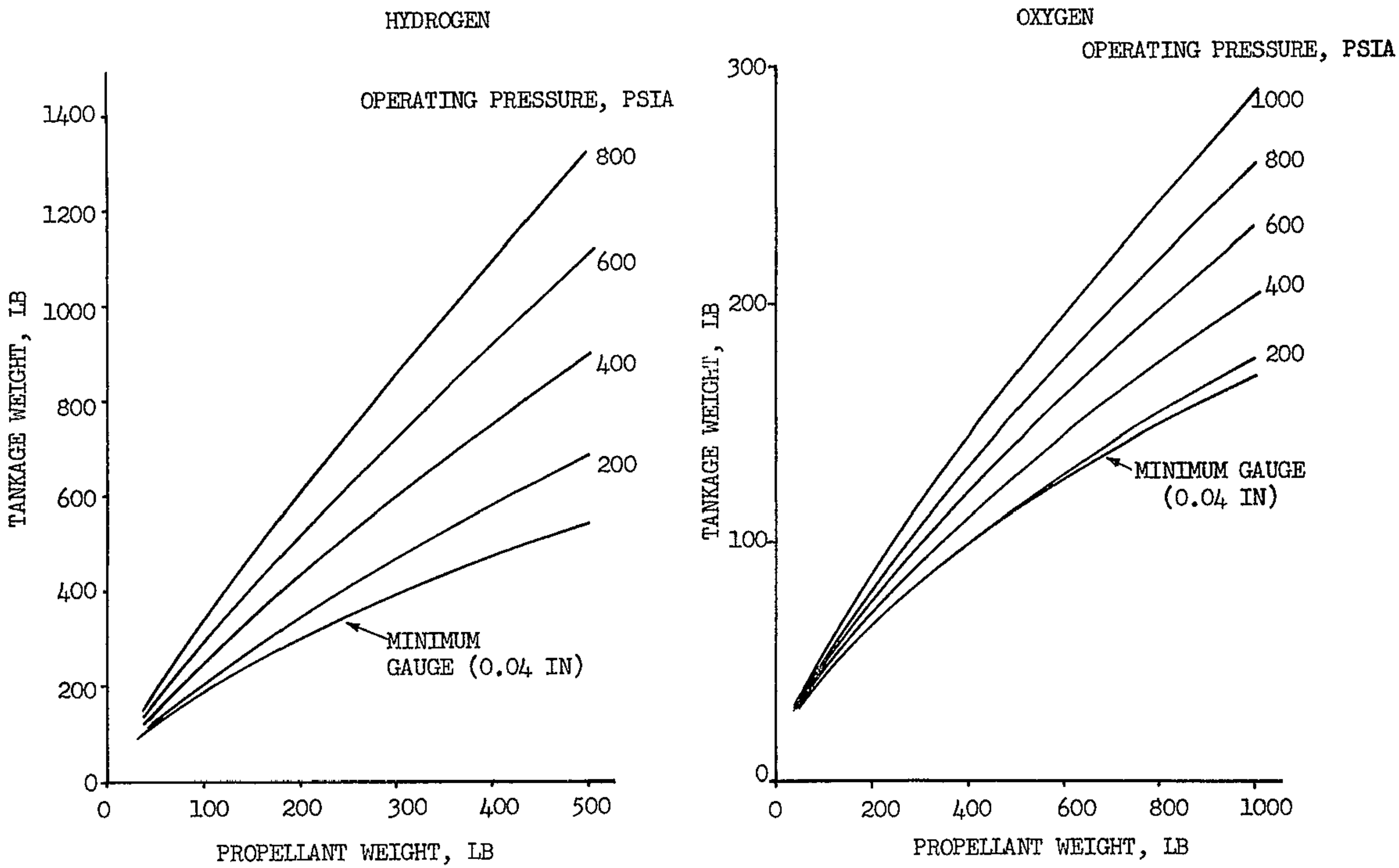

FIGURE 63

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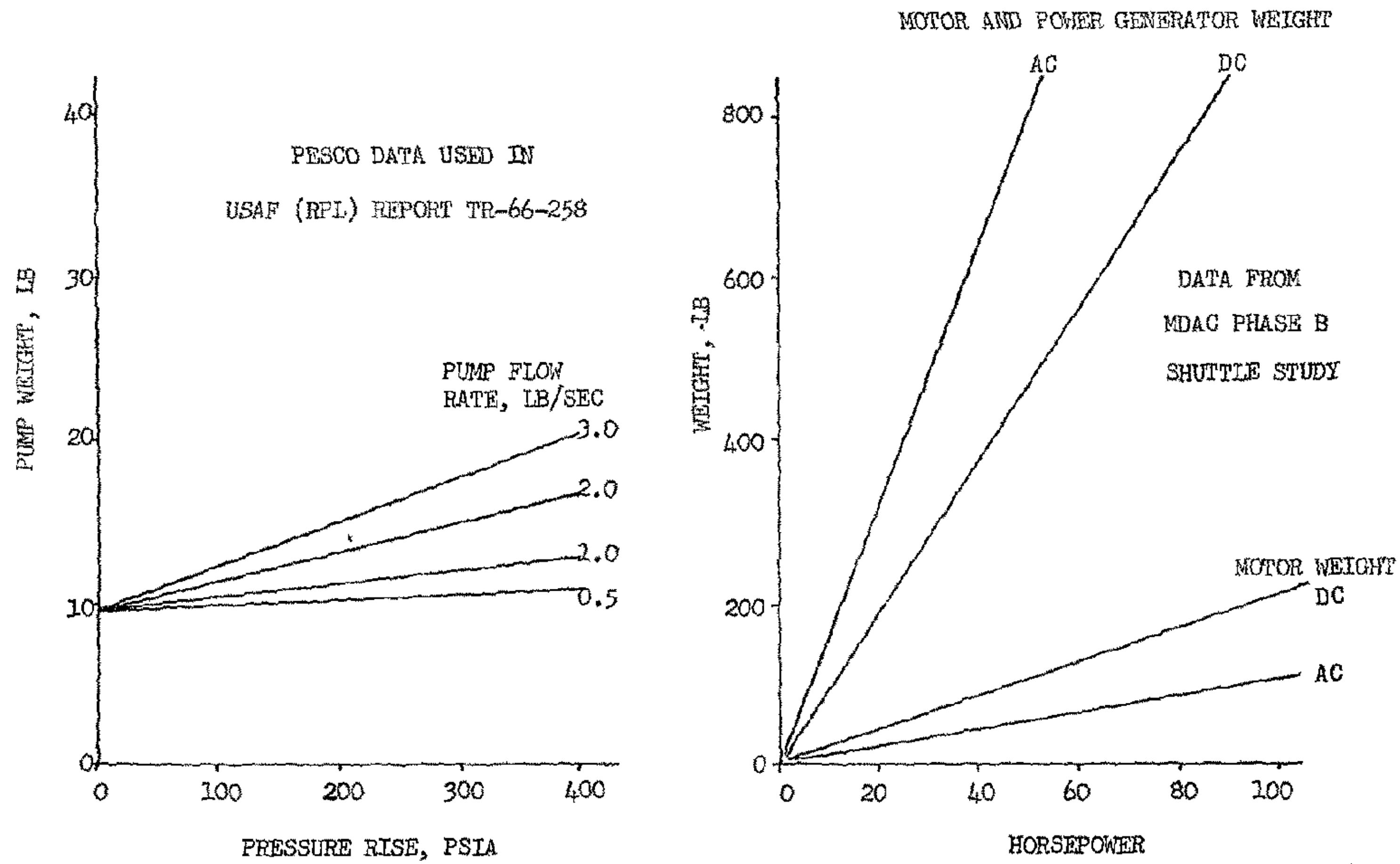
FIGURE 64

HYDROGEN PUMP/MOTOR CHARACTERISTICS



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