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ADVANCED ENGINE STUDY FOR MIXED-MODE ORBIT-TRANSFER VEHICLES

by J. A. Mellish

AEROJET LIQUID ROCKET COMPANY

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS 3-21049

FOREWORD

The work described herein was performed at the Aerojet Liquid Rocket Company under NASA Contract NAS 3-21049 with Mr. Dean D. Scheer, NASA-Lewis Research Center, as Project Manager. The ALRC Program Manager was Mr. Larry B. Bassham and the Project Engineer was Mr. Joseph A. Mellish.

The technical period of performance for this study was from 22 September 1977 to 15 September 1978.

The author wishes to acknowledge the efforts of the following ALRC engineering personnel who contributed significantly to the study effort and this report:

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I also wish to thank Mr. Rudi Beichel, ALRC Senior Scientist, for his comments and assistance throughout the study effort.

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SECTION I

SUMMARY

A. STUDY OBJECTIVES AND SCOPE

The major objectives of this study program were to provide design characteristics, parametric data and identify technology requirements for advanced engines to be used on mixed-mode orbit-transfer vehicles (OTV).

Three baseline engine concepts (tripropellant, plug cluster, and dual-expander) were studied. Oxygen (O_2), kerosene (RP-1) and hydrogen (H_2) were evaluated as the propellants for these engines. A baseline Mode 1 thrust level of 88,964N (20,000 lbs) and a thrust split of 0.5 were preselected. (Thrust split is defined as the ratio of the O_2/RP-1 thrust to the total engine thrust.) This established the base point for parametric evaluations.

To accomplish the study program objectives, the effort was divided into four technical tasks plus a reporting task. In Task I, the properties and/or theoretical performance of the propellants and propellant combinations were determined over a parametric range. Task II involved the evaluation of thrust chamber cooling methods for each of the concepts to determine the maximum attainable chamber pressures within the constraints of low cycle thermal fatigue and propellant properties. Upon completion of Task II, cooling methods were selected and the operating parameters for each of the baseline engines were updated for use in the remaining effort. In Task III, cycle power limits were established, point design chamber pressures were selected, and delivered performance, weight and envelope dimensions were deteremined for each of the baseline engines. Using the Task III results as a base, parametric analyses were then conducted over ranges of thrust level, thrust split and Mode 1 area ratio in Task IV to provide the engine data and descriptions necessary for mixed-mode orbit-transfer-vehicle studies.

B. RESULTS AND CONCLUSIONS

Simplified engine cycle schematics of the concepts selected as baselines and for parametric analyses are shown on Figures 1 through 6.

The tripropellant engine uses a staged combustion engine cycle and a conventional bell nozzle. To conserve space in the shuttle payload bay, an extendible/retractable nozzle extension is used. Three preburners are used to drive the turbines. Oxygen/hydrogen fuel-rich gas drives the hydrogen turbopump, oxygen/hydrogen oxidizer-rich gas drives the oxygen turbopump and oxygen/RP-1 fuel-rich gas drives the RP-1 turbopump. The exhausts of all turbines are burned in the main thrust chamber during Mode 1 operation. Only the O_2/H_2 propellants are burned during Mode 2 operation.

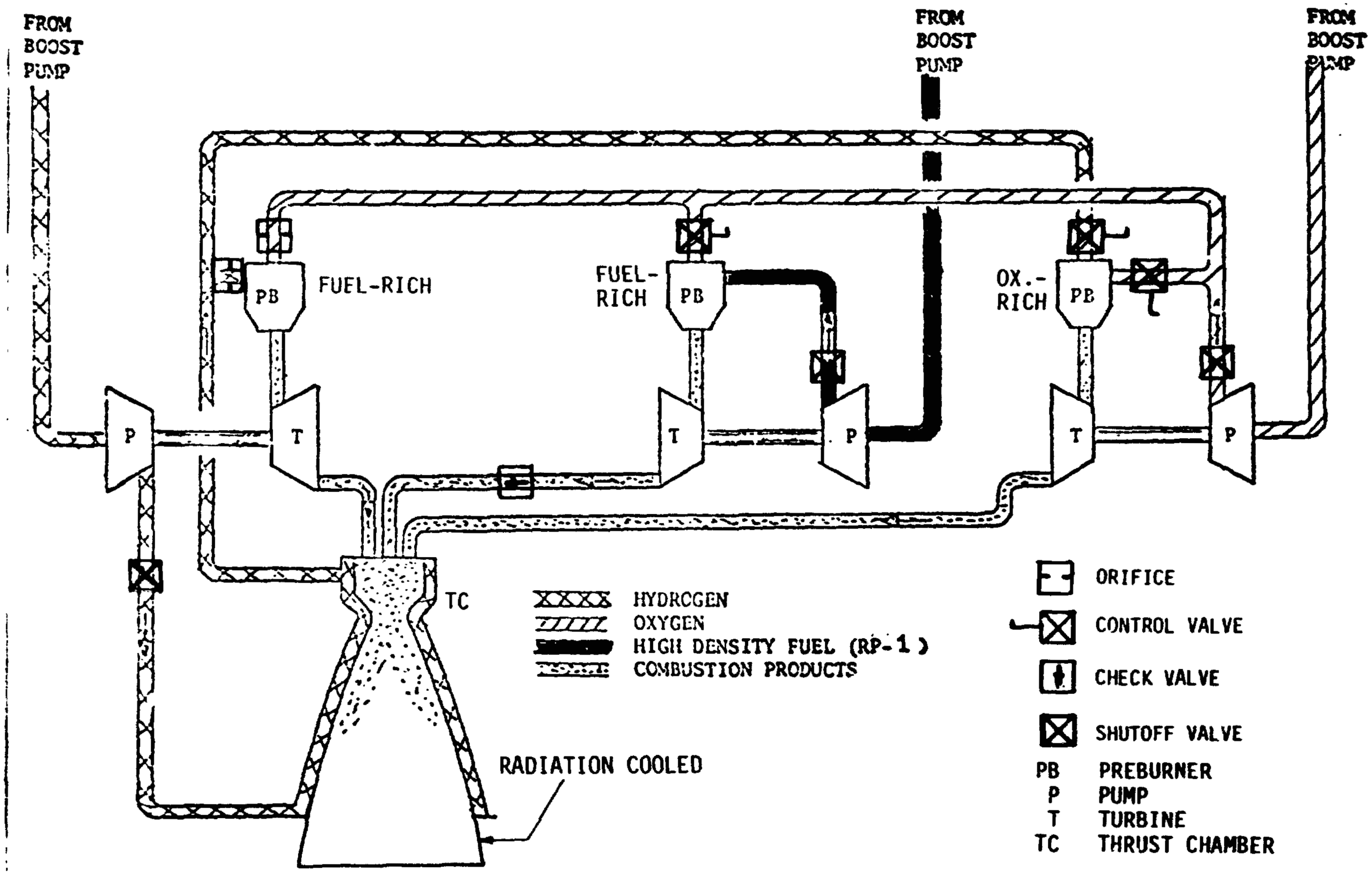


Figure 1. Mode 1 Tripropellant Engine Cycle Schematic

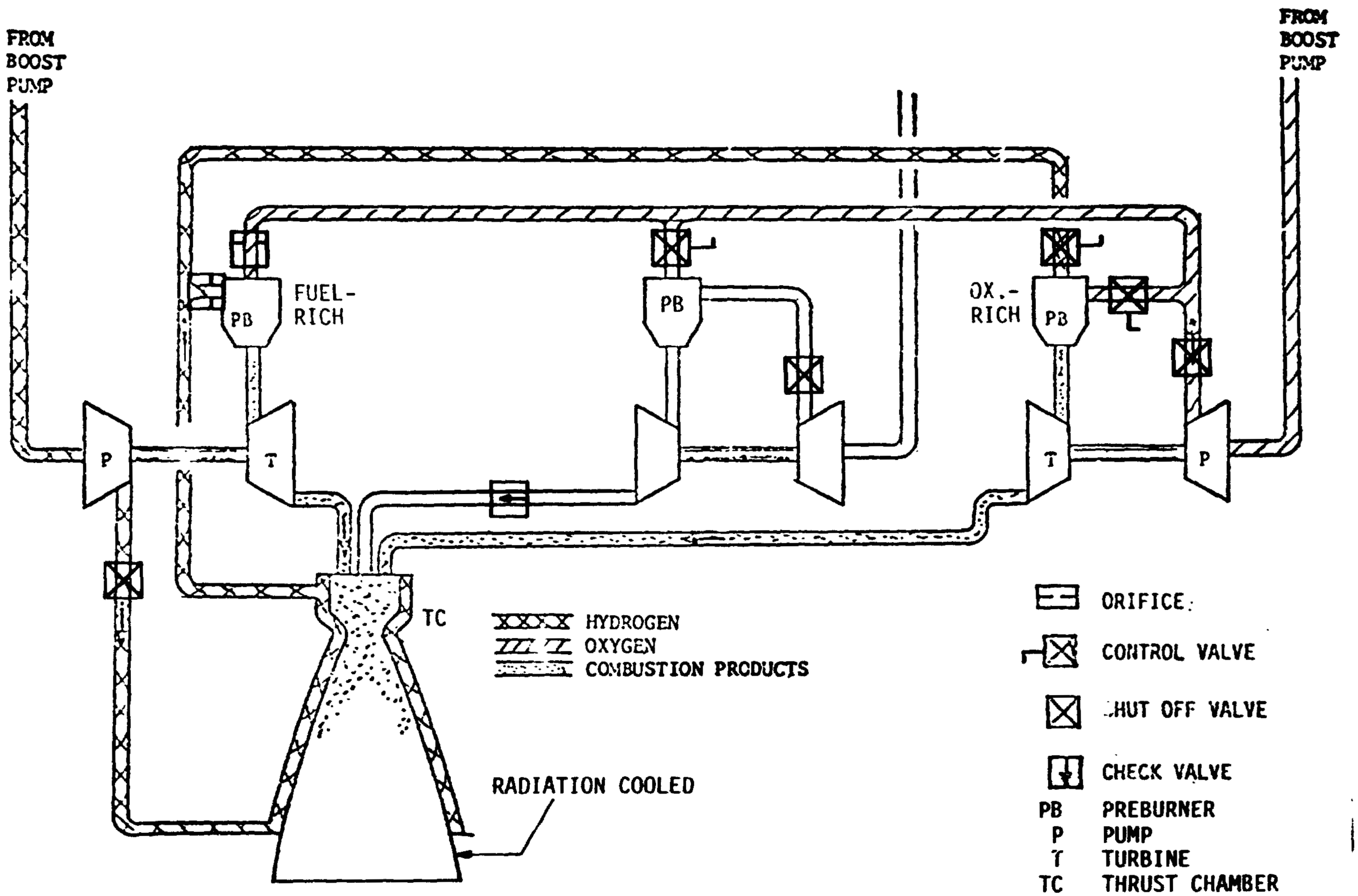


Figure 2. Mode 2 Tripropellant Engine Cycle Schematic

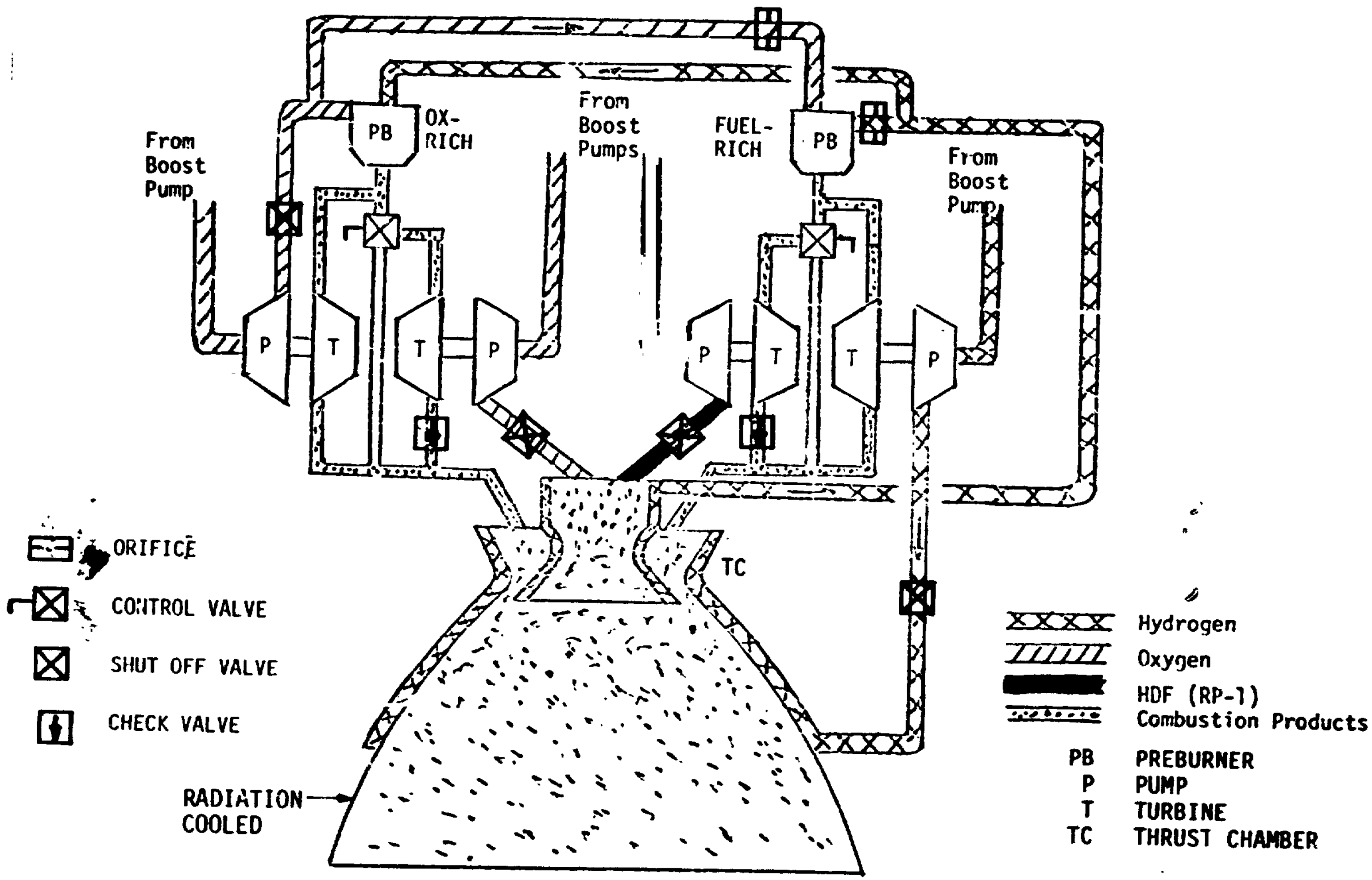


Figure 3. Dual-Expander Engine, Mode 1 Schematic

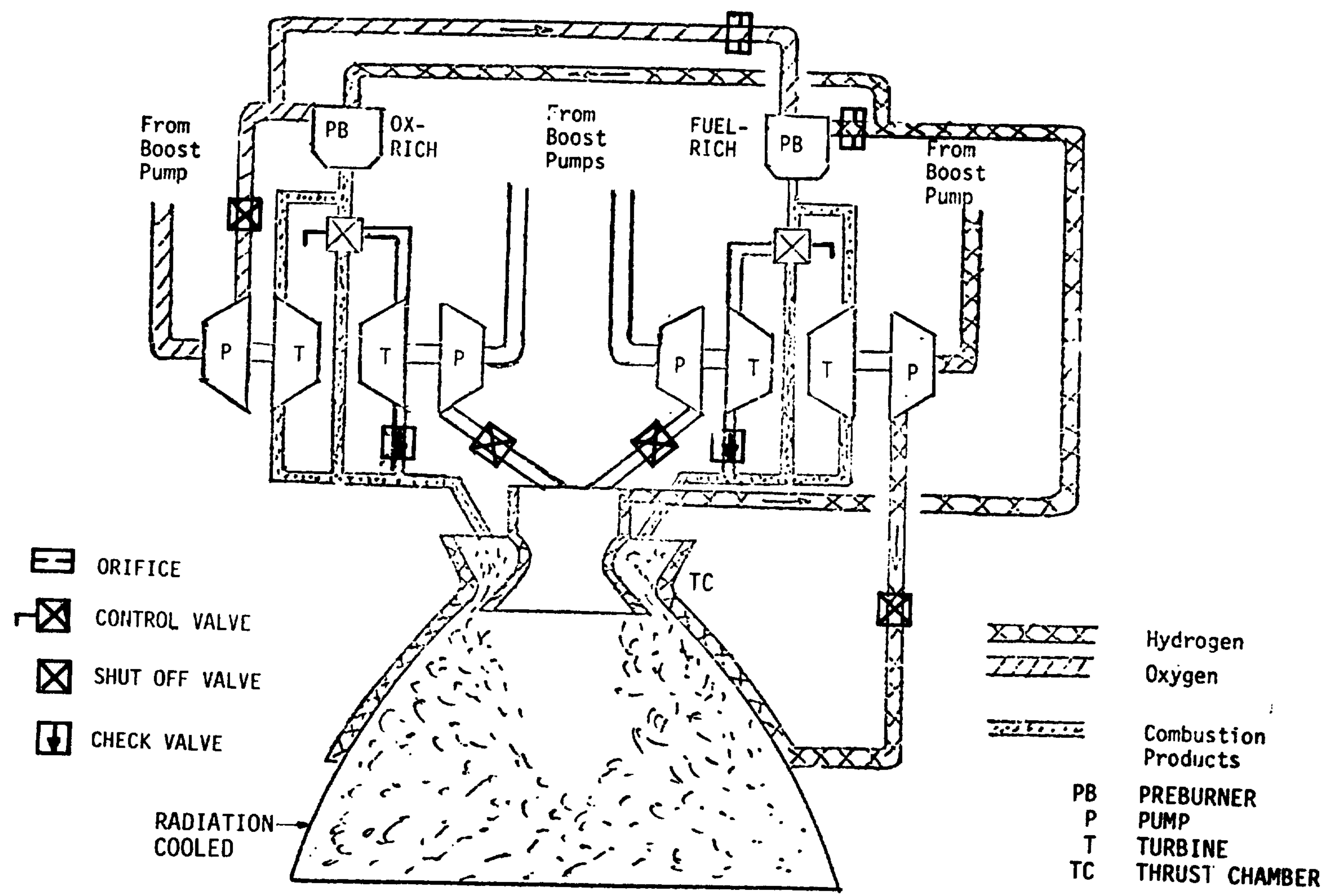


Figure 4. Dual-Expander Engine, Mode 2 Schematic

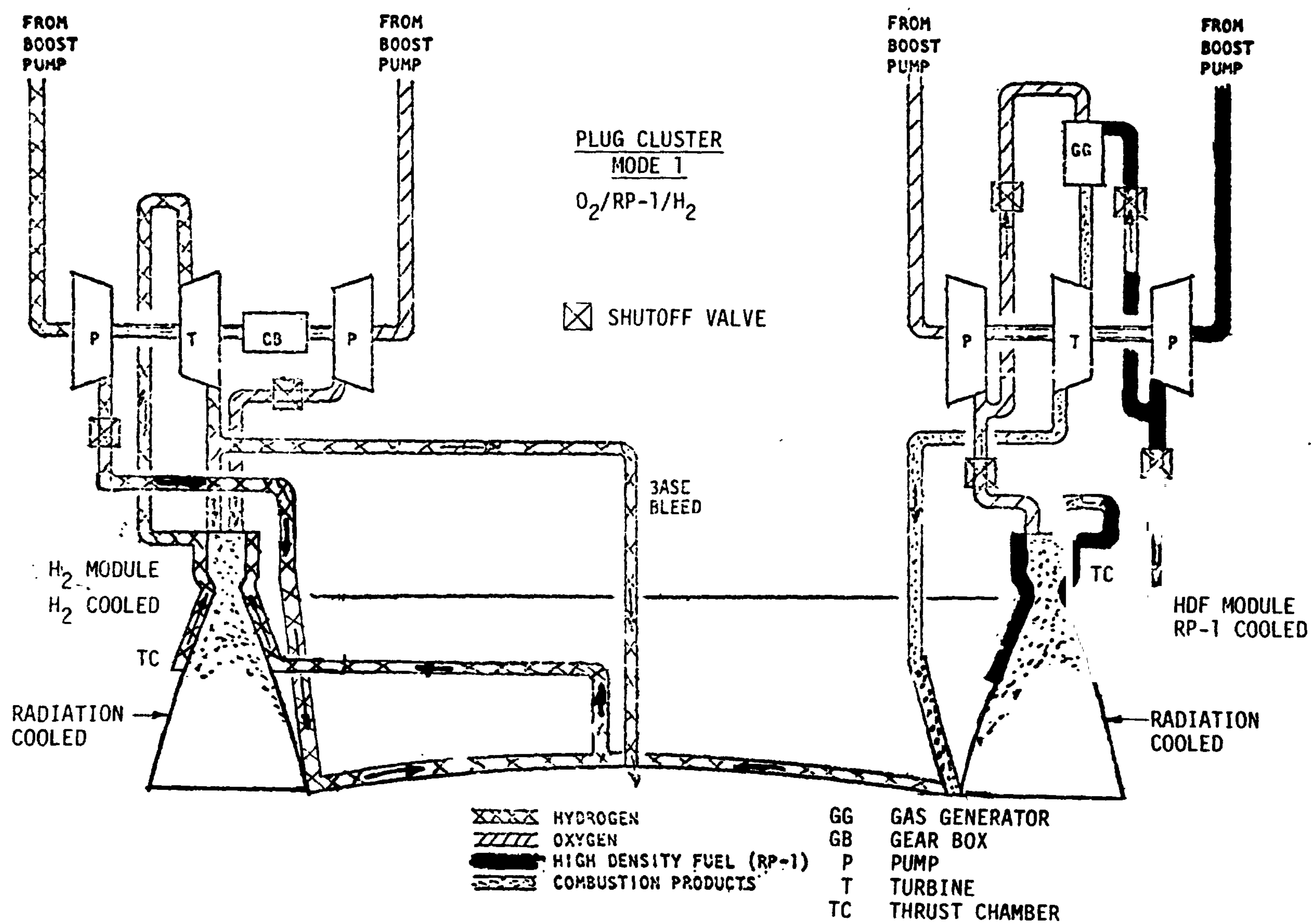


Figure 5. Mode 1 Plug Cluster Cycle Schematic

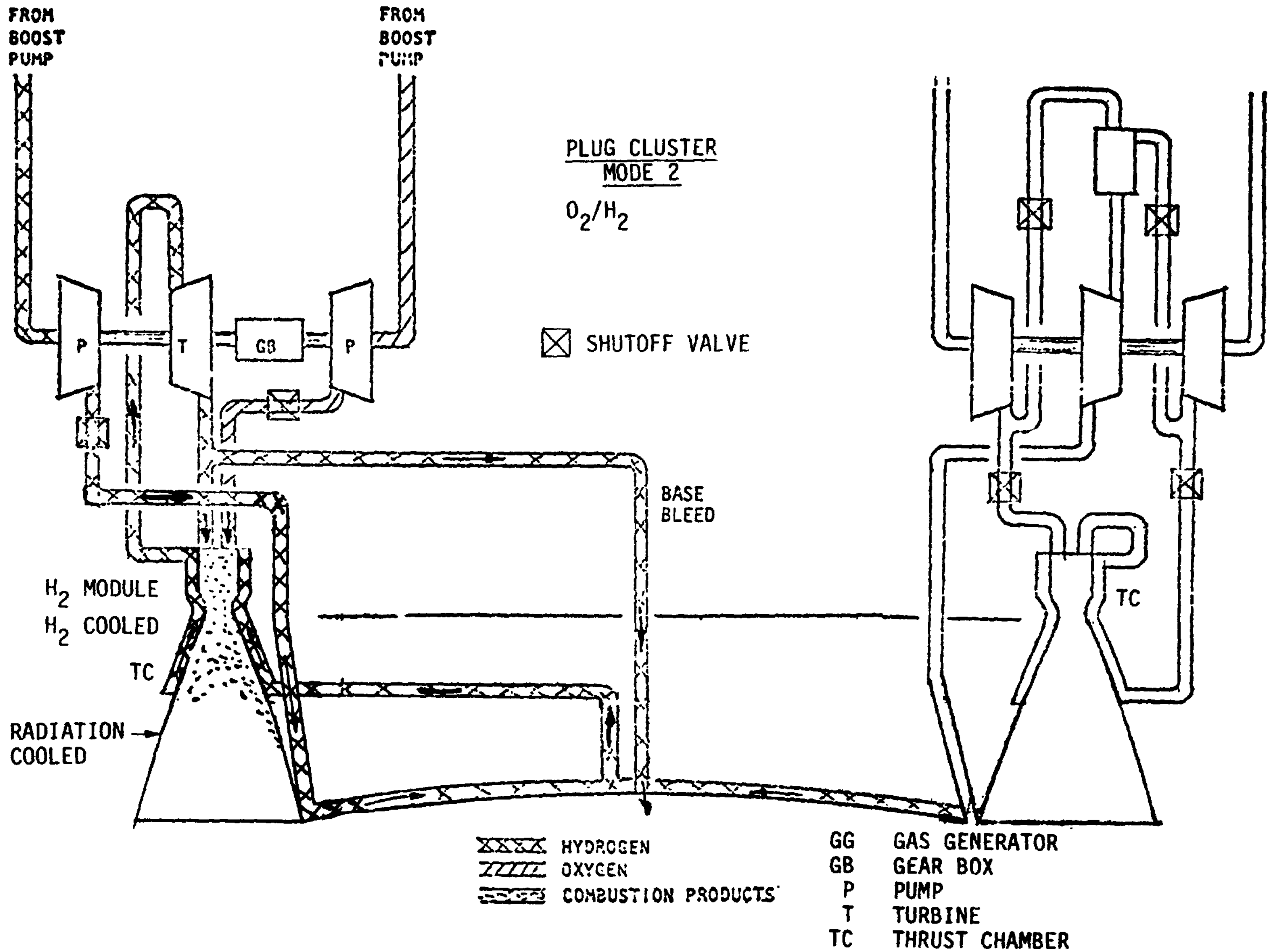


Figure 6. Mode 2 Plug Cluster Cycle Schematic

The dual-expander engine burns oxygen as the oxidizer and RP-1 and hydrogen as the fuels in Mode 1. Some of the oxygen and all of the RP-1 are delivered to a central thrust chamber injector as liquids. These propellants are combusted and partially expanded in a conventional bell nozzle. The rest of the oxygen and the hydrogen are combusted in preburners. An oxidizer-rich preburner is used to provide the oxygen turbopump drive gases and a fuel-rich preburner is used to provide the RP-1 and hydrogen turbopump drive gases. The turbine exhaust gases are delivered to an annular combustion chamber. Expansion of the O_2/H_2 combustion products occurs in a forced deflection nozzle extension along with the complete expansion of the O_2/RP-1 center core combustion gases. During Mode 2 operation, the center thrust chamber is inactive and only the O_2/H_2 combustion gases are expanded in the forced deflection nozzle. This substantially increases the Mode 2 area ratio.

The plug cluster engine uses O_2/H_2 and O_2/RP-1 thrust chamber modules clustered around a central plug of zero isentropic length with the module exits touching. The oxygen/hydrogen system employs an expander drive cycle and the oxygen/RP-1 turbopumps are driven by fuel-rich oxygen/RP-1 gas-generator. Some of the heated hydrogen is used as base-bleed to improve the base thrust contribution in both Mode 1 and Mode 2. The O_2/RP-1 fuel-rich turbine exhaust products are expanded through a 5:1 nozzle. All of the modules fire in Mode 1 operation while only the O_2/H_2 modules operate during Mode 2.

Hydrogen was selected as the coolant for the tripropellant and dual-expander engines and the LOX/LH_2 module of the plug cluster. Hydrogen cooled tripropellant engines are practical for the entire chamber pressure range of 34 to 136 atm (500 to 2000 psia) and thrust split range of 0.4 to 0.8 investigated. Dual-expander engines are cooling limited and the maximum operating chamber pressures were defined as a function of thrust split at a baseline thrust of 88,964N (20,000 lb) as follows:

Thrust Split	Mode 1 Chamber Pressure, atm (psia)	Mode 2 Chamber Pressure, atm (psia)
0.4	88.4 (1300)	44.2 (650)
0.5	74.8 (1100)	37.4 (550)
0.6	61.2 (900)	30.6 (450)
0.8	13.6 (200)	6.8 (100)

It may be possible to raise these chamber pressure limits if advanced technology chambers using a combination of regenerative and transpiration cooling are considered. However, this was beyond the study scope.

I, B, Results and Conclusions (cont.)

Cooling of the LOX/LH_2 plug cluster engine module was practical over the entire chamber pressure range of 20.4 to 68 atm (300 to 1000 psia) investigated. However, both oxygen and RP-1 cooling of the LOX/RP-1 module was found to be impractical over the entire chamber pressure range. Oxygen cooling of the module in the plug cluster engine is impractical because of phase changes at low pressures and shifts in transport properties near the critical temperature and pressure points at the higher pressures. RP-1 cooling of these modules results in excessive bulk temperature rises because of wall temperature limitations imposed in order to prohibit cracking, gumming and coking of the RP-1 in the coolant channels. The plug cluster study proceeded assuming that if some of the impurities were removed from the RP-1, the coolant bulk temperature would not be limiting. A baseline LOX/RP-1 chamber pressure of 20.4 atm (300 psia) was selected for the parametric evaluations.

With the cooling evaluation results as a foundation, baseline engine operating points were selected. The baseline engine weight, performance and envelope data for each of the engine concepts were established and are summarized on Tables I, II and III. Parametric studies were then conducted around these baselines. The parametric data is presented in Section VI for a thrust range of 66.7 kN to 400 kN (15,000 to 90,000 lb), thrust splits from 0.4 to 0.8, and overall Mode 1 area ratios from 200:1 to at least 600:1.

TABLE I. - BASELINE TRIPROPELLANT ENGINE DATA SUMMARY

	Mode 1		Mode 2
Thrust, N (lb)	88,964 (20,000)		44,106 (9,915)
Thrust Split		0.5	
Chamber Pressure, atm (psia)	137 (2,000)		69 (1,007)
Mixture Ratio			
LOX/RP-1	3.1		---
LOX/LH_2	7.0		7.0
Overall	4.25		---
Nozzle Area Ratio	400:1		400:1
Engine Vacuum Delivered Specific Impulse, sec	418.6		460.6
Engine Dry Weight, kg (lb)		253 (557)	
Nozzle Exit Diameter, m (in.)		1.25 (49.3)	
Engine Length, m (in.)			
Extendible Nozzle Retracted		1.63 (64.2)	
Extendible Nozzle Deployed		2.42 (95.2)	

TABLE II. - BASELINE DUAL-EXPANDER ENGINE DATA SUMMARY

	Mode 1		Mode 2
Thrust, N (lb)	88,964 (20,000)		45,497 (10,228)
Thrust Split		0.5	
Chamber Pressure, atm (psia)			
LOX/RP-1 Chamber	74.8 (1,100)		---
LOX/LH_2 Chamber	37.4 (550)		37.4 (550)
Mixture Ratio			
LOX/RP-1	3.1		---
LOX/LH_2	7.0		7.0
Overall	4.28		---
Nozzle Area Ratio			
LOX/RP-1	316.5:1		---
LOX/LH_2	141.8:1		300:1
Overall	200.0:1		---
Engine Vacuum Delivered Specific Impulse, sec	403.6		451.1
Engine Dry Weight, kg (lb)		249 (550)	
Nozzle Exit Diameter, m (in.)		1.48 (58.5)	
Engine Length, m (in.)		2.28 (89.8)	

TABLE III. - BASELINE PLUG CLUSTER ENGINE DATA SUMMARY

	Mode 1		Mode 2
Thrust, N (lb)	88,964 (20,000)		43,254 (9,724)
Thrust Split		0.5	
Number of Modules	10		5
LOX/RP-1	5		-
LOX/LH_2	5		5
Gap Between Modules/Module Exit Dia.	0		1.0
% Isentropic Plug Length		0	
Chamber Pressure, atm (psia)			
LOX/RP-1 Modules	20.4 (300)		---
LOX/LH_2 Modules	20.4 (300)		20.4 (300)
Mixture Ratio			
LOX/RP-1	3.1		---
LOX/LH_2	7.0		7.0
Overall	4.18		---
Area Ratio			
LOX/RP-1 Modules	200:1		---
LOX/LH_2 Modules	200:1		200:1
Overall Geometric	358:1		715:1
Engine Vacuum Delivered Specific Impulse, sec	395.0		448.9
Engine Dry Weight, kg (lb)		297 (655)	
Engine Diameter, m (in.)		3.114 (122.6)	
Engine Length, m (in.)		1.545 (60.8)	

SECTION II

INTRODUCTION

A. BACKGROUND

From the early to mid-1970's, the NASA and DOD sponsored a number of studies which examined both interim and so-called full capability vehicles for the inter-orbit transfer of payloads. These studies, which considered solid, storable, and cryogenic propellants for main engine propulsion, generally concluded that a high area ratio, high pressure staged combustion cycle engine in a hydrogen-oxygen stage offered the highest payload capability. Several vehicle and propulsion system concepts, however, did not receive in-depth study as candidates in this early orbit-transfer-vehicle (OTV) effort. Not considered, for example, were the plug cluster engine and the more recent mixed-mode propulsion concept. Work was initiated in 1976 (Contract NAS 3-20109) to provide plug cluster engine data for use in future hydrogen-oxygen OTV studies. With regard to mixed-mode propulsion, studies of single-stage-to-orbit (SSTO) vehicles conducted by both industry and NASA have shown that mixed-mode propulsion offers significant benefits in vehicle performance and size for advanced earth-to-orbit transportation systems. This suggests that mixed-mode propulsion might also be beneficial in orbit-transfer vehicles.

Mixed-mode propulsion consists of two separate modes (herein called Mode 1 and Mode 2) of combustion in the same propulsive stage. This can be accomplished either sequentially or in parallel. During a Mode 1 parallel burn, a high density fuel, like kerosene (RP-1) or monomethylhydrazine (MMH), is burned together with oxygen and hydrogen. Only the high density fuel and oxygen are burned during Mode 1 of the series concept. Oxygen (O_2) and hydrogen (H_2) are used in the Mode 2 burn of both concepts. In Reference 1, Beichel and Salkeld compare an O_2/MMH/H_2 mixed-mode OTV with a reference O_2/H_2 OTV which utilized the RL10-IIB engine (standard RL10-3 with addition of idle-mode capability and an extendable nozzle to an area ratio of 205:1). Results showed that the mixed-mode OTV was 60% shorter than the reference design at no penalty in payload weight or 43% shorter with a geosynchronous payload increase of 21%. The cited improvements were accomplished by the application of the mixed-mode propulsion principle in a high pressure oxygen-cooled dual-fuel engine (Mode 1 area ratio = 130:1, Mode 2 area ratio = 400:1), use of a lightweight columbium rolling diaphragm nozzle extension, an O_2/H_2 mixture ratio of 7:1, and storage of the oxygen in a toroidal tank of spherical segments. The work of Beichel and Salkeld was extended to include O_2/RP-1/H_2. These ALRC in-house efforts showed that the OTV length could be reduced by 27% and the vehicle dry weight reduced by 19% for essentially no penalty in payload weight. All studies have shown that the requirements for a small size, high performance OTV drives the mixed-mode propulsion to high chamber pressures and large nozzle area ratios.

The purpose of this work was to provide the data necessary for the study of orbit-transfer-vehicles utilizing mixed-mode propulsion. The effort involved parametric analyses to establish engine data and descriptions and the identification of technology needs in the propulsion area.

B. OTV ENGINE REQUIREMENTS

The requirements for the mixed-mode OTV engines used in this study are summarized on Table IV. In addition, the study was conducted assuming currently achievable component performance levels and currently available materials.

C. APPROACH

A summary of the study program effort is shown on Figure 7. This figure shows the major past study efforts which provided basic data and inputs to this effort, the study tasks conducted and the outputs obtained. Much of the basic propellant data, properties and theoretical performance was available from Contract NAS 3-19727 (Reference 2) to support this study. The results of work performed for Contract NAS 3-20109 (Reference 3) were used to establish the plug cluster engine parameters such as, plug isentropic length, module gap ratio and module nozzle expansion ratios.

The engine concepts described by Figure 8 were analyzed in this study. Those baseline engine guidelines and parameters that could be identified prior to the initiation of all detailed analyses are shown on Tables V, VI and VII. All items marked TBD (to be determined) were established during the study by conducting the tasks which follow.

° Task I - Propellant Properties and Performance

This task generated fundamental data necessary for the performance of the remaining tasks.

° Task II - Cooling Evaluation

This task established the best coolant for each of three baseline engines and determined the maximum attainable chamber pressure on the basis of coolant pressure drop or propellant property limits.

° Task III - Baseline Engine Cycle, Weight and Envelope Analysis

This task consisted of engine cycle power balance analysis, engine delivered performance evaluations, engine and component weight estimation, and engine envelope analysis for three baseline engine concepts selected on the basis of the Task I and II results.

° Task IV - Engine Performance, Weight and Envelope Parametrics

Engine delivered performance weight and envelope data were generated over parametric ranges of thrust, thrust-split and Mode 1 area ratio for each of the selected engine concepts.

TABLE IV. - MIXED-MODE OTV ENGINE REQUIREMENTS

Propellants:	
Oxidizer	Oxygen
Mode 1 Fuel	RP-1
Mode 2 Fuel	Hydrogen
Propellant Inlet Temperature:	
Oxygen Boost Pump	90.4°K (162.7°R)
RP-1 Boost Pump	298°K (537°R)
Hydrogen Boost Pump	21°K (37.8°R)
NPSH at Boost Pump Inlet (full thrust):	
Oxygen	0.61 m (2 ft)
RP-1	13.7 m (45 ft)
Hydrogen	4.57 m (15 ft)
Service Life Between Overhauls:	300 thermal cycles or 10 hours accumulated run time
Service Free Life:	60 thermal cycles or 2 hours accumulated run time

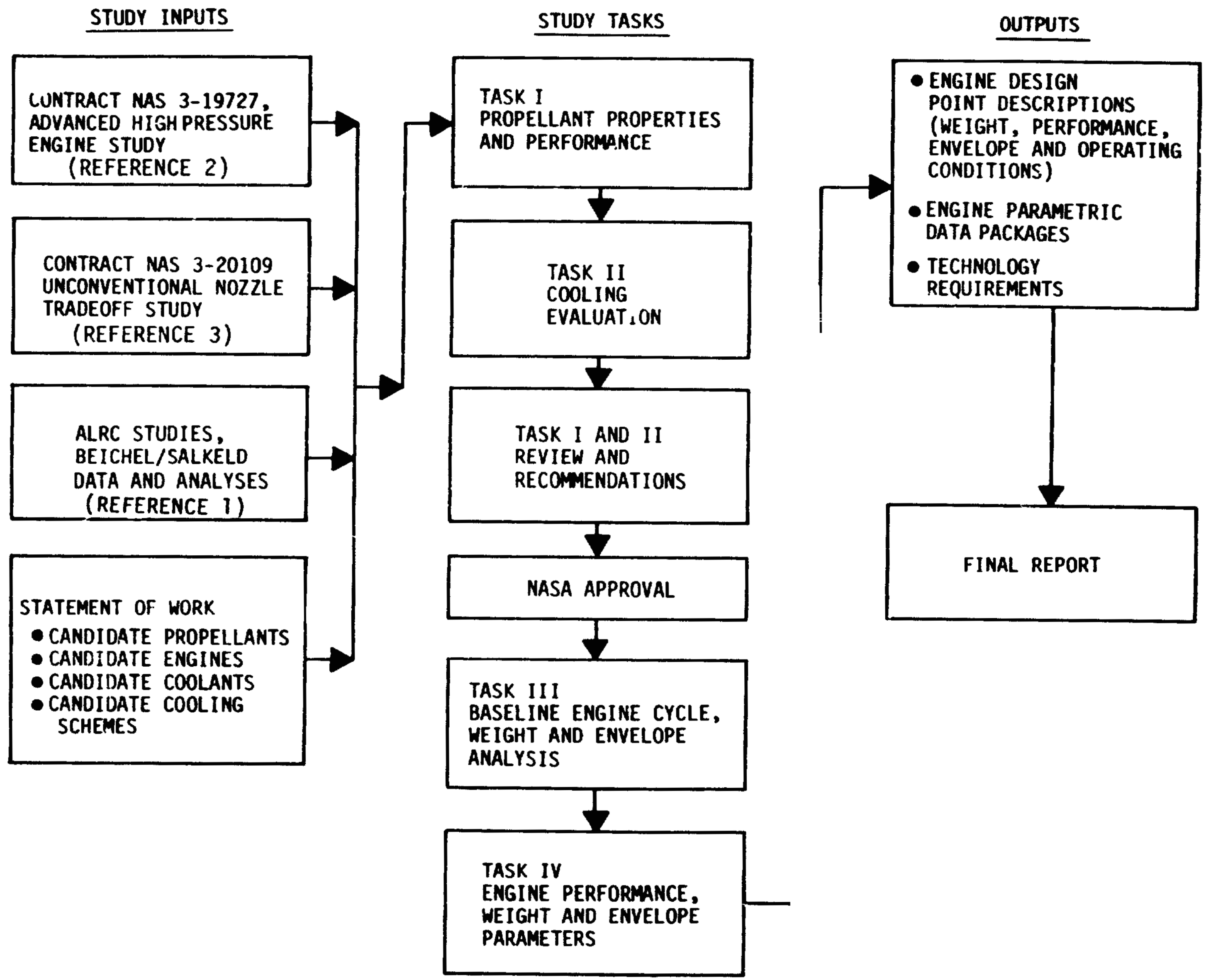


Figure 7. Advanced Engine STudy for Mixed-Mode OTV Program Summary

ENGINE CONCEPT	MODE	CYCLE	PROPELLANTS	CANDIDATE COOLANTS
TRIPROPELLANT	1	STAGED COMBUSTION	O_2/RP-1/H_2	H_2
	2	STAGED COMBUSTION	O_2/H_2	H_2
PLUG CLUSTER	1	GAS - GENERATOR	O_2/RP-1	RP-1 OR O_2 (MODULE)
	1	EXPANDER	O_2/H_2	H_2 (MODULE); H_2 (PLUG)
	2	EXPANDER	O_2/H_2	H_2 (MODULE); H_2 (PLUG)
DUAL-EXPANDER	1	DEFINED BY STUDY	O_2/RP-1	H_2
	2	DEFINED BY STUDY	O_2/H_2	H_2

Figure 8. Study Baseline Engines

TABLE V. - BASELINE TRIPROPELLANT ENGINE GUIDELINES

	MODE 1		MODE 2
PROPELLANTS: OXIDIZER	O_2	O_2	O_2
FUEL	RP-1	H_2	H_2
MIXTURE RATIO (O/F)	3.1	7.0	7.0
CHAMBER PRESSURE	TBD		TBD
VACUUM THRUST, N (lbf)	88,964 (20,000)		TBD
THRUST SPLIT $\left(\frac{O_2/\text{RP-1 THRUST}}{\text{TOTAL THRUST}}\right)$	.5		-
VACUUM IMPULSE, SEC.	TBD		TBD
DRIVE CYCLE	STG. COMB.	STG. COMB.	STG. COMB.
NOZZLE TYPE	90% BELL		90% BELL
NOZZLE EXPANSION RATIO	400:1		400:1

TABLE VI. - BASELINE DUAL-EXPANDER ENGINE GUIDELINES

	MODE 1		MODE 2
PROPELLANTS: OXIDIZER	O_2	O_2	O_2
FUEL	RP-1	H_2	H_2
MIXTURE RATIO (O/F)	3.1	7.0	7.0
CHAMBER PRESSURE	TBD	TBD	TBD
VACUUM THRUST, N (lbf)	88,964 (20,000)		TBD
THRUST SPLIT $\frac{(O_2\text{/RP-1 THRUST})}{\text{TOTAL THRUST}}$	.5		-
VACUUM IMPULSE, SEC	TBD		TBD
DRIVE CYCLE	TBD	TBD	TBD
NOZZLE TYPE	BELL	Expansion-Deflection	Expansion-Deflection
NOZZLE EXPANSION RATIO	200		TBD

TABLE VII. - BASELINE PLUG CLUSTER ENGINE GUIDELINES

	MODE 1		MODE 2
PROPELLANTS: OXIDIZER	O_2	O_2	O_2
FUEL	RP-1	H_2	H_2
MIXTURE RATIO (O/F)	3.1	7.0	7.0
CHAMBER PRESSURE	TBD	TBD	TBD
VACUUM THRUST, N (lbf)	88,964 (20,000)		TBD
THRUST SPLIT $\frac{(O_2\text{/RP-1 THRUST})}{\text{TOTAL THRUST}}$	.5		-
VACUUM IMPULSE, SEC.	TBD		TBD
DRIVE CYCLE	Gas Gen.	Expander	Expander
NUMBER OF MODULES	5	5	5
MODULE NOZZLE TYPE	90% BELL	90% BELL	90% BELL
MODULE NOZZLE EXPANSION RATIO	TBD	TBD	TBD
MODULE GAP RATIO (GAP BETWEEN MODULES/MODULE EXIT DIA)	0		1
CLUSTER EXPANSION RATIO	TBD		TBD
PLUG ISENTROPIC LENGTH, %	TBD		TBD

SECTION III

TASK I - PROPELLANT PROPERTIES AND PERFORMANCE

A. OBJECTIVES AND GUIDELINES

The objectives of this task were to provide propellant and combustion gas property data, and theoretical performance for the propellants and propellant combinations considered in this study. To accomplish these objectives, literature surveys and analyses were conducted. Much of the propellant property data is readily available in the literature and the best references are cited herein.

The logic diagram and variables considered in conducting this task are shown on Figure 9. As noted by the figure, much of the basic propellant property data was already available from Contract NAS 3-19727 (Ref. 2). In addition, combustion product and theoretical performance data available from Contracts NAS 3-19727 and NAS 3-20109 (Ref. 3) were extended to meet the study requirements.

The thermodynamic and transport property data for the combustion products were obtained from the One-Dimensional Equilibrium Computer Program with Transport Properties (TRAN 72), described in Reference 4. This computer program was obtained from NASA/LeRC and includes ODE and frozen specific impulse and characteristic velocity data in addition to the extensive combustion gas transport property output.

Main chamber theoretical performance data was also generated using the previously referenced TRAN 72 computer program. The ODE performance portion of the program is equivalent to the JANNAF one-dimensional equilibrium program.

B. PROPELLANT PROPERTY DATA

The physical and thermal property data for oxygen, RP-1, and hydrogen, were assembled for Contract NAS 3-19727 (Ref. 2). Properties of these various propellants and their data sources are:

- Oxygen - References 5,6,7,8
- Hydrogen - Reference 9
- RP-1 - References 10,11

The data is summarized on Table VIII.

In addition to these data, Reference 2 presents data on the propellant operational characteristics (i.e., safety, availability, cost handling, chemical stability, material compatibility, thermal stability, and corrosiveness).

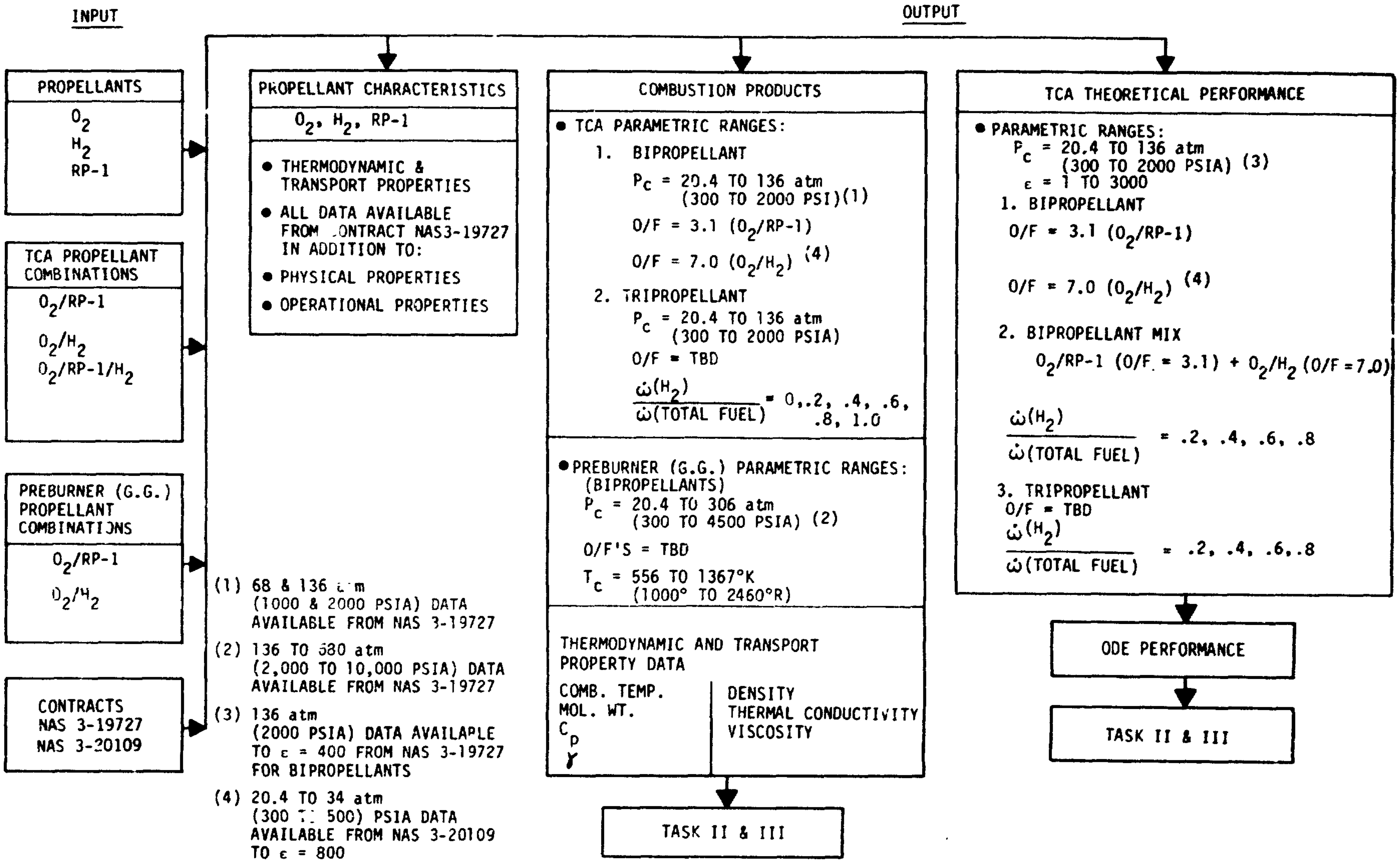


Figure 9. Task I: Propellant Properties and Performance

TABLE VIII. - PROPERTIES OF CANDIDATE PROPELLANTS

	Oxygen	Hydrogen	RP-1
Formula	O_2	H_2	$(CH_2)_{12.37}$
Molecular Weight	31.9988	2.01594	173.5151
Freezing Point, °K (°F)	54.372 (-361.818)	13.835 (-434.767)	224.8 (-55)
Boiling Point, °K (°F)	90.188 (-297.346)	20.268 (-423.187)	$\sim$492.6 ($\sim$427)
Critical Temperature, °K (°F)	154.581 (-181.433)	32.976 (-400.313)	679 (763)
Critical Pressure, MN/m^2 (psia)	5.043 (731.4)	1.2928 (187.51)	2.344 (340)
Critical Density, kg/m^3 (lb/ft^3)	436.1 (27.23)	31.43 (1.962)	-- --
Vapor Pressure at 298.15°K, kN/m^2 (at 77°F, psia)	-- --	-- --	1.8 (.26)
Density, liquid at 298.15°K, kg/m^3 (at 77°F, lb/ft^3)	1140.8[a] (71.23)	70.78[a] (4.419)	800 (49.94)
Heat Capacity, liquid at 298.15°K, J/g-°K (at 77°F, Btu/lb-°F)	1.696[a] (.405)	9.690[a] (2.316)	1.98 (.474)
Viscosity, liquid at 298.15°K, mN/m^2 (at 77°F, lb_m/ft-sec)	.1958[a] (1.316×10^{-4})	.0132[a] ($.887 \times 10^{-5}$)	1.53 (1.04×10^{-3})
Thermal Conductivity, liq. at 298.15°K, W/m-°K (at 77°F, Btu/ft-sec-°F)	.1515[a] (2.433×10^{-5})	.0989[a] (1.589×10^{-5})	.137 (2.2×10^{-5})
Heat of Formation, liquid at 298.15°K, kcal/mol (at 77°F, Btu/lb)	-3.093[a] (-174.0)	-2.134[a] (-1905)	-6.2[b] (-796)

a At NBP
b kcal/g CH_2 unit

C. THRUST CHAMBER COMBUSTION GAS PROPERTIES AND THEORETICAL PERFORMANCE DATA

This subtask consisted of the parametric evaluation of one-dimensional equilibrium (ODE) specific impulse, gas stagnation temperature, characteristic exhaust velocity, molecular weight, thermal conductivity, dynamic viscosity, specific heat, specific heat ratio (γ), and Dittus-Boelter factor for the LO_2/RP-1/LH_2 tri-propellant combination. The parametric mixture ratio range varied from 3.1:1 (LO_2/RP-1 only) to 7.0:1 (LO_2/LH_2 only). Chamber pressure values included in the study were 20.4, 34, 68, and 136 atm (300, 500, 1000 and 2000 psia). ODE specific impulse was also evaluated over an expansion area ratio range from 1:1 to 3000:1. The TRAN 72 computer program (Ref. 4) was used to calculate the ODE TCA performance and gas properties. Propellant molecular formulas and heats of formation used were presented in Table VIII.

The data were calculated for hydrogen to total fuel flow ratios (fuel fractions) of 0, 0.2, 0.4, 0.6, 0.8 and 1.0 and the following overall oxidizer to total fuel mixture ratios:

Fuel Fraction, MR_f	Overall Mixture Ratio, MR_o
0.0	3.10 (LOX/RP-1 only)
0.2	3.88
0.4	4.66
0.6	5.44
0.8	6.22
1.0	7.00 (LOX/LH_2 only)

The rationale for the selection of the overall mixture ratio points for each of the fuel fractions is described in the following paragraph.

The theoretical one-dimensional vacuum specific impulse was calculated for the LOX/LH_2/RP-1 tripropellant combination at an area ratio of 400:1 and a chamber pressure of 68 atm (1000 psia). This is shown for the various fuel fractions on Figure 10. Both maximum I_s and maximum bulk density specific impulse occur at a mixture ratio 3.1 for LOX/RP-1 at this high area ratio. Hence, this mixture ratio was selected for LOX/RP-1 operation. The contract Statement of Work specified a mixture ratio of 7.0 for the LOX/LH_2 Mode 2 operation. This selection is based upon analyses such as

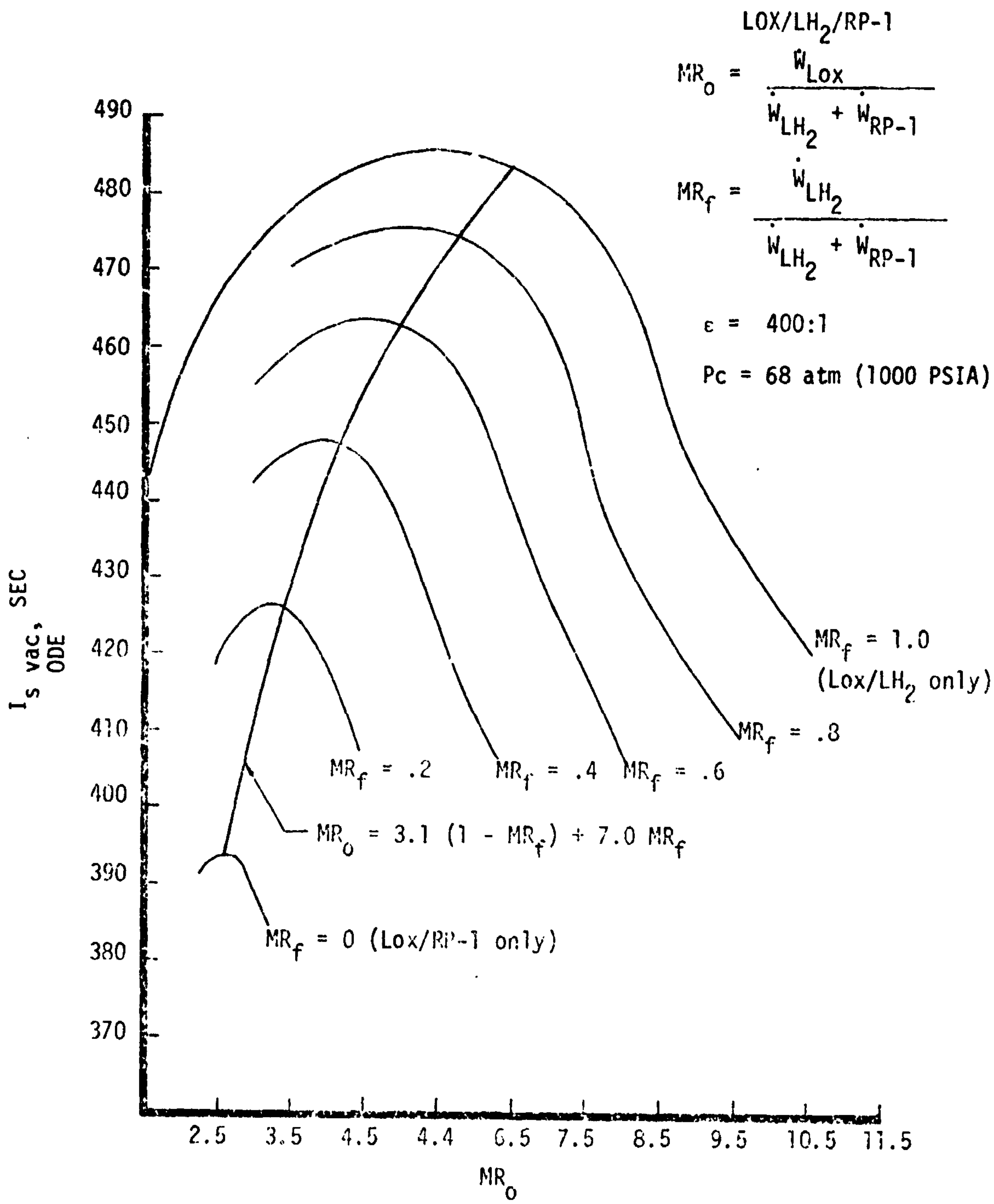


Figure 10. Tri-Propellant ODE Specific Impulse

III, C, Thrust Chamber Combustion Gas Properties and Theoretical Performance Data (cont.)

Beichel's and Salkeld's (Ref. 1) which conclude that some penalty in O_2/H_2 engine performance is warranted to obtain a higher propellant bulk density. Therefore, as higher percentages of H_2 are put into the tripropellant system, it is desirable to move slightly off peak performance. This is represented by the line passing through the various fuel fraction performance curves. The equation for this line is a function of the mixture ratios for the LOX/RP-1 and LOX/LH_2 systems as well as the fuel fraction. For the selected mixture ratios:

$$MR_o = 3.1\ (1 - MR_f) + 7.0\ (MR_f)$$

$$MR_o = \text{Overall mixture ratio}$$

$$= \frac{\dot{W}_{LOX}}{\dot{W}_{LH_2} + \dot{W}_{RP-1}}$$

$$MR_f = \text{Fuel Fraction}$$

$$= \frac{\dot{W}_{LH_2}}{\dot{W}_{LH_2} + \dot{W}_{RP-1}}$$

ODE specific impulse is plotted versus area ratio for each fuel fraction calculation point on Figures 11, 12, 13, 14, 15 and 16. The very high area ratio data was established in an attempt to cover all possible points that might result for the various engine concepts over a wide thrust split range.

The TCA combustion gas property data is shown on Table IX. The symbols used on this table are:

P_c = chamber pressure
MR_o = overall mixture ratio
MR_f = fuel fraction
C* = characteristic exhaust velocity
T_o = combustion temperature (gas stagnation temperature)
M_w = molecular weight

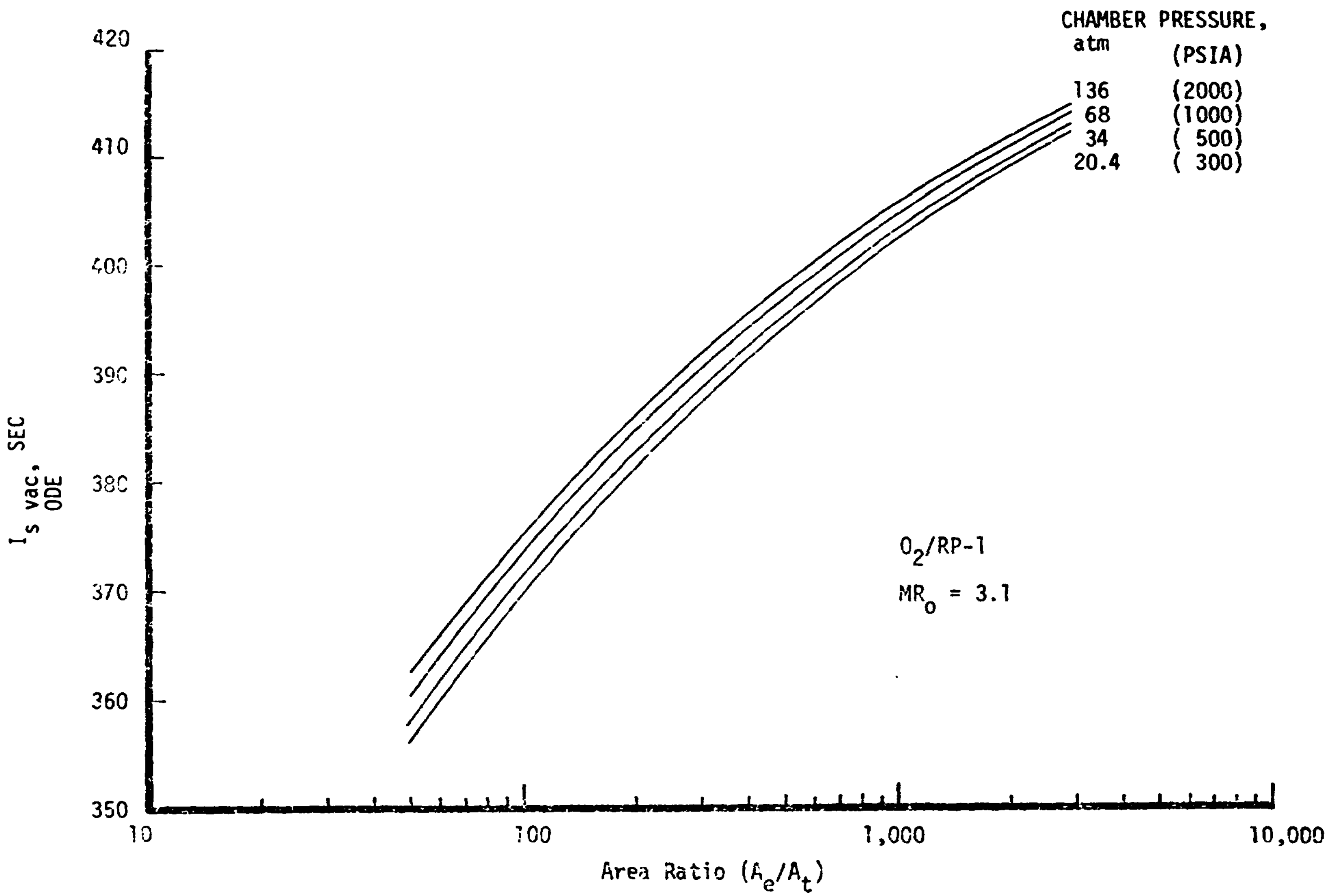


Figure 11. O_2/RP-1 ODE Specific Impulse

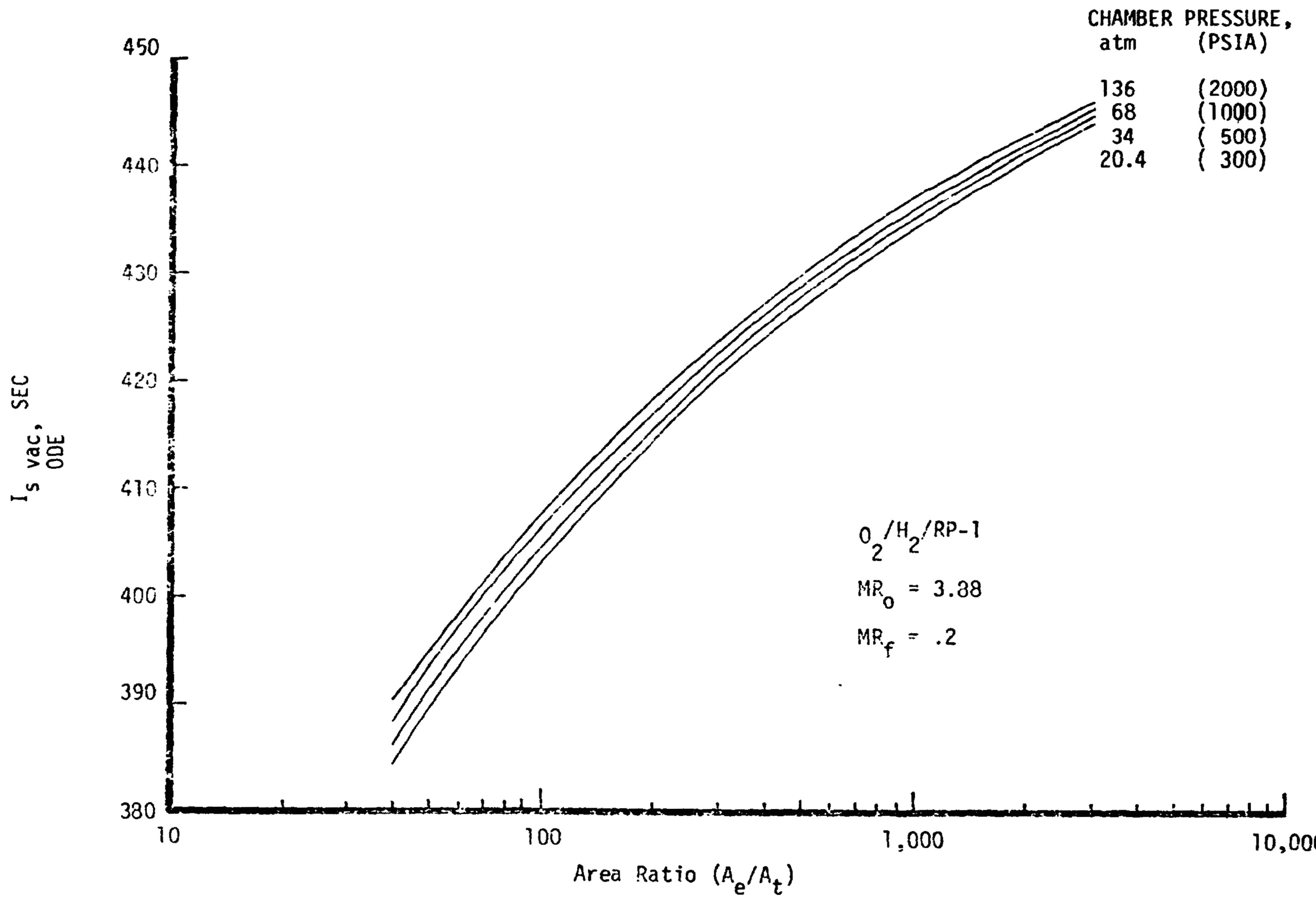


Figure 12. O_2/H_2/RP-1 ODE (MR_f = .2) ODE Specific Impulse

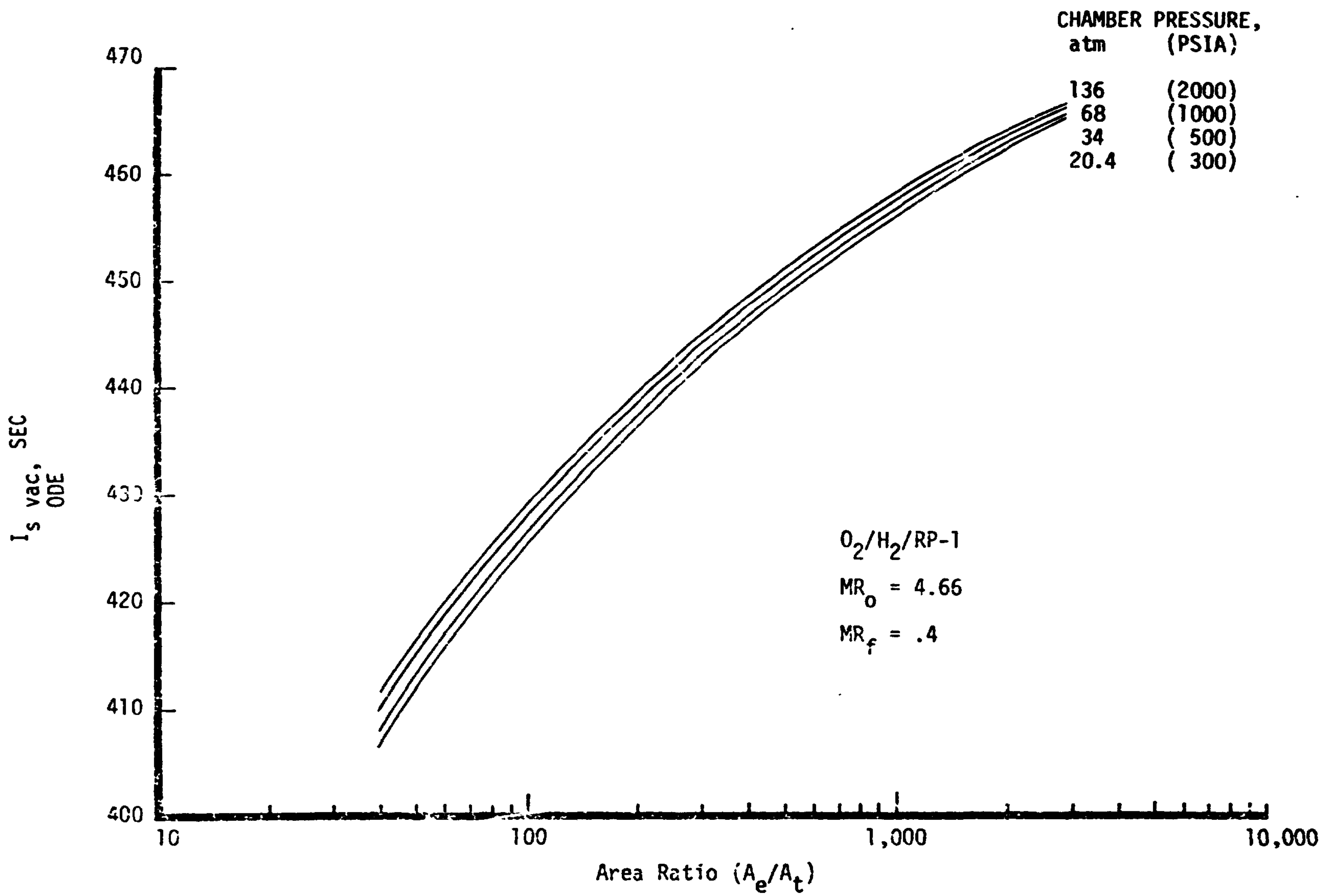


Figure 13. $O_2/H_2/RP-1$ ODE (MR_f = .4) ODE Specific Impulse

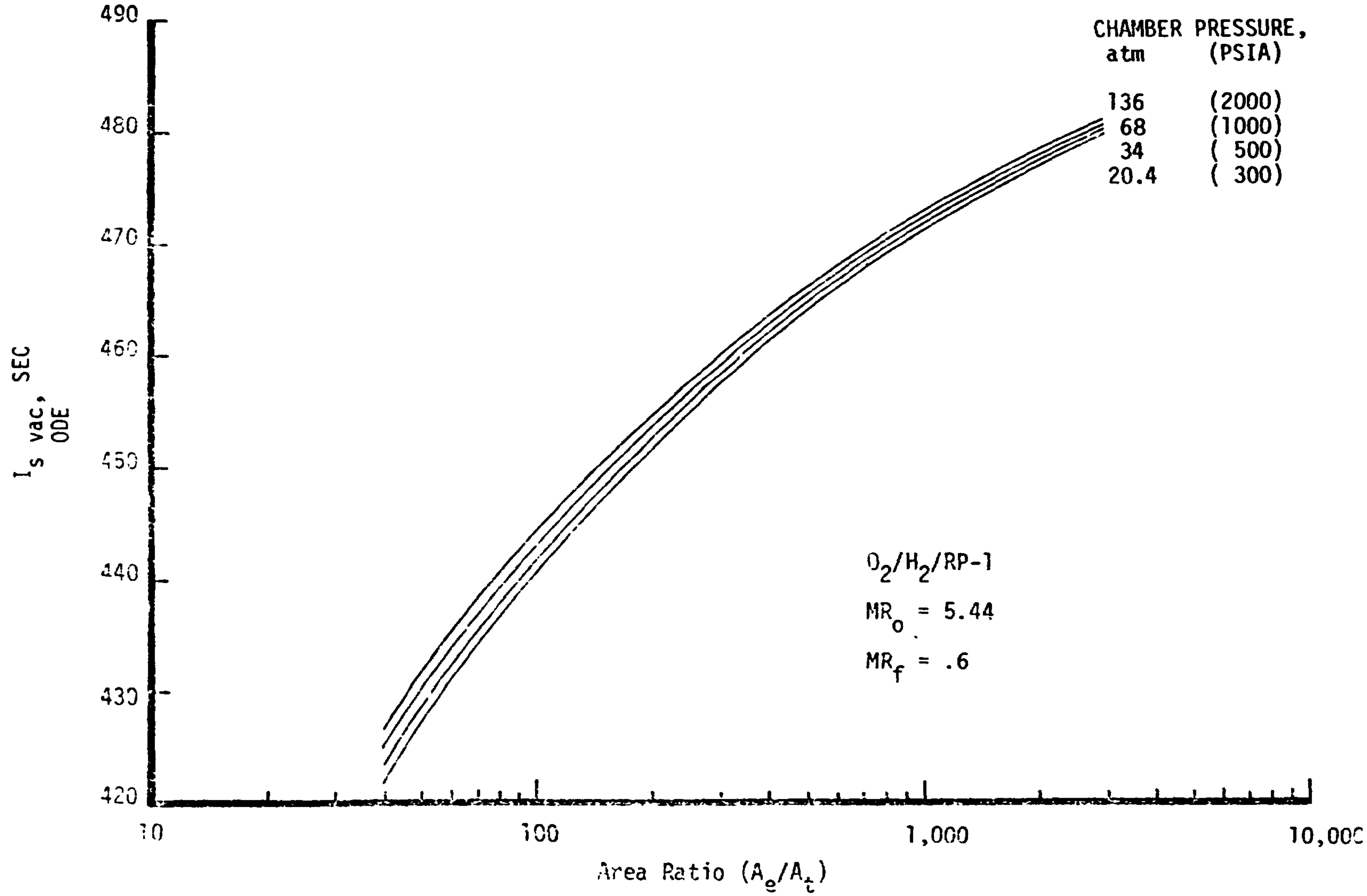


Figure 14. $O_2/H_2/RP-1$ ODE ($MR_f = .6$) ODE Specific Impulse

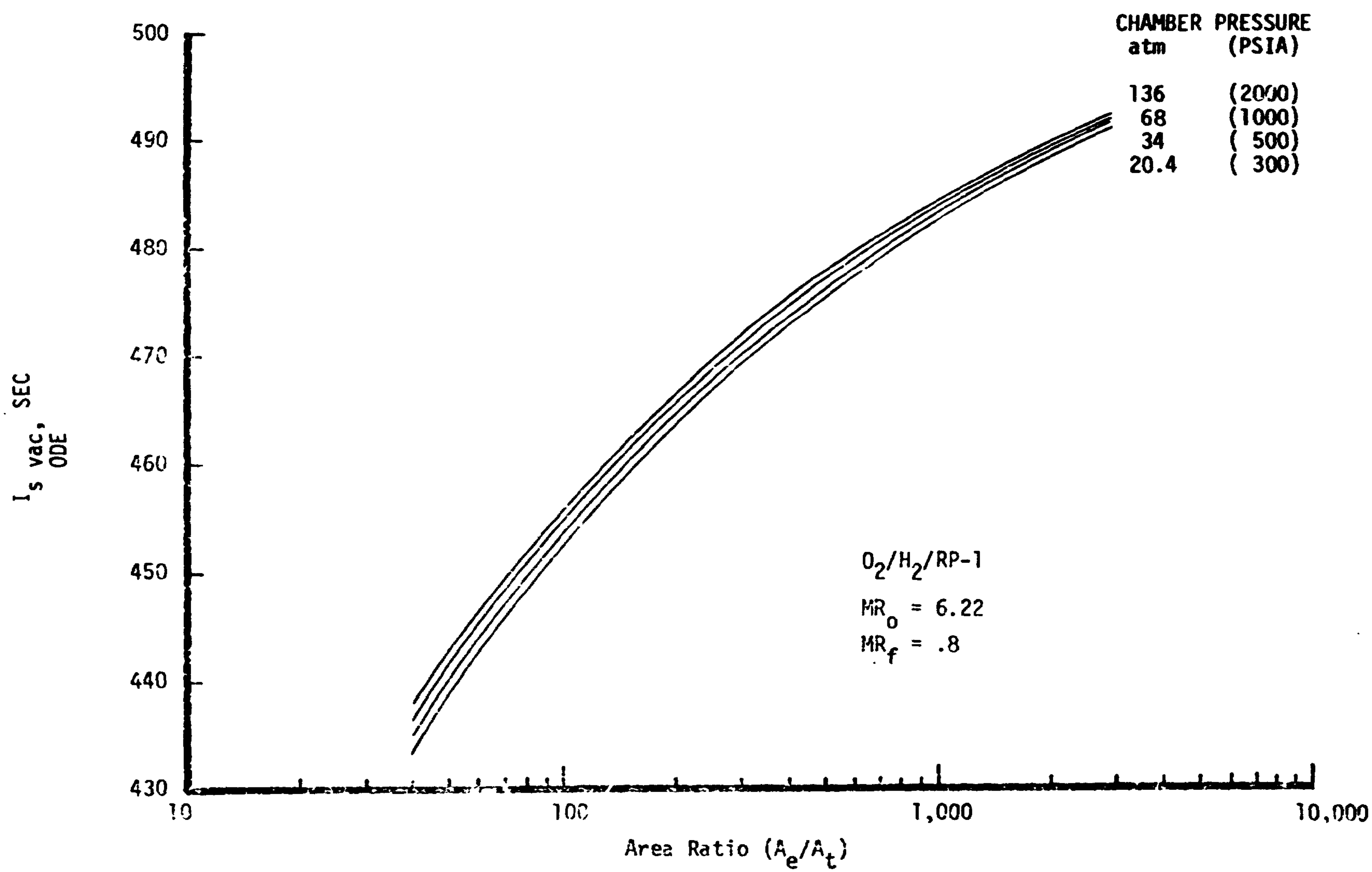


Figure 15. O_2/H_2/RP-1 ODE (MR_f = .8) ODE Specific Impulse

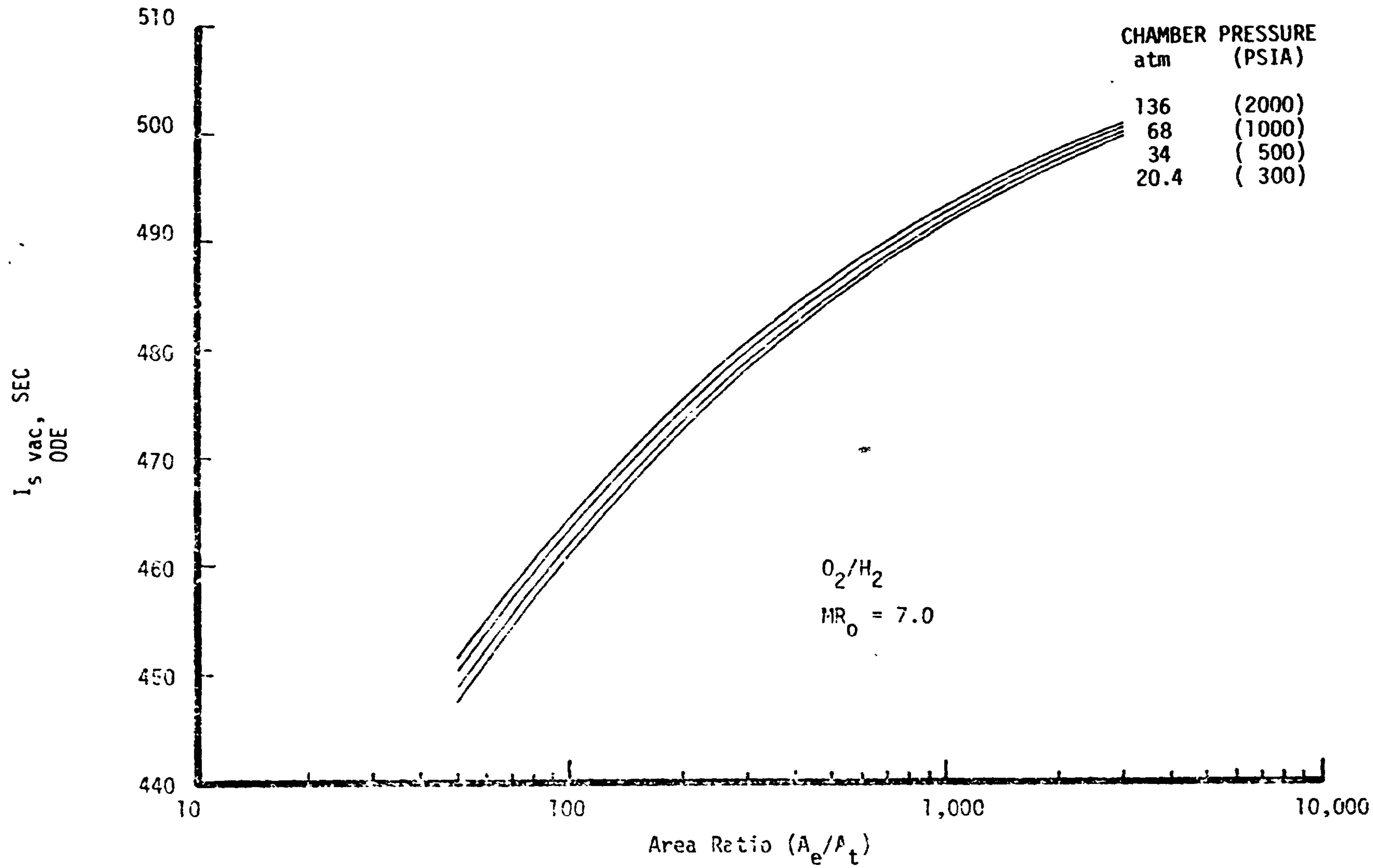


Figure 16. O_2/H_2 ODE Specific Impulse

TABLE IX. - LOX/RP-1/H_2 TRIPROPELLANT TCA GAS PROPERTIES

INTERNATIONAL SYSTEM OF UNITS

P_c atm	MR_o (MR_f)	C*, m/sec	T_o, °K	M_w g/Mole	K_f W/m-°K	γ_e	γ_f	μ N-sec/m^2 x 10^6	CP_e Cal/g-°K	CP_f Cal/g-°K	Db_f x 10^2
20.4	3.10 (.0)	1729	3517	24.4	.321	1.13	1.21	.711	2.02	.463	.175
	3.88 (.2)	1897	3476	20.0	.414	1.13	1.21	.722	2.34	.577	.221
	4.66 (.4)	2010	3454	17.7	.476	1.13	1.21	.730	2.56	.659	.252
	5.44 (.6)	2091	3441	16.3	.520	1.13	1.20	.735	2.72	.722	.256
	6.22 (.8)	2153	3429	15.3	.553	1.13	1.20	.739	2.84	.772	.292
	7.00 (1.0)	2201	3423	14.6	.579	1.13	1.20	.742	2.93	.811	.306
34.0	3.10	1740	3594	24.6	.326	1.13	1.21	.722	1.90	.464	.175
	3.88	1909	3549	20.2	.420	1.13	1.21	.734	2.18	.578	.221
	4.66	2022	3527	17.9	.483	1.13	1.20	.742	2.38	.661	.253
	5.44	2104	3462	16.4	.527	1.13	1.20	.748	2.52	.724	.275
	6.22	2166	3501	15.4	.561	1.13	1.20	.752	2.63	.773	.293
	7.00	2214	3492	14.7	.567	1.13	1.20	.755	2.71	.813	.306
68.0	3.10	1755	3702	24.8	.332	1.13	1.21	.738	1.73	.465	.176
	3.88	1924	3652	20.4	.428	1.13	1.20	.751	1.98	.580	.247
	4.66	2038	3626	18.0	.492	1.13	1.20	.760	2.15	.622	.256
	5.44	2120	3609	16.6	.537	1.13	1.20	.765	2.27	.726	.276
	6.22	2182	3596	15.6	.571	1.13	1.20	.770	2.37	.776	.294
	7.00	2231	3586	14.9	.598	1.13	1.20	.773	2.44	.816	.307
136.0	3.10	1770	3811	25.1	.338	1.13	1.20	.754	1.59	.467	.176
	3.88	1939	3754	20.6	.436	1.13	1.20	.768	1.80	.581	.223
	4.66	2053	3726	18.2	.501	1.14	1.20	.777	1.95	.665	.254
	5.44	2136	3706	16.7	.547	1.14	1.20	.783	2.05	.728	.277
	6.22	2198	3691	15.7	.582	1.14	1.19	.787	2.13	.778	.295
	7.00	2246	3679	15.0	.609	1.14	1.19	.790	2.19	.818	.308

TABLE IX (cont.)

ENGLISH UNITS

Pc (psia)	MR_o (MR_f)	C* (ft/sec)	T_o (°R)	M_W (lbm/mole)	K_f (Btu/in-sec-°R) x 10^6	γe	γf	μ (lbm/in-sec) x 10^6	CP_e (Btu/lbm-°R)	CP_f (Btu/lbm-°R)	Db_f (x 10^2)
300	3.10 (.0)	5673	6330	24.4	4.301	1.13	1.21	5.730	2.02	.463	.175
	3.88 (.2)	6223	6256	20.0	5.545	1.13	1.21	5.820	2.34	.577	.221
	4.66 (.4)	6594	6218	17.7	6.371	1.13	1.21	5.884	2.56	.659	.252
	5.44 (.6)	6961	6193	16.3	6.961	1.13	1.20	5.928	2.72	.722	.256
	6.22 (.8)	7064	6173	15.3	7.403	1.13	1.20	5.959	2.84	.772	.292
	7.00 (1.0)	7222	6161	14.6	7.747	1.13	1.20	5.984	2.93	.811	.306
500	3.10	5710	6470	24.6	4.361	1.13	1.21	5.823	1.90	.464	.175
	3.88	6262	6389	20.2	5.622	1.13	1.21	5.919	2.18	.578	.221
	4.66	6634	6348	17.9	6.460	1.13	1.20	5.985	2.38	.661	.253
	5.44	6902	6231	16.4	7.058	1.13	1.20	6.031	2.52	.724	.275
	6.22	7105	6301	15.4	7.507	1.13	1.20	6.063	2.63	.773	.293
	7.00	7264	6285	14.7	7.857	1.13	1.20	6.088	2.71	.813	.306
1000	3.10	5759	6663	24.8	4.444	1.13	1.21	5.951	1.73	.465	.176
	3.88	6313	6573	20.4	5.727	1.13	1.20	6.055	1.98	.580	.247
	4.66	6687	6526	18.0	6.580	1.13	1.20	6.125	2.15	.622	.255
	5.44	6955	6495	16.6	7.190	1.13	1.20	6.172	2.27	.726	.276
	6.22	7159	6472	15.6	7.647	1.13	1.20	6.205	2.37	.776	.294
	7.00	7318	6454	14.9	8.003	1.13	1.20	6.230	2.44	.816	.307
2000	3.10	5808	6859	25.1	4.529	1.13	1.20	6.080	1.59	.467	.176
	3.88	6363	6758	20.6	5.833	1.13	1.20	6.191	1.80	.581	.223
	4.66	6737	6706	18.2	6.700	1.14	1.20	6.264	1.95	.665	.254
	5.44	7007	6670	16.7	7.320	1.14	1.20	6.313	2.05	.728	.277
	6.22	7211	6643	15.7	7.785	1.14	1.19	6.347	2.13	.778	.293
	7.00	7370	6623	15.0	8.147	1.14	1.19	6.371	2.19	.818	.303

K_f = thermal conductivity

γ_e = ratio of specific heats, equilibrium

γ_f = ratio of specific heats, frozen

μ = dynamic viscosity

C_{p_e} = specific heat at constant pressure, equilibrium

C_{p_f} = specific heat at constant pressure, frozen

Db_f = Dittus-Bolelter factor

D. PREBURNER COMBUSTION GAS PROPERTIES AND PERFORMANCE DATA

This subtask consisted of calculating the combustion gas properties for fuel-rich and oxidizer-rich LO_2/RP-1 and LO_2/LH_2 preburner operation. These data were developed over a chamber pressure range from 20.4 to 408 atm (300 to 6000 psia) and mixture ratio ranges corresponding to gas temperatures between at least 700 to 1367°K (1260 to 2460°R).

The data presented in this report is a compilation of results obtained during this program and applicable data for pressures of 136 to 408 atm (2000 to 6000 psia) developed during a similar task on the Advanced High Pressure Engine Study, Contract NAS 3-19727 (Ref. 2). The LO_2/RP-1 preburner gas property data presented in this reference at pressures of 136, 272 and 408 atm (2000, 4000, 6000 psia) was expanded to the lower chamber pressures of 20.4, 34, and 68 atm (300, 500, and 1000 psia) used in this study. No propellant pre-heating was allowed for since H_2 was the baseline TCA coolant for this study. The non-equilibrium performance of the fuel-rich LO_2/RP-1 performance was accounted for as described in Ref. 2. Also, the LO_2/LH_2 preburner gas property data presented in the reference was verified as accurate for the 20.4 to 68 atm (300 to 1000 psia) pressure range. Therefore, the LO_2/LH_2 data is valid for all pressures from 20.4 to 408 atm (300 to 6000 psia).

Study preburner gas properties were also calculated with the TRAN 72 computer program (Ref. 4). LO_2/RP-1 preburner gas properties are tabulated in Table X. The symbols used on this table were defined in Section III,C. The stagnation temperature, characteristic exhaust velocity, molecular weight and specific heat ratio data shown on this table were adjusted from their ODE values for the LO_2/RP-1 fuel-rich preburner data. The adjusted T_0 and C* data along with molecular weight and specific heat ratio are plotted in Figure 17. This adjustment accounts for the empirically observed non-equilibrium performance of fuel-rich hydrocarbon/oxygen mixtures. Efficiency factors were developed versus equivalence ratio, as described in Ref. 2, and used to predict T_0 and C* values at the stated chamber pressures.

LO_2/LH_2 preburner data were also calculated at chamber pressures of 20.4, 34 and 68 atm (300, 500, and 1000 psia). These data agreed with

TABLE X. - LOX/RP-1 PREBURNER ODE GAS PROPERTIES

S.I. UNITS

P_c, atm	O/F	C*, m/sec	T_o, °K	M_w g/mole	K_f W/m-°K	γ_f	μ, N-sec/m^2 x 10^6	CP_f, Cal/g-°K	Db_f, x 10^2
20.4	.1	869	884	33.7	.173	1.05	.183	1.002	.282
	.3	1064	1036	27.2	.241	1.115	.227	.926	.306
	.6	1224	1243	17.5	.236	1.17	.261	.702	.194
	20(1)	1024	1743	31.8	.126	1.26	.475	.307	.099
	30	851	1226	31.9	.0925	1.28	.382	.284	.087
	50	658	749	31.9	.0601	1.32	.276	.257	.074
34	.1	871	904	33.7	.173	1.05	.186	1.000	.280
	.3	1069	1118	27.2	.241	1.115	.233	.921	.302
	.6	1232	1281	17.5	.238	1.17	.268	.704	.255
68	.1	874	928	33.7	.172	1.05	.190	.997	.277
	.3	1074	1163	27.2	.241	1.115	.240	.917	.298
	.6	1242	1336	17.5	.242	1.17	.277	.707	.202
[illegible]	.1	877	952	33.7	.172	1.05	.193	.996	.224
	.3	1079	1208	27.2	.241	1.115	.248	.915	.294
	.6	1252	1394	17.5	.245	1.17	.287	.710	.253
272	.1	879	972	33.7	.171	1.05	.196	.995	.272
	.3	1083	1254	27.2	.241	1.115	.256	.914	.290
	.6	1261	1457	17.5	.248	1.17	.298	.714	.251
408	.1	880	983	33.7	.171	1.05	.198	.995	.271
	.3	1085	1282	27.2	.241	1.115	.260	.915	.288
	.6	1266	1494	17.5	.249	1.17	.305	.716	.251

NOTES: (1) Oxidizer-rich properties do not change as a function of chamber pressure from 20.4 to 408 atm.

TABLE X (cont.)

ENGLISH UNITS

P_c (psia)	O/F	C* (ft/sec)	T_o (°R)	M_W (lbm/mole)	K_f (Btu/in-sec-°R) x 10^6	γf	μ (lbm/in-sec) x 10^6	CP_f (Btu/lbm-°R)	Db_f (x 10^2)
300	.1	2850	1592	33.7	2.314	1.05	1.474	1.002	.282
	.3	3491	1954	27.2	3.228	1.115	1.832	.926	.306
	.6	4016	2237	17.5	3.156	1.17	2.104	.702	.194
	20(1)	3359	3137	31.8	1.684	1.26	3.831	.307	.099
	30	2793	2206	31.9	1.238	1.28	3.080	.284	.087
	50	2159	1349	31.9	.805	1.32	2.222	.257	.074
500	.1	2859	1628	33.7	2.311	1.05	1.498	1.000	.280
	.3	3506	2012	27.2	3.226	1.115	1.877	.921	.302
	.6	4042	2305	17.5	3.192	1.17	2.158	.704	.255
1000	.1	2869	1672	33.7	2.305	1.05	1.530	.997	.277
	.3	3524	2093	27.2	3.224	1.115	1.939	.917	.298
	.6	4075	2404	17.5	3.237	1.17	2.236	.707	.202
2000	.1	2877	1713	33.7	2.299	1.05	1.558	.996	.224
	.3	3540	2174	27.2	3.222	1.115	2.000	.915	.294
	.6	4107	2510	17.5	3.279	1.17	2.318	.710	.253
4000	.1	2883	1749	33.7	2.293	1.05	1.583	.995	.272
	.3	3553	2258	27.2	3.220	1.115	2.061	.914	.290
	.6	4136	2622	17.5	3.318	1.17	2.405	.714	.251
6000	.1	2886	1769	33.7	2.289	1.05	1.596	.995	.271
	.3	3559	2307	27.2	3.220	1.115	2.096	.915	.288
	.6	4152	2690	17.5	3.339	1.17	2.458	.716	.251

NOTES: (1) Oxidizer Rich Properties Do Not Change as a Function of Chamber Pressure from 300-6000 psia

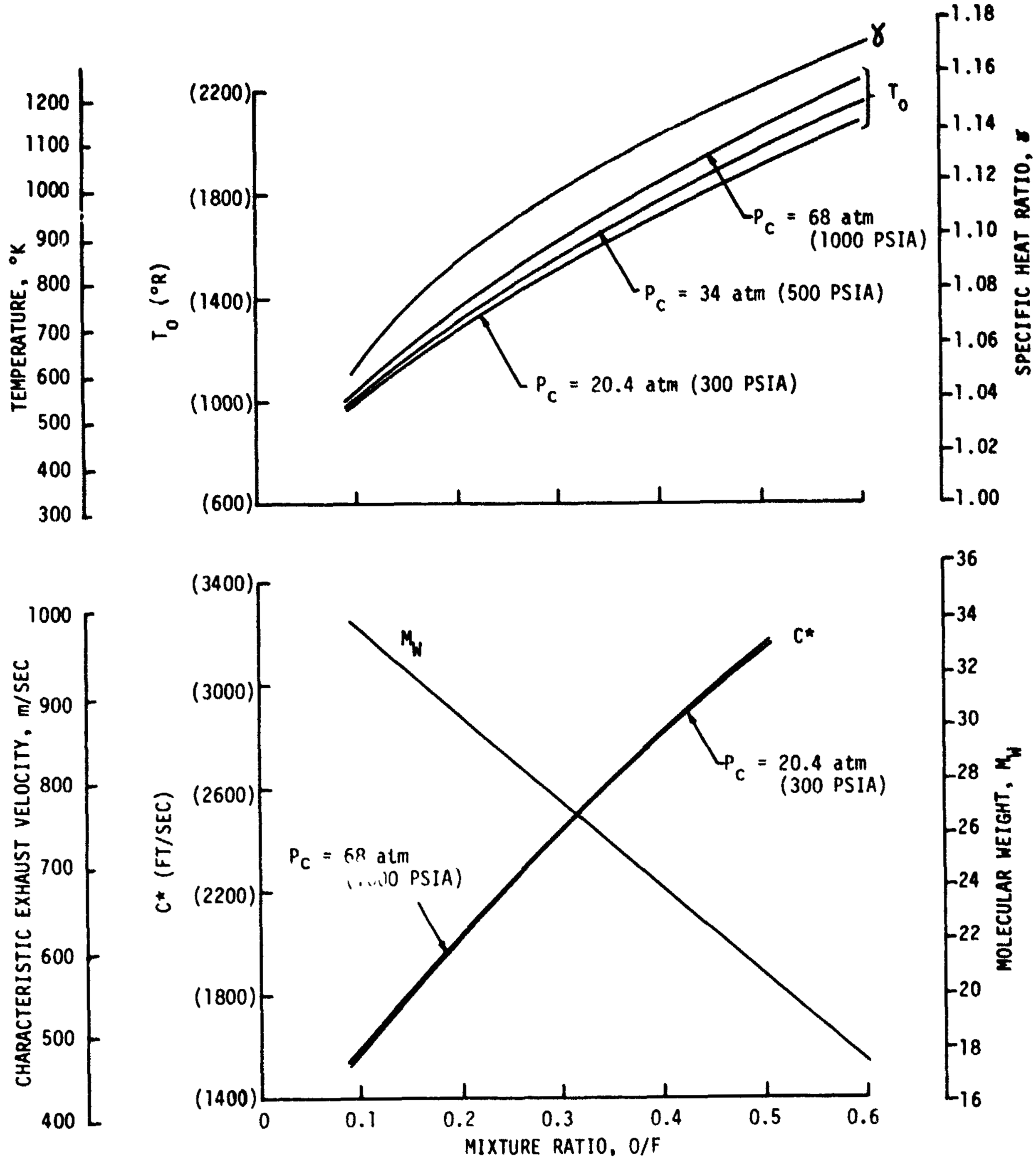


Figure 17. LO_2/RP-1 Fuel-Rich Preburner Performance

previous data developed for the 136 to 408 atm (2000 to 6000 psia) pressure range. The LO_2/LH_2 preburner data is shown on Table XI. It was concluded that the LO_2/LH_2 preburner performance curves presented in Ref. 2 were valid for the parametric pressure range of this study.

TABLE XI. - LOX/LH_2 PREBURNER ODE GAS PROPERTIES

S.I. UNITS

P_c, atm	O/F	C* m/sec	T_o, °K	M_w, g/mole	K_f, W/m-°K	γ_f	μ, N-sec/m^2 x 10^6	CP_f Cal/g-°K	Db_f x 10^2
20.4 to 408	.5	1770	503	3.04	.241	1.39	.101	2.392	.623
	1.0	2095	979	4.03	.370	1.36	.183	1.868	.571
	1.5	2275	1414	5.04	.478	1.32	.260	1.643	.550
20.4 to 408	70	929	1334	29.2	.109	1.28	.403	.311	.098
	120	706	819	30.3	.0683	1.32	.292	.273	.080
	200	549	499	31.6	.0424	1.36	.207	.240	.065

ENGLISH UNITS

P_c (psia)	O/F	C* (ft/sec)	T_o (°R)	M_W (lbm/mole)	K_f (Btu/in-sec-°R) x 10^6	γf	μ (lbm/in-sec) x 10^6	CP_f (Btu/lbm-°R)	Db_f (x 10^2)
300 to 6000	.5	5807	905	3.04	3.224	1.39	.817	2.392	.623
	1.	6873	1763	4.03	4.949	1.36	1.473	1.868	.571
	1.5	7463	2545	5.04	6.403	1.32	2.093	1.643	.550
300 to 6000	70	3047	2402	29.2	1.463	1.28	3.251	.311	.098
	120	2317	1474	30.3	.914	1.32	2.358	.273	.080
	200	1800	898	31.6	.567	1.36	1.671	.240	.065

SECTION IV

TASK II - COOLING EVALUATION

A. OBJECTIVES AND GUIDELINES

The primary objective of this task was to determine the relative capability of oxygen, RP-1, and hydrogen to cool the thrust chamber and nozzle of the tripropellant, plug cluster, and dual-expander OTV engine concepts. Secondary objectives were to: (1) establish cooling methods and associated power cycles for the dual-expander engine concept, and (2) define the geometry of the thrust chamber and nozzle for each of the baseline OTV engine concepts.

Parametric hydraulic, heat transfer and low cycle fatigue analyses were conducted over the following ranges of chamber pressure and thrust split.

Engine Concept	Chamber Pressure atm (psia)	Thrust Split
Tripropellant	34 to 136 (500 to 2000)	.4 to .8
Plug Cluster	20.4 to 68 (300 to 1000)	.5
Dual-Expander	34 to 136 (500 to 2000)	.4 to .8

The relative merit of the various coolants considered (Figure 8) were evaluated on the basis of attainable chamber pressure, as reflected in the coolant pressure drop. This evaluation was conducted within the constraints of the study criteria listed in Table XII and consideration of the potential problems and limitations such as coking of RP-1 and instabilities in subcritical oxygen heat exchangers.

The Task II guidelines provided by NASA/LeRC are summarized on Table XII and Figures 18 through 21. Rectangular channel construction was specified in the high heat flux portion of the chambers using a zirconium-copper alloy. The channel dimension and wall thickness limits are presented on Table XII. Figures 18 through 21 show the zirconium-copper properties used in this study.

The cooling methods and associated power cycles evaluated for the tripropellant and plug cluster concepts are shown on Figures 22 through 26. These concepts were defined by the contract statement of work. The dual-expander concept was defined during the study and is described in the next section. As shown by the figures, the baseline plug cluster concept is regeneratively cooled. The tripropellant engine is regeneratively cooled to a nozzle area ratio corresponding to the point where a radiation cooled nozzle can be utilized. This transition area ratio was established during the study.

TABLE XII. - COOLANT EVALUATION STUDY CRITERIA

° Coolant Inlet Temperature

H_2 - 50°K (90°R)
O_2 - 111°K (200°R)
RP-1 - 311°K (560°R)

° Coolant Inlet Pressure

Staged Combustion Cycle:	2.25 times chamber press.
Gas Generator Cycle:	1.8 times chamber press.
Expander Cycle:	2.25 times chamber press.

° Service Life: 300 cycles times a safety factor of 4

° High heat flux portion of chamber shall be of nontubular construction with the following dimensional limits:

Minimum Slot Width	= 0.762 mm (.03 in.)
Maximum Slot Depth/Width	= 4 to 1
Minimum Web Thickness	= 0.762 mm (.03 in.)
Minimum Wall Thickness	= 0.635 mm (.025 in.)

° Material (nontubular portion): Copper alloy (Zirconium Copper) conforming to properties given in Figures 18 through 21

° Maximum Coolant Velocity

Liquid: To Be Determined
Gas: To Be Determined

° Possible Benefit of Carbon Deposition on Hot Gas Wall shall be Neglected

° Coking Limit

RP-1 Coolant Side Wall Temperature = 589°K (600°F)

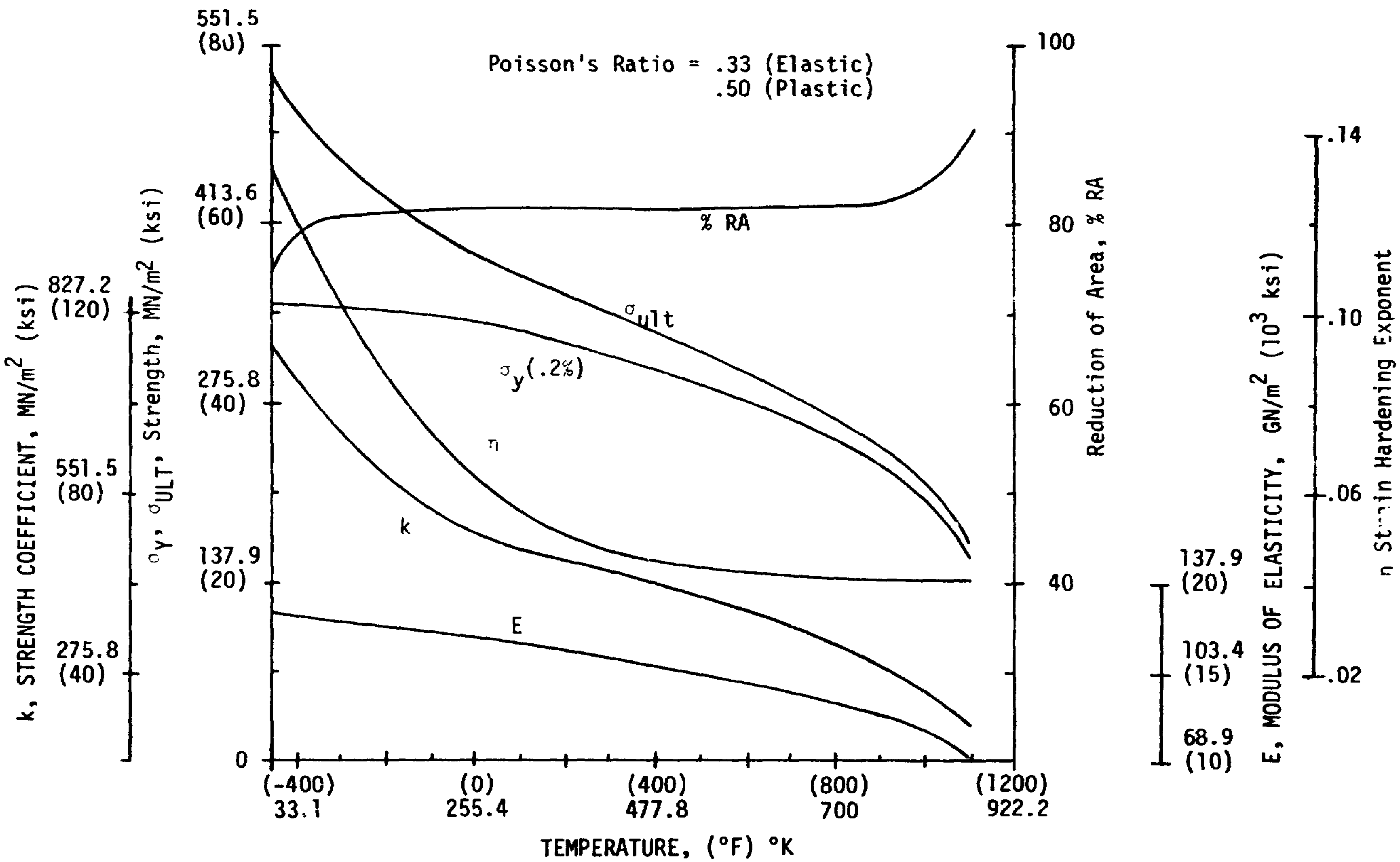


Figure 18. Tensile Properties (Zirconium Copper)

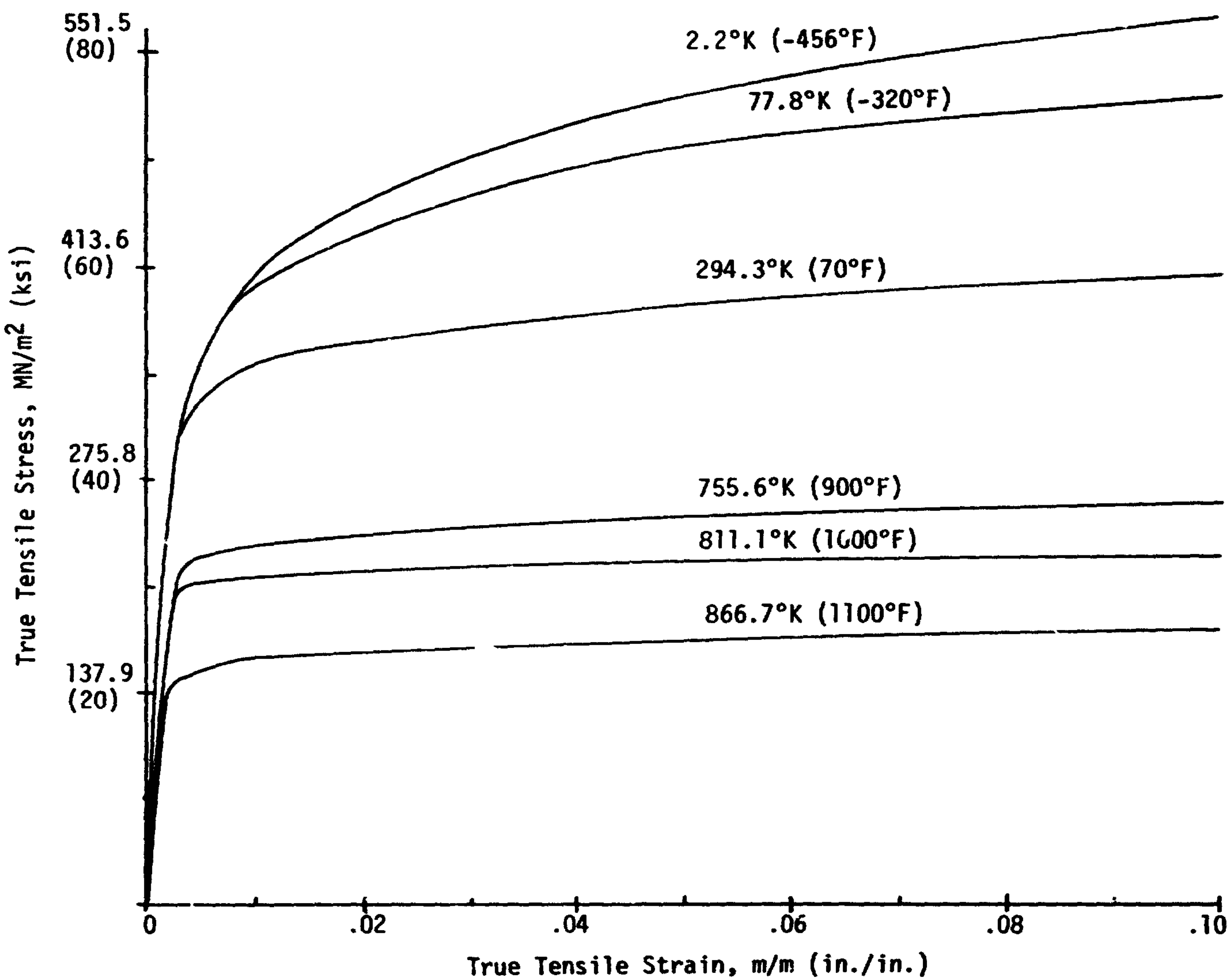


Figure 19. Tensile Stress-Strain

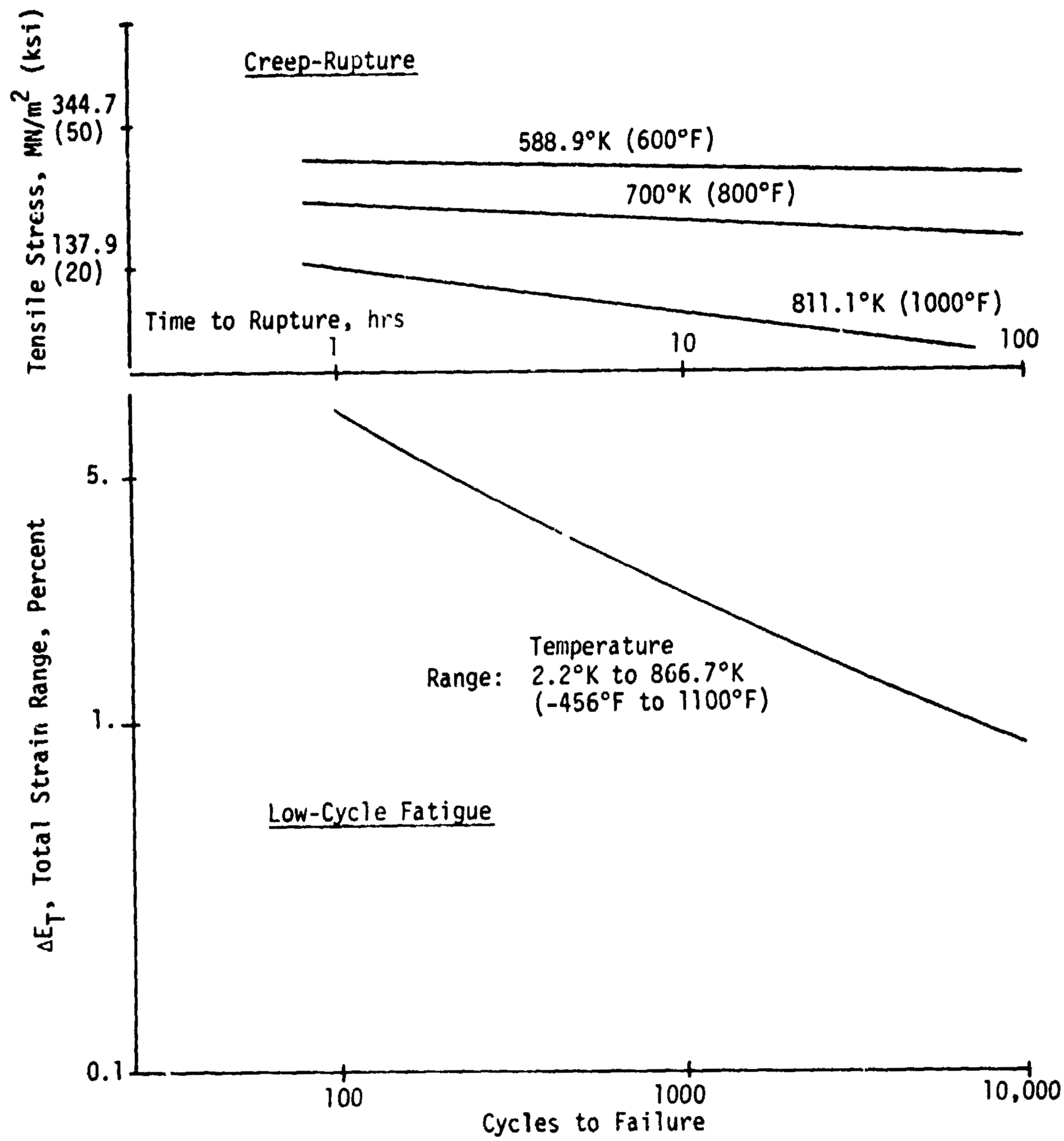


Figure 20. Creep-Rupture and Low Cycle Fatigue

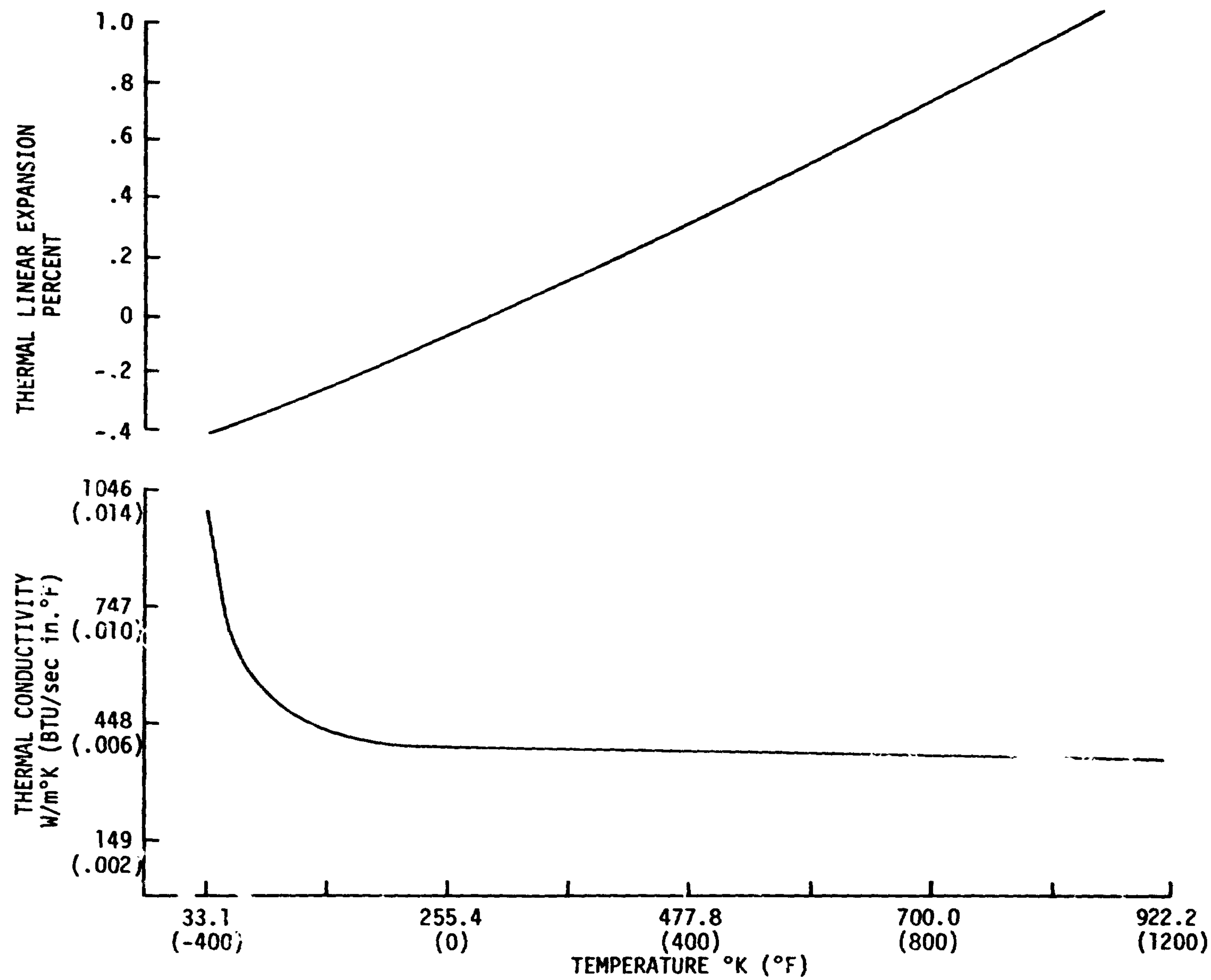


Figure 21. Conductivity and Expansion

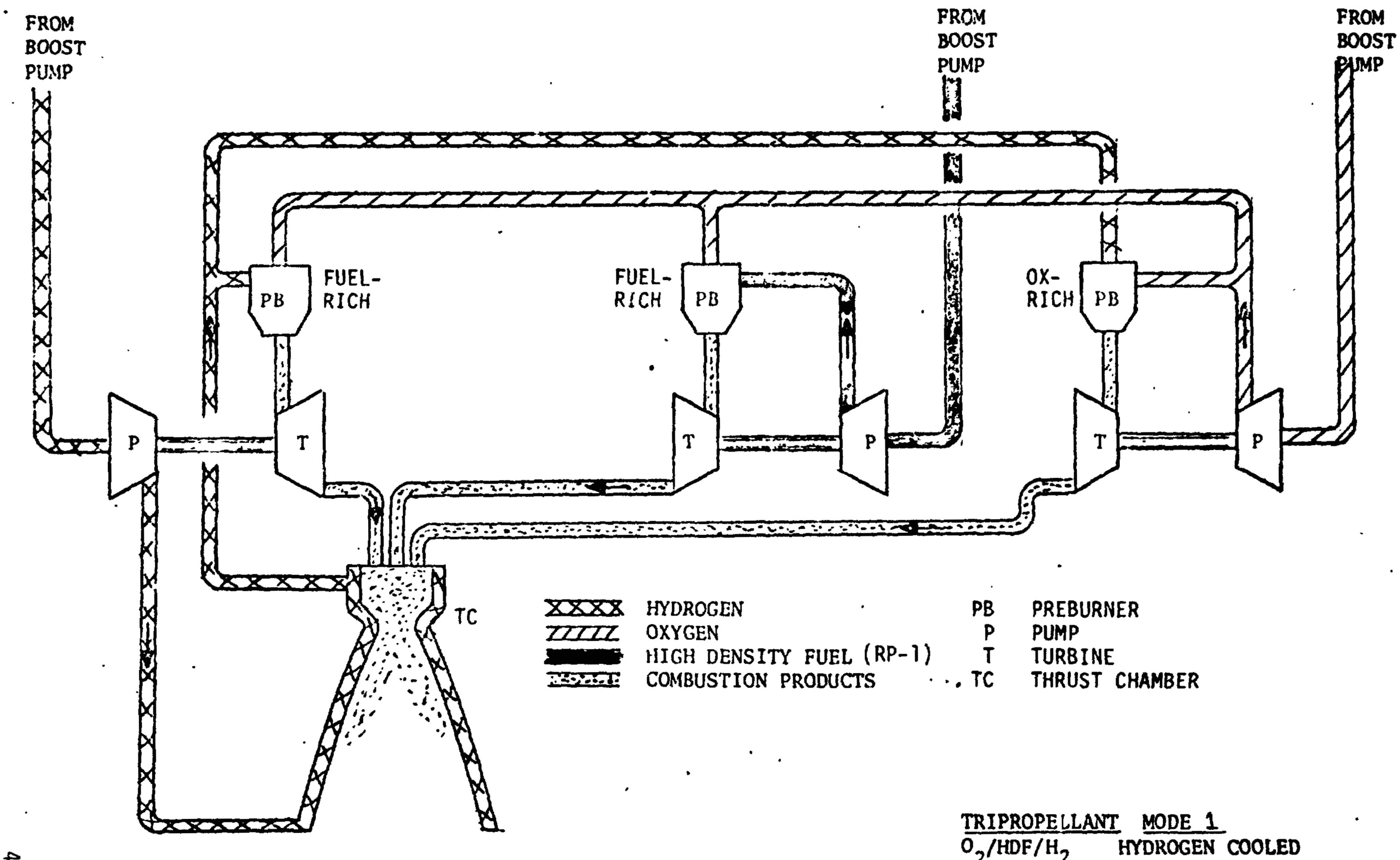


Figure 22. Preliminary Mode 1 Tripropellant Engine Schematic

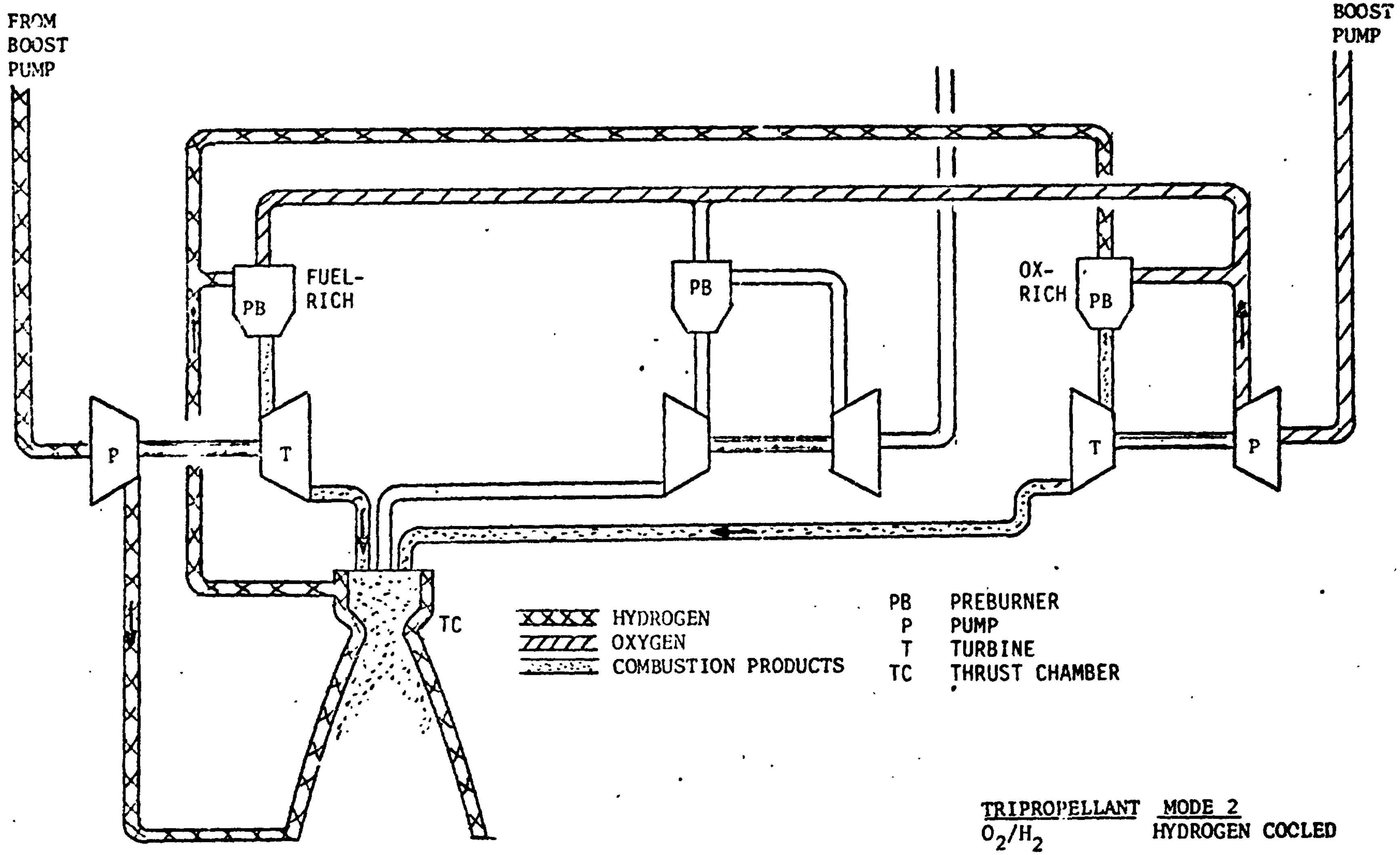


Figure 23. Prel'minary Mode 2 Tripropellant Engine Schematic

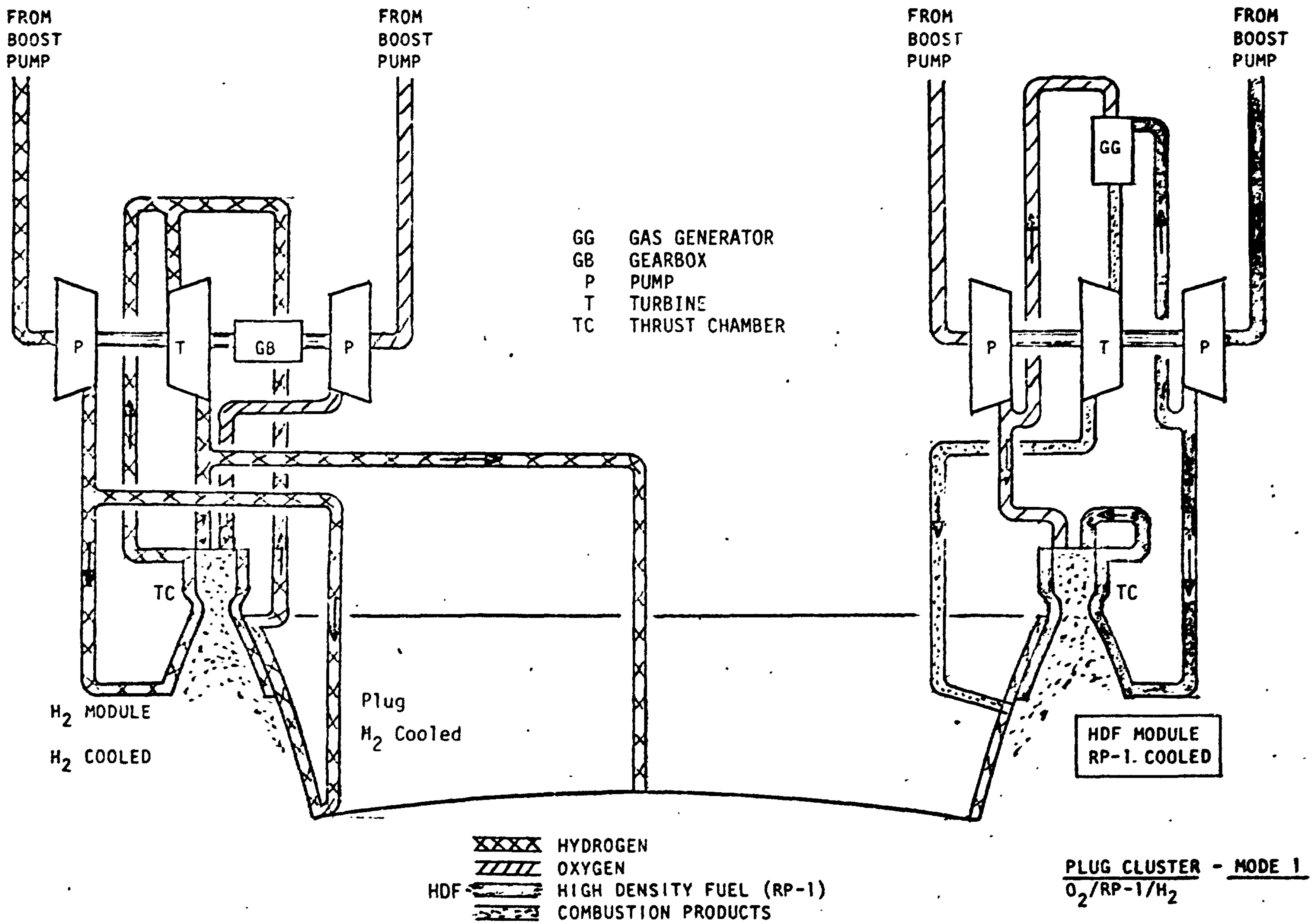


Figure 24. Preliminary Mode 1 Plug Cluster Engine Schematic with HDF Module RP-1 Cooled

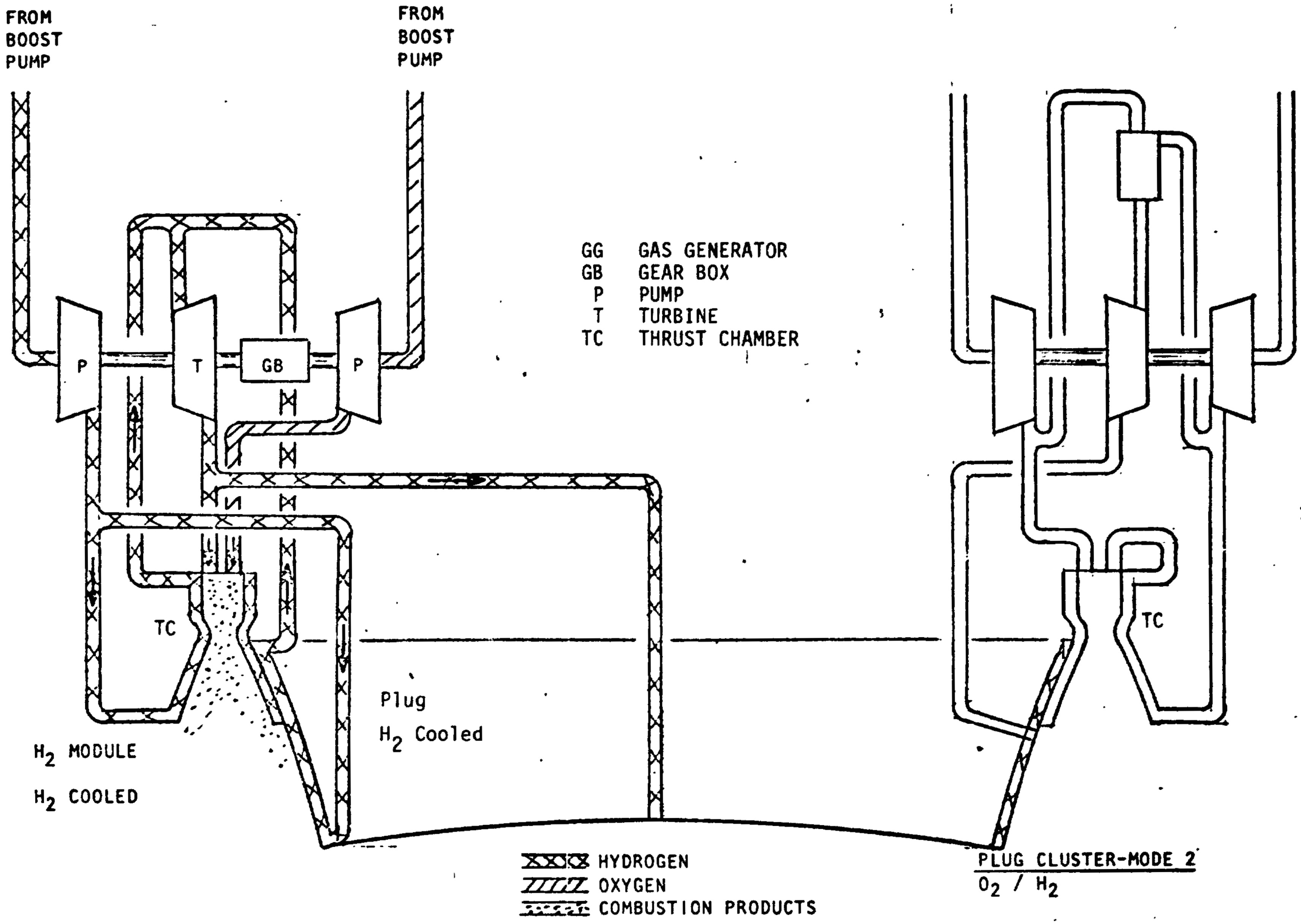


Figure 25. Preliminary Mode 2 Plug Cluster Engine Schematic

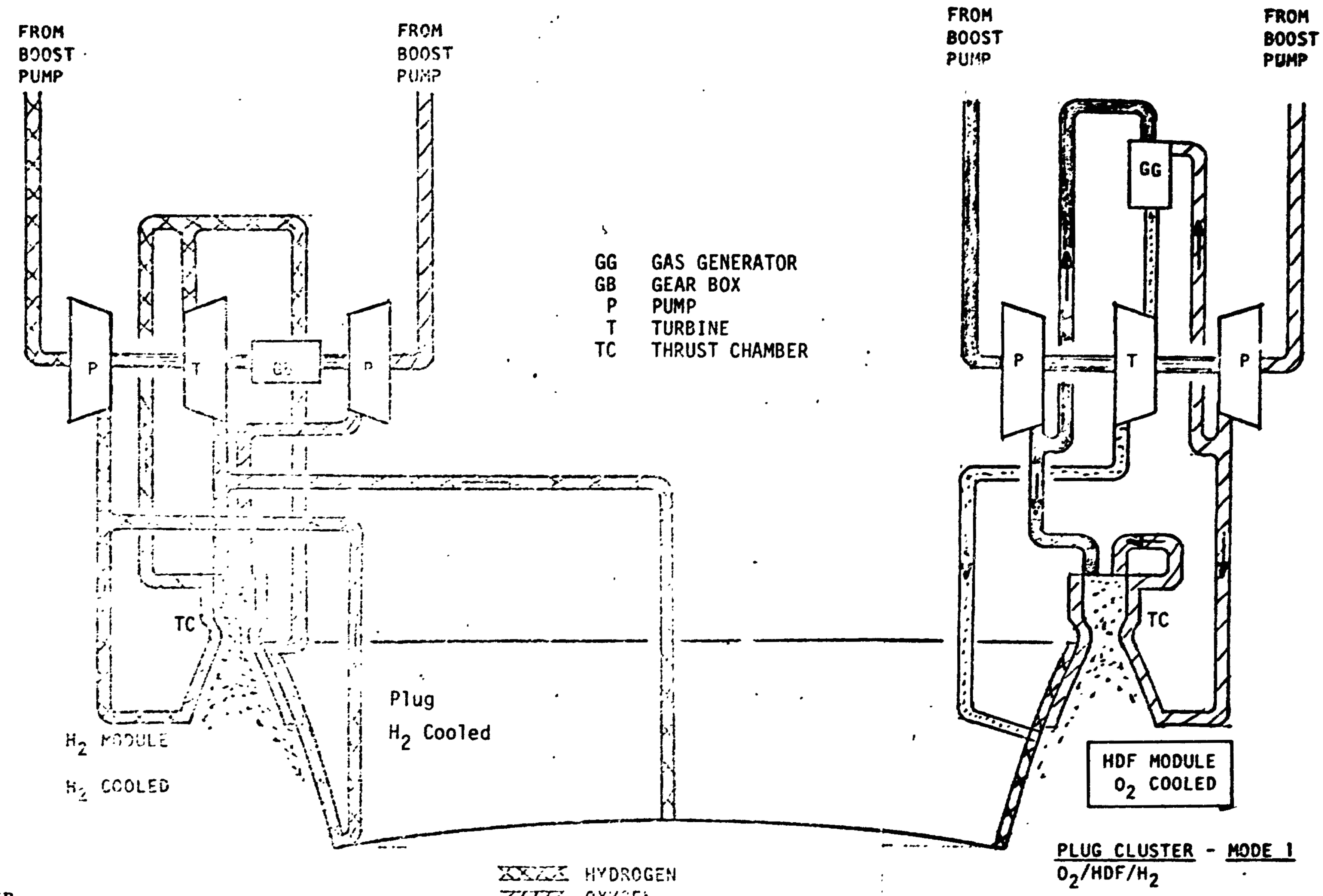


Figure 26. Preliminary Mode 1 Plug Cluster Engine Schematic with HDF Module O_2 Cooled

B. DUAL-EXPANDER ENGINE CONCEPT DEFINITION

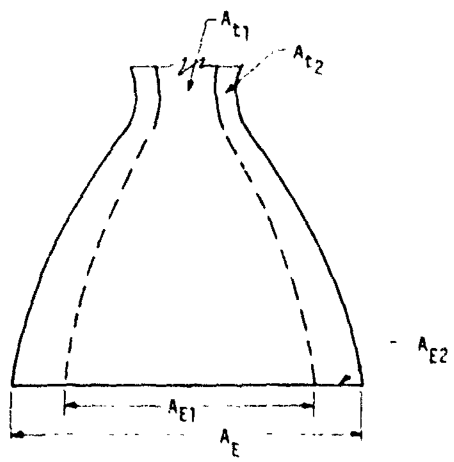
The dual-expander engine concept analyzed during this study was defined and is shown schematically on Figures 27 and 28.

The dual-expander engine burns oxygen as the oxidizer and RP-1 and hydrogen as the fuels in the tripropellant Mode 1. Some of the oxygen and all of the RP-1 are pumped to high pressure and delivered to a central thrust chamber injector as liquids. These propellants are combusted and partially expanded in a conventional bell nozzle extension. The rest of the oxygen and the hydrogen are combusted in preburners. An oxidizer-rich preburner is used to provide the oxygen turbopump drive gases and a fuel-rich preburner is used to provide the RP-1 and hydrogen turbopump drive gases. The turbine exhaust gases are delivered to an annular combustion chamber. Expansion of the O_2/H_2 combustion products occurs in a forced deflection nozzle extension along with the complete expansion of the O_2/RP-1 center core combustion gases.

During Mode 2 operation, the center thrust chamber is inactive and only the O_2/H_2 combustion gases are expanded in the forced deflection nozzle. This substantially increases the Mode 2 area ratio.

The statement of work specified a baseline thrust of 88964N (20,000 lb) a thrust split of 0.5 and a Mode 1 nozzle area ratio of 200:1 for the dual-expander engine. In addition, the cooling evaluation was performed for a thrust chamber pressure range of 34 to 136 atm (500 to 2,000 psia) and thrust splits from 0.4 to 0.8.

To establish the dual-expander engine geometries, it was necessary to define the individual system area ratios and Mode 2 engine area ratio for the fixed baseline Mode 1 area ratio of 200:1. The following sketch and equations show the areas, area ratios and interrelationships.



$$\epsilon_o = \epsilon \left(\frac{A_{t_1}}{A_{t_2}} + 1\right) \qquad (1)$$

$$\epsilon_o = \frac{A_{t_1}}{A_{t_2}} \epsilon_1 + \epsilon_2 \qquad (2)$$

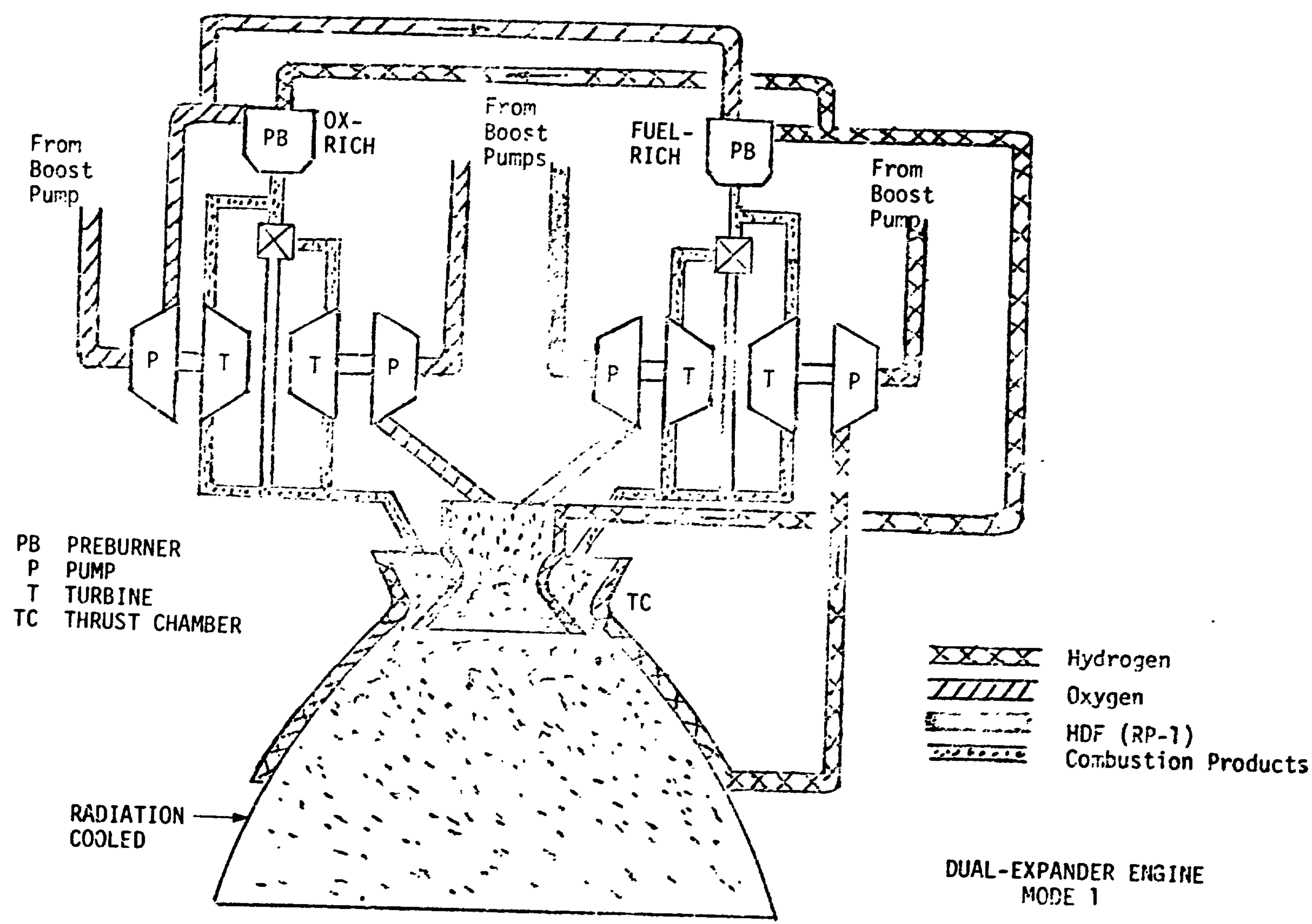


Figure 27. Preliminary Dual-Expander Engine Schematic, Mode 1

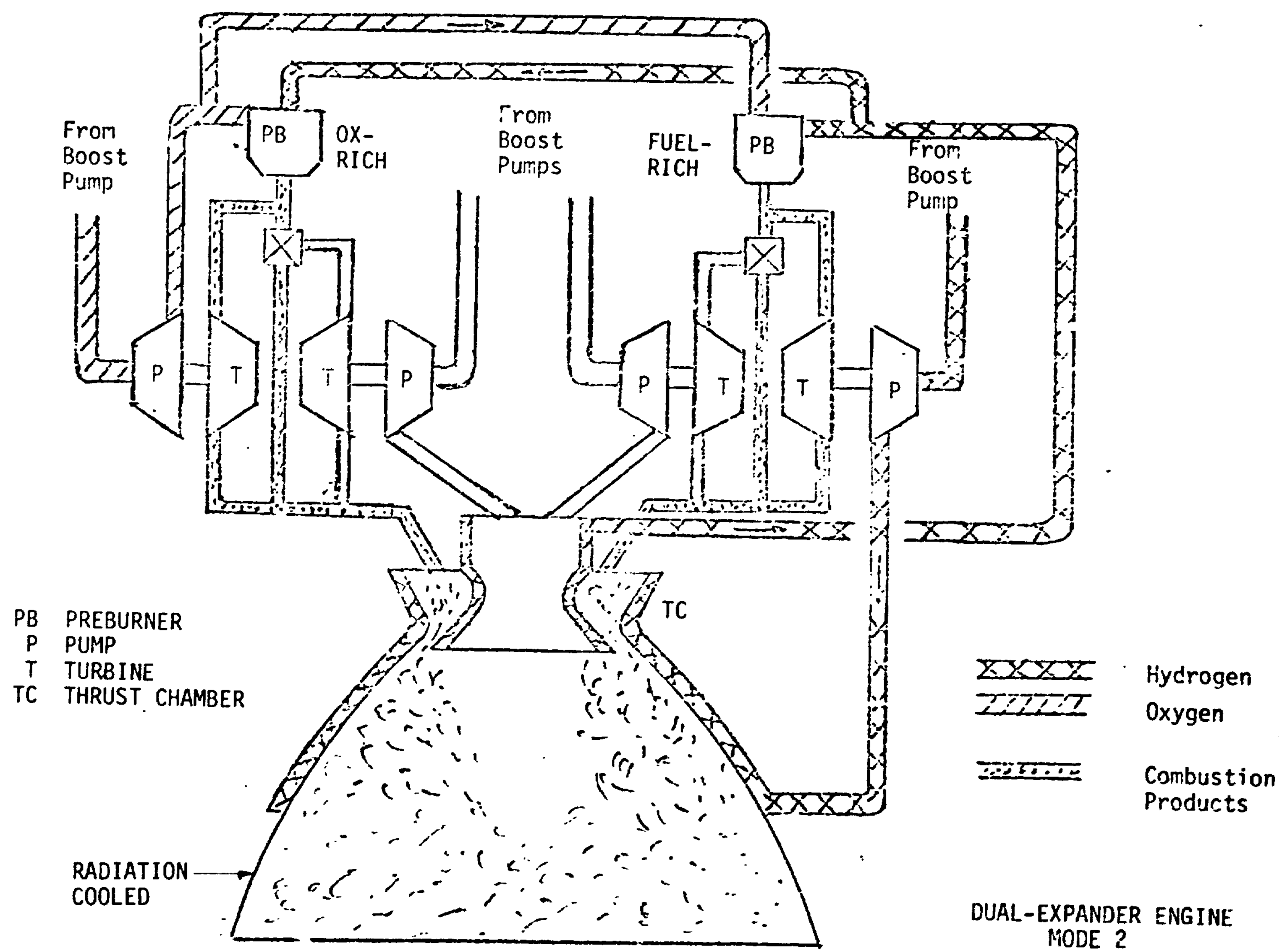


Figure 28. Preliminary Dual-Expander Engine Schematic, Mode 2 O_2/H_2

$$\varepsilon = \frac{\varepsilon_1 \dfrac{A_{t_1}}{A_{t_2}} + \varepsilon_2}{\dfrac{A_{t_1}}{A_{t_2}} + 1} \qquad (3)$$

where:

ε_0 = Mode 2 Area Ratio = A_E/A_{t2}

ε_1 = Mode 1 LOX/RP-1 Area Ratio = A_{E1}/A_{t1}

ε_2 = Mode 1 LOX/LH_2 Area Ratio = A_{E2}/A_{t2}

ε = Mode 1 Area Ratio (LOX/RP-1/LH_2) = $A_E/(A_{t1} + A_{t2})$

A_{t_1} = Throat Area LOX/RP-1 Nozzle

A_{t_2} = Throat Area LOX/LH_2 Nozzle

Equations (2) and (3) can be approximated by:

$$\varepsilon_0 \cong \left(\frac{FS}{1 - FS}\right)\left(\frac{P_{c2}}{P_{c1}}\right) \varepsilon_1 + \varepsilon_2 \qquad (4)$$

$$\varepsilon \cong \frac{\varepsilon_1 \left(\dfrac{FS}{1 - FS}\right)\left(\dfrac{P_{c2}}{P_{c1}}\right) + \varepsilon_2}{\left(\dfrac{FS}{1 - FS}\right)\left(\dfrac{P_{c2}}{P_{c1}}\right) + 1} \qquad (5)$$

where:

FS = Thrust Split

P_{c2} = LOX/LH_2 Chamber Pressure

P_{c1} = LOX/RP-1 Chamber Pressure

For a fixed Mode 1 engine area ratio, numerous values of ε_1 and ε_2 can be chosen to satisfy Equation (5). However, the nozzle exit pressures at ε_1 and ε_2 must be equal and this closes the solution providing that the ratio of the LOX/LH_2 and LOX/RP-1 system pressures are known.

Preliminary heat transfer analysis indicated that it is desirable to maintain a 0.5 ratio of the LOX/LH_2 system chamber pressure to LOX/RP-1 system chamber pressure. This is based upon maintaining approximately equivalent throat heat fluxcs in the annular and bell nozzles. This was used throughout the rest of the coolant evaluation study and more detailed thermal analyses (Section IV,E,5) verified this assumption.

Based upon the foregoing analysis, nozzle area ratios can be defined for all modes of operation as a function of thrust split. Typical results are displayed on Figure 29 for an overall Mode 1 (tripropellant operation) area ratio of 200:1.

C. THRUST CHAMBER ASSEMBLY (TCA) GEOMETRY DEFINITIONS

Thrust chamber geometry analyses were conducted to define the chamber length and contraction ratio for the tripropellant, plug cluster and dual-expander engines over the parametric design ranges. The results of these analyses are summarized on Table XIII. A brief description of the geometry analysis conducted for each engine concept follows.

1. Tripropellant Engine

The baseline tripropellant engine concept utilizes a staged combustion cycle comprised of parallel O_2/H_2 (H_2rich), O_2/H_2 (O_2rich), and O_2/RP-1 (RP-1 rich) preburners and a gas/gas injected primary thrust chamber. In Mode 1, all three preburners operate. The TCA is hydrogen cooled, and the total preburner flow rates are inlet to the injector. In Mode 2, the O_2/RP-1 (RP-1 rich) preburner is shutdown. TCA gas conditions were established to provide input conditions for a gas/gas mixing performance analysis which was used to establish chamber length requirements to meet an ERE (energy release efficiency) goal of 98%.

Injector energy release efficiency was evaluated as a function of chamber length (L'), chamber pressure (Pc), chamber contraction ratio (ε_c), and injector pressure drop using a simplified gas/gas mixing model (Ref. 12). The analysis was initiated by selecting an initial design point and evaluating injector ERE as a function of chamber length for a shear coaxial injector. The shear coaxial injector was selected on the basis of analysis and evaluations conducted for the Advanced High Pressure Engine Study (Reference 2). The chamber length study was conducted for a constant thrust per element (F/E) of 703N (158 lbf) which results in 127 elements at the baseline 88964N (20,000 lbf) thrust level. This element size was selected on the basis of Aerojet Liquid Rocket Company (ALRC) Space Snuttle Auxiliary Propulsion System (APS) and M-1 Engine design experience.

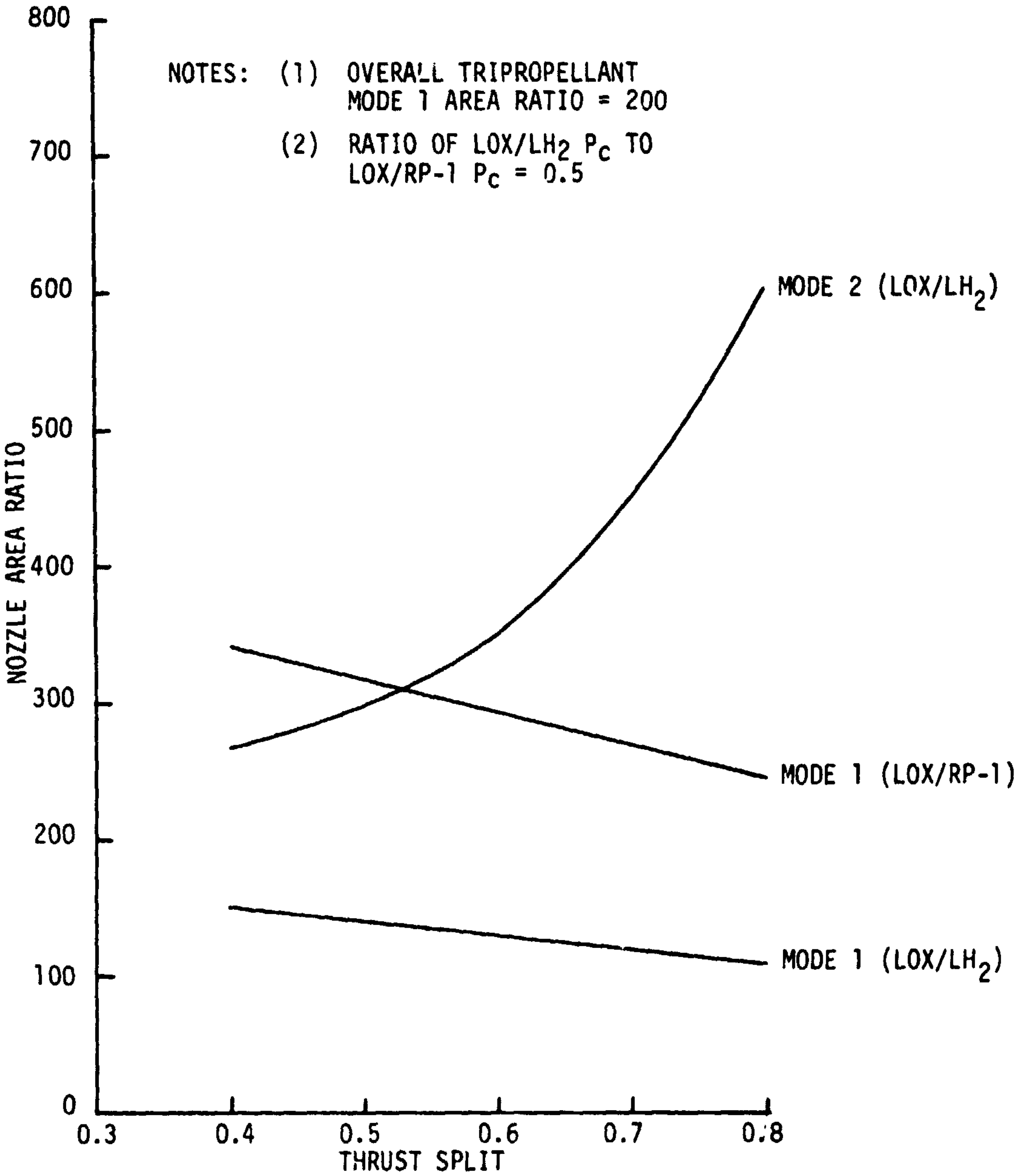


Figure 29. Dual-Expander Engine Nozzle Area Ratios

TABLE XIII. - THRUST CHAMBER GEOMETRY DEFINITION SUMMARY

Engine Concept	Engine Cycle	Propellants	Propellant Injection State	Chamber Contraction Ratio	L' cm	L' (inches)
° Tripropellant	Stg. Comb.	$O_2/RP\text{-}1/H_2$	Gas-Gas	2.0	$5.51\sqrt{68/P_c} + 15.24$	$2.17\sqrt{(1000)/P_c} + 6.0$
° Plug Cluster						
O_2/H_2 Module	Expander	O_2/H_2	Liquid-Gas	3.3	$6.35\sqrt{23.1/P_c} + 9.91$	$2.50\sqrt{(340)/P_c} + 3.9$
O_2/RP-1 Module	Gas-Gen.	O_2/RP-1	Liquid-Liquid	3.3	$6.68\sqrt{20.4/P_c} + 30.48$	$2.63\sqrt{(300)/P_c} + 12.0$
° Dual Expander						
O_2/RP-1 Center Chamber	Composite	O_2/RP-1	Liquid-Liquid	3.3	$6.68\sqrt{20.4/P_c} + 30.48$	$2.63\sqrt{(300)/P_c} + 12.0$
O_2/H_2 Annular Chamber	Stg. Comb.	O_2/H_2	Gas-Gas	3.3	$6.35\sqrt{23.1/P_c} + 9.91$	$2.50\sqrt{(340)/P_c} + 3.9$

L' = Chamber Length = Cylindrical Length + Conical Section Length

P_c = Chamber Pressure, atm (psia)

Figure 30 shows ERE versus chamber length and notes the initial analysis design conditions. Three fuel injection pressure drop values were evaluated because shear coaxial element performance is sensitive to the relative fuel to oxidizer injection velocity. Figure 30 indicates a maximum chamber length requirement of 17.8 to 22.9 cm (7-9 inches) to guarantee the 98% ERE goal. A length of 20.3 cm (8 inches) was selected for the nominal design point.

After the selection of a design chamber length of 20.3 cm (8 inches), the influences of chamber contraction ratio and chamber pressure on ERE were determined. Figure 31 presents these results. The top plot indicates that ERE increases as chamber contraction ratio (ε_c) decreases. The bottom plot shows that, for a constant thrust per element, ERE increases as chamber pressure increases. The selection of the design chamber contraction ratio was tempered with the knowledge that the Rayleigh line combustion pressure loss increases with decreasing contraction ratio, as shown on Figure 32. A design contraction ratio value of 2.0:1 was selected to minimize the combustion pressure loss and chamber weight and to attain near maximum performance.

TCA throat area requirements were evaluated for thrust splits from 0.2 to 0.8 and for a chamber pressure range from 34 to 136 atm (500 to 2000 psia). Thrust split does not significantly influence the required chamber throat area. Using a radius equal to one throat radius, R_T, to blend in the chamber cylindrical and convergent sections and the convergent section to the throat, the following formula was developed to account for chamber length variations with chamber pressure:

$$L' = 3.18\, R_T + 15.24; \text{ for chamber length in cm.} \qquad (6)$$

$$L' = 1.253\, R_T + 6.0; \text{ for chamber length in inches.} \qquad (6a)$$

The equations result in a chamber length requirement of about 20.8 cm (8.2 in.) at a nominal chamber pressure of 68 atm (1000 psia). Scaling to any chamber pressure results in:

$$L' = 5.51 \sqrt{68/P_c} + 15.24; \text{ for chamber length in cm and } P_c \text{ in atm} \qquad (7)$$

$$L' = 2.17 \sqrt{(1000)/P_c} + 6.0; \text{ for chamber length in inches and } P_c \text{ in psia} \qquad (7a)$$

2. Plug Cluster Engine

The baseline plug cluster engine is composed of five O_2/H_2 and five O_2/RP-1 modules alternately mounted on a plug. The thrust per module

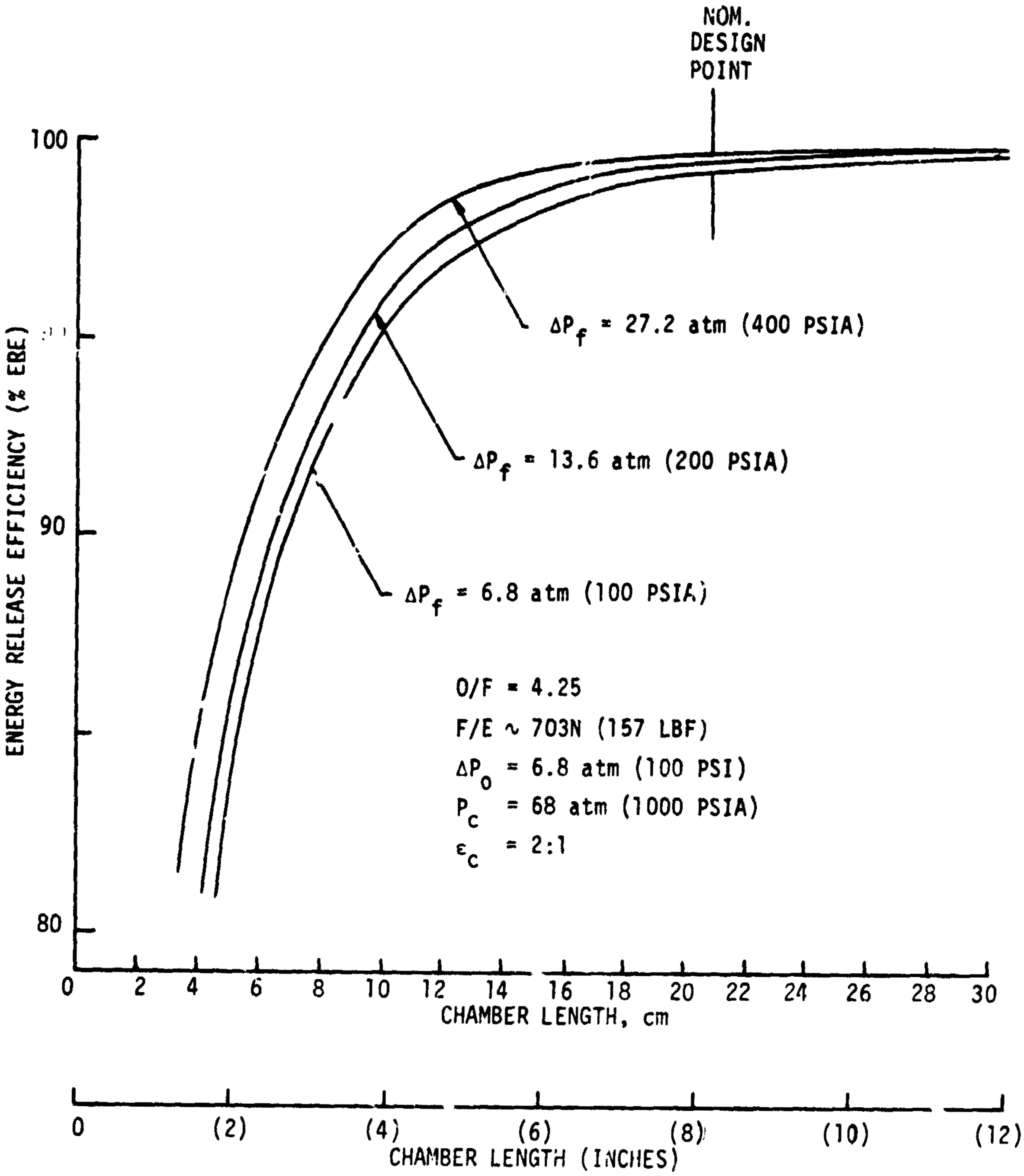


Figure 30. LO_2/RP-1/H_2 Tripropellant Engine Shear Coaxial Element Performance

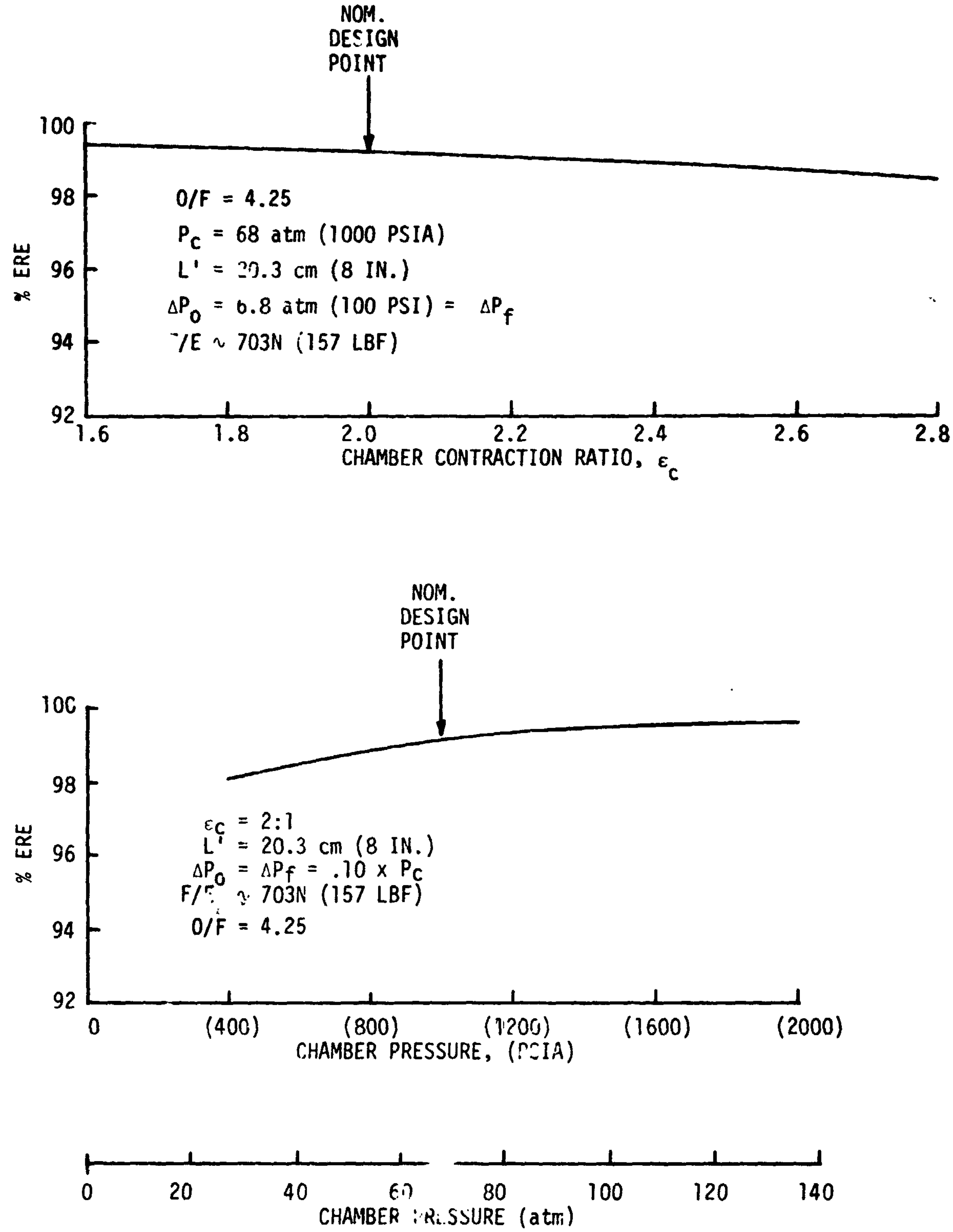


Figure 31. LO_2/RP-1/H_2 Tripropellant Engine Shear Coaxial Element Performance Versus Contraction Ratio and Chamber Pressure

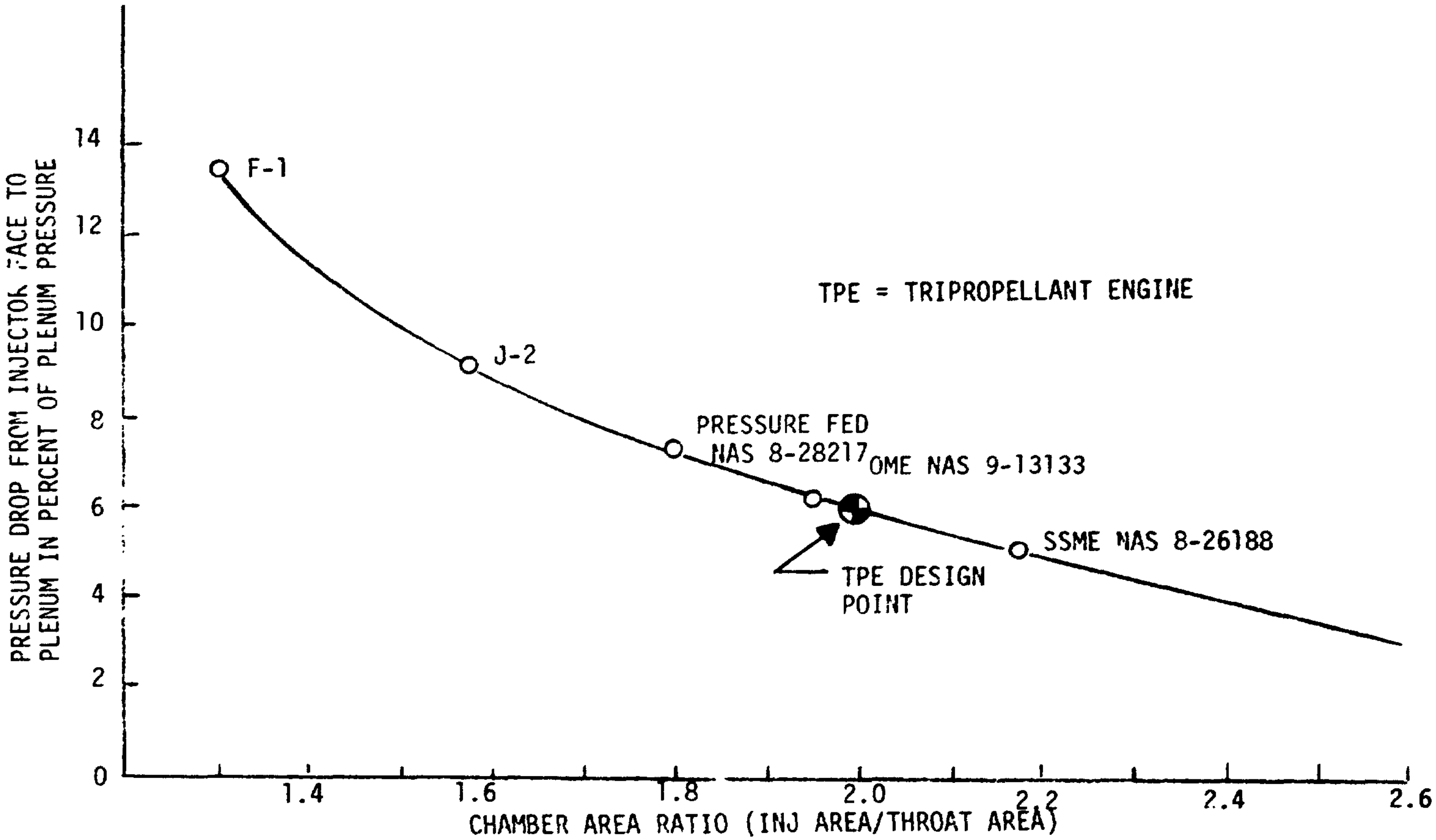


Figure 32 Chamber Pressure Drop Due to Combustion

is 8896N (2000 lbf) and thrust split is 0.5. The O_2/H_2 baseline module is the ALRC Integrated Thruster Assembly (ITA) engine, as defined by the Unconventional Nozzle Trade-Off Study (Ref. 3). The ITA, modified to an all regeneratively cooled configuration with a 40:1 nozzle expansion ratio, will deliver 8896N (2000 lbf) thrust at a chamber pressure of 23.1 atm (340 psia). The following formula scales the O_2/H_2 thrust chamber radius for the study chamber pressure range of 20.4 to 68 atm (300 to 1000 psia):

$$R_T = \sqrt{23.1/P_c} \times 2.44; \text{ for throat radius in cm and } P_c \text{ in atm.} \quad (8)$$

$$R_T = \sqrt{(340)/P_c} \times 0.96; \text{ for throat radius in inches and } P_c \text{ in psia.} \quad (8a)$$

The nominal ITA chamber length is 16.26 cm (6.4 inches) and the design contraction ratio is 3.3:1. The following formula was derived to calculate chamber length for the study operating chamber pressure range:

$$L' = 6.35 \sqrt{23.1/P_c} + 9.91; \text{ for chamber length in cm and } P_c \text{ in atm} \quad (9)$$

$$L' = 2.50 \sqrt{(340)/P_c} + 3.9; \text{ for chamber length in inches and } P_c \text{ in psia} \quad (9a)$$

A vaporization limited performance calculation was conducted to estimate the chamber length requirement for the O_2/RP-1 module. The calculation indicated a 35.6 to 38.1 cm (14-15 inch) L' would result in attainment of the program 98% ERE goal at an operating chamber pressure of 20.4 atm (300 psia). This calculation agrees with the baseline 35.6 cm (14 inch) chamber length selected for the High Density Fuel Combustion and Cooling Investigation, Contract NAS 3-21030. A contraction ratio of 3.3:1 was also baselined for the O_2/RP-1 module. The following formula scales the chamber length for the study:

$$L' = 6.68 \sqrt{20.4/P_c} + 30.48; \text{ for chamber length in cm and } P_c \text{ in atm.} \quad (10)$$

$$L' = 2.63 \sqrt{(300)/P_c} + 12.0; \text{ for chamber length in inches and } P_c \text{ in psia} \quad (10a)$$

3. Dual-Expander Engine

The central chamber for this concept uses liquid/liquid propellant injection. This injection scheme is similar to that employed on the O_2/RP-1 module of the plug cluster. Therefore, the chamber length for the

O_2/RP-1 engine of the dual-expander concept is specified with the formula previously developed for the plug cluster engine (equations 10 and 10a). The O_2/RP-1 chamber contraction ratio was selected to be 3.3:1 which is also identical to the plug cluster module value.

The gas/gas O_2/H_2 injection for this concept is similar to that employed on the O_2/H_2 module of the plug cluster engine. Therefore, the plug cluster chamber length formula was utilized for the dual-expander annular combustor (equations 9 and 9a).

A contraction ratio of 3.3:1 was also selected for this combustion chamber.

Further design guidelines were established for the chamber and nozzle contours. These guidelines were the result of ALRC in-house studies and are as follows:

a. O_2/RP-1 nozzle contour truncated at an area ratio of 8.8:1

x/Rt	0.000	0.324	0.791	1.401	2.685
r/Rt	1.000	1.119	1.513	2.015	2.962

b. Annular inner wall expansion half angle 31 degrees; outer wall expansion half angle 38.5 degrees.

c. Minimum wall thickness separating combustors of 1.02 cm (0.4 inches).

d. Outer wall contour (O_2/H_2) is parabolic. The attach angle at O_2/RP-1 nozzle truncation plane is 38.5 degrees. The nozzle exit half angle is 11 degrees.

Typical dual-expander combustion chamber and nozzle geometries are shown in Figures 33 and 34, respectively.

D. STRUCTURAL ANALYSIS

Structural analyses were undertaken to determine the design constraints imposed by low cycle thermal fatigue and creep-rupture strength. These analyses were conducted in conjunction with the coolant heat transfer evaluation to establish the chamber temperature, pressure and coolant channel geometry limits created by the chamber service life requirements. For this analysis the service life between overhauls is 300 cycles times a safety factor of 4 (1200 total cycles) or 10 hours accumulated run time.

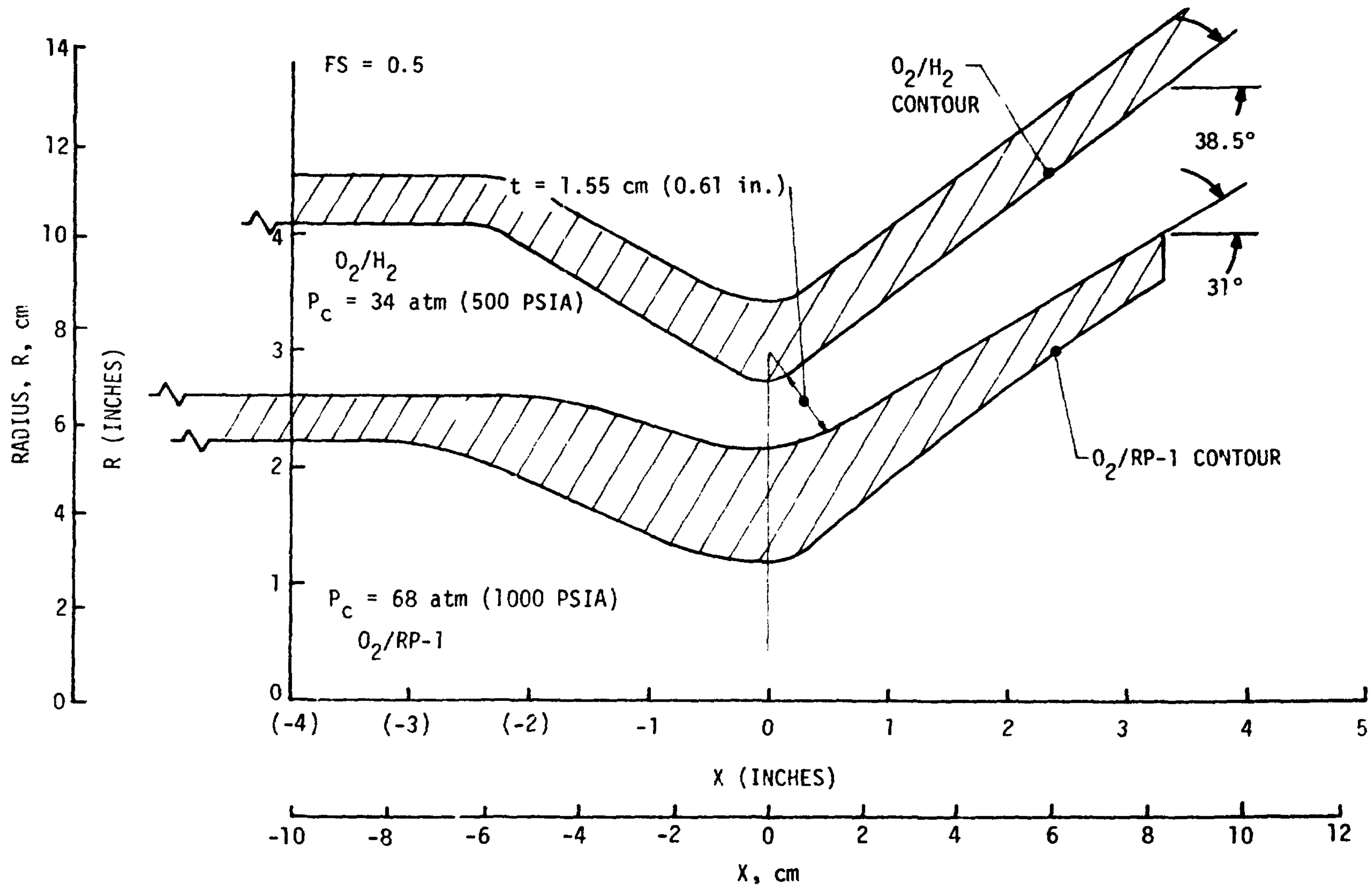


Figure 33. Dual-Expander Combustion Chamber Geometry

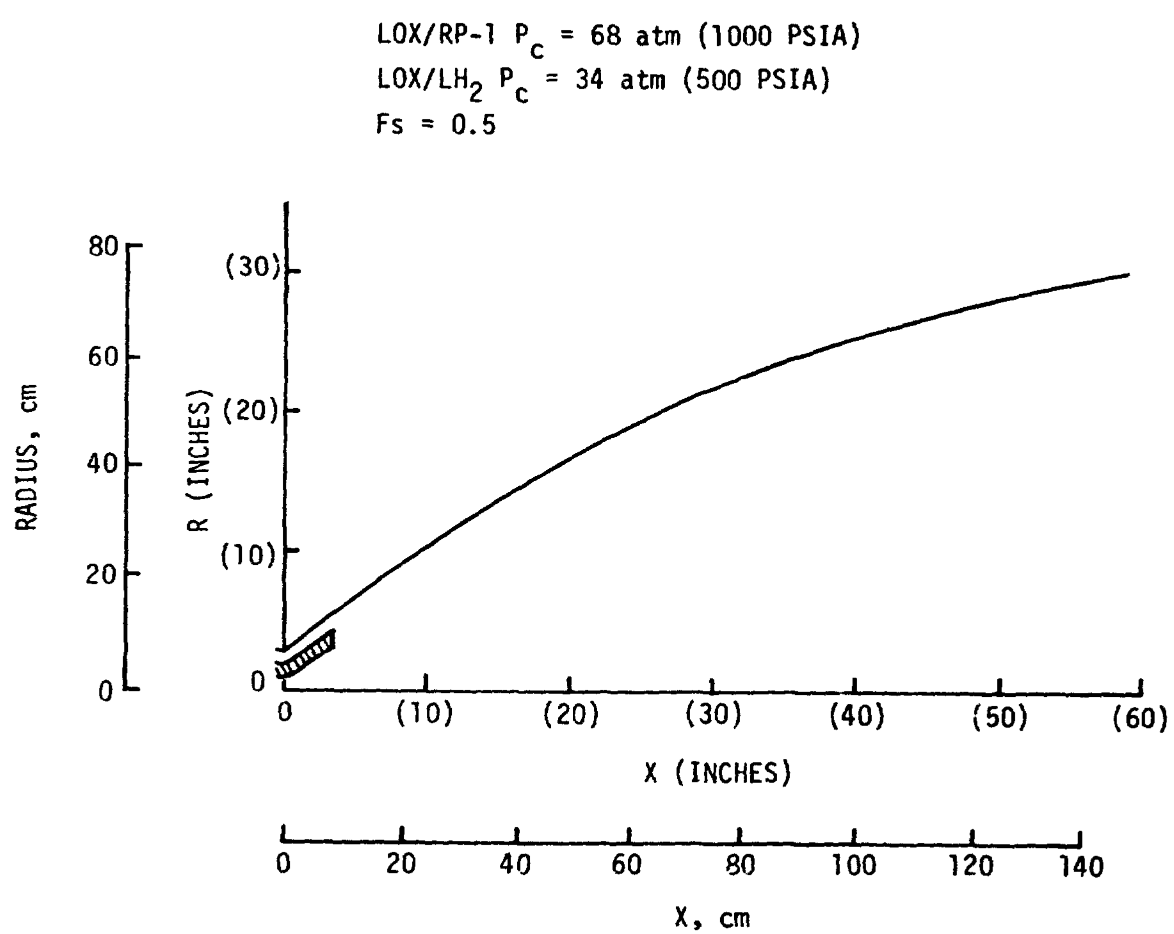


Figure 34. Dual-Expander Nozzle Geometry

The parametric structural analyses of all three MMOTV engine concepts were conducted over the study chamber pressure and thrust split ranges at a baseline thrust level of 88964N (20,000 lb).

The material used for the combustion chamber (non-tubular portion) is zirconium copper with material properties assumed to conform to those shown on Figures 18 through 21. The low cycle fatigue data for zirconium copper was assumed to have compressive hold time effects included, so no creep damage fraction was used in the low-cycle fatigue analyses. The outer shell of the tripropellant and plug cluster engine chambers is electroformed nickel with adequate thickness to remain elastic under the outward pressure and copper expansion forces. Total strain ranges in the copper liner could be reduced and fatigue life increased by further optimization of the shell thickness but this was beyond the scope of these parametric studies. The central chamber of the dual-expander engine has mill-slotted copper channels on both sides of an inner nickel structure shell. The outer annular chamber for the dual-expander engine is also of zirconium copper construction with an electroformed nickel shell whose thickness was not optimized.

The low cycle fatigue life is dependent upon the total strain range induced on the hot gas-side wall of the regen-cooled thrust chamber. The large number of chamber configurations and thermal loadings in the parametric studies precluded the use of finite element computer analysis at each design point. A simplified strain prediction method was developed, based upon a strain concentration factor (K_ε), thermal expansion coefficient (α), and the temperature differential between gas and backside temperatures (ΔT).

$$\varepsilon = K_\varepsilon \, \alpha \, \Delta T \tag{11}$$

The value of K_ε for a biaxially constrained "hot spot" in the plastic range is 2.0 (Reference 13). Finite element model computer solutions for selected MMOTV configurations and previous studies (Ref. 2) are plotted on Figure 35 and verify this factor. Lower gas-side wall temperatures exhibit lower K_ε values due to reduced plasticity and relief from outward deflection of the outer chamber shell. Higher gas-side temperatures exhibit higher K_ε values due to less outward deflection of the shell when the copper softens, and from uneven strain distributions when the copper liner moves further into the plastic range and pressure-induced strains become significant.

The design curve of Figure 35 was used to determine K_ε and Equation (11) was used to predict total strain ranges for the MMOTV regen-chambers. This strain range was then compared to copper low cycle fatigue allowables of Figure 20 to ensure a 1200-cycle life (maximum strain range of 2.15%).

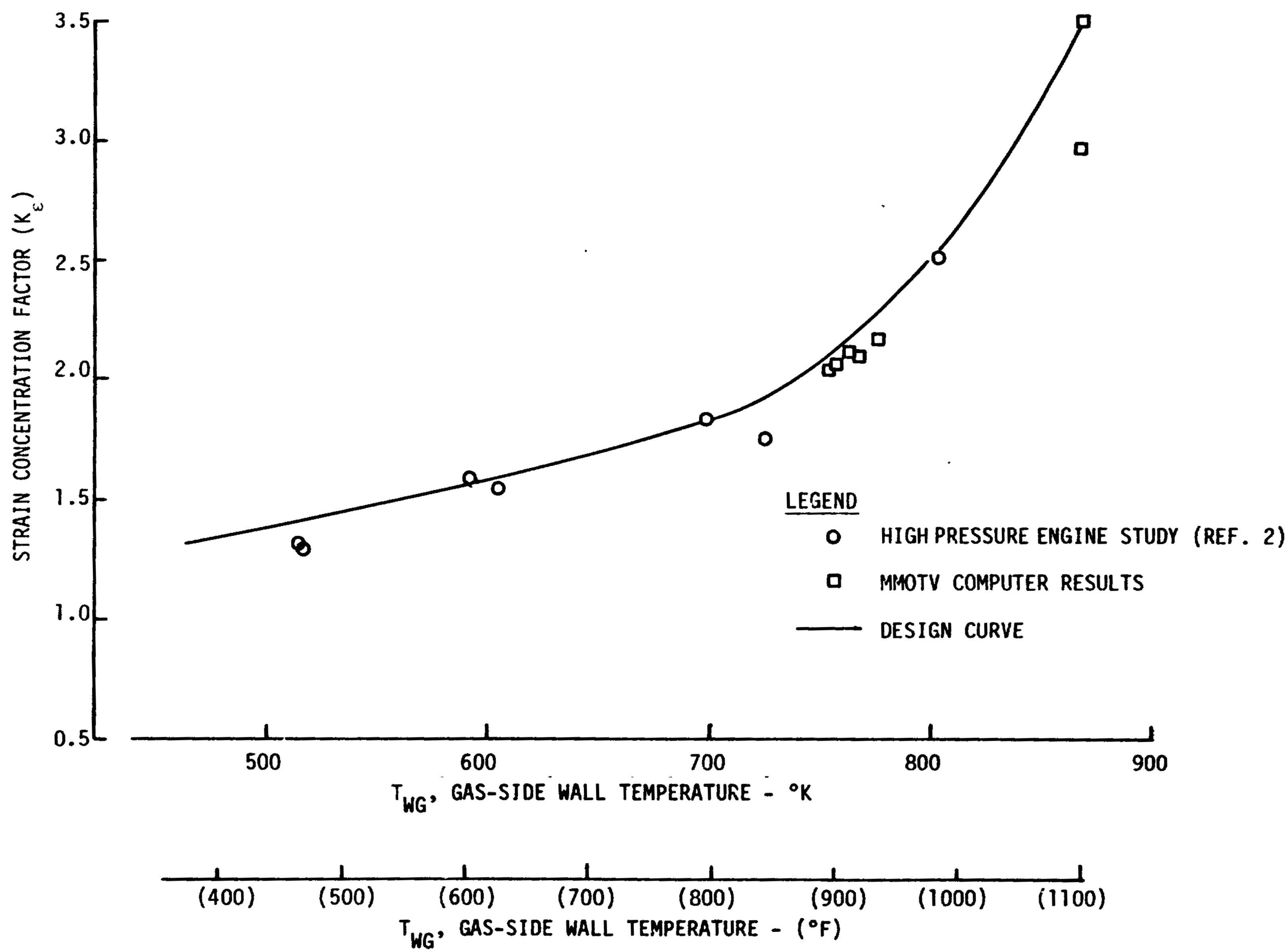


Figure 35. Copper Channel Strain Concentration Factor

Thermal stresses are self-equilibrating and do not significantly affect strength margins of safety. Mechanical (pressure) loads must be carried by the channels for the full engine duration, however. The mechanical stresses were predicted by a three-hinge point method and compared to yield strength below the creep regime. A fully plastic limit analysis was used in the creep regime, and the stresses compared to the lower 10-hour creep rupture strength. The most critical channel location for mechanical stresses is near the coolant inlet where nearly full coolant pressure acts on high aspect ratio channels at maximum temperatures. Since low aspect ratios at that location would require a large number of coolant channels and the 10-hour strength at 867°K (1100°F) is estimated to be very low, the gas-side temperatures were limited to 811°K (1000°F).

The results of the analyses show that the low-cycle fatigue life requirement limits the maximum temperature differential between the gas-side surface and the surrounding cooler structure. This (ΔT) value for the regeneratively-cooled thrust chambers is shown in Figure 36. Maximum ΔT is limited by fatigue life for outer jacket surface temperatures below 394°K (250°F) and by engine duration for outside temperatures above 394°K (250°F).

The gas-side temperature is limited to 811°K (1000°F) as a result of low 10-hour creep-rupture life for copper. Higher temperatures would require the use of many very narrow coolant channels, which is felt to be impractical. Enhanced creep damage effects on the low-cycle fatigue life are also likely.

Coolant channel geometry is limited by copper yield strength at low temperatures and creep-rupture life at elevated temperatures. The channel width/thickness (aspect ratio) is limited by yield strength at gas-side wall temperatures up to 700°K (800°F) and by creep-rupture 10-hour life at higher temperatures in the creep regime as shown on Figure 37.

E. THERMAL ANALYSES

Cooling analyses were conducted at a Mode 1 thrust level of 88964N (20,000 lb). Parametric studies over a chamber pressure range from 6.8 to 136 atm (100 psia to 2000 psia) and over a thrust split range from 0.40 to 0.80 were covered in different portions of the study. The chamber pressure ranges, and thrust split ranges considered for Mode 1 and Mode 2 operation of each of the engine systems is summarized below:

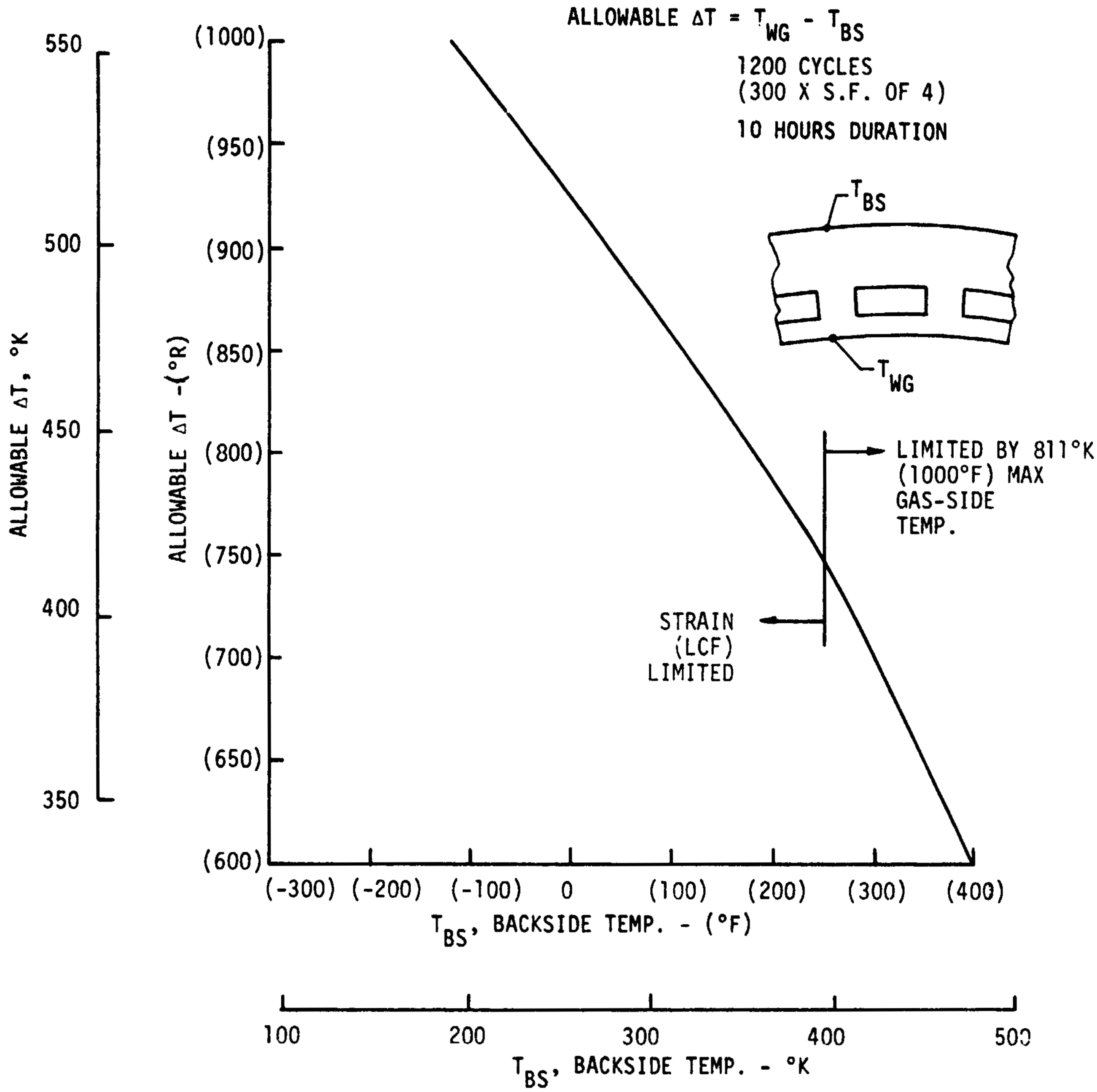


Figure 36. Allowable Temperature Differentials for MMOTV Regen Chambers

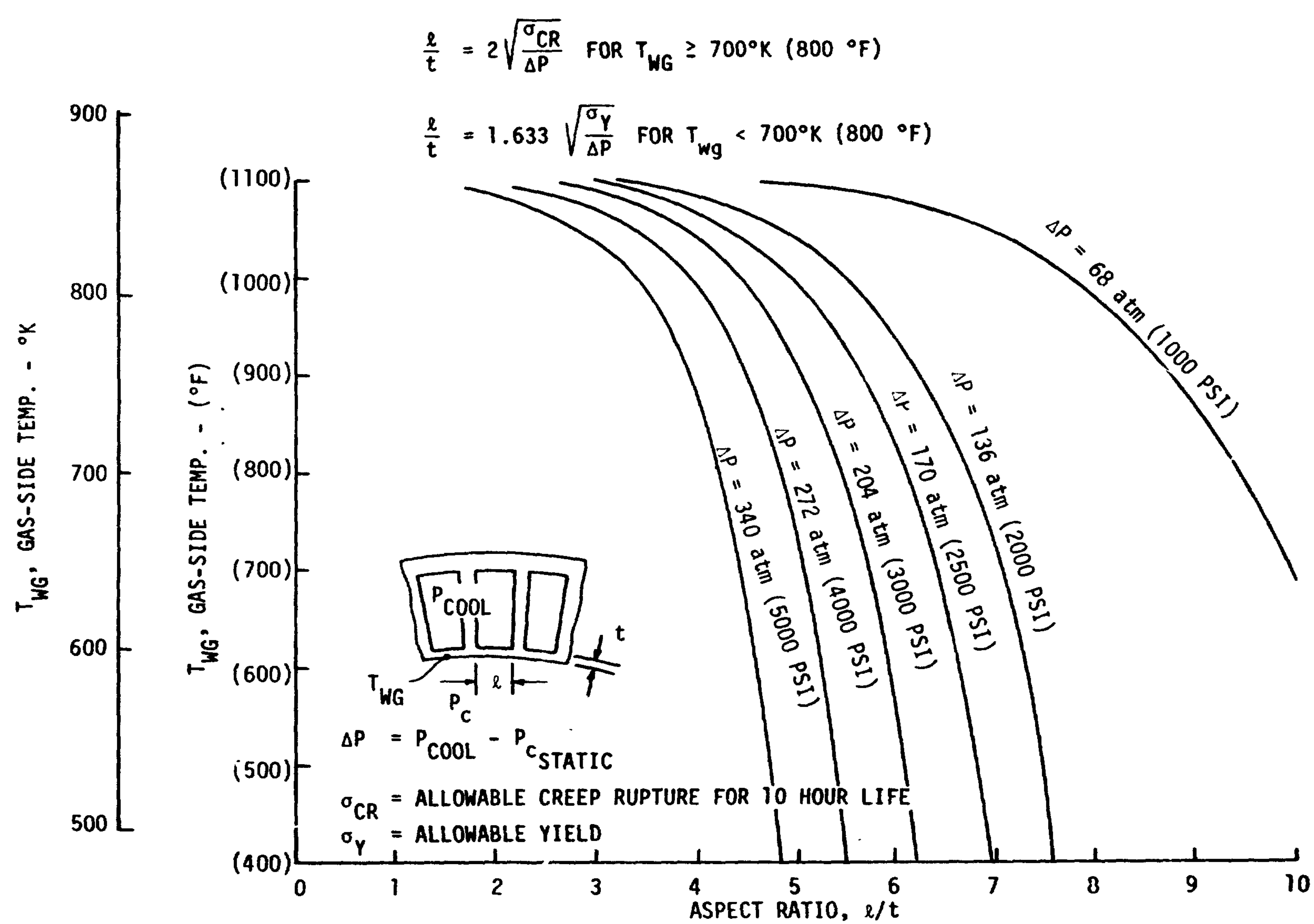


Figure 37. Allowable Channel Aspect Ratios for MMOTV Regen Chambers

Engine Type	Mode 1 Pc Range	Mode 2 Pc Range	Mode 1 Thrust Split Range
Tripropellant	34-136 atm (500-2000 psia)	6.8-81.6 atm (100-1200 psia)	.4-.8
Plug Cluster	20.4-68 atm (300-1000 psia)	20.4-68 atm (300-1000 psia)	.5
Dual Expander	34 to 136 atm (500-2000 psia)	17-68 atm (250-1000 psia)	.4-.8

The relative feasibility of the different engine systems was assessed based on the attainable chamber pressure, as determined by the respective pressure drop requirements.

Rectangular channel construction was used for all the engine chamber designs. A gas side wall thickness of .635 mm (0.025 in.), the minimum allowed by the study criteria (Table XII), was used wherever possible. Larger wall thicknesses were dictated in some of the designs because of structural requirements. The maximum gas-side wall temperatures were limited to 811°K (1000°F) because of the 10 hour life requirement. The gas-side wall thickness and wall temperature limitations used in this study were presented in section IV,D.

All designs are based on straddle-mill machining with a constant land width of 1.02 mm (0.040 in.). Based on channel optimization studies for hydrogen cooling, the 4:1 channel depth/width limit of Table XII was used in the throat region. Applying this 4:1 depth/width limit at the throat resulted in the selection of the number of coolant channels for most of the designs. The channel width was not allowed to go below 1.02 mm (0.040 inches), however, and in some designs this limit was used to set the number of channels.

1. Methods of Analysis

A two dimensional nozzle expansion performance analysis for a chamber pressure of 68 atm (1000 psia), 50/50 thrust split, ε_{exit} = 400:1 and the previously referenced TRAN 72 computer runs were used to determine gas-side wall boundary layer properties needed in the analyses of the tripropellant engines. Two dimensional nozzle expansion performance and TRAN 72 programs were also used for analyses of the LOX/LH_2 and LOX/RP-1 modules of the plug cluster engine systems. One dimensional wall boundary layer properties were used for the plug sidewall analyses, and Cornell data (Reference 14) were used for the plug base heat load approximation. One dimensional properties were also employed in the dual-expander engine systems analyses.

Heat transfer from the combustion products to the chamber wall was calculated by the following non-reactive formulation:

$$\emptyset = 0.026 \; Cg \; \rho_f \; u_e \; Re_f^{-0.2} \; Pr_f^{-0.6} \; C_{p_f} \; (Taw - Twg)$$

in which subscript f refers to the film temperature T_f, defined as T_f = 0.5 (Taw + Twg) with $\rho_f = \rho_e \; T_e/T_f$ and $Re_f = \rho_f \; u_e \; D/\mu_f$. The coefficient C_g accounts for flow acceleration effects and is shown in Figure 38 as a function of area ratio.

The symbols used in this section are defined on Table XIV.

The design data were generated with a regenerative-cooling program similar to the HOCOOL program (Ref. 15) constructed for NASA/Lewis under Contract NAS 3-17813. The option designated WALL = 5 was used with some added modifications to simulate two-dimensional conduction effects and the spatial variation of the coolant heat transfer coefficient. This option, shown schematically on Figure 39 represents the hot wall, the land and that part of the external wall adjacent to the channel as fins. That part of the external wall adjacent to the land is assumed to be isothermal. The modified wall = 5 model establishes three correlation coefficients which are applied to the hot wall, the land, and the back wall separately. The film coefficient for the hot wall is the product of an input factor (HFAC) and the correlation coefficient evaluated at a temperature which is the average of the wall temperature at the center of the channel (TWL 2) and the wall temperature at the corner of the channel (TCORN). The film coefficient for the back wall is evaluated at the back side wall temperature at the center of the channel (TBS). The film coefficient which is applied to the land surface is the product of an input factor (GFAC) times the back wall coefficient plus 1-GFAC times the hot wall coefficient. The selection of the HFAC and GFAC parameters provides a means of simulating the actual coolant coefficient variation.

A limited number of two dimensional node network analyses using SINDA (Ref. 16) were performed at the maximum heat flux location near the throat. These studies accomplished the following:

a. Provided the basis for determining the Wall = 5 simulation parameters for hydrogen cooling.

b. Established the optimum channel geometry for a fixed coolant flow area with hydrogen cooling.

A channel optimization study was conducted to define the channel geometry which minimizes the local gas-side wall temperature for a fixed

GAS-SIDE HEAT TRANSFER CORRELATION COEFFICIENT

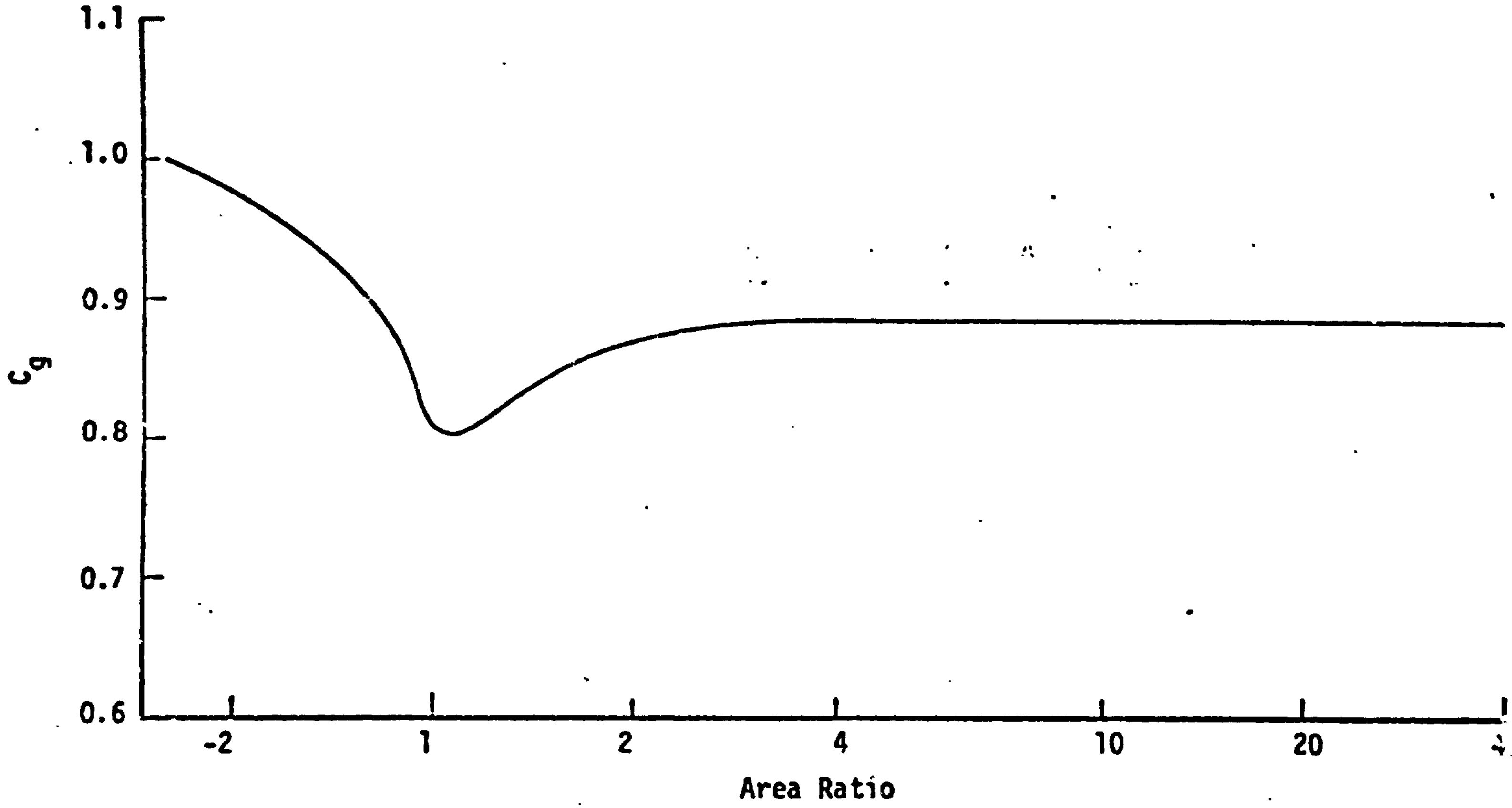


Figure 38. Gas-Side Heat Transfer Correlation Coefficient

TABLE XIV. - THERMAL ANALYSIS NOMENCLATURE

English Letters

C_g	Gas-side heat transfer correlation coefficient
c_p	Specific heat; $\overline{C}_p$ is an integrated average between the coolant bulk temperature and the wall temperature
D	Local chamber diameter
g_h	Factor applied to the coolant heat transfer coefficient evaluated at the centerline wall temperature to obtain the average coefficient for the gas-side wall
k	Thermal conductivity
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
T	Temperature
u	Axial velocity

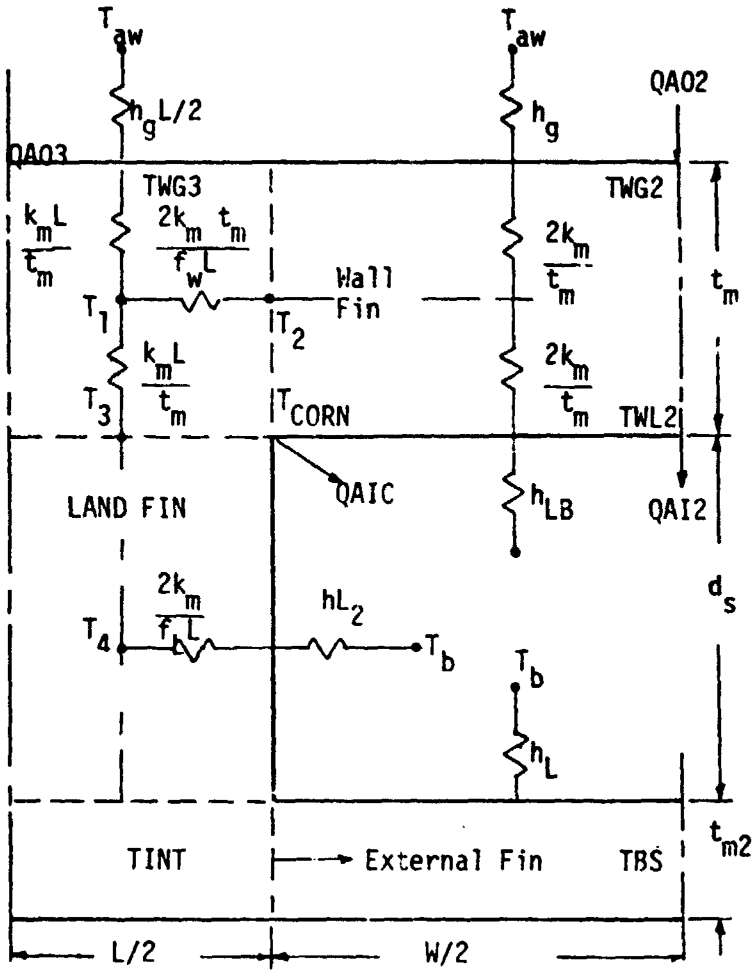
Greek Letters

μ	Viscosity
ρ	density
ϕ	Gas-side heat flux

Subscripts

aw	Adiabatic wall
b	Coolant bulk or mixed mean temperature
e	Freestream
f	Film temperature, 0.5 $(T_{aw} + T_{wg})$
w	Coolant-side wall surface
wg	Gas-side wall surface

SCHEMATIC OF MODIFIED WALL = 5 MODEL



wher $h_{LB} = f \left[HFAC \left(\frac{TWL2 + TCORN}{2} \right) \right]$

$h_L = f\,[TBS]$

$h_{L_2} = f\,[GFAC\ h_L + (1-GFAC)h_{LB}]$

Figure 39. Schematic of Modified Wall = 5 Model

pressure gradient. This study assumed a local throat static pressure of 102 atm (1500 psia), and a bulk temperature of 111°K (200°R). The heat transfer coefficient for hydrogen is greater at lower wall temperatures, due primarily to the film property effects in the Hess and Kunz correlation (Reference 17). The land is therefore a very effective fin and the maximum wall temperatures occur at the center of the channel. Figure 40 presents the results of the channel optimization study. Channel depth is plotted against channel width with lines of varying land width superimposed. Two dimensional SINDA network analyses with a hot wall thickness of .635 mm (0.025 in.) were used, and the resulting maximum wall temperatures are displayed on the figure. The figure also indicates that channel width affects the maximum wall temperature much more than channel depth does. Minimizing the land width for a given channel width reduces the maximum wall temperatures primarily because of the channel depth reduction allowed for a fixed pressure gradient. Therefore, the optimum channel configuration has the channel width and land width minimized. The channel depth is the design variable used to adjust local coolant velocities. Use of a 1.02 mm (0.040 in.) land in the present designs instead of the .762 mm (0.030 in.) minimum allowed by the study criteria results in approximately a 11°K (20°R) higher maximum wall temperature.

Simulation parameters HFAC and GFAC used in the Wall = 5 model were also based on two dimensional SINDA network analyses. The coolant bulk temperature used to generate the parameters was slightly higher, but the same general techniques were used. The maximum temperatures produced by the computer program used for this analysis matched the SINDA results when the HFAC parameter was set at 1.0, and the GFAC parameter was 0.5.

Curvature enhancement of the coolant film coefficient was included in the tripropellant and plug cluster engine systems analyses. The dual-expander system analyses did not include the enhancement effects. The enhancement of the local heat transfer coefficient due to chamber curvature was applied in the same manner as described in Reference 18 for friction coefficients.

The enhancement for the portion of the throat region where the bulk momentum is being forced against the coolant side wall nearest the hot gas side is expressed as $[Re_b\ (r/R)^2]^{0.05}$ where Re_b is the Reynolds number based upon the bulk properties, r is the inside radius of the local passage, and R is the local radius of curvature of the passage. Conversely, the portion of the throat region where the bulk momentum is forcing the coolant away from the hot gas side is expressed as the following multiplier $[Re_b\ (r/R)^2]^{-0.05}$. For the purposes of this analysis, only the heat transfer coefficient of the gas side liquid wall was corrected. The other walls of the passage were exempted from curvature effects and treated separately.

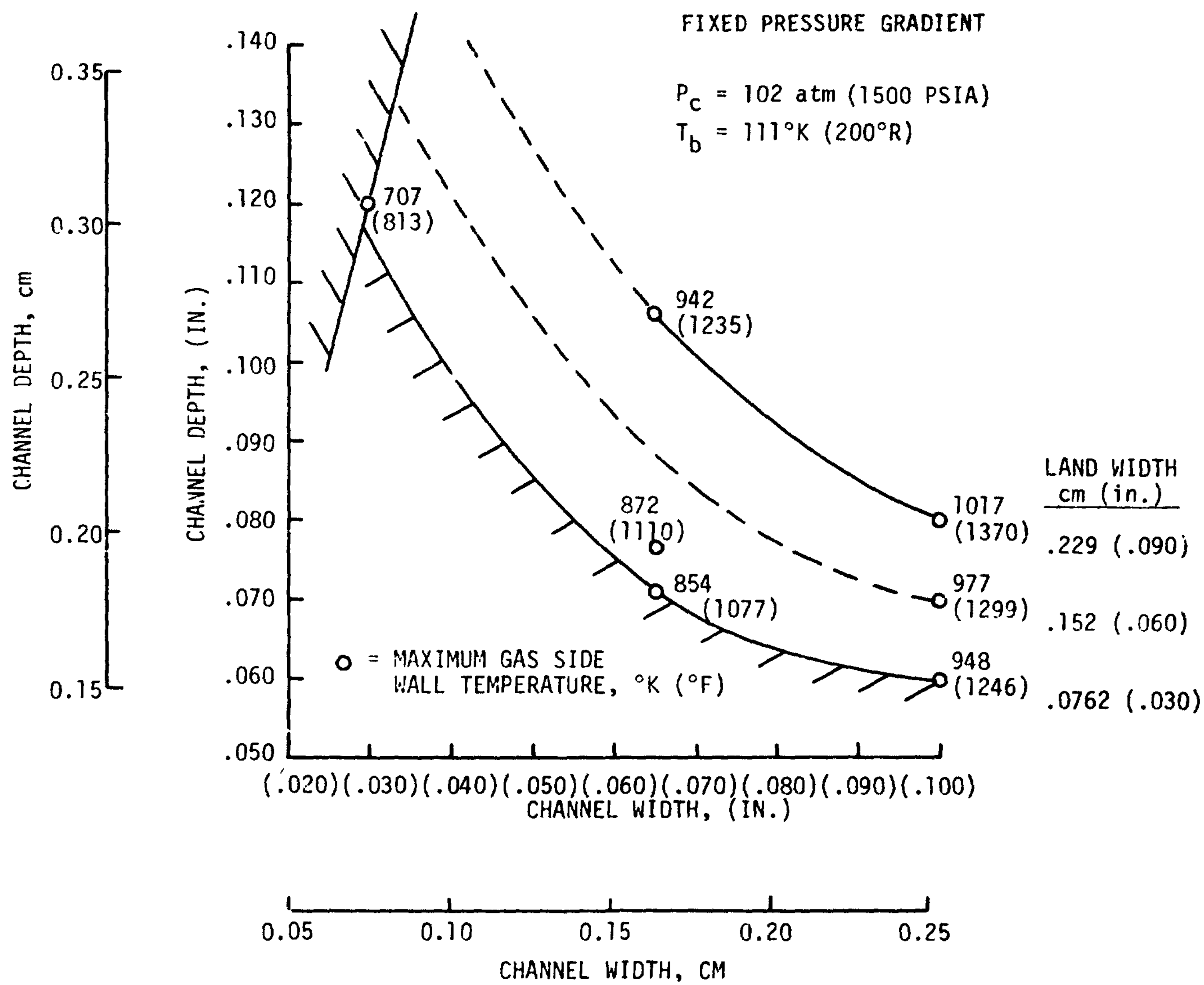


Figure 40. Channel Design Optimization Study at Throat for Hydrogen Cooling

2. Chamber Wall Construction

Zirconium-copper was specified as the gas-side wall material for all the chambers of the engine systems analyzed. The analyses assumed a Nickel closeout of .254 cm (0.10) inches in all the designs. A single design scheme was selected for all the chambers based on the imposed channel design constraints, the hydrogen cooling optimization study and fabricability. Straddle-mill machining, which yields a constant land width was selected as the primary fabrication method. To simplify the analyses no bifurcation of the coolant channels was assumed in the nozzle regions of the chamber.

A constant land width of .102 cm (.040 in.) was selected based upon the hydrogen cooling optimization study conducted, and OMS engine design practice. While the optimization study indicated a slight advantage in using the minimum allowable land width of .0762 cm (C.030 in.), the OMS channel designs limit the minimum land thickness to approximate .102 cm (0.040 inches) to insure adequate bond area on the land for the Nickel closeout process.

The minimum allowable gas-side wall thickness of .0635 cm (0.025 in.) was used in the designs whenever possible. However, the large channel widths encountered in the nozzle regions of some of the chamber designs dictated wall thicknesses as large as .305 cm (0.120 in.) based on the structural requirements shown on Figure 37. These thicker gas-side wall dimensions do not cause excessive pressure drop requirements because they only occur in the low heat flux regions of the chambers.

Other channel geometry parameters which were determined for each design were the number of channels and the channel depth axial profile. With the land width fixed and the channel depth limited to four times the channel width, the maximum local coolant flow area was set by the number of channels. Channel optimization studies with hydrogen cooling indicated that it was desirable to design at the channel depth/width limit of four. However, this could be accomplished at only one axial position in most cases. At other locations, it was necessary to satisfy the thermal design criteria with lower depth/width ratios or to overcool, i.e., not reach the applicable wall temperature limits. In order to avoid overcooling in high flux regions, the number of channels in each design was set by satisfying the design criteria at the throat with a channel depth/width ratio as close to four to one as possible.

The minimum channel width was limited to .102 cm (0.040 in.) in the study for practical fabrication reasons. This resulted in a few chamber designs whereby the depth to width ratio at the throat fell below four to one.

3. Tripropellant Engine Cooling Evaluation

Tripropellant engine designs combined three different methods of thrust chamber assembly fabrication. Mill-slotted zirconium copper channel construction was employed to cool the chamber from an exit area ratio of 8:1 to the injector. A tube bundle constructed of A-286 was then used from the 8:1 area ratio to the applicable radiation cooled nozzle transition area ratio.

The tripropellant engine cooling schematic is shown on Figure 41. This scheme was used to evaluate the coolant pressure drop requirements over the entire range of chamber pressures 34 to 136 atm (500 to 2000 psia), and thrust splits, 0.4 to 0.8. The coolant enters at an area ratio of 8:1 and flows counter to the gases through the mill-slotted zirconium copper chamber. The total hydrogen flow exits at the injector, is brought back externally to the tube bundle inlet manifold, and is then used to cool the two pass A-286 tube bundle nozzle from 8:1 to the radiation cooled nozzle transition point. The tube bundle nozzle was used to conserve weight. An inlet area ratio of 8:1 was established at a thrust chamber pressure of 136 atm (2000 psia) and a thrust split of 0.5. The tube bundle transition area ratio could be varied with thrust split and chamber pressure. However, the tube bundle pressure drop was very small (about 1% of the total) and hence, the affect of the entry area ratio upon pressure drop is small. Therefore, to simplify the geometric scaling, the coolant inlet was fixed at an area ratio of 8:1 throughout the study.

Radiation cooled nozzle transition area ratios are presented in Figure 42. The attach point area ratios vary as functions of chamber pressure and thrust split. FS-85 columbium with an R512-E silicide coating was selected as the nozzle material. Based on OMS engine design experience, a gas-side wall temperature maximum of 1617°K (2450°F) was used for the analyses.

A single tube bundle design was investigated and then analytical scaling techniques were used to estimate the pressure drops for the other chamber pressures and thrust splits. Tube bundle pressure drops are generally small when compared to the chamber pressure drops. Only the high thrust split cases at high chamber pressure result in tube bundle pressure drops greater than .54 atm (8 psia). Table XV presents the tube bundle pressure drops for the tripropellant engines.

Table XVI and Figures 43 and 44 present the results of the zirconium-copper chamber analyses. Table XVI presents pertinent design parameters as a function of the Mode 1 chamber pressure and thrust split

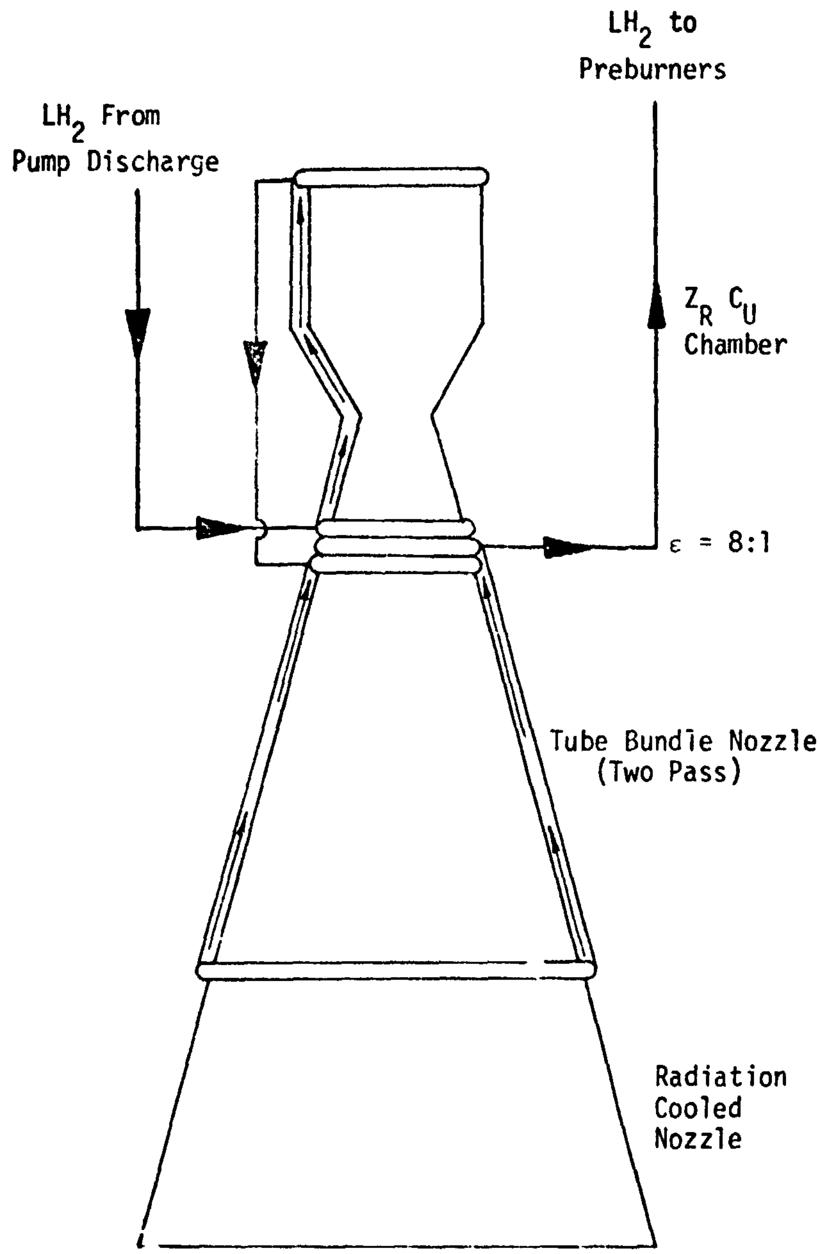


Figure 41. Tripropellant Engine Cooling Schematic

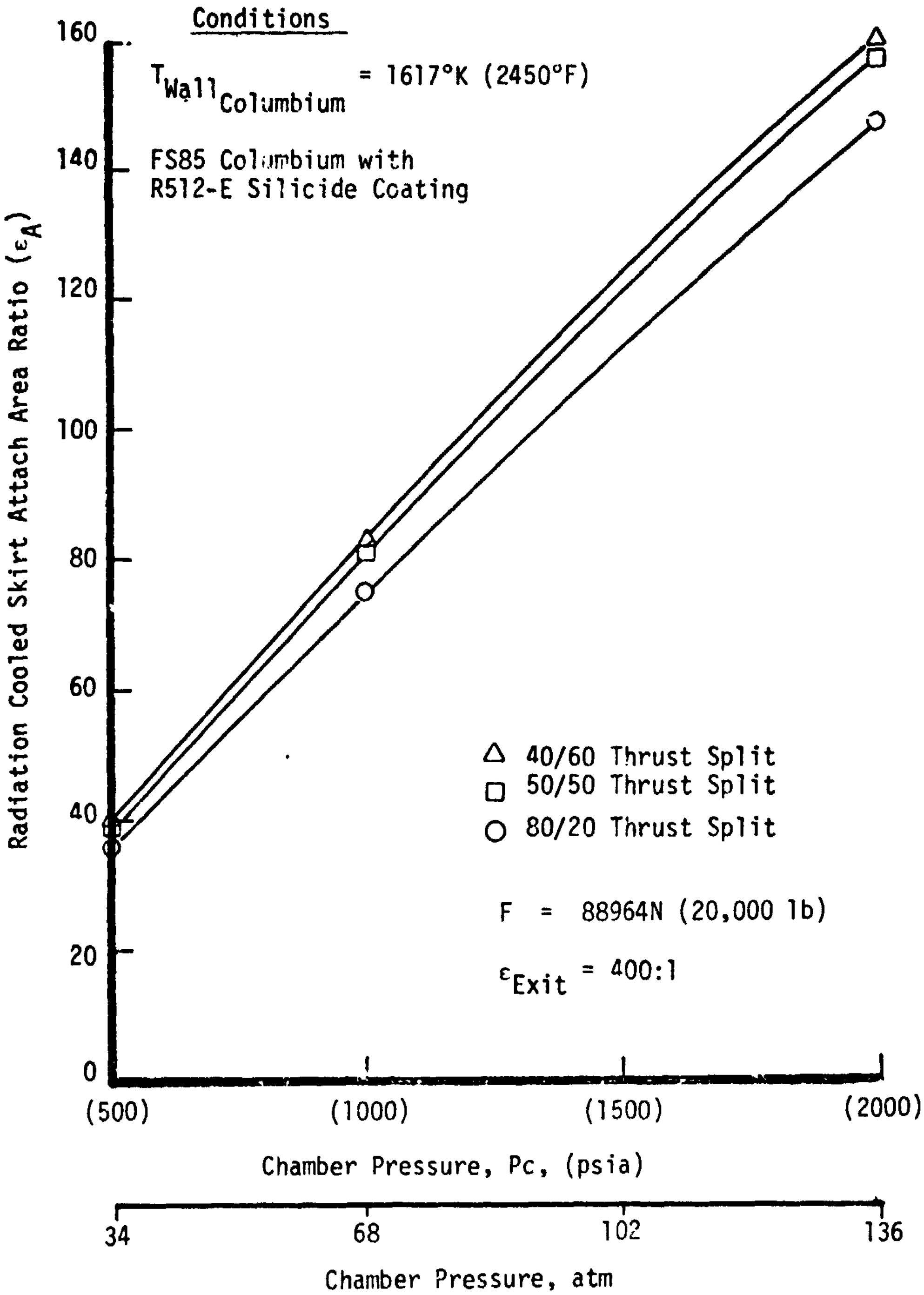


Figure 42. OTV Tripropellant Radiation Cooled Nozzle Attach Area Ratio

TABLE XV. - TRIPROPELLANT ENGINE TUBE BUNDLE PRESSURE DROPS

Chamber Pressure, atm (psia)	Thrust Split	Tube Bundle Area Ratio	Pressure Drop, atm (psi)
34 (500)	40/60	40	0.21 (3.1)
	50/50	39	0.20 (3.0)
	80/20	36	0.41 (6.0)
68 (1000)	40/60	83	0.35 (5.1)
	50/50	81	0.33 (4.8)
	80/20	75	1.36 (20.0)
136 (2000)	40/60	160	0.48 (7.1)
	50/50	157	0.46 (6.7)
	80/20	147	13.6 (200)

TABLE XVI. - TRIPROPELLANT ENGINE COOLING SUMMARY

S.I. UNITS

Coolant Inlet at ϵ = 8:1 T_{Inlet} = 50°K $T_{WG_{Max}}$ = 811°K F = 88964N

Chamber Pressure atm	Thrust Split	$\Delta P_{Chamber}$ atm	ΔT_{Bulk} °K	$\dot{W}_{Coolant}$ kg/sec	Total Heat Load, KW	Max. Heat Flux, W/m^2	Max Mach No.	Number of Channels	Max DB_F
34	40/60	0.53	121.8	1.47	2925	22.6×10^6	0.061	132	0.00203
	50/50	0.48	138.1	1.22	2772	21.4×10^6	0.057	132	0.00194
	80/20	0.63	298.5	0.49	2346	18.0×10^6	0.068	150	0.00167
68	40/60	2.43	142.7	1.47	3449	44.1×10^6	0.082	122	0.00206
	50/50	2.07	162.3	1.22	3273	41.8×10^6	0.076	124	0.00196
	80/20	4.15	355.2	0.49	2776	35.1×10^6	0.116	136	0.00168
136	40/60	19.52	174.0	1.47	4187	86.0×10^6	0.148	9[illegible]	0.00207
	50/50	16.85	198.2	1.22	3940	81.5×10^6	0.138	98	0.00198
	80/20	54.67	426.3	0.49	3369	69.0×10^6	0.287	98	0.00169

<u>A-286 Tube Bundle Design</u>

ϵ = 8:1 to Radiation Cooled Skirt, ϵ = 160 $T_{WG_{max}}$ = 867°K

Chamber Pressure atm	Thrust Split	$\Delta P_{Chamber}$ atm	ΔT_{Bulk} °K	$\dot{W}_{Coolant}$ kg/sec	Total Heat Load, KW	Max. Heat Flux, W/m^2	Max Mach No.	Number of Channels	Max DB_F
136	50/50	0.46	79.6	1.22	1834	10.1×10^6	0.032	100	0.00195

TABLE XVI (cont.)

ENGLISH UNITS

Coolant Inlet at ε = 8:1 T_{Inlet} = 90°R $T_{WG_{max}}$ = 1000°F F = 20,000 lb

Chamber Pressure (psia)	Thrust Split	$\Delta P_{Chamber}$ (psia)	ΔT_{Bulk} (°R)	$\dot{w}_{Coolant}$ (lbm/sec)	Total Heat Load (Btu/sec)	Max Heat Flux (Btu/in.^{2}-sec)	Max Mach No.	Number of Channels	Max DB_F
500	40/60	7.8	219.2	3.24	2774	13.8	0.061	132	0.00203
	50/50	7.0	248.6	2.70	2629	13.1	0.057	132	0.00194
	80/20	9.3	537.3	1.08	2225	11.0	0.068	150	0.00167
1000	40/60	35.7	256.8	3.24	3271	27.0	0.082	122	0.00206
	50/50	30.4	292.1	2.70	3104	25.6	0.076	124	0.00196
	80/20	61.0	639.3	1.08	2633	21.5	0.116	136	0.00168
2000	40/60	286.9	313.2	3.24	3971	52.6	0.148	98	0.00207
	50/50	247.7	356.7	2.70	3767	49.9	0.138	98	0.00198
	80/20	803.6	767.4	1.08	3195	42.2	0.287	98	0.00169

A-286 Tube Bundle Design

ε = 8:1 to Radiation Cooled Skirt, ε = 160 $T_{WG_{max}}$ = 1100°F

Chamber Pressure (psia)	Thrust Split	$\Delta P_{Chamber}$ (psia)	ΔT_{Bulk} (°R)	$\dot{w}_{Coolant}$ (lbm/sec)	Total Heat Load (Btu/sec)	Max Heat Flux (Btu/in.^{2}-sec)	Max Mach No.	Number of Channels	Max DB_F
2000	50/50	6.7	143.3	2.70	1769	6.2	0.032	100	0.00195

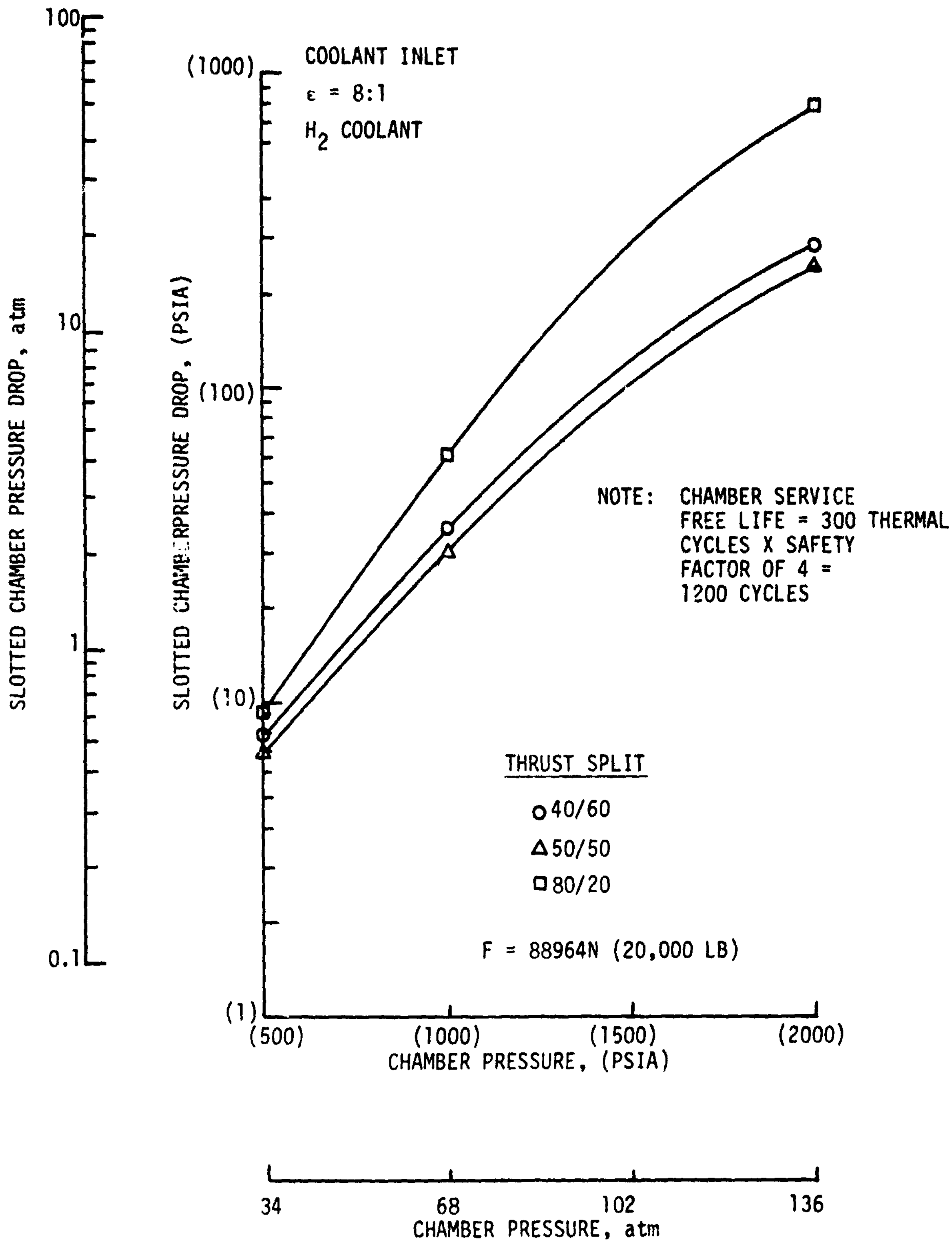


Figure 43. OTV Tripropellant Chamber Pressure Drop

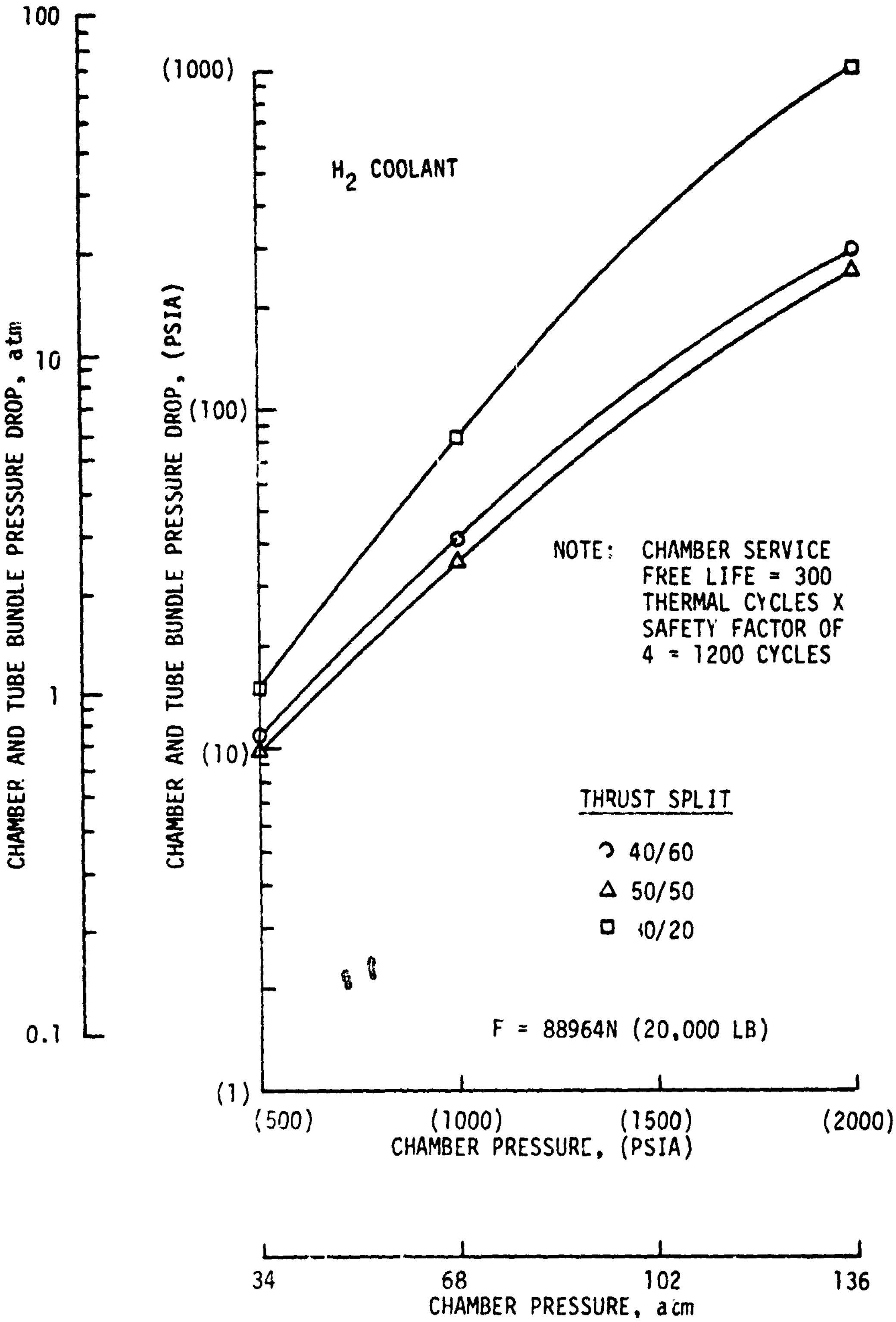


Figure 44. OTV Tripropellant Chamber Pressure Drop Including Tube Bundle

for the nine chambers analyzed. The chamber pressure range covered in this study was from 34 to 136 atm (500 to 2000 psia) in Mode 1 operation. The Mode 2 chamber pressure range ran from approximately 6.8 to 81.6 atm (100 to 1200 psia). Mode 1 operation was used to design the chambers. Mode 2 O_2/H_2 operation is less severe thermally because the coolant flow rate remains a constant and the chamber pressure is reduced. Figures 43 and 44 present the pressure drop vs chamber pressure results for the zirconium-copper chambers only and chambers plus A-286 tube bundles, respectively. The effect of thrust split upon pressure drop is also displayed on these figures. The highest pressure drops occur at the highest thrust split (80/20). This occurs primarily because of the lower coolant flow rate which results in higher hydrogen bulk temperatures and thus, lower heat transfer coefficients for a given pressure gradient. However, the pressure drops for the 40/60 thrust split cases are greater than for the 50/50 thrust split cases. This is caused primarily by the slightly more severe gas environment at the lower thrust split. Even though the coolant flow rate is greater, the maximum heat fluxes and total heat loads are also greater than at the 50/50 thrust split points. The pressure drop versus thrust split optimization point appears to be limited on the high thrust split side by the bulk temperature rise influence, and on the low thrust split side by the higher heat fluxes and heat loads encountered.

Cooling of the tripropellant engine over the entire thrust split and chamber pressure range is practical.

4. Plug Cluster Engine Cooling Evaluation

The plug cluster engine cooling schematic analyzed is displayed on Figure 45. The hydrogen is first used to cool the plug, flowing from the low area ratio regions to the high area ratio regions, and then across the base of the plug. The hydrogen is then brought back up to the LOX/LH_2 module exits (ε = 40) and flows up the nozzle through the throat region and chamber to exit at the injector. Several different coolant flow paths were tested for the oxygen cooling cases of the LOX/RP-1 module. RP-1 cooling of the LOX/RP-1 module was also investigated.

During the course of this study, the results from the Unconventional Nozzle Tradeoff Study (Ref. 3) showed that it is desirable to have the module exits touch to maximize performance. This results in very high area ratio modules. To minimize the weight of the module nozzle extensions, radiation cooled nozzles are used. The following attachment area ratios were established:

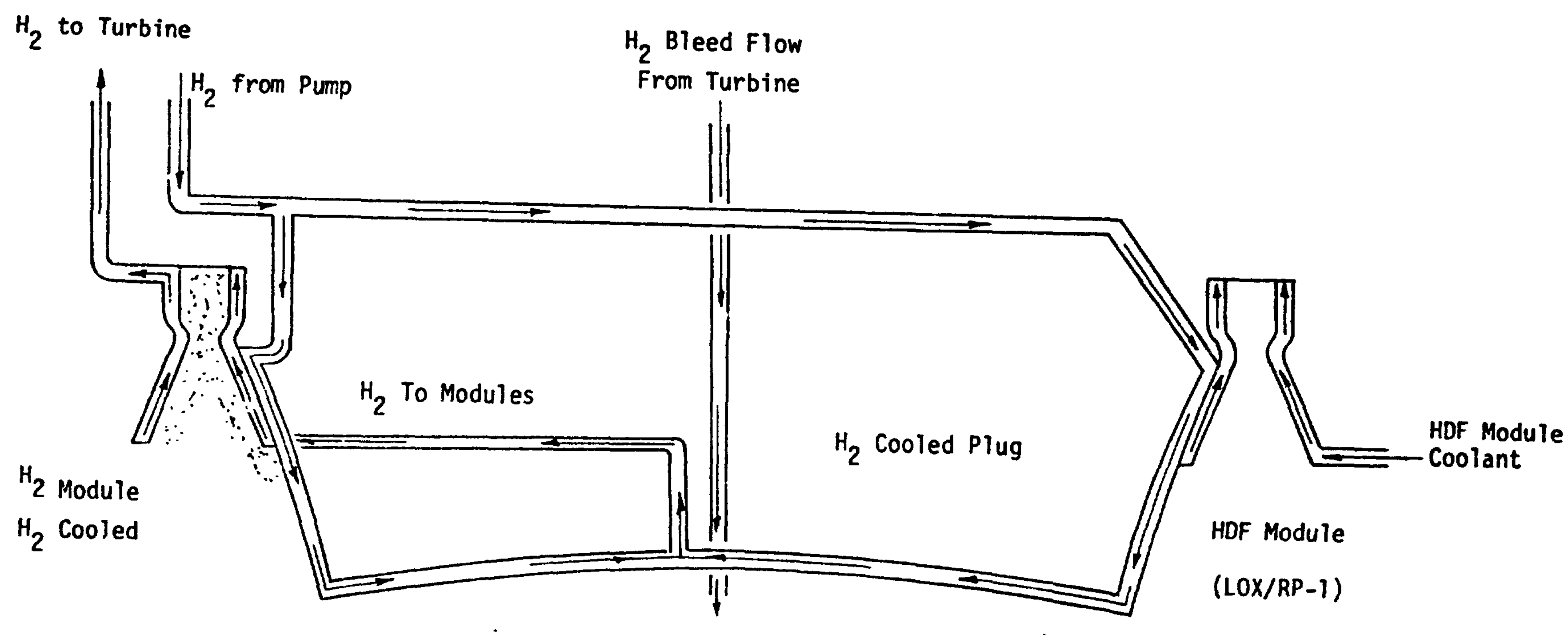


Figure 45. Plug Cluster Engine Cooling Schematic

Thrust Chamber Pressure, atm (psia)	Radiation Cooled Nozzle Attachment Area Ratio	
	LOX/RP-1 Module	LOX/LH_2 Module
20.4 (300)	26	33
34 (500)	36	50

For these cases, the cooling schematic is essentially the same as described except that the hydrogen enters the module cooling jacket at the above area ratios after cooling the plug base instead of at the module exit.

Results from the plug cluster engine design thermal analyses are presented in Table XVII and Figure 46. Table XVII presents pertinent design parameters as a function of chamber pressure. Thrust split was fixed at 50/50. The four cases investigated included the H_2 cooled LOX/LH_2 module, RP-1 cooled LOX/RP-1 module, O_2 cooled LOX/RP-1 module and H_2 cooled plug. Conclusive results were obtained only for the H_2 cooled cases for reasons to be explained later in this section. Figure 46 displays the effect of chamber pressure upon pressure drop for the H_2 cooled LOX/LH_2 mdolue.

The LOX/LH_2 module coolant channel designs all result in practical pressure drops. These results were obtained by assuming that the plug surfaces would be cooled initially followed by the module. This assumption resulted in different coolant inlet temperatures for the module as a function of chamber pressure.

Detailed coolant channel designs for the plug were not pursued in this study. Preliminary results indicated that the pressure drops associated with the plug were extremely low. Computer modeling of the plug was therefore done only to estimate the heat load associated with the plug to obtain the bulk temperature rise to be used in the module analyses.

RP-1 cooling the LOX/RP-1 module proved to be impractical because of bulk temperature rise limitations. The RP-1 coolant inlet temperature specified is 311°K (100°F) and a liquid-side wall temperature limit of 589°K (600°F) is required to minimize cracking and coking of the RP-1. These limits result in a practical bulk temperature rise limit of 250-278°K (450-500°F). The O_2/RP-1 module employs a gas-generator cycle. In order to meet the 98% combustion efficiency goal this results in chamber L' values on the order of 33 to 38 cm (13 to 15 inches). These long chamber lengths result in total heat loads which are 17 to 30%

TABLE XVII. - PLUG CLUSTER ENGINE COOLING SUMMARY

S.I. UNITS

Thrust Split = 50/50

F = 88964N

$T_{Inlet\,H_2}$ = 50°K
$T_{Inlet\,O_2}$ = 111°K
$T_{Inlet\,RP\text{-}1}$ = 311°K

$T_{WG_{Max}}$ = 811°K

$T_{WL_{Max}}$ (RP-1) = 589°K

Engine Type	Chamber Pressure, atm	$\Delta P_{Chamber}$, atm	ΔT_{Bulk} °K	$\dot{W}_{Coolant}$, kg/sec	Total Heat Load, kW	Max. Heat Flux, W/m²	Max. Mach. No.	Number of Channels
LOX/LH$_2$ Module	20.4	0.3	210	.249	855	18×10^6	.065	62
(ϵ_{Exit} = 40:1)	34	1.33	239	.249	919	29.6×10^6	.118	60
(Inlet @ ε = 40:1)	68	23.1	264	.249	1024	57.7×10^6	.380	46
LOX/RP-1 Module	20.4	--	498*	.599	1006	13.9×10^6	---	--
RP-1 Coolant	34	--	539*	.599	1133	22.7×10^6	---	--
(ϵ_{Exit} = 40:1)								
(Inlet @ ε = 40:1)								
LOX/RP-1 Module	20.4	--**	---	1.86	--	15.0×10^6	---	80
LOX Coolant	68	--**	---	1.86	--	48.7×10^6	---	43
(ϵ_{Exit} = 40:1)								
(Inlet @ ε = 40:1)								
Plug	20.4	<.07	91	1.25	1877	$.65\times10^6$	---	--
(ϵ_{Exit} = 223:1)	34	<.07	122	1.25	2466	$.98\times10^6$	---	--
(Inlet @ ε = 40:1)	68	<.07	168	1.25	4156	1.96×10^6	---	--

*Bulk temperature rise exceeds design limit of 278°K
**Oxygen cooling was impractical because of coolant density changes encountered at the critical temperature and/or critical pressure points

TABLE XVII (cont.)

ENGLISH UNITS

Thrust Split = 50/50 | T_{Inlet} H_2 = 90°R | $T_{WG_{Max}}$ = 1000°F

F = 20,000 lbs | T_{Inlet} O_2 = 200°R | $T_{WL_{Max}\ (RP-1)}$ = 600°F

T_{Inlet} RP-1 = 560°R

Engine Type	Chamber Pressure (psia)	$\Delta P_{Chamber}$ (psia)	ΔT_{Bulk} (°R)	$\dot{W}_{Coolant}$ (lbm/sec)	Total Heat Load (Btu/sec)	Max. Heat Flux (Btu/in^2-sec)	Max. Mach No.	Number of Channels
LOX/LH_2 Module	300	4.4	392	.55	811	11.0	.065	62
(ϵ_{Exit} = 40:1)	500	19.5	430	.55	872	18.1	.118	60
(Inlet @ ϵ= 40:1)	1000	340	475	.55	971	35.3	.380	46
LOX/RP-1 Module	300	-	896*	1.32	954	8.5	-	-
RP-1 Coolant	500	-	971*	1.32	1075	13.9	-	-
(ϵ_{Exit} = 40:1)								
(Inlet @ ϵ= 40:1)								
LOX/RP-1 Module	300	-**	-	4.10	-	9.2	-	80
LOX Coolant	1000	-**	-	4.10	-	29.8	-	43
(ϵ_{Exit} = 40:1)								
(Inlet @ ϵ= 40:1)								
Plug	300	<1	164	2.75	1780	.4	-	-
(ϵ_{Exit} = 223:1)	500	<1	219	2.75	2339	.6	-	-
(Inlet @ ϵ= 40:1)	1000	<1	303	2.75	3942	1.2	-	-

* Bulk temperature rise exceeds design limit of 500°R
** Oxygen cooling was impractical because of coolant density changes encountered at the critical temperature and/or critical pressure points

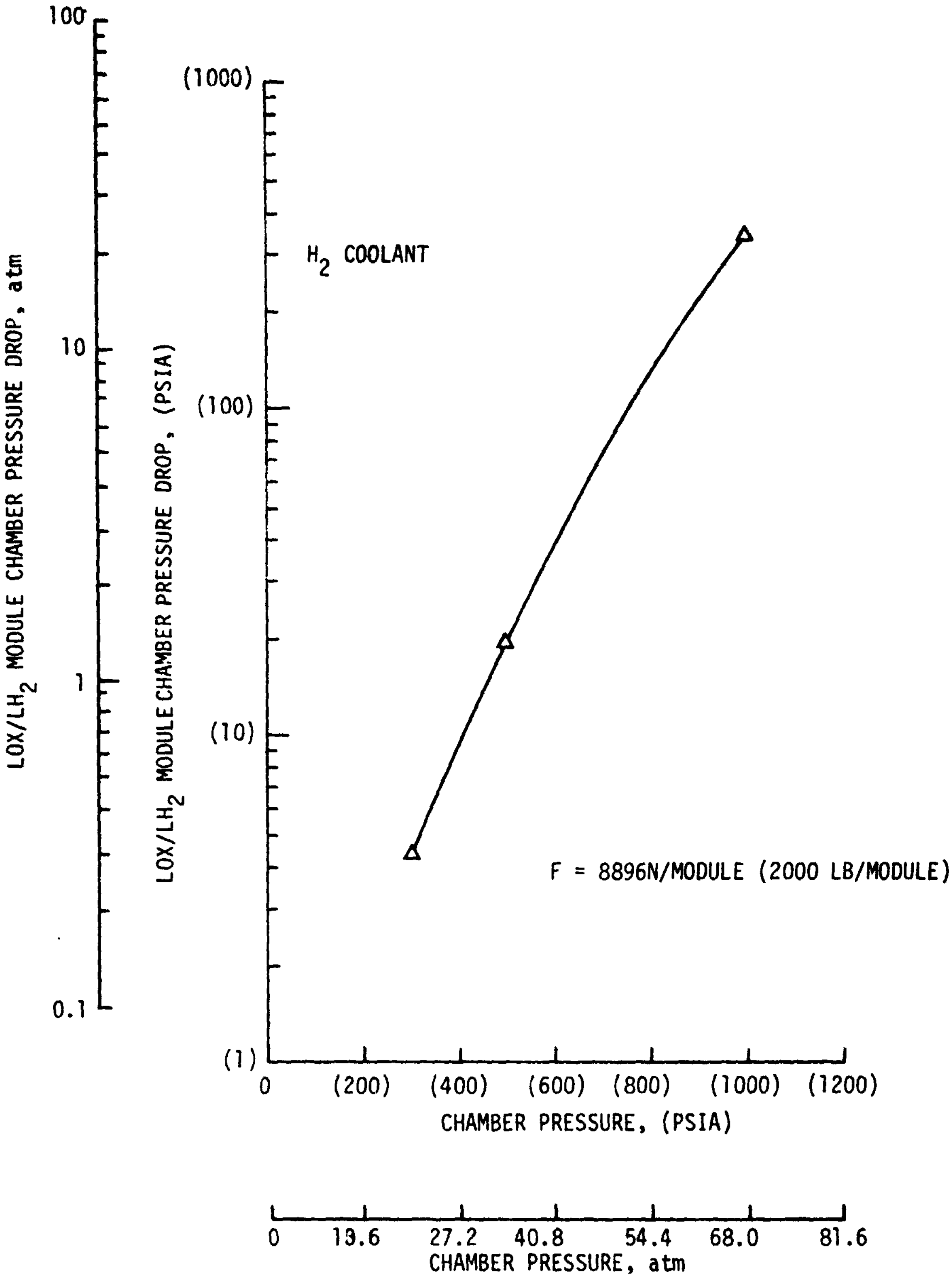


Figure 46. OTV Plug Cluster LOX/LH_2 Module Pressure Drop

greater than those for the LOX/LH_2 modules at the same chamber pressure even though the gas environment is less severe. Bulk temperature rise values of 498 and 539°K (896 and 971°F) were obtained for the 20.4 and 34 atm (300 and 500 psia) Pc cases, respectively. RP-1 coolant heat transfer coefficients were determined from the Hines correlation (Ref. 19).

Oxygen cooling of the LOX/RP-1 module also proved to be impractical. The oxygen cooling cases are affected by a phase change at low chamber pressures and by shifts in transport properties near the critical temperature and pressure points at the higher chamber pressures. Oxygen critical temperature and pressure values are 1548°K (278.6°R) and 49.7 atm (730.4 psia), respectively. With the 1.8 inlet pressure to chamber pressure ratio specified for gas generator cycles in the study guidelines, the resulting inlet pressures for chamber pressures of 20.4 and 68 atm (300 and 1000 psia) are 36.7 and 122.4 atm (540 and 1800 psia), respectively. The specified oxygen inlet temperature is 111°K (200°R). For the low chamber pressure point, O_2 is a compressed liquid at the coolant channel inlet. As the O_2 passes down the coolant channels, the bulk temperature rises until the saturation temperature is reached and a phase change from a compressed liquid to a vapor begins. The corresponding shifts in the oxygen transport properties greatly reduce its cooling effectiveness until at a point near the critical temperature, the pressure drop requirements become excessive. Similarly, at the high chamber pressure point the O_2 is supercritical at the coolant channel inlet, being above the critical pressure value but below the critical temperature value. As the coolant passes down the coolant channels the bulk temperature rises past the critical temperature value. This has no adverse effect because only gradual shifts in transport properties occur at pressures significantly above critical. As the bulk temperature continues rising and the coolant static pressure drops, the oxygen cooling effectiveness decreases until the pressure drop requirements become excessive.

Therefore, it appears that oxygen cooling at the low chamber pressures is limited because of the shift in transport properties caused by the phase change from liquid to vapor. At the high chamber pressure, it is limited by the transport properties changes associated with the bulk temperature rise and also with the coolant static pressure degradation. Oxygen appears to be an impractical coolant over the entire chamber pressure range covered at this 88964N (20,000 lb) thrust level. The relatively low thrustto chamber pressure ratio covered in this study, resulted in low coolant flow rate per unit heat flux levels which limited the feasibility of oxygen cooling. Oxygen cooling was dropped from further study efforts.

Oxygen cooling heat transfer coefficients were calculated based on the supercritical oxygen heat transfer correlation of Reference 20. Sub-critical heat transfer coefficients were evaluated using the same correlation. No applicable sub-critical cooling correlations for oxygen were known to exist.

To continue the mixed mode plug cluster evaluations in the remaining study tasks, RP-1 cooling and a module chamber pressure of 20.4 atm (300 psia) was selected. This assumes that impurities can be removed from the RP-1 to raise the bulk temperature limit above 589°K (600°F). The RP-1 module cooling analyses then proceeded assuming that the coolant temperature was not limiting. This was done in order to obtain coolant ΔP data at the baseline thrust level and over a range of thrusts for use in the power balance analyses and engine parametric studies. The results of this analyses are shown on Figures 47 and 48. Even with this assumption a 8896N/module (2000 lb) thrust module design cooled with RP-1 is very marginal to meet the life requirements as noted by Figure 48.

Other potential solutions to the HDF module cooling problem which might be considered in future efforts if the concept proves to be attractive for other reasons are:

- Reduction in chamber life goals.
- Reduction in performance goals to reduce chamber length.
- Consideration of dump or film cooling.
- Hydrogen cooled O_2/RP-1 module.

Some of these approaches might be considered in combination rather than alone.

5. Dual-Expander Engine Cooling Evaluation

The dual-expander engine cooling schematic is presented on Figure 49. The hydrogen flow is split into two parallel flow paths in this scheme. To optimize the cooling capability of hydrogen, it is necessary to keep the coolant bulk temperature low when it passes through the high heat flux regions. The dual-expander concept results in three separate surfaces which must be cooled. Each of these surfaces has a high heat flux (throat) region instead of the single region encountered in a conventional chamber design. The selection of parallel flow paths permits the coolant flowrate to be split in order to minimize pressure drop. In this scheme, the smaller percentage of the total coolant flow is used to cool the outer annular chamber wall. This coolant introduced at the injector plane, flows through the throat, and exits at a manifold located in the forced deflection nozzle extension. The coolant flowrate split was chosen

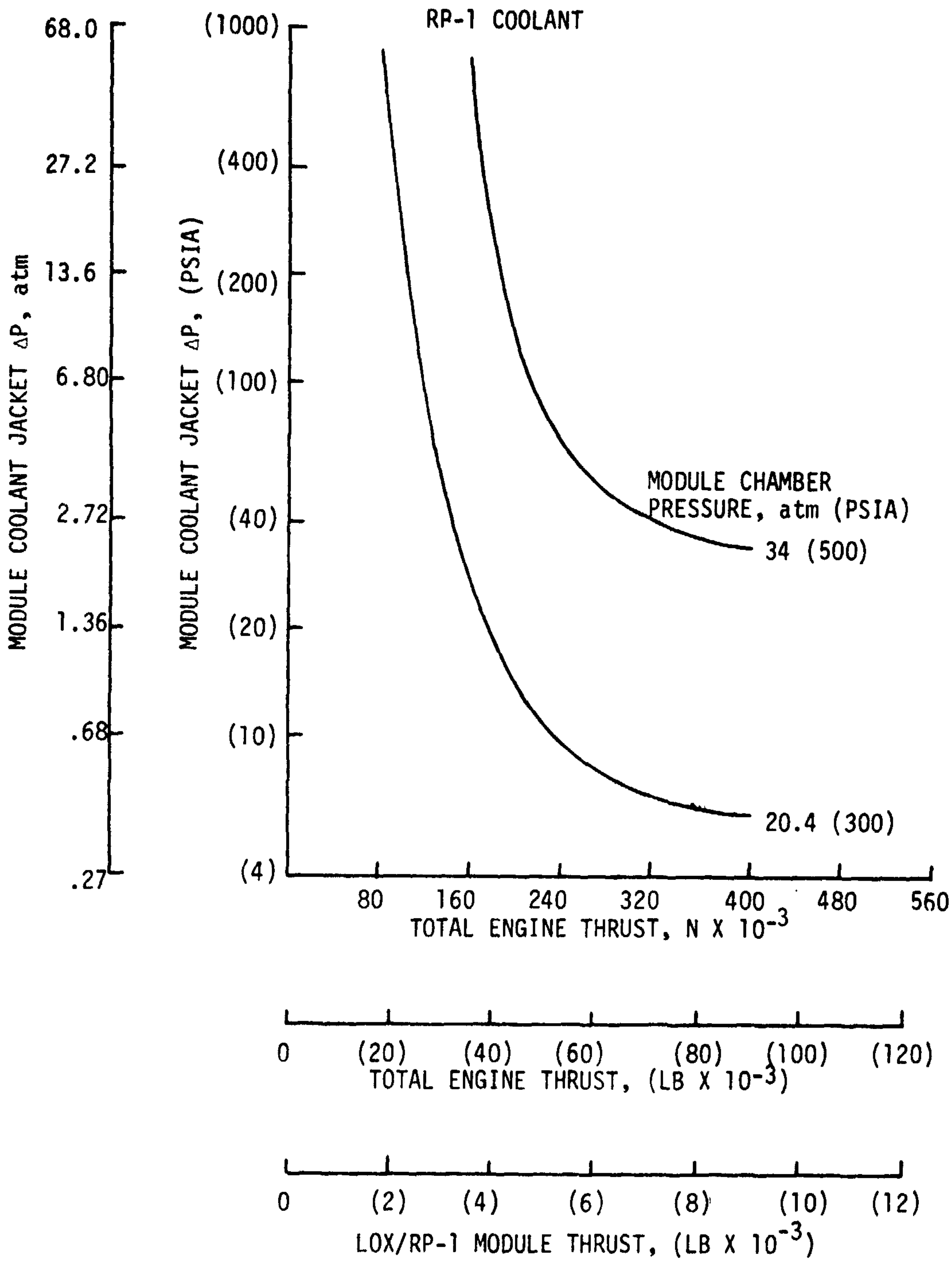


Figure 47. Plug Cluster LOX/RP-1 Module Coolant Jacket ΔP

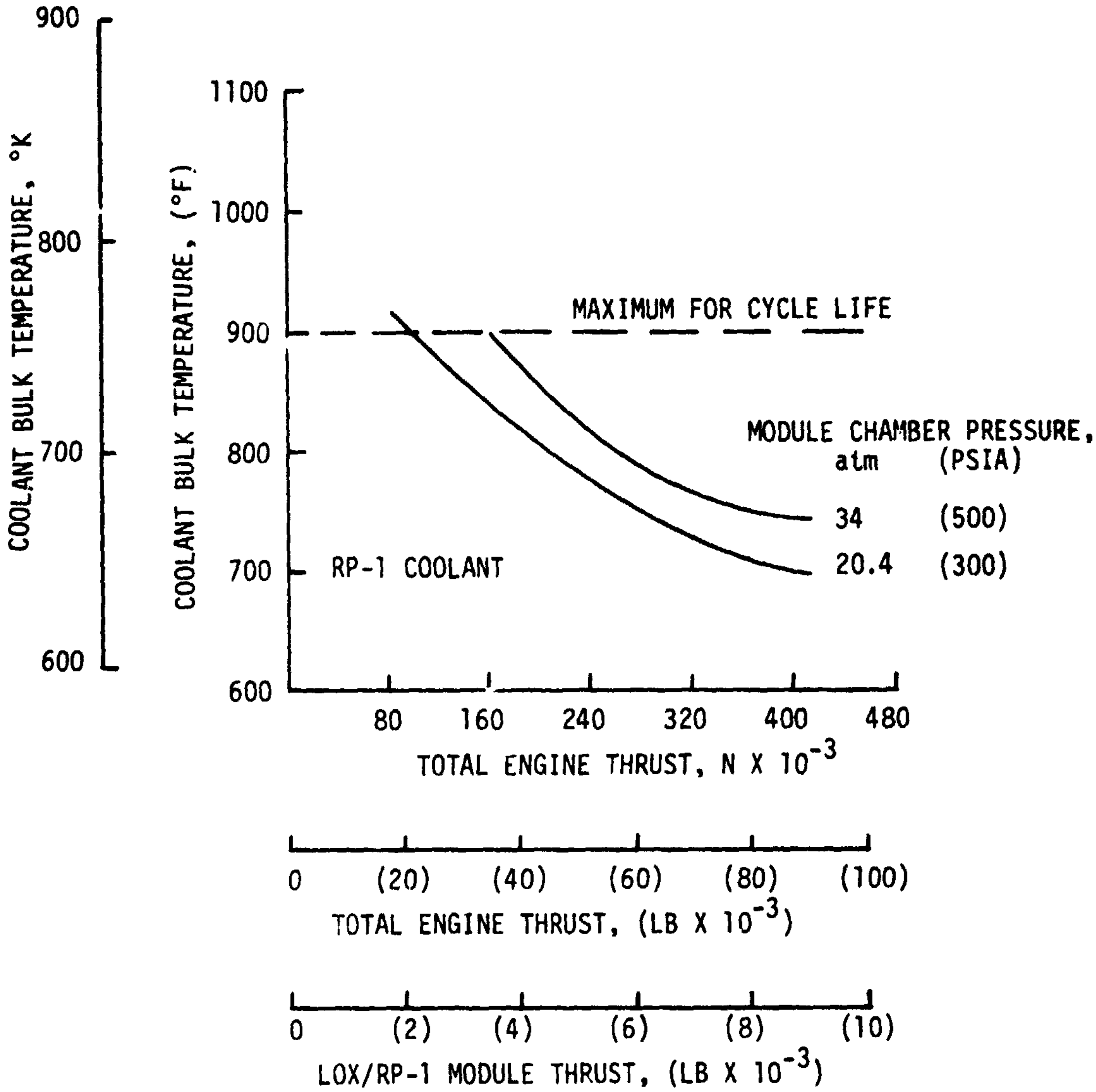


Figure 48. Plug Cluster LOX/RP-1 Module Coolant Bulk Temperature

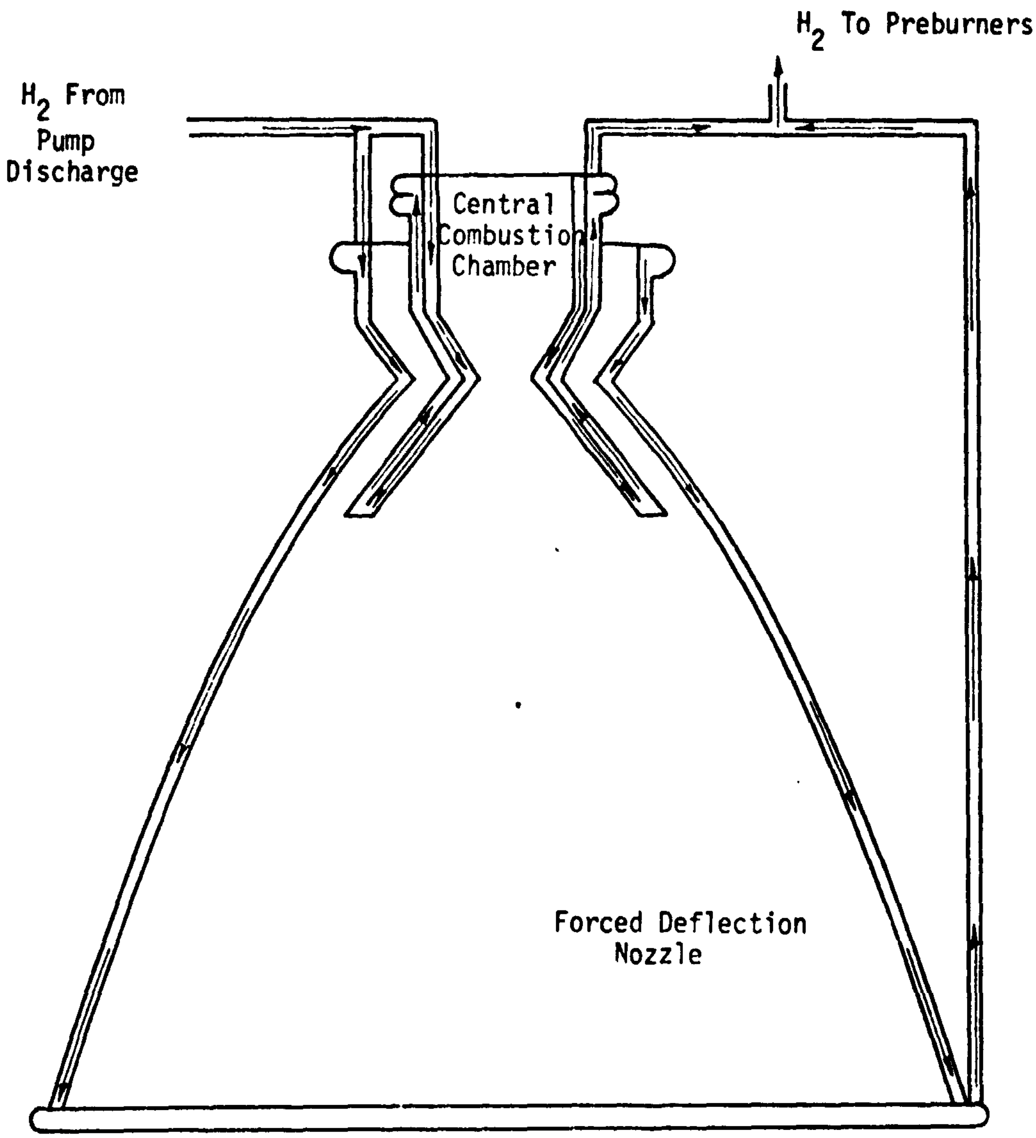


Figure 49. Dual-Expander Engine Cooling Schematic

to keep the bulk temperature of the coolant at the forced deflection nozzle exit at approximately 756°K (900°F). The larger percentage of the flow is brought from the central combustion chamber injector plane to the throat, through the truncated nozzle, turns and flows up the inside wall of the annular chamber and exits at the injector. It is the second throat region which limits the design.

Results from the dual expander engine design analyses are displayed in Table XVIII and Figure 50. Table XVIII presents pertinent design parameters as a function of chamber pressure and thrust split. Figure 50 shows the required pressure drop as a function of thrust split and chamber pressure.

Four different design points were studied in these analyses. Thrust splits of 40% and 50% were evaluated at central/annular chamber pressures of 68/34 atm (1000/500 psia). The 50% thrust split designs were also investigated at 102/51 and 136/68 atm (1500/750 and 2000/1000 psia) central/annular chamber pressures. The 80% thrust split values were also investigated. For the chamber pressure range used in this study, regenerative cooling for the 80% thrust split designs proved impractical because of bulk temperature rise limitations.

The 136/68 atm (2000/1000 psia) design point resulted in impractical coolant velocities which exceeded sonic velocity. It appears that there are two sets of constraints which limit the dual-expander engine design concept. They are bulk temperature limits and coolant Mach number limits. The gas-side wall temperature must be limited to a maximum value of 811°K (1000°F) in order to meet the cycle life requirements. This in turn implies a practical coolant bulk temperature limit of roughly 756-783°K (900-950°F). When the coolant flow rate to the total heat load ratio gets too low, a bulk temperature problem exists. This is the case for the 80% thrust split level. Coolant Mach number limitations must be applied in order to minimize local velocity effects and shock wave phenomena.

An appropriate bulk temperature rise limit line is shown on Figure 50. Approximate coolant Mach number limitation lines are also plotted. The coolant Mach No. of 0.5 is the more practical limiting case. The limiting lines roughly outline the acceptable/nonacceptable design limits for a 88964N (20,000 lb) thrust engine. At the low chamber pressure point, 34 atm (500 psia), practical designs can be achieved for thrust splits ranging from 40% to roughly 70%. As chamber pressure is increased however, the acceptable thrust split range must be reduced. At 68 atm (1000 psia), thrust splits ranging from 40% to roughly 60% would prove feasible. The maximum chamber pressure values for 50% and 40% thrust splits are roughly 88.4 and 102 atm (1300 and 1500 psia), respectively. Any chamber pressure design above 102 atm (1500 psia) appears to be unacceptable for the range of thrust splits studied within the design guidelines assumed at the baseline thrust level.

TABLE XVIII. - DUAL-EXPANDER ENGINE COOLING SUMMARY

S.I. UNITS

F = 88964N

$T_{Inlet\ H_2}$ = 50°K $T_{WG_{Max}}$ = 811°K

Chamber Section	Chamber Pressure, atm	Thrust Split	ΔP Chamber, atm	ΔT Bulk °K	$\dot{W}$ Coolant kg/sec	Total Heat Load, KW	Max. Heat Flux, W/m²	Max. Mach. No.	Number of Channels
Central Combustion	68	40/60	1.48	162	.962	2581	41.2×10^6	.175	74
Annular Inside	34		3.02	153	.962	2265	37.9×10^6	.166	158
Annular Outside	34		4.05	708	.544	5876	37.8×10^6	.207	220
Overall Engine	68/34		4.50	457	1.506	10722	41.2×10^6	.207	-
Central Combustion	68	50/50	1.68	266	.635	2729	39.4×10^6	.165	92
Annular Inside	34		8.15	238	.635	2330	39.9×10^6	.418	172
Annular Outside	34		1.82	627	.621	5953	39.9×10^6	.188	226
Overall Engine	68/34		9.83	565	1.256	11012	39.9×10^6	.418	-
Central Combustion	102	50/50	6.53	287	.708	3274	59.2×10^6	.302	80
Annular Inside	51		39.05	192	.708	2537	60.1×10^6	.883	160
Annular Outside	51		1 .44	708	.544	5924	60.1×10^6	.419	192
Overall Engine	102/51		45.58	578	1.252	11735	60.1×10^6	.883	-
Central Combustion	136	50/50	17.21	292	.708	3361	77.1×10^6	.492	70
Annular Inside	68		*	-	.708	2707	80.4×10^6	>1.0	130
Annular Outside	68		48.3	704	.544	6067	80.4×10^6	.768	172
Overall Engine	136/68		*	-	1.252	12135	80.4×10^6	>1.0	-

*Coolant Mach no. exceeded 1.0

TABLE XVIII (cont.)

ENGLISH UNITS

$T_{Inlet\,H_2}$ = 90°R F = 20,000 lb $T_{WG_{max}}$ = 1000°F

Chamber Section	Chamber Pressure (psia)	Thrust Split	$\Delta P_{Chamber}$ (psia)	ΔT_{Bulk} (°R)	$\dot{W}_{Coolant}$ (lbm/sec)	Total Heat Load (Btu/sec)	Max Heat Flux (Btu/in^2-sec)	Max Mach No.	Number of Channels
Central Combustion	1000	40/60	21.7	292	2.12	2448	25.2	.175	74
Annular Inside	500		44.4	275	2.12	2148	23.2	.166	158
Annular Outside	500		59.6	1275	1.20	5573	23.1	.207	220
Overall Engine	1000/500		66.1	823	3.32	10169	25.2	.207	-
Central Combustion	1000	50/50	24.7	479	1.40	2586	24.1	.165	92
Annular Inside	500		119.8	429	1.40	2210	24.4	.418	172
Annular Outside	500		26.8	1128	1.37	5646	24.4	.188	226
Overall Engine	1000/500		144.5	1017	2.77	10444	24.4	.418	-
Central Combustion	1500	50/50	96	516	1.56	3105	36.2	.302	80
Annular Inside	750		574	345	1.56	2406	36.8	.883	160
Annular Outside	750		227	1275	1.20	5619	36.8	.419	192
Overall Engine	1500/750		670	1041	2.76	11130	36.8	.883	-
Central Combustion	2000	50/50	253	525	1.56	3188	47.2	.492	70
Annular Inside	1000		-*	-	1.56	2567	49.2	>1.0	130
Annular Outside	1000		710	1268	1.20	5754	49.2	.768	172
Overall Engine	2000/1000		-*	-	2.76	11509	49.2	>1.0	-

*Coolant Mach no. exceeded 1.0

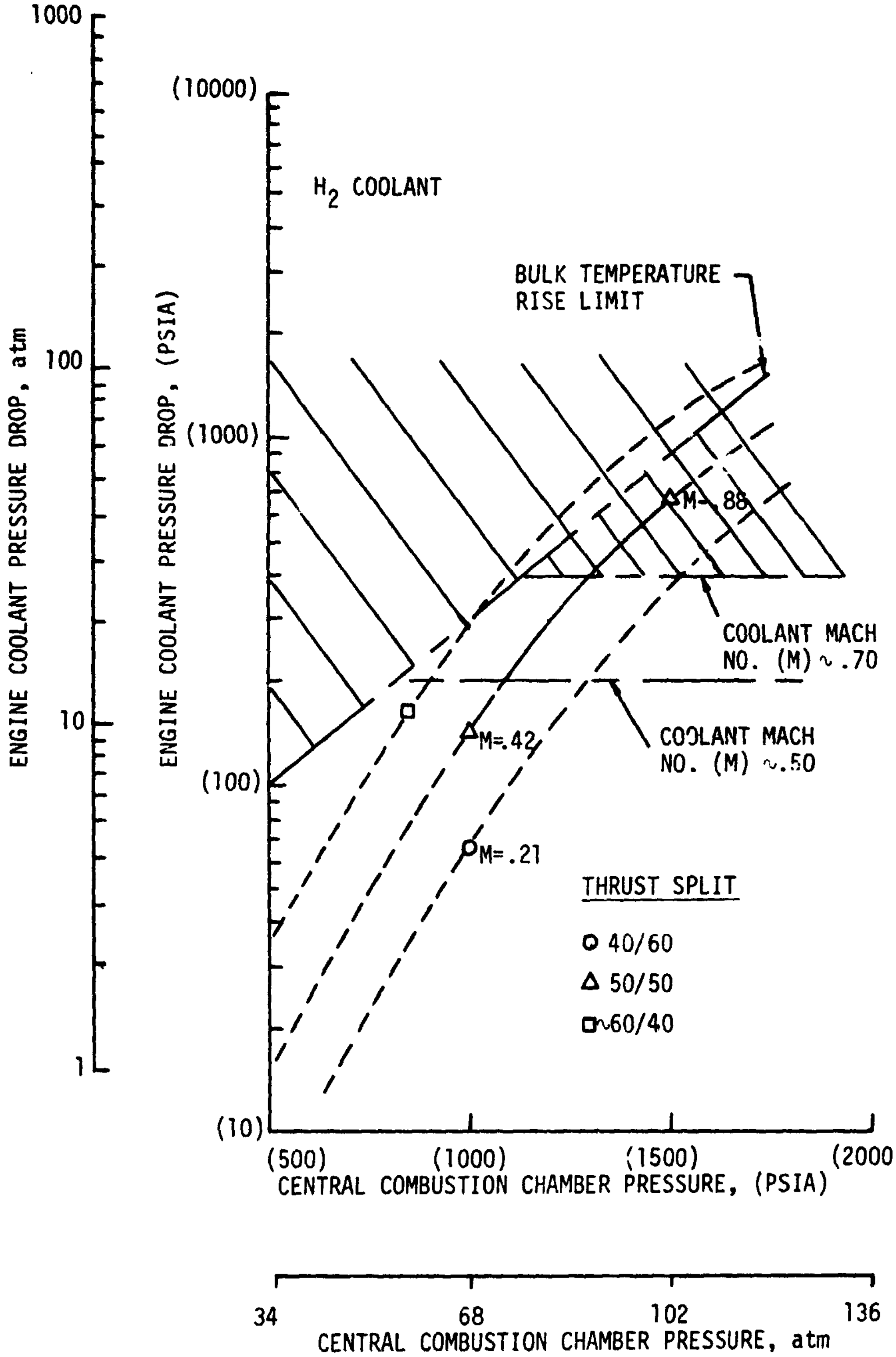


Figure 50. Dual-Expander Engine Coolant Pressure Drop

SECTION V

TASK III - BASELINE ENGINE CYCLE, WEIGHT AND ENVELOPE ANALYSIS

A. OBJECTIVES AND GUIDELINES

The objectives of this task were to determine the engine system pressures, temperatures, and delivered performance for each of the baseline OTV engine concepts previously described in Tables V, VI and VII. For each of the baseline concepts described by the schematics shown on Figures 1 through 6, point design summaries of Mode 1 and 2 operation were established. These summarizes include the cycle schematic, delivered specific impulse, engine system weight flows, pressures and temperatures, pump and turbine speeds, efficiencies and horsepowers, engine system weight and overall envelope dimensions. Coolants and cooling schemes used in this task are as defined in Task II, Section IV. Each of the baseline concepts were analyzed to determine the maximum Mode 1 and Mode 2 chamber pressure attainable within the constraints of the cycle power limit, thrust chamber thermal fatigue limit, propellant property limit or ability of components to operate at both Mode 1 and Mode 2 design conditions.

Engine cycle power balances were performed at the baseline thrust level of 88964N (20,000 lb). Engine performance data were evaluated for a combustion efficiency of 98%. Simplified JANNAF performance prediction techniques (Ref. 21) were used to determine the other performance losses. The boundary layer loss charts in the simplified procedures were adjusted to agree with the latest experimental data obtained at area ratio of 400:1, a thrust level of 88964N (20,000 lb) and 136 atm (2000 psia) chamber pressure (Ref. 22). For these test conditions, the experimental data indicates that the old procedures predicted a boundary layer loss approximately 4 secs too high.

Additional study guidelines are as follows:

- System Pressure Losses ($\Delta P/P_{upstream}$)

    Injectors:

    Liquid - 15% (minimum)
    Gas - 8% (minimum)

    Valves:

    Shutoff - 1%
    Liquid Control - 5% (minimum)
    Gas Control - 10% (minimum)

- Boost Pump Drive Requirements

  Boost pumps are not evaluated in the power balancing. However, appropriate main pump inlet conditions were calculated and main pump horsepower penalties of 3% were assumed to account for the flow required for hydraulically driven boost pumps.

- Main Pump Suction Specific Speed

$$S = 387 \frac{(RPM)(m^3/sec)^{1/2}}{(m)^{3/4}} \text{ (maximum) SI Units}$$

$$S = 20{,}000 \frac{(RPM)(GPM)^{1/2}}{(ft)^{3/4}} \text{ (maximum) English Units}$$

- Maximum Bearing DN Values (Roller and Ball)

  LH_2 Pump - 2×10^6 (RPM) (mm)

  LOX Pump - 1.5×10^6 (RPM) (mm)

  RP-1 Pump - 1.8×10^6 (RPM) (mm)

- Minimum Bearing Size: 20 mm

- Turbine Inlet Temperatures

  LH_2 TPA - 1033°K (1860°R) (Fuel-Rich O_2/H_2 Drive Gas)

  LOX TPA - 922°K (1660°R) (Ox-Rich O_2/H_2 Drive Gas)

  RP-1 TPA - 1089°K (1960°R) (Fuel-Rich O_2/RP-1 Drive Gas)

B. ENGINE SYSTEM EVALUATIONS

1. Tripropellant Engine

Engine power balance analyses were conducted at the baseline Mode 1 thrust level of 88964N (20,000 lb) and a thrust split of 0.5. The effect of thrust split was also established. The tripropellant engine system considered in these evaluations is shown schematically on Figures 51 and 52. Power balances were conducted as a function of thrust chamber pressure over the entire study range of 34 to 168 atm (500 to 2000 psia)

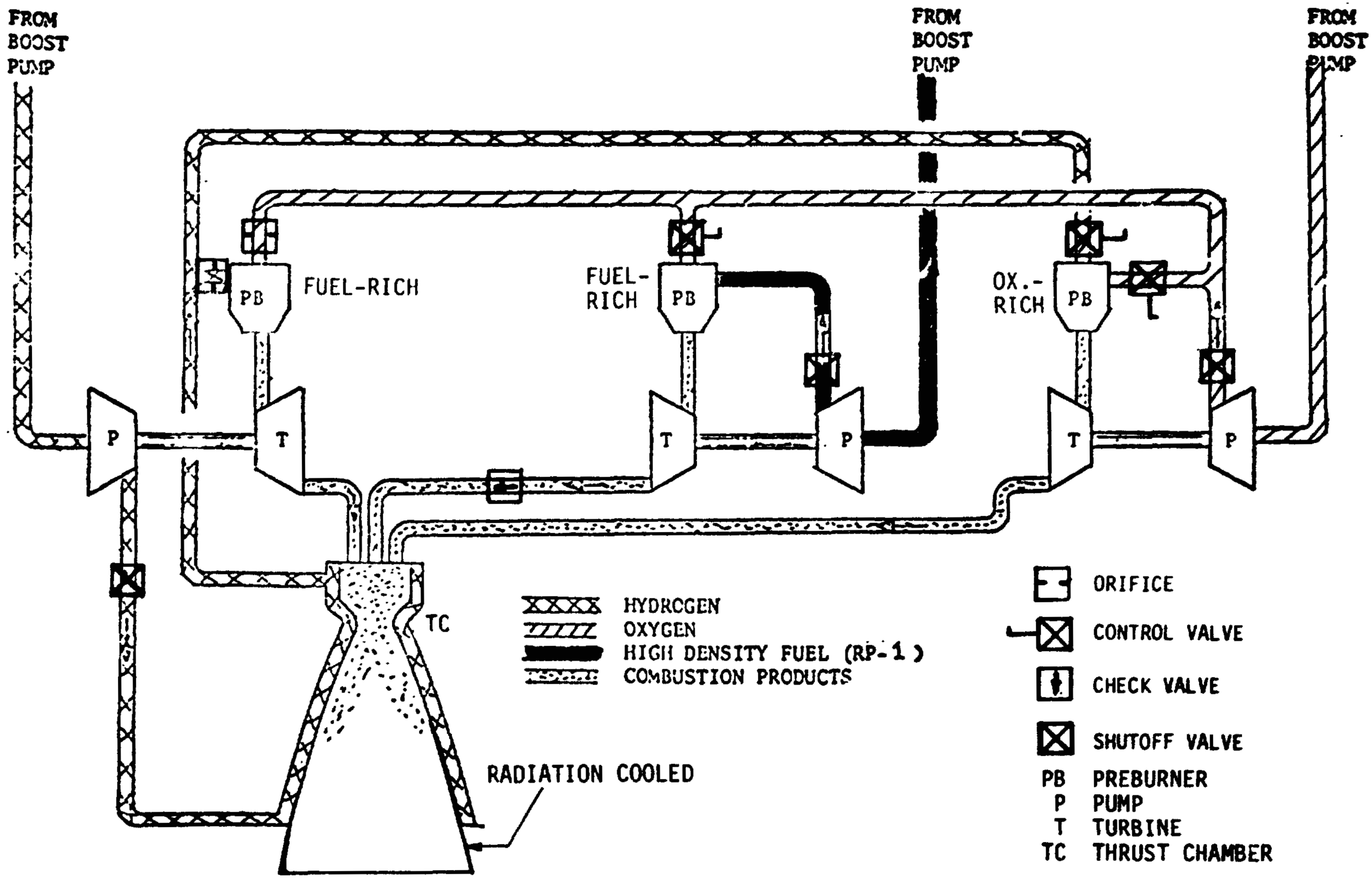


Figure 51. Mode 1 Tripropellant Engine Schematic

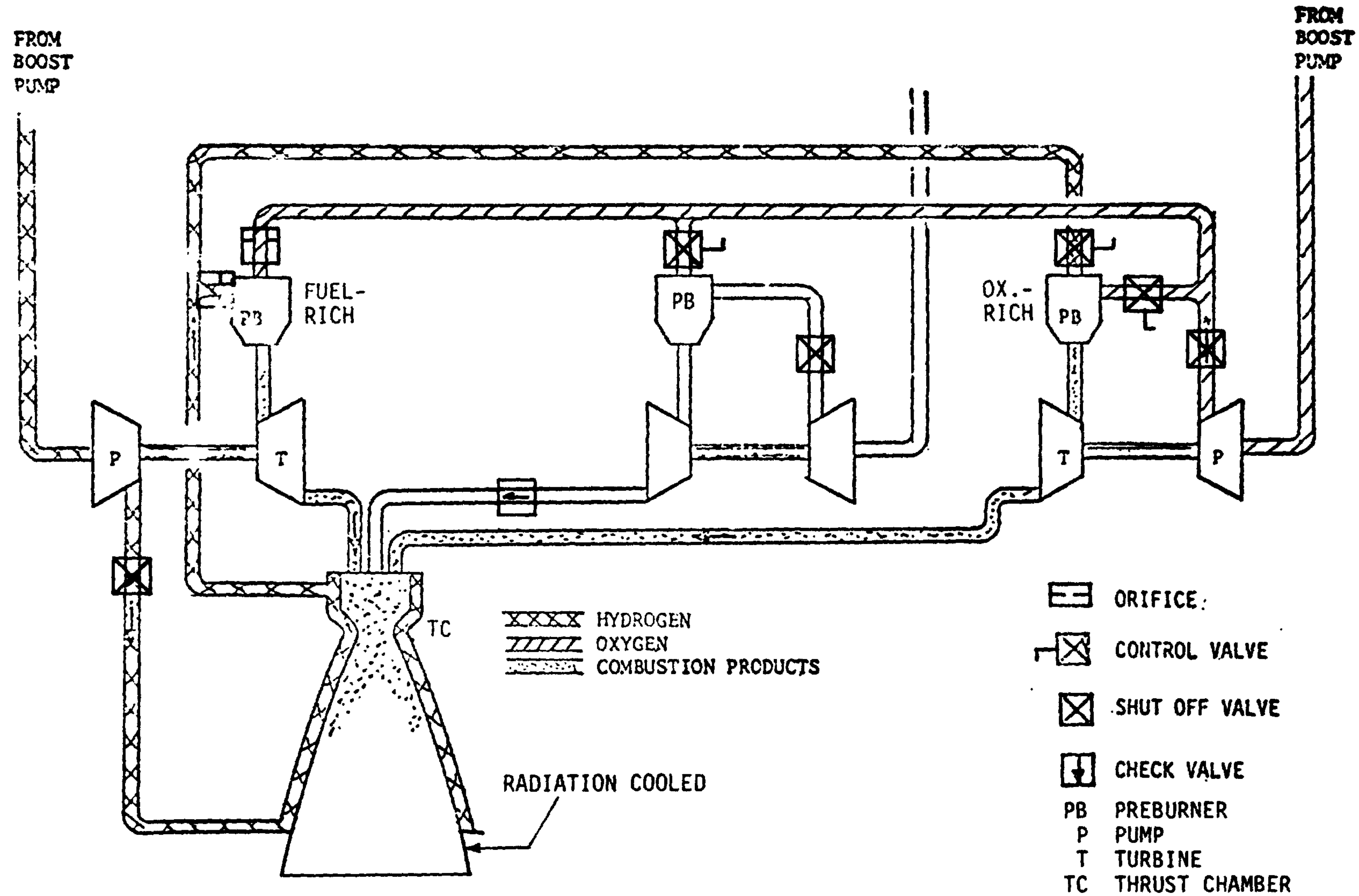


Figure 52. Mode 2 Tripropellant Engine Schematic

because the Task II results did not show this concept to be cooling limited. The results of the Task II, cooling evaluation provided the necessary coolant jacket pressure drop data for use in this analysis.

Preliminary turbopump analyses were conducted initially to establish component efficiencies to be used in further evaluations. The main pump speeds were evaluated as a function of pump discharge pressure within the bearing DN and suction specific speed constraints. The number of pump stages were selected to maintain a pump specific speed (N_s) greater than [600 (RPM) $(GPM)^{1/2}/(FT)^{3/4}$] to get reasonable efficiencies. Pump tip speeds and impeller diameters were calculated with the aid of Figure 53 and pump efficiency estimates were made from Figures 54 and 55 which are based upon data in Reference 23. Results of preliminary calculations, which formed the foundation for further power balancing, are shown on Table XIX.

Turbine efficiencies were estimated as:

LH_2 TPA - 80%

LOX TPA - 75%

RP-1 TPA - 75%

Pump discharge pressure requirements are shown as function of thrust chamber pressure on Figure 56 for a thrust split of 0.5. The figure shows that the LOX pump discharge pressure requirements are approximately equal to those of the hydrogen TPA. All of the oxygen is pumped to high pressure to meet the preburner and turbine inlet pressure requirements. Both the hydrogen and oxygen pump discharge pressures are functions of the thrust chamber pressure, coolant jacket pressure drop and turbine pressure ratio requirements. The RP-1 pump discharge pressure is primarily only a function of the chamber pressure and turbine pressure ratio. All of the RP-1 is combusted in a fuel-rich preburner. Figure 56 also shows that the cycle is not power balance limited. Therefore, a thrust chamber pressure of 136 atm (2000 psia) was selected as a baseline for generating the engine operating specifications.

The tripropellant engine and component Mode 1 operating specifications, for a thrust chamber pressure of 136 atm (2000 psia), are shown on Table XX. The pressure budget for this engine which resulted from the study guidelines and power balance analysis is shown on Table XXI. From this table, it can be noted that the power balance is governed by the LH_2 TPA turbine pressure ratio. The Mode 2 operating conditions for this engine and components are shown on Table XXII. This preliminary design analysis indicates that the component operating parameters for both Mode 1 and 2 are reasonable. The pressure schedule for Mode 2 operation is shown on

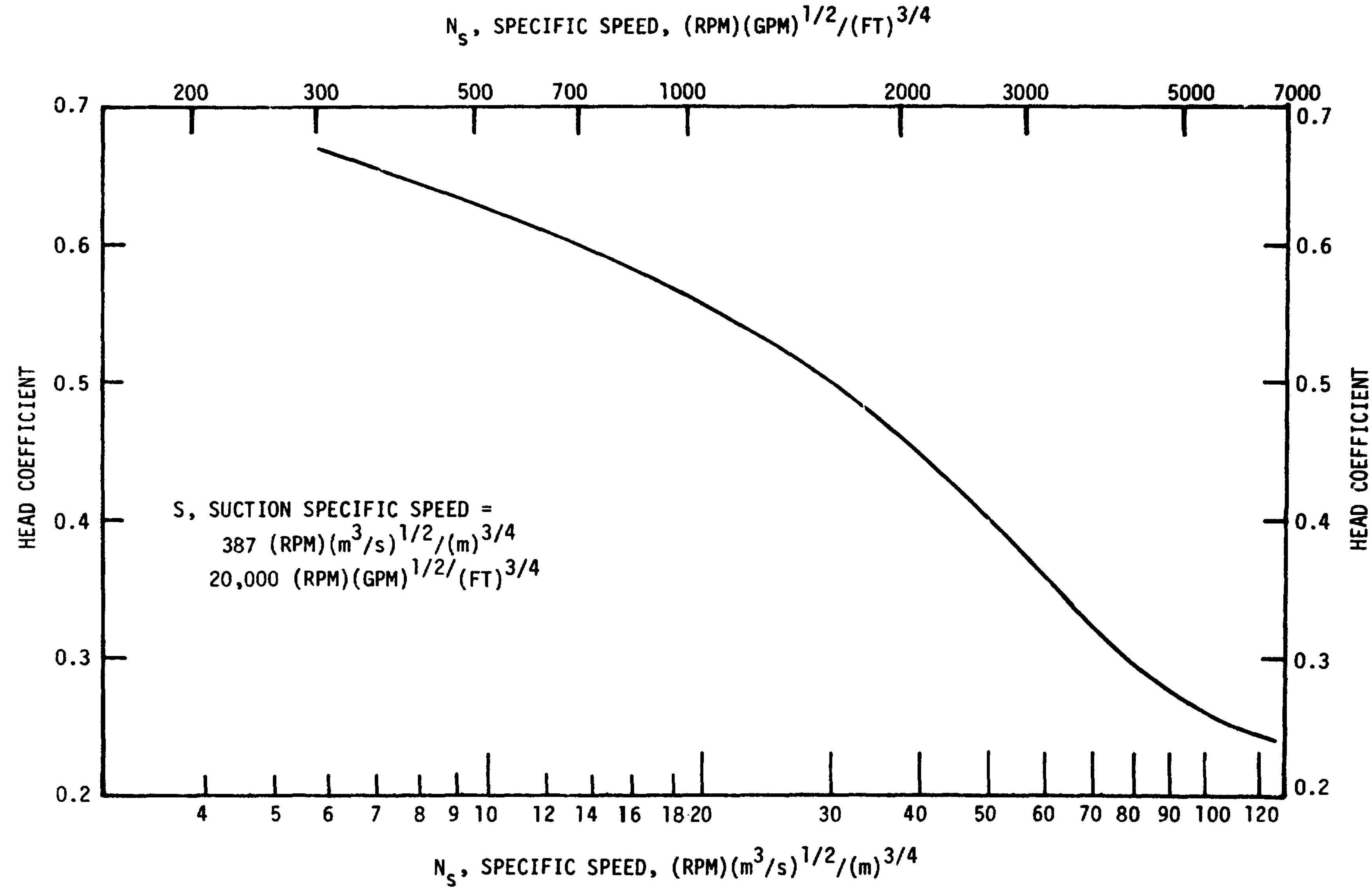


Figure 53. Head Coefficient vs Specific Speed

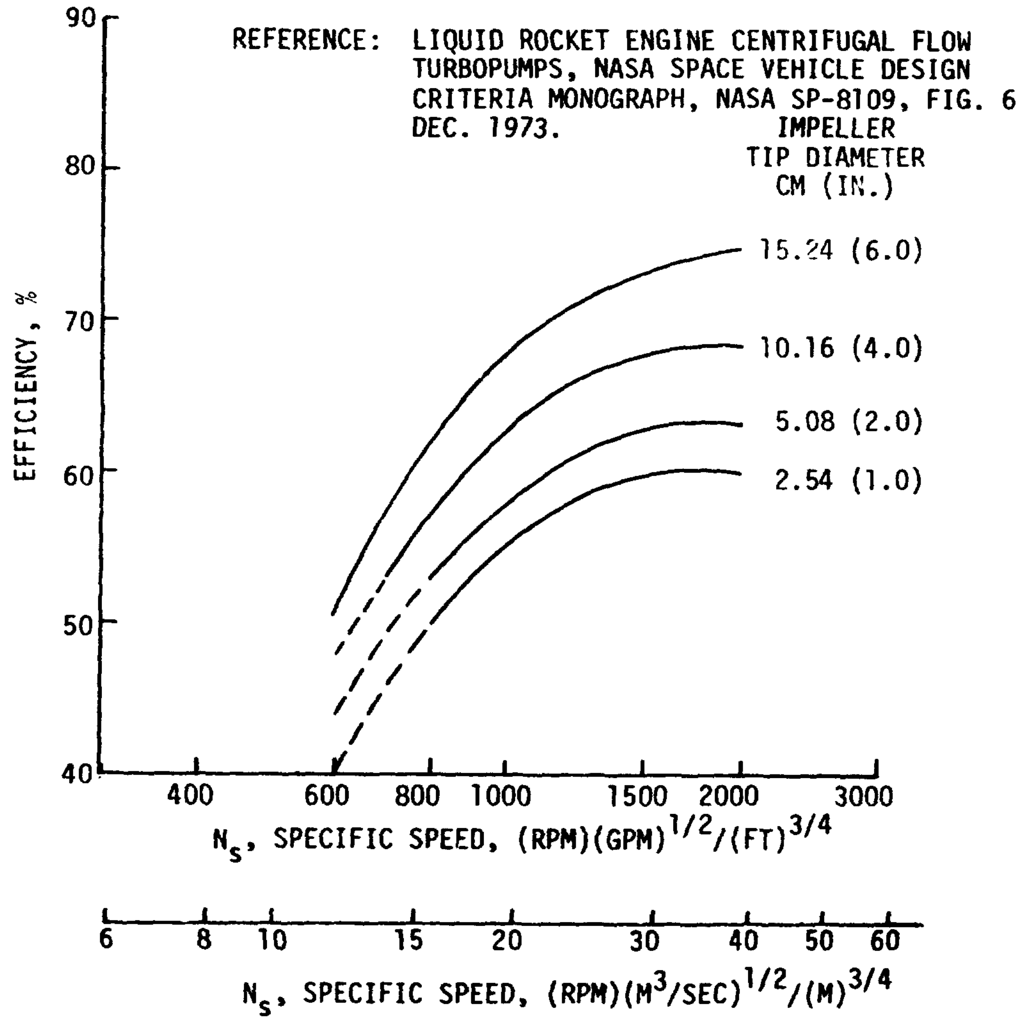


Figure 54. Influence of Pump Size Upon Efficiency

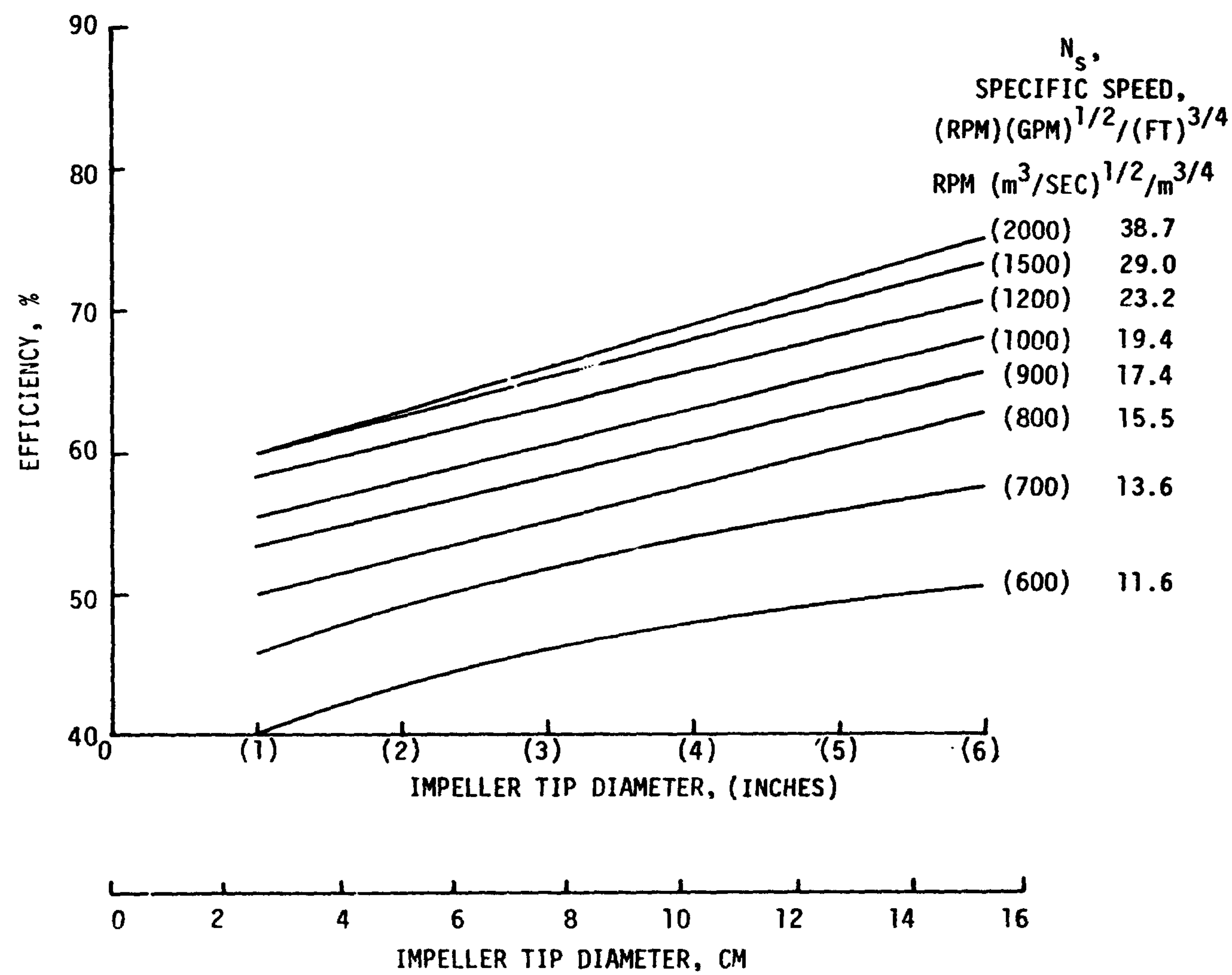


Figure 55. Pump Efficiency vs Impeller Tip Diameter

TABLE XIX. - PRELIMINARY TRIPROPELLANT ENGINE PUMP ANALYSIS

S.I. UNITS

Thrust = 88964N　　　　Thrust Split = 0.5

Nozzle Area Ratio = 400

Mode 1 Thrust Chamber Pressure, atm	34	68	136
Total Engine Flow Rate, kg/sec	22.1	22.0	21.8
Oxygen Flow Rate, kg/sec	17.9	17.8	17.7
Hydrogen Flow Rate, kg/sec	1.24	1.23	1.23
RP-1 Flow Rate, kg/sec	2.97	2.96	2.93

	LOX Pump			LH_2 Pump			RP-1 Pump		
Discharge Pressure, atm	68	136	306	81.6	150	306	68	136	306
Volumetric Flow Rate, m^3/sec	.0157	.0157	.0155	.0176	.0175	.0174	.00372	.00370	.00367
Suction Specific Speed, (RPM) $(m^3/sec)^{1/2}/(m)^{3/4}$	387	387	387	155	155	155	387	387	387
Net Positive Suction Pressure, atm	3.02	6.04	7.69	2.57	2.56	2.56	2.65	2.64	2.63
Net Positive Suction Head, m	27.5	54.9	69.8	377	376	375	34.3	34.2	34.0
Speed, RPM	37,060	62,370	75,000	100,000	100,000	100,000	90,000	90,000	90,000
Total Head Rise, m	591	1,181	2,712	11,595	21,570	46,510	845	1,725	3,926
No. of Stages	1	1	1	2	3	4	1	1	2
Specific Speed, $(RPM)(m^3/sec)^{1/2}/(m)^{3/4}$	38.7	38.7	24.9	19.9	16.9	11.8	35.0	20.5	18.5
Head Coefficient	.46	.46	.53	.56	.578	.612	.48	.555	.57
Tip Speed, m/sec	112	159	224	319	349	432	136	175	184
Impeller Diameter, cm	5.77	4.85	5.69	6.07	6.65	8.23	2.87	3.71	3.91
Pump Efficiency, %	64	62.5	62	59.5	56.5	47	60	57.5	56

TABLE XIX (cont.)

ENGLISH UNITS

Thrust = 20,000, Thrust Split = 0.5
Nozzle Area Ratio = 400

Mode 1 Thrust Chamber Pressure, psia	500	1000	2000
Total Engine Flow Rate, lb/sec	48.69	48.51	48.14
Oxygen Flow Rate, lb/sec	39.41	39.27	38.97
Hydrogen Flow Rate, lb/sec	2.73	2.72	2.71
RP-1 Flow Rate, lb/sec	6.55	6.52	6.46

	LOX Pump			LH_2 Pump			RP-1 Pump		
Discharge Pressure, psia	1000	2000	4500	1200	2200	4500	1000	2000	4500
Volumetric Flow Rate, GPM	249.1	248.3	246.4	278.5	277.5	276.5	58.92	58.65	58.11
Suction Specific Speed, (RPM) $(GPM)^{1/2}/(FT)^{3/4}$	20,000	20,000	20,000	8,000	8,000	8,000	20,000	20,000	20,000
Net Positive Suction Pressure, psia	44.4	88.8	113	37.8	37.7	37.6	39.0	38.9	38.6
Net Positive Suction Head, ft	90.1	180	229	1237	1234	1231	112.5	112.1	111.5
Speed, RPM	37,060	62,370	75,000	100,000	100,000	100,000	90,000	90,000	90,000
Total Head Rise, ft	1,938	3,876	8,898	38,040	70,770	152,600	2,773	5,659	12,880
No. of Stages	1	1	1	2	3	4	1	1	2
Specific Speed, (RPM) $(GPM)^{1/2}/(FT)^{3/4}$	2000	2000	1285	1030	875	609	1808	1056	954
Head Coefficient	.46	.46	.53	.56	.578	.612	.48	.555	.57
Tip Speed, ft/sec	368	521	735	1045	1146	1416	445	573	603
Impeller Tip Diameter, inches	2.27	1.91	2.24	2.39	2.62	3.24	1.13	1.46	1.54
Pump Efficiency, %	64	62.5	62	59.5	56.5	47	60	57.5	56

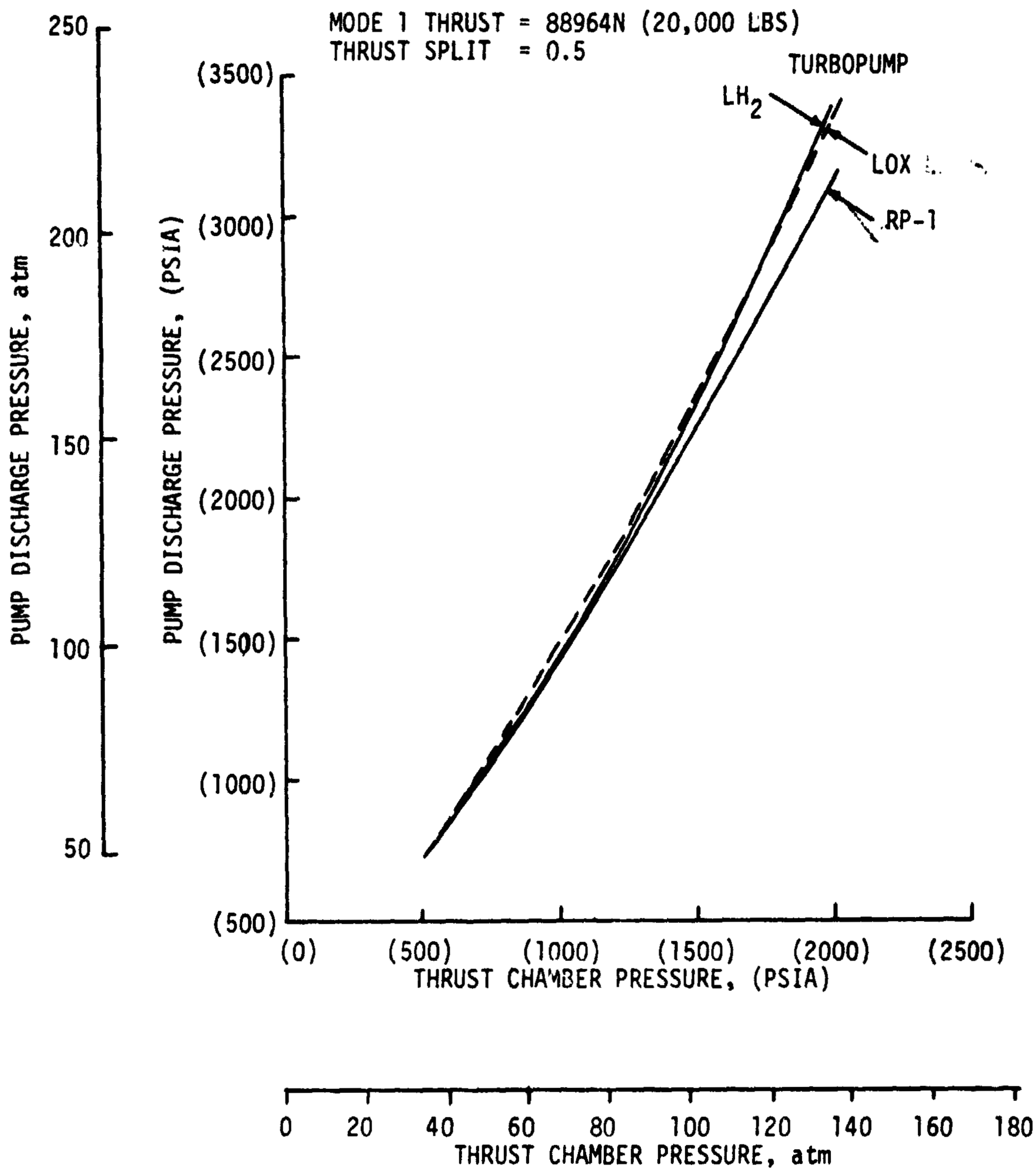


Figure 56. Tripropellant Engine Pump Discharge Pressure Requirements

TABLE XX. - TRIPROPELLANT ENGINE OPERATING SPECIFICATIONS

Mode 1
Thrust Split = 0.5

S.I. UNITS

Engine	
Vacuum Thrust, N	88,964
Vacuum Specific Impulse, sec	418.6
Total Flow Rate, kg/sec	21.67
Overall Mixture Ratio	4.25
Fraction of LH_2 to Total Fuel Flow	0.296
Oxygen Flow Rate, kg/sec	17.54
Hydrogen Flow Rate, kg/sec	1.22
RP-1 Flow Rate, kg/sec	2.91
Thrust Chamber	
Vacuum Thrust, N	88,964
Vacuum Specific Impulse, sec	418.6
Chamber Pressure, atm	136.0
Nozzle Area Ratio	400
Overall Mixture Ratio	4.25
Throat Diameter, cm	6.25
Chamber Diameter, cm	8.84
Nozzle Exit Diameter, cm	125.2
Coolant Jacket LH_2 Flow Rate, kg/sec	1.22
Coolant Inlet Temperature, °K	50
Coolant Exit Temperature, °K	328
Coolant Jacket ΔP, atm(1)	17.3
Injector Gas Flow Rates, kg/sec	
O_2/H_2 Fuel-Rich	1.84
O_2/H_2 Oxidizer-Rich	15.8[illegible]
O_2/RP-1 Fuel-Rich	3.98

(1) Combined Copper Chamber and Tube Bundle Pressure Drop

Preburners	O_2/H_2 Fuel-Rich	O_2/H_2 Ox-Rich	O_2/RP-1 Fuel-Rich
Chamber Pressure, atm	183.1	179.1	175.2
Combustion Temperature, °K	1033	922	1089
Mixture Ratio	0.71	110	0.37
Ox Flow Rate, kg/sec	0.764	15.705	1.075
Fuel Flow Rate, kg/sec	1.077	0.143	2.907

Turbines	LH_2 Turbopump	LOX Turbopump	RP-1 Turbopump
Inlet Pressure, atm	183.1	179.1	175.2
Inlet Temperature, °K	1033	922	1089
Gas Flow Rate, kg/sec	1.841	15.848	3.98
Gas Properties			
C_p, Specific Heat at Constant Pressure, cal/g°K	2.19	0.277	0.685
γ, Ratio of Specific Heats	1.358	1.312	1.132
Shaft Horsepower(1), mHP	1038	770	181.5
Efficiency, %	80	75	75
Pressure Ratio (Total to Static)	1.238	1.211	1.132

(1) Includes 3% horsepower penalty for boost pump hydraulic turbine drive flow.

Main Pumps	LH_2 Pump	LOX Pump	RP-1 Pump
Outlet Flow Rate, kg/sec	1.22	17.54	2.91
Volumetric Flow Rate, m^3/sec	.0173	.0154	.00364
NPSH, m	373	69.4	33.8
Suction Specific Speed, (RPM)$(m^3/sec)^{1/2}/(m)^{3/4}$	155	387	387
Speed, rpm	100,000	75,000	90,000
Discharge Pressure, atm	230.6	227.2	210.9
Head Rise, m	33,437	1,995	2,693
Number of Stages	4	1	2
Specific Speed (N_s), (RPM)$(m^3/sec)^{1/2}(m)^{3/4}$	15.0	31.2	24.4
Head Coefficient	0.59	0.497	0.535
Impeller Tip Speed, m/sec	373	198	157
Impeller Tip Diameter, cm	7.11	5.05	3.33
Efficiency, %	54	62.5	59.5

Weight and Envelope

Engine Weight = 252.7 kg

Engine Length:

Extendible Nozzle Deployed = 241.8 cm
Extendible Nozzle Stowed = 163.[illegible] cm

Engine Nozzle F[illegible] 125.2 cm

TABLE XX (cont.)

ENGLISH UNITS

Engine

Vacuum Thrust, lb	20,000
Vacuum Specific Impulse, sec	418.6
Total Flow Rate, lb/sec	47.78
Overall Mixture Ratio	4.25
Fraction of LH_2 to Total Fuel Flow	0.296
Oxygen Flow Rate, lb/sec	38.68
Hydrogen Flow Rate, lb/sec	2.69
RP-1 Flow Rate, lb/sec	6.41

Thrust Chamber

Vacuum Thrust, lb	20,000
Vacuum Specific Impulse, sec	418.6
Chamber Pressure, psia	2,000
Nozzle Area Ratio	400
Overall Mixture Ratio	4.25
Throat Diameter, in.	2.45
Chamber Diameter, in.	3.48
Nozzle Exit Diameter, in.	49.3
Coolant Jacket LH_2 Flow Rate, lb/sec	2.69
Coolant Inlet Temperature, °R	90
Coolant Exit Temperature, °R	590
Coolant Jacket ΔP, psi (1)	255
Injector Gas Flow Rates, lb/sec	
O_2/H_2 Fuel-Rich	4.06
O_2/H_2 Oxidizer-Rich	34.94
O_2/RP-1 Fuel-Rich	8.78

(1) Combined Copper Chamber and Tube Bundle Pressure Drop.

Preburners	O_2/H_2 Fuel-Rich	O_2/H_2 Ox-Rich	O_2/RP-1 Fuel-Rich
Chamber Pressure, psia	2631	2633	2575
Combustion Temperature, °R	1860	1660	1960
Mixture Ratio	0.71	110	0.37
Ox. Flow Rate, lb/sec	1.685	34.625	2.37
Fuel Flow Rate, lb/sec	2.375	.315	6.41

Turbines	LH_2 Turbopump	LOX Turbopump	RP-1 Turbopump
Inlet Pressure, psia	2691	2633	2575
Inlet Temperature, °R	1860	1660	1960
Gas Flow Rate, lb/sec	4.06	34.94	8.78
Gas Properties			
Cp, Specific Heat at Constant Pressure, Btu/lb °R	2.19	0.277	0.685
γ, Ratio of Specific Heats	1.358	1.312	1.132
Shaft Horsepower (1)	1024	759	179
Efficiency, %	80	75	75
Pressure Ratio (Total to Static)	1.238	1.211	1.132

(1) Includes 3% horsepower penalty for boost pump hydraulic turbine drive flow.

Main Pumps	LH_2 Pump	LOX Pump	RP-1 Pump
Outlet Flow Rate, lb/sec	2.69	38.68	6.41
Volumetric Flow Rate, GPM	274.4	244.5	57.66
NPSH, ft	1225	227.8	110.9
Suction Specific Speed, $(RPM)(GPM)^{1/2}/(FT)^{3/4}$	8000	20,000	20,000
Speed, rpm	100,000	75,000	90,000
Discharge Pressure, psia	3390	3340	3100
Head Rise, ft	109,700	6546	8835
Number of Stages	4	1	2
Specific Speed (N_s), $(RPM)(GPM)^{1/2}/(FT)^{3/4}$	777	1611	1261
Head Coefficient	0.59	0.497	0.[illegible]5
Impeller Tip Speed, ft/sec	1223	651	515
Impeller Tip Diameter, in.	2.80	1.99	1.31
Efficiency, %	54	62.5	59.5

Weight and Envelope

Engine Weight = 557 lb

Engine Length:

Extendible Nozzle Deployed = 95.2 in.
Extendible Nozzle Stowed = 64.2 in.

Engine Nozzle Exit Dia. = 49.3 in.

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TABLE XXI. - TRIPROPELLANT ENGINE PRESSURE SCHEDULE

MODE 1
Thrust Split = 0.5

Preburner	Fuel-Rich		Ox-Rich		Fuel-Rich	
Propellant / Pressure, atm (psia)	LOX	LH_2	LOX	LH_2	LOX	RP-1
Main Pump Discharge	227.2 (3340)	230.6 (3390)	227.2 (3340)	230.6 (3390)	227.2 (3340)	210.9 (3100)
ΔP Line	1.36 (20)	1.36 (20)	1.36 (20)	1.36 (20)	1.36 (20)	1.36 (20)
Shutoff Valve Inlet	225.8 (3320)	229.2 (3370)	225.8 (3320)	229.2 (3370)	225.8 (3320)	209.5 (3380)
ΔP Shutoff Valve	2.24 (33)	2.31 (34)	2.24 (33)	2.31 (34)	2.24 (33)	2.11 (31)
Shutoff Valve Outlet	223.6 (3287)	226.9 (3336)	223.6 (3287)	226.9 (3336)	223.6 (3287)	207.4 (3049)
ΔP Line	1.36 (20)	1.36 (20)	1.36 (20)	1.36 (20)	1.36 (20)	1.36 (20)
Coolant Jacket Inlet	-- (--)	225.6 (3316)	-- (--)	225.6 (3316)	-- (--)	-- (--)
ΔP Coolant Jacket	-- (--)	17.3 (255)	-- (--)	17.3 (255)	-- (--)	-- (--)
Coolant Jacket Outlet	-- (--)	208.2 (3061)	-- (--)	208.2 (3061)	-- (--)	-- (--)
ΔP Line	-- (--)	2.72 (40)	-- (--)	1.36 (20)	-- (--)	-- (--)
Preburner Control Inlet	222.2 (3267)	205.5 (3021)	222.2 (3267)	206.9 (3041)	222.2 (3267)	-- (--)
ΔP Control	6.87 (101)	6.53 (96)	11.5 (169)	12.2 (179)	16.2 (238)	-- (--)
Preburner Inlet	215.3 (3166)	199.0 (2925)	210.7 (3098)	194.7 (2862)	206.0 (3029)	206.0 (3029)
ΔP Preburner	32.3 (475)	15.9 (234)	31.6 (465)	15.6 (229)	30.8 (454)	30.8 (454)
Turbine Inlet	183.1 (2691)		179.1 (2633)		175.2 (2575)	
ΔP Turbine (Total to Static)	35.2 (517)		31.2 (459)		20.4 (300)	
Check Valve Inlet	-- (--)		-- (--)		154.8 (2275)	
ΔP Check Valve	-- (--)		-- (--)		6.9 (101)	
Main Injector Inlet	147.9 (2174)		147.9 (2174)		147.9 (2174)	
ΔP Injector	11.9 (174)		11.9 (174)		11.9 (174)	
Chamber Pressure	136.0 (2000)		136.0 (2000)		136.0 (2000)	

TABLE XXII. - TRIPROPELLANT ENGINE OPERATING SPECIFICATIONS

Mode 2
Thrust Split = 0.5

S.I. UNITS

Engine	
Vacuum Thrust, N	44,104
Vacuum Specific Impulse, sec	460.6
Total Flow Rate, kg/sec	9.77
Overall Mixture Ratio	7.0
Fraction of LH_2 to Total Fuel Flow	1.0
Oxygen Flow Rate, kg/sec	8.55
Hydrogen Flow Rate, kg/sec	1.22
RP-1 Flow Rate, kg/sec	--
Thrust Chamber	
Vacuum Thrust, N	44,104
Vacuum Specific Impulse, sec	460.6
Chamber Pressure, atm	68.5
Nozzle Area Ratio	400
Overall Mixture Ratio	7.0
Throat Diameter, cm	6.25
Chamber Diameter, in.	8.84
Nozzle Exit Diameter, in.	125.2
Coolant Jacket LH_2 Flow Rate, kg/sec	1.22
Coolant Inlet Temperature, °K	50
Coolant Exit Temperature, °K	328
Coolant Jacket ΔP, atm	17.3
Injector Gas Flow Rates, kg/sec	
O_2/H_2 Fuel-Rich	1.97
O_2/H_2 Oxidizer-Rich	7.80
O_2/RP-1 Fuel Rich	--

Preburners	O_2/H_2 Fuel-Rich	O_2/H_2 Ox-Rich
Chamber Pressure, atm	92.65	85.99
Combustion Temperature, °K	1033	922
Mixture Ratio	0.71	110
Ox Flow Rate, kg/sec	0.82	7.73
Fuel Flow Rate, kg/sec	1.15	0.07

Turbines	LH_2 Turbopump	LOX Turbopump
Inlet Pressure, atm	92.65	85.99
Inlet Temperature, °K	1033	922
Gas Flow Rate, kg/sec	1.97	7.80
Gas Properties		
C_p, Specific Heat at Constant Pressure, Cal/g°K	2.19	0.277
γ, Ratio of Specific Heats	1.358	1.312
Shaft Horsepower(1), hp	658.1	249.9
Efficiency, %	77	72
Pressure Ratio (Total to Static)	1.139	1.149

(1) Includes 3% horsepower penalty for boost pump hydraulic turbine drive flow.

Main Pumps	LH_2 Pump	LOX Pump
Outlet Flow Rate, kg/sec	1.22	8.55
Volumetric Flow Rate, m^3/sec	.0173	.00751
NPSH, m	373	34.9
Suction Specific Speed, $(RPM)(m^3/sec)/(m)^{3/4}$	139	347
Speed, rpm	90,000	56,270
Discharge Pressure, atm	141.9	138.5
Head Rise, m	20,420	1,225
Number of Stages	4	1
Specific Speed (N_s), $(RPM)(m^3/sec)/(m)^{3/4}$	19.6	23.6
Head Coefficient	0.575	0.54
Impeller Tip Speed, m/sec	335	149
Impeller Tip Diameter, cm	7.11	5.05
Efficiency, %	52	57.5

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TABLE XXII (cont.)

ENGLISH UNITS

Engine	
Vacuum Thrust, lb	9915
Vacuum Specific Impulse, sec	460.6
Total Flow Rate, lb/sec	21.53
Overall Mixture Ratio	7.0
Fraction of LH_2 to Total Fuel Flow	1.0
Oxygen Flow Rate, lb/sec	18.84
Hydrogen Flow Rate, lb/sec	2.69
RP-1 Flow Rate, lb/sec	--

Thrust Chamber	
Vacuum Thrust, lb	9915
Vacuum Specific Impulse, sec	460.6
Chamber Pressure, psia	1007
Nozzle Area Ratio	400
Overall Mixture Ratio	7.0
Throat Diameter, in.	2.46
Chamber Diameter, in.	3.48
Nozzle Exit Diameter, in	49.2
Coolant Jacket LH_2 Flow Rate, lb/sec	2.69
Coolant Inlet Temperature, °R	90
Coolant Jacket Exit Temperature, °R	590
Coolant Jacket ΔP, psi	255
Injector Gas Flow Rates, lb/sec	
O_2/H_2 Fuel-Rich	4.335
O_2/H_2 Oxidizer-Rich	17.195
O_2/RP-1 Fuel-Rich	--

Preburners	O_2/H_2 Fuel-Rich	O_2/H_2 Ox-Rich
Chamber Pressure, psia	1362	1264
Combustion Temperature, °R	1860	1660
Mixture Ratio	0.71	110
Ox Flow Rate, lb/sec	1.800	17.04
Fuel Flow Rate, lb/sec	2.535	0.155

Turbines	LH2 Turbopump	LOX Turbopump
Inlet Pressure, psia	1362	1264
Inlet Temperature, °R	1860	1660
Gas Flow Rate, lb/sec	4.335	17.195
Gas Properties		
C_p, Specific Heat at Constant Pressure Btu/lb °R	2.19	0.277
γ, Ratio of Specific Heats	1.358	1.312
Shaft Horsepower(1)	649.1	246.5
Efficiency, %	77	72
Pressure Ratio (Total to Static)	1.139	1.140

(1) Includes 3% horsepower penalty for boost pump hydraulic turbine drive flow.

Main Pumps	LH_2 Pump	LOX Pump
Outlet Flow Rate, lb/sec	2.69	18.84
Volumetric Flow Rate, gpm	274.4	119.1
NPSH, ft	1225	111.5
Suction Specific Speed, $(RPM)(GPM)^{1/2}/(FT)^{3/4}$	7200	17,300
Speed, rpm	90,000	56,270
Discharge Pressure, psia	2086	2036
Head Rise, ft	67,000	4,018
Number of Stages	4	1
Specific Speed (N_s), $(RPM)(GPM)^{1/2}/(FT)^{3/4}$	1013	1217
Head Coefficient	0.575	0.54
Impeller Tip Speed, ft/sec	1100	489
Impeller Tip Diameter, in.	2.80	1.99
Efficiency, %	52	57.5

Table XXIII. Thi table shows that the oxygen-rich preburner oxygen injection pressure drop decreases from a design point 15% of the upstream pressure to 8.4%. This problem could be solved by redistributing pressure drop between control valve and the injector. However, this solution would result in higher Mode 1 pump discharge pressure requirements and heavier turbomachinery.

Baseline engine weight and envelope data are also shown on Table XX. The weights were obtained by scaling of historical component data with thrust, pressure, surface area, dimensions, etc. Detailed component weight breakdowns and dimensions are presented in the next section under Task IV.

Based upon the cycle analyses and a comparison of the Mode 1 and 2 pressure schedules, the following control requirement conclusions were reached. Preburner controls in the O_2/H_2 fuel-rich preburner should be simple orifices to minimize pressure drop requirements. Control valves are required in the fuel and oxidizer feed lines for the O_2/H_2 oxidizer-rich preburner to properly distribute flow and balance the engine in Mode 2. Either a control valve or an orifice can be used in the oxidizer line of the O_2/RP-1 fuel-rich preburner. A hot-gas check valve is required between the RP-1 TPA and main injector to prohibit main chamber combustion products from backing through the turbopump shaft and into the suction line when the RP-1 pump is inactive (Mode 2). Main propellant shutoff valves are placed in the lines just downstream of the turbopumps. These control requirements have been identified on Figures 51 and 52.

The effect of thrust split upon the engine cycle power balance was also investigated. The results of these analyses are shown on Figures 57, 58 and 59.

Figure 57 shows the effect of thrust split upon the hydrogen pump discharge pressure requirements. Hydrogen pump discharge pressure requirements at thrust splits of 0.4 and 0.5 are almost equal. Fuel pump horsepower requirements at a thrust split of 0.4 are higher but the fuel preburner flow rate is also higher. This actually results in a reduced hydrogen pump turbine pressure ratio at a thrust split of 0.4. A slightly higher coolant jacket pressure drop requirement at a thrust split of 0.4 results in the small increase in pump discharge pressure at a fixed chamber pressure. For example, at a chamber pressure of 136 atm (2000 psia), the hydrogen pump discharge pressure requirements are 231 and 233 atm (3390 and 3420 psia) at thrust splits of 0.5 and 0.4, respectively. Coolant jacket pressure drops at 136 atm (2000 psia) chamber pressure are 17.3 and 20 atm (255 and 295 psi) at thrust splits of 0.5 and 0.4, respectively.

TABLE XXIII. - TRIPROPELLANT ENGINE PRESSURE SCHEDULE

MODE 2
Thrust Split = 0.[illegible]

Preburner / Propellant / Pressure, atm (psia)	Fuel-Rich LOX	Fuel-Rich LH_2	Ox-Rich LOX	Ox-Rich LH_2
Main Pump Discharge	138.5 (2036)	141.9 (2086)	138.5 (2036)	141.9 (2086)
ΔP Line	.34 (5)	1.36 (20)	.34 (5)	1.36 (20)
Shutoff Valve Inlet	138.2 (2031)	140.5 (2066)	138.2 (2031)	140.5 (2066)
ΔP Shutoff Valve	.54 (8)	2.31 (34)	.54 (8)	2.31 (34)
Shutoff Valve Outlet	137.6 (2023)	138.2 (2032)	137.6 (2023)	138.2 (2032)
ΔP Line	.34 (5)	1.36 (20)	.34 (5)	1.36 (20)
Coolant Jacket Inlet	-- (--)	136.8 (2012)	-- (--)	136.8 (2012)
ΔP Coolant Jacket	-- (--)	17.3 (255)	-- (--)	17.3 (255)
Coolant Jacket Outlet	-- (--)	119.5 (1757)	-- (--)	119.5 (1757)
ΔP Line	-- (--)	2.93 (43)	-- (--)	0.7 (10)
Preburner Control Inlet	137.3 (2018)	116.6 (1714)	137.3 (2018)	118.8 (1747)
ΔP Control	7.8 (115)	6.9 (102)	44.8 (659)	26.3 (386)
Preburner Inlet	129.5 (1903)	109.7 (1612)	92.5 (1359)	92.5 (1359)
ΔP Preburner	36.8 (541)	17.0 (250)	7.7 (113)	7.7 (113)
Turbine Inlet	92.7 (1362)		84.8 (1246)	
ΔP Turbine (Total to Static)	11.3 (166)		10.4 (153)	
Check Valve Inlet	-- (--)		-- (--)	
ΔP Check Valve	-- (--)		-- (--)	
Main Injector Inlet	81.4 (1196)		74.4 (1093)	
ΔP Injector	12.9 (189)		5.9 (86)	
Chamber Pressure	68.5 (1007)		68.5 (1007)	

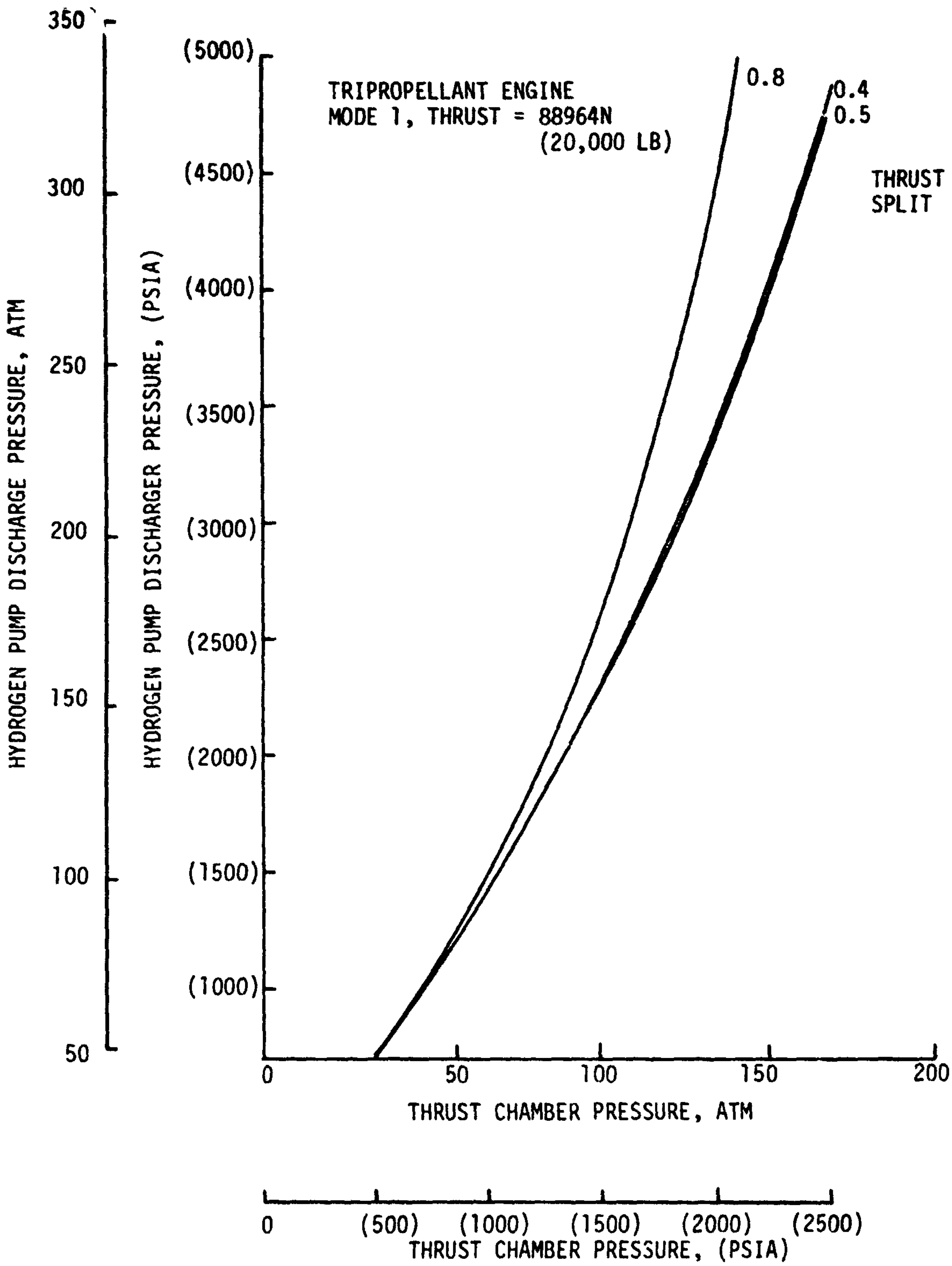

Figure 57. Effect of Thrust Split Upon Hydrogen Pump Discharge Pressure Requirements

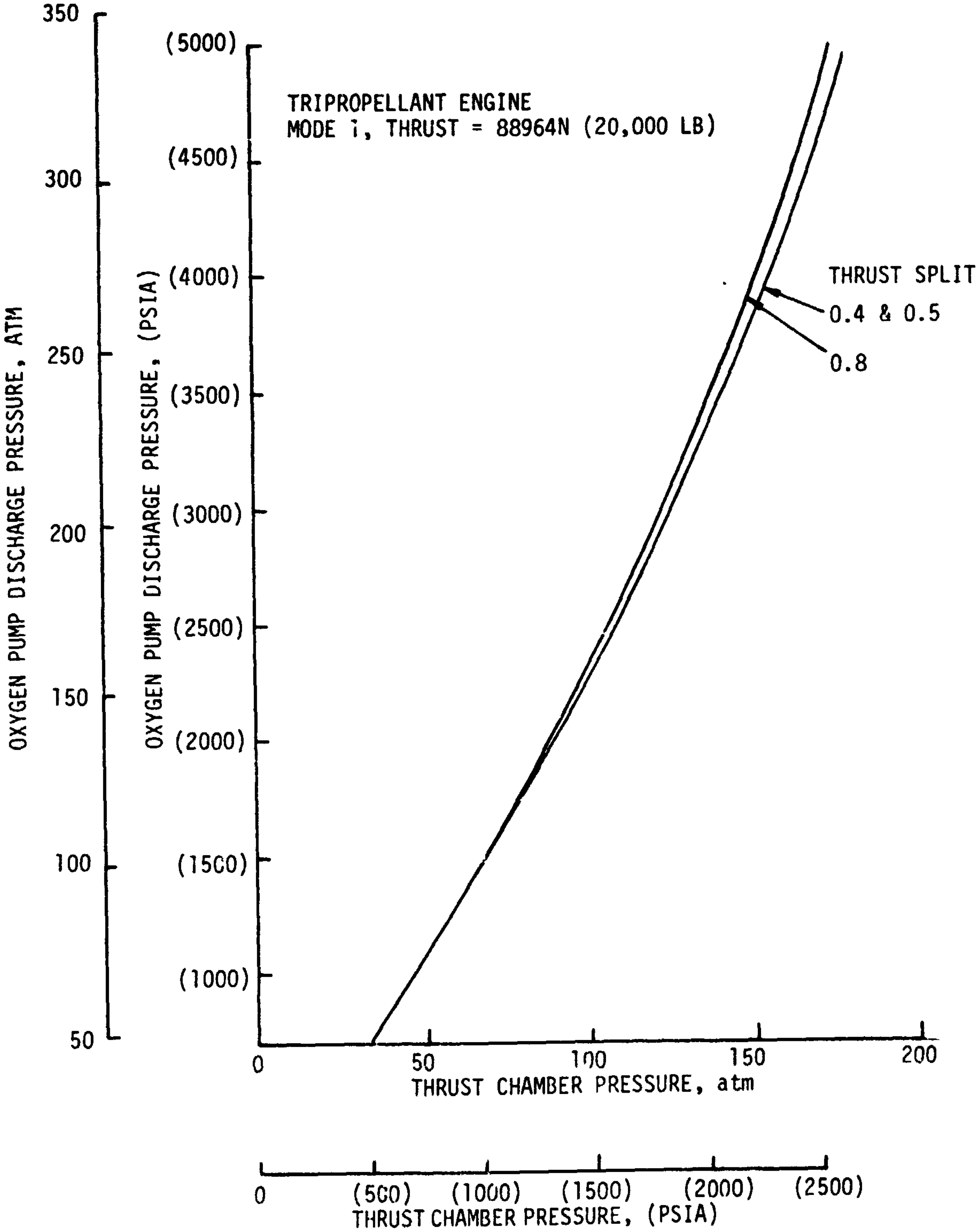

Figure 58. Effect of Thrust Split Upon Oxygen Pump Discharge Pressure Requirements

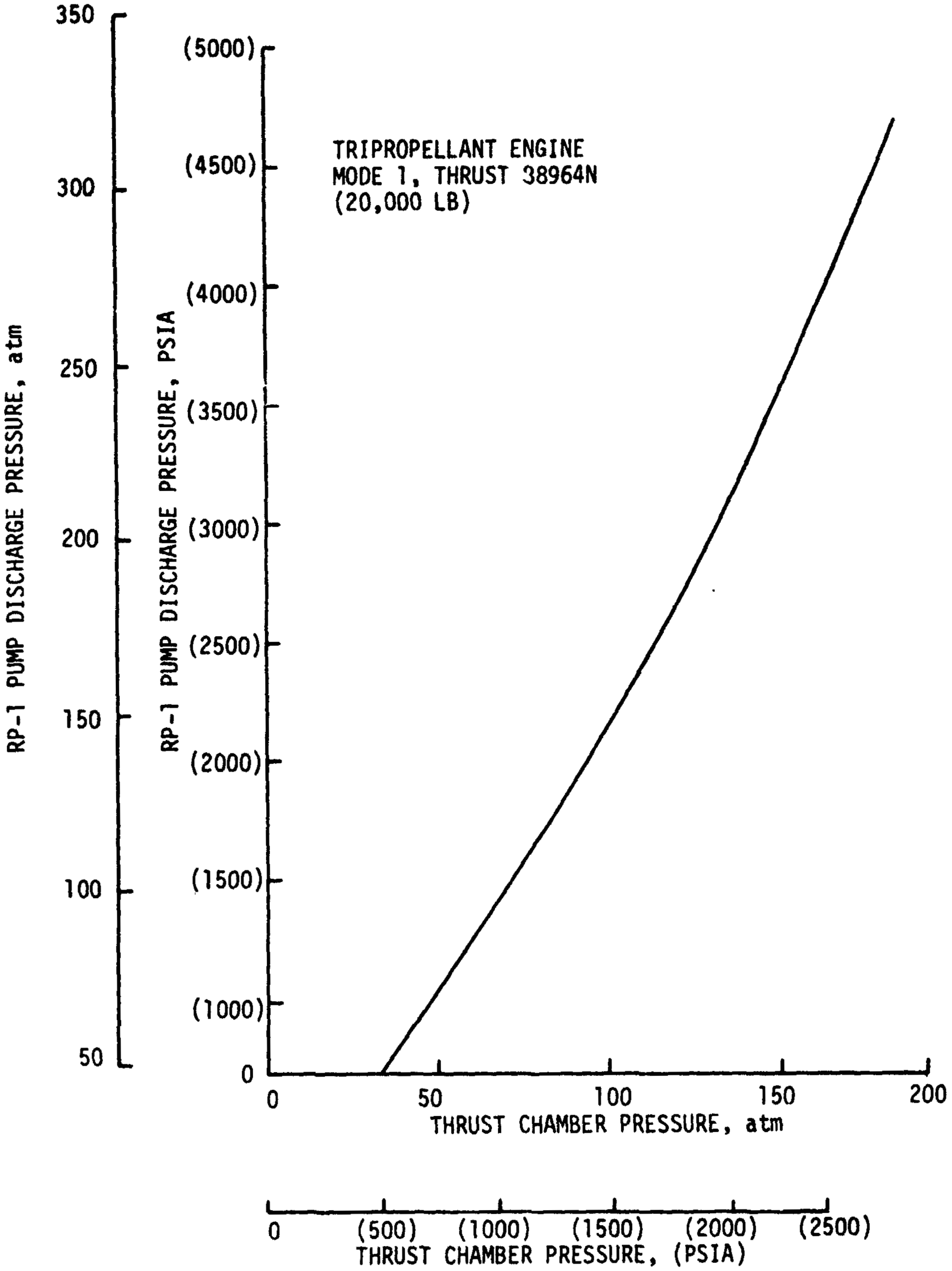

Figure 59. RP-1 Pump Discharge Pressure Requirements for All Thrust Splits

At a thrust split of 0.8, the hydrogen flow is reduced substantially. The fuel pump turbine pressure ratio is slightly larger for a given pump discharge pressure because the turbine horsepower to flow rate ratio increases. The coolant jacket pressure drop requirement for a fixed thrust chamber pressure is also much greater. For example, at a thrust chamber pressure of 136 atm (2000 psia), the coolant jacket pressure drop is 68 atm (1000 psi) at a thrust split of 0.8. These effects result in increased hydrogen pump discharge pressure requirements. However, even at a thrust split of 0.8, the cycle is not power balance limited.

Figure 58 shows the effect of thrust split upon the oxidizer pump discharge pressure requirements. The effect is almost negligible. The total oxidizer flow rate and oxidizer-rich preburner total flow rates are almost constant as a function of thrust split. At a thrust split of 0.8, the oxidizer flow must be pumped to a pressure high enough to meet the turbine inlet pressure requirements which are fixed by the fuel side pressure drops.

Because all of the RP-1 is combusted in a fuel-rich preburner to drive the RP-1 turbopump, the total preburner flow increases almost directly with the RP-1 flow rate. Therefore, thrust split does not affect the RP-1 pump discharge pressure requirements. The RP-1 pump discharge pressure data is shown on Figure 59.

2. Dual-Expander Engine

Initial power balance analyses were conducted at the nominal Mode 1 thrust level of 88964N (20,000 lb) and a thrust split of 0.5. The effect of thrust split upon the power balance was also established. With the discharge pressure requirements and operating chamber pressure identified, baseline performance, weight, and envelope data were determined.

Simplified dual-expander engine cycle schematics are shown on Figures 60 and 61 for Mode 1 and 2 operation, respectively. During Mode 1 operation the preburner hot gas control valves split the preburner gas flow rates to the turbines. In Mode 2 operation, these preburner hot gas control valves provide the proper flow rates to the hydrogen and oxygen pump turbines and bypass the flows previously used to drive the RP-1 pump turbine and Mode 1 oxygen pump turbine. Hot gas check valves are shown between the Mode 1 TPA turbines and the main injector to prohibit main chamber combustion products from backing through the turbopump shaft and up the pump suction line when these turbopumps are inoperative in Mode 2. Main shutoff valves are also provided in each pump discharge line.

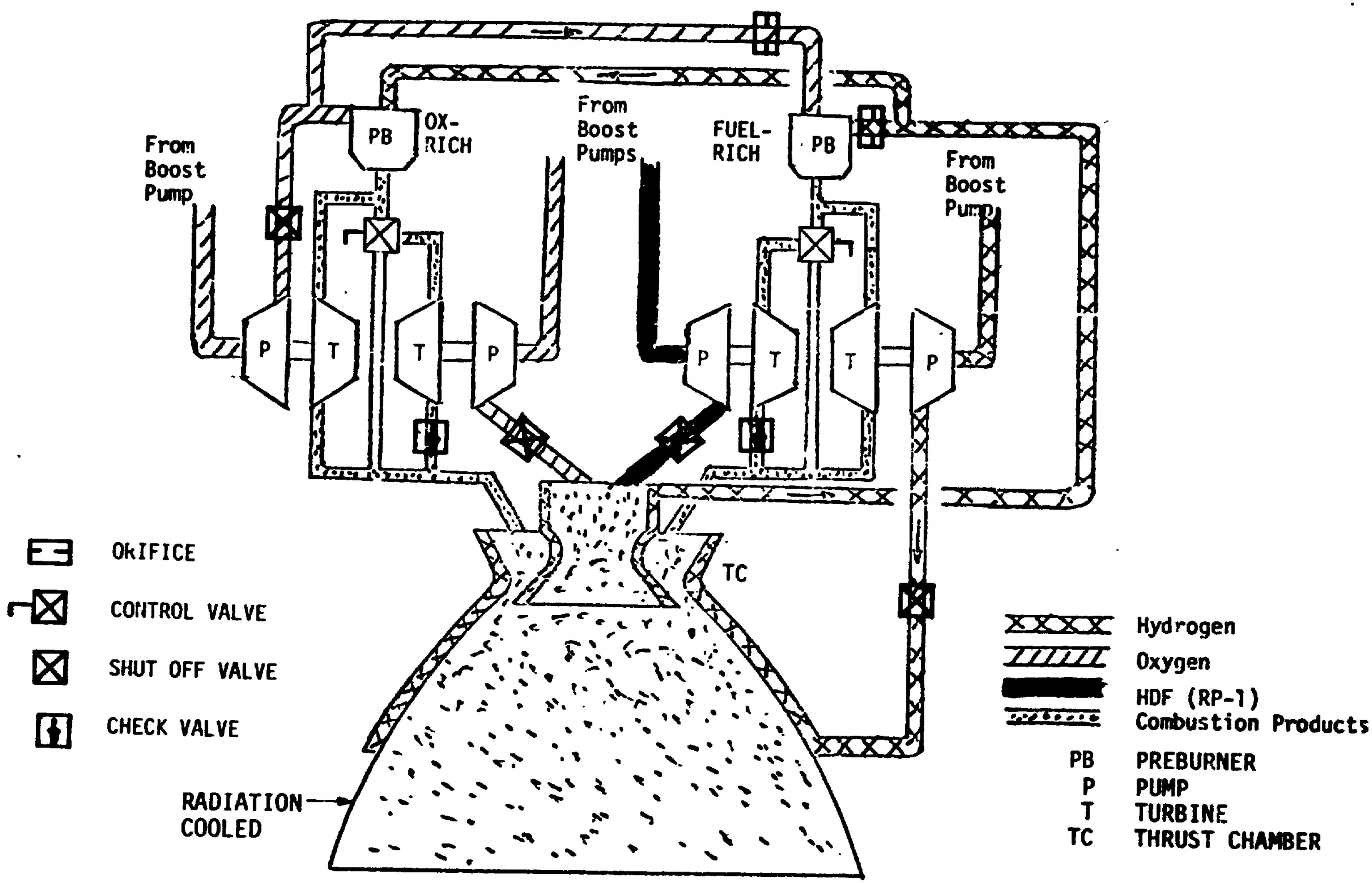

Figure 60. Mode 1 Dual-Expander Engine Schematic

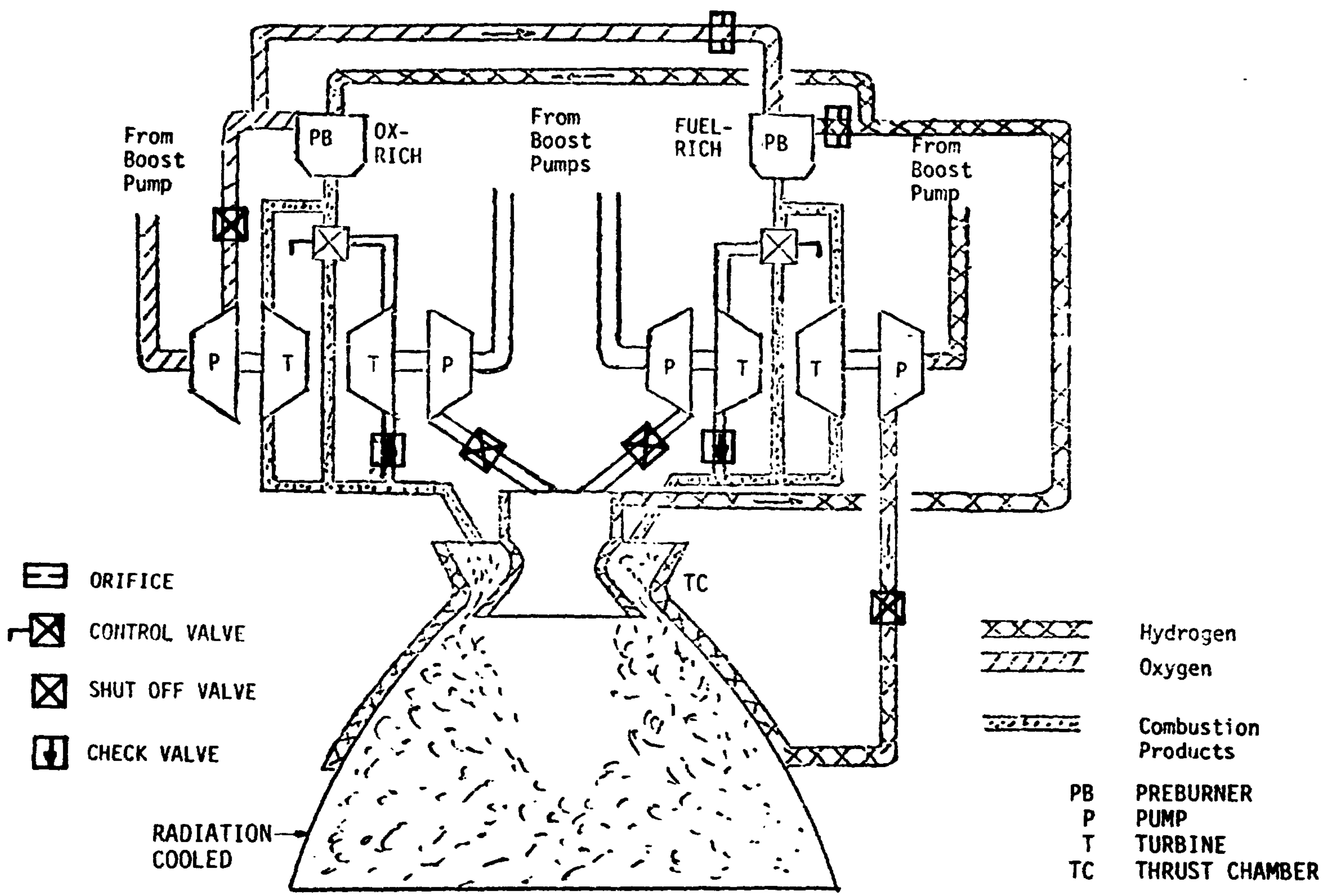

Figure 61. Mode 2 Dual-Expander Engine Schematic

Pump efficiencies used in the power balance analyses were derived as described for the tripropellant engine in Section V,B,1. Design point turbine efficiencies were estimated as:

LH_2 TPA - 80%

LOX TPAs - 70%

RP-1 TPA - 60%

The coolant jacket pressure drop and coolant outlet temperature data required in the power balance analysis was established in Task II. This data showed that the maximum operating chamber pressure of the dual-expander engine is cooling limited. However, for the parametric power balance analyses, it was assumed that the limits could be exceeded and the pressure drop and coolant outlet temperature data at higher thrust splits and pressures were estimated from the Task II data. It was assumed that cooling could be accomplished within the bulk temperature, 756°K (1360°R), limit and the coolant Mach number of 0.5 exceeded. The values used in the power balance analyses are:

Thrust Split	Central Chamber Pressure, atm (psia)	Annular Chamber Pressure, atm (psia)	Coolant Jacket Pressure Drop, atm (psia)	Coolant Outlet Temp., °K (°R)
0.4	34 (500)	17 (250)	.54 (8)	492 (885)
	68 (1000)	34 (500)	4.49 (66)	507 (913)
	102 (1500)	51 (750)	24.5 (360)	519 (935)
	136 (2000)	68 (1000)	74.8 (1100)	533 (960)
0.5	34 (500)	17 (250)	1.09 (16)	602 (1083)
	68 (1000)	34 (500)	9.86 (145)	615 (1107)
	102 (1500)	51 (750)	45.6 (670)	628 (1131)
	136 (2000)	68 (1000)	136 (2000)	642 (1155)
0.8	34 (500)	17 (250)	6.80 (100)	756 (1360)
	68 (1000)	34 (500)	19.7 (290)	756 (1360)
	102 (1500)	51 (750)	57.1 (840)	756 (1360)
	136 (2000)	68 (1000)	163 (2400)	756 (1360)

Based upon the above coolant data and turbine inlet temperature requirements, the following preburner mixture ratios were established to obtain the turbine drive gas properties.

Thrust Split	Central Chamber Pressure, atm (psia)	Fuel-Rich Preburner MR	Ox-Rich Preburner MR	Turbine Inlet Temperatures, °K (°R) Fuel-Rich	Ox-Rich
0.4	34 (500)	0.53	110	1033 (1860)	922 (1660)
	68 (1000)	0.51			
	102 (1500)	0.50			
	136 (2000)	0.50			
0.5	34 (500)	0.42			
	68 (1000)	0.41			
	102 (1500)	0.40			
	136 (2000)	0.40			
0.8	34 (500)	0.27			
	68 (1000)				
	102 (1500)				
	136 (2000)				

The power balance analyses results are displayed in Figures 62 through 65.

Figure 62 shows the LOX/RP-1 system pump discharge pressure as a function of the central chamber thrust chamber pressure. Because the turbines for the pumps are driven in a mode of operation similar to a gas generator engine cycle, the pump discharge pressures required are only a function of the chamber pressure. Thrust split has no effect.

The hydrogen pump and oxygen pump discharge pressure requirements for the LOX/LH_2 system are shown on Figure 63 at a thrust split of 0.5. The hydrogen pump discharge pressure is much greater than the oxygen pump because of the ΔP incurred in the coolant jacket. Because the pumps for the LOX/LH_2 system are driven in a staged combustion cycle mode of operation, the discharge pressures are a function of the turbine pressure ratios. The analyses showed that the oxygen turbopump turbine pressure ratio was greater than the hydrogen turbopump turbine pressure ratio. Therefore, the oxygen-rich preburner circuits govern the power balance. This also means that the preburner controls should be placed in the fuel-rich preburner because additional pressure drop is available. Simple balancing orifices are shown in these circuits on the schematics. However, the excess pressure available is enough to accommodate a liquid oxygen control valve and almost enough for a hydrogen gas control valve.

Figure 63 also shows that the discharge pressure requirements for the engine are not unreasonable and the cycle is not power balance limited up to a chamber pressure of 68 atm (1000 psia) at a thrust split of 0.5.

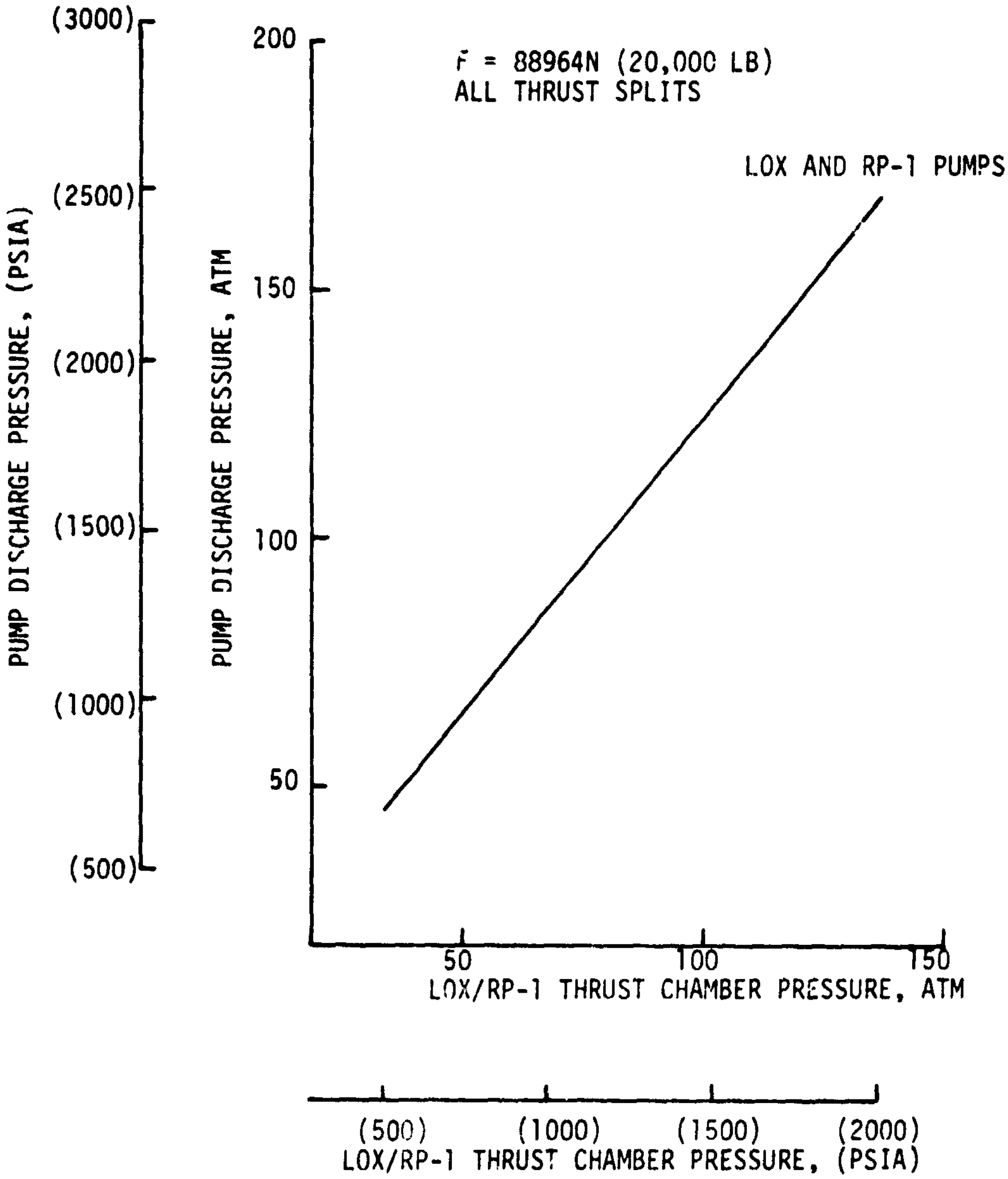

Figure 62. Pump Discharge Pressure Requirements for Dual-Expander Engine LOX/RP-1 System

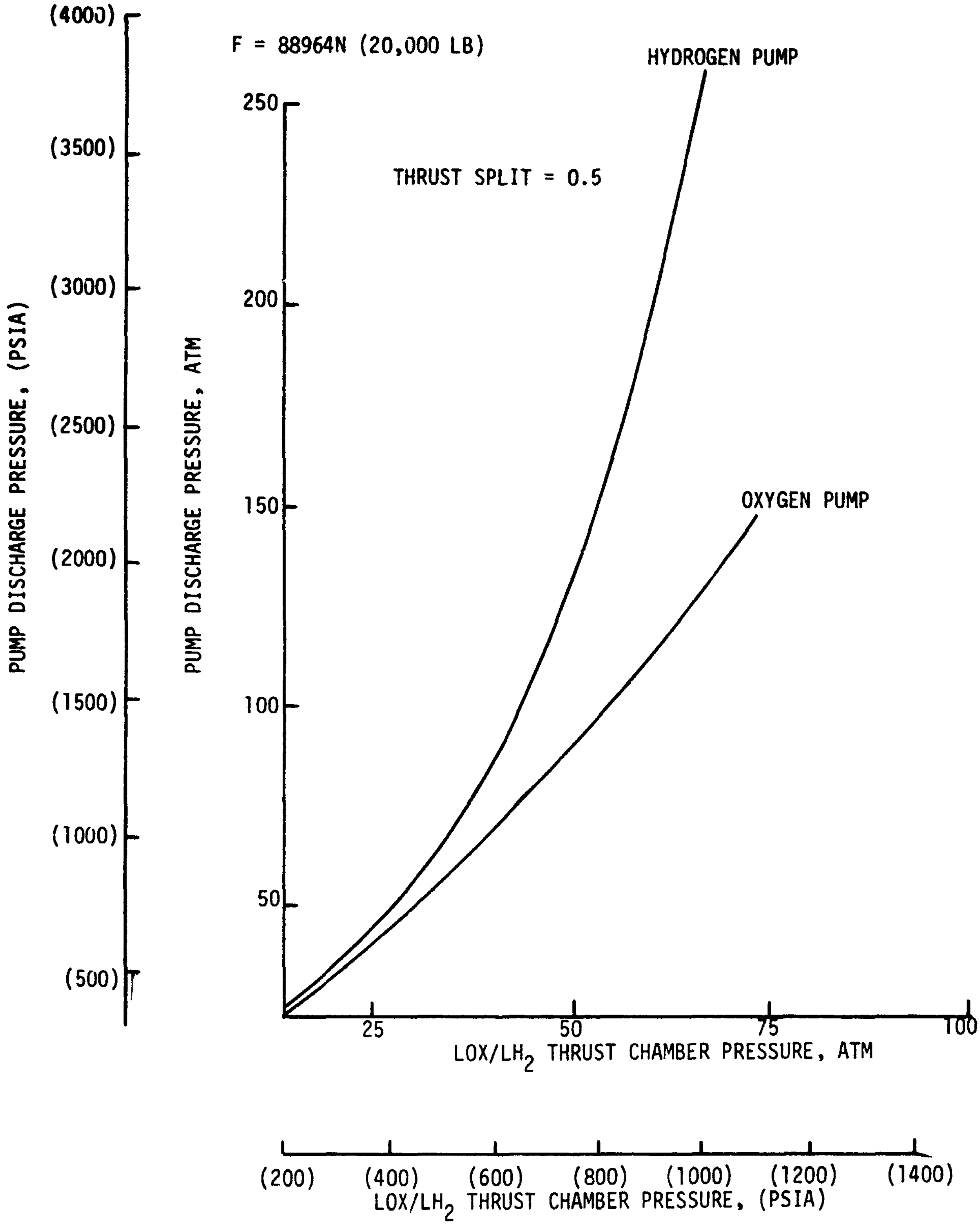

Figure 63. Pump Discharge Pressure Requirements for Dual-Expander Engine LOX/LH_2 System

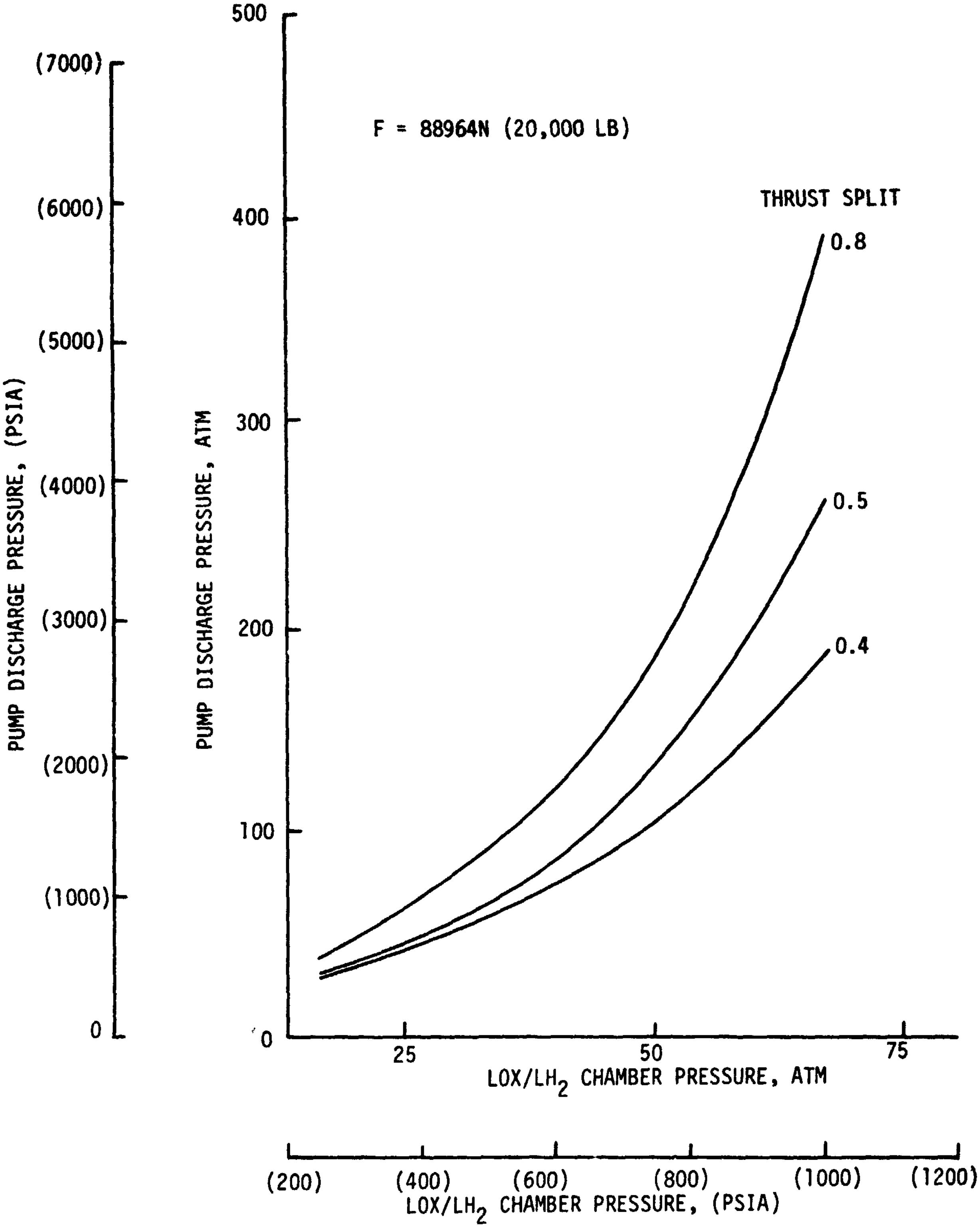

Figure 64. Effect of Thrust Split Upon Hydrogen Pump Discharge Pressure, Dual-Expander Engine

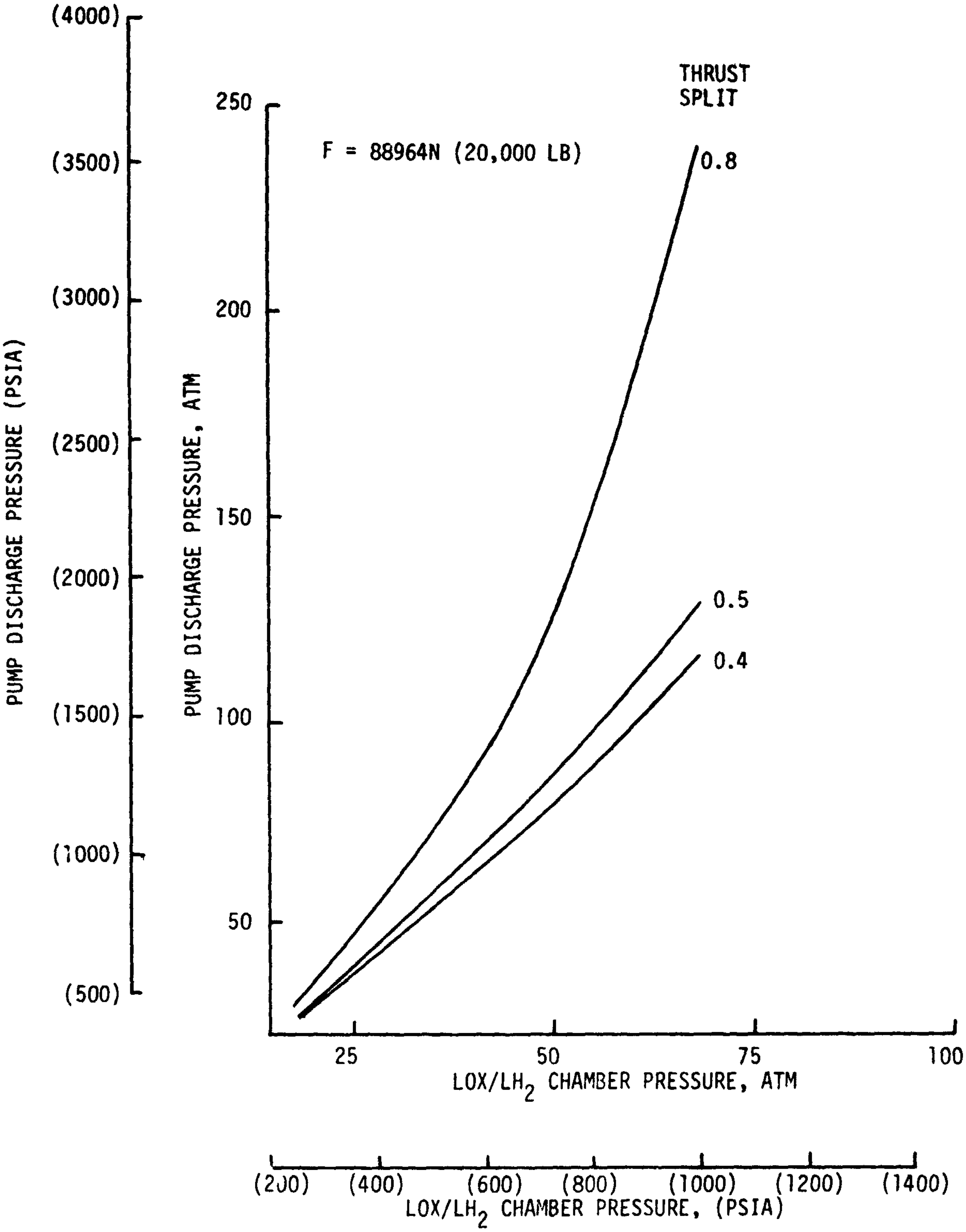

Figure 65. Effect of Thrust Split Upon LOX/LH_2 Oxygen Pump Discharge Pressure, Dual-Expander Engine

The effect of thrust split upon the hydrogen pump and LOX/LH_2 system oxygen pump discharge pressure requirements are shown on Figures 64 and 65, respectively. The required discharge pressures increase with increasing thrust split because the total preburner flow rate used to drive all four pumping systems decreases as thrust split increases (i.e., only the LOX/LH_2 system flows are precombusted and used as turbine drive gases). The cycle is not power balance limited but is very marginal at a thrust split of 0.8 and a LOX/LH_2 system chamber pressure of 68 atm (1000 psia). A turbine pressure ratio in excess of 2.5 is required for the oxygen turbopump which is high for a staged combustion cycle.

Because the engine is cooling limited, the maximum operating thrust chamber pressures selected for the LOX/RP-1 central chamber and LOX/LH_2 annular chamber are 74.8 and 37.4 atm (1100 and 550 psia), respectively at the baseline thrust split of 0.5. The baseline dual-expander engine and component preliminary operating specifications for these maximum chamber pressures are shown on Table XXIV. During Mode 2 operation, the LOX/RP-1 system turbopumps are shutdown. The preburner and LOX/LH_2 pump and turbine operating parameters in Mode 2 are the same as in Mode 1. The preburner flow rates used to drive the LOX/RP-1 system pumps bypass the turbines and are delivered to the annular thrust chamber. Only some of the thrust chamber parameters change in Mode 2 due to the area ratio amplification and non-operating central chamber as shown on Table XXV.

The pressure schedule for the baseline dual-expander engine which resulted from the study system pressure loss guidelines and the cycle power balance analysis is shown on Table XXVI. From this table it can be noted that the power balance is governed by the LOX TPAs turbine pressure ratios. Therefore, the preburner flow controls are shown in the fuel-rich preburner circuits. The ΔP across these controls is 7.4% of the upstream pressure.

The pump discharge pressure requirements determined through the power balance analyses were incorporated in the engine parametric data model so that weight effects were accounted for with changing discharge pressures. Baseline engine weight, envelope and performance data are also shown on Table XXIV for this engine concept.

3. Plug Cluster Engine

Power balance analyses were conducted and weight, envelope, and performance data were also established at the nominal Mode 1 thrust level of 88964N (20,000 lb) and a thrust split of 0.5 for the mixed-mode plug cluster concept.

TABLE XXIV. - BASELINE DUAL-EXPANDER ENGINE OPERATING SPECIFICATIONS, MODE 1

Thrust Split = 0.5

S.I. UNITS

Engine	LOX/RP-1	LOX/LH_2	COMBINED LOX/RP-1 & LH_2
Vacuum Thrust, N	44,482	44,482	88,964
Vacuum Specific Impulse, sec	372.1	441.1	403.6
Total Flow Rate, kg/sec	12.19	10.28	22.47
Mixture Ratio	3.1	7.0	4.26
Oxygen Flow Rate, kg/sec	9.22	9.00	18.22
RP-1 Flow Rate, kg/sec	2.97	--	2.97
Hydrogen Flow Rate, kg/sec	--	1.28	1.28
Thrust Chamber			
Vacuum Thrust, N	44,482	44,482	88,964
Vacuum Specific Impulse, sec	372.1	441.1	403.6
Chamber Pressure, atm	74.8	37.4	--
Nozzle Area Ratio	316.5	141.8	200
Throat Area, cm^2	27.74	58.90	86.64
Coolant Jacket LH_2 Flow Rate, kg/sec	--	--	1.28
Coolant Inlet Temperature, °K	--	--	50
Coolant Exit Temperature, °K	--	--	617
Coolant Jacket ΔP, atm	--	--	14.3
Injector Flow Rates, kg/sec			
Oxygen	9.22	--	9.22
RP-1	2.97	--	2.97
O_2/H_2 Fuel-Rich Gas	--	1.69	1.69
O_2/H_2 Ox-Rich Gas	--	8.59	8.59

Preburners	O_2/H_2 Fuel-Rich	O_2/H_2 Ox-Rich
Chamber Pressure, atm	47.2	51.0
Combustion Temp., °K	1033	922
Mixture Ratio	0.4	110
Ox. Flow Rate, kg/sec	0.48	8.518
Fuel Flow Rate, kg/sec	1.21	0.077

Turbines	RP-1 Turbopump	LH_2 Turbopump	LOX/RP-1 LOX Turbopump	LOX/LH_2 LOX Turbopump
Inlet Pressure, atm	42.5	47.2	45.9	51.0
Inlet Temperature, °K	1033	1033	922	922
Gas Flow Rate, kg/sec	1.02	0.67	6.49	2.10
Gas Properties				
Cp, Specific heat at constant pressure, Cal/g°K	2.60	2.60	0.277	0.277
γ, Ratio of specific heats	1.363	1.363	1.312	1.312
Shaft Horsepower[(1)], mHP	80.94	315.4	169.0	109.5
Efficiency, %	60	80	70	70
Pressure Ratio (Total to Static)	1.033	1.16	1.115	1.248

(1) Includes 3% Horsepower penalty for boost pump drive flow.

Main Pumps	RP-1 Pump	LOX/RP-1 LOX Pump	LOX/LH_2 LOX Pump	LH_2 Pump
Outlet Flow Rate, kg/sec	2.97	9.22	9.00	1.28
Volumetric Flow Rate, m^3/sec	.00372	.00811	.00791	.0182
NPSH, m	34.3	38.2	25.5	386
Suction Specific Speed, $(RPM)(m^3/sec)^{1/2}/(m)^{3/4}$	387	387	387	155
Speed, RPM	90,000	66,080	49,470	100,000
Discharge Pressure, atm	94.55	94.55	63.27	75.85
Head Rise, m	1188	821	549	10,736
Number of Stages	1	1	1	2
Specific Speed (N_s), $(RPM)(m^3/sec)^{1/2}/(m)^{3/4}$	27.1	38.7	38.7	21.5
Head Coefficient	0.52	0.46	0.46	0.55
Impeller Tip Speed, m/sec	150	132	108	309
Impeller Tip Diameter, cm	3.18	3.84	4.17	5.89
Efficiency, %	60	61.5	62	60

Weight and Envelope

Engine Weight = 249.5 kg

Engine Length = 228.1 cm

Engine Exit Dia. = 148.6 cm

TABLE XXIV (cont.)

[illegible]

Engine	LOX/RP-1	LOX/LH_2	Combined LOX/RP-1 & LH_2
Vacuum Thrust, lb	10,000	10,000	20,000
Vacuum Specific Impulse, sec	372.1	441.1	403.6
Total Flow Rate, lb/sec	26.88	22.67	49.55
Mixture Ratio	3.1	7.0	4.26
Oxygen Flow Rate, lb/sec	20.32	19.84	40.16
RP-1 Flow Rate, lb/sec	6.56	---	6.56
Hydrogen Flow Rate, lb/sec	---	2.83	2.83
Thrust Chamber			
Vacuum Thrust, lb	10,000	10,000	20,000
Vacuum Specific Impulse, sec	372.1	441.1	403.6
Chamber Pressure, psia	1100	550	---
Nozzle Area Ratio	316.5	141.8	200
Throat Area, $in.^2$	4.30	9.13	13.43
Coolant Jacket LH_2 Flow Rate, lb/sec	---	---	2.83
Coolant Inlet Temperature, °R	---	---	90
Coolant Exit Temperature, °R	---	---	1110
Coolant Jacket ΔP, psia	---	---	210
Injector Flow Rates, lb/sec			
Oxygen	20.32	---	20.32
RP-1	6.56	---	6.56
O_2/H_2 Fuel-Rich Gas	---	3.72	3.72
O_2/H_2 Ox-Rich Gas	---	18.95	18.95

Preburners	O_2/H_2 Fuel-Rich	O_2/H_2 Ox-Rich
Chamber Pressure, psia	694	749
Combustion Temp., °R	1860	1660
Mixture Ratio	0.4	110
Ox. Flow Rate, lb/sec	1.06	18.78
Fuel Flow Rate, lb/sec	2.66	0.17

Turbines	RP-1 Turbopump	LH_2 Turbopump	LOX/RP-1 LOX Turbopump	LOX/LH_2 LOX Turbopump
Inlet Pressure, psia	625	694	674	749
Inlet Temperature, °R	1860	1860	1660	1660
Gas Flow Rate, lb/sec	2.25	1.47	14.32	4.63
Gas Properties				
Cp, Specific heat at constant pressure Btu/lb·°R	2.60	2.60	0.277	0.277
γ, Ratio of specific he.	1.363	1.363	1.312	1.312
Shaft Horsepower(1)	79.83	311.1	166.7	108.0
Efficiency, %	60	80	70	70
Pressure Ratio (Total to Static)	1.033	1.16	1.115	1.248

(1) Includes 3% Horsepower penalty for boost pump drive flow.

Main Pumps	RP-1 Pump	LOX/RP-1 LOX Pump	LOX/LH_2 LOX Pump	LH_2 Pump
Outlet Flow Rate, lb/sec	6.56	20.32	19.84	2.83
Volumetric Flow Rate, GPM	59.0	128.5	125.4	288.7
NPSH, ft	112.6	125.3	83.8	1267
Suction Specific Speed, $(RPM)(GPM)^{1/2}/(ft)^{3/4}$	20,000	20,000	20,000	8,000
Speed, RPM	90,000	66,080	49,470	100,000
Discharge Pressure, psia	1390	1390	930	1115
Head Rise, ft	3899	2694	1802	35,224
Number of Stages	1	1	1	2
Specific Speed (N_s), $(RPM)(GPM)^{1/2}/(ft)^{3/4}$	1401	2000	2000	1111
Head Coefficient	0.52	0.46	0.46	0.55
Impeller Tip Speed, ft/sec	491	434	355	1015
Impeller Tip Diameter, in.	1.25	1.51	1.64	2.32
Efficiency, %	60	61.5	62	60

Weight and Envelope

Engine Weight = 550 lb

Engine Length = 89.8 in.

Engine Nozzle Exit Dia. = 58.5 in.

TABLE XXV. - BASELINE DUAL-EXPANDER ENGINE OPERATING SPECIFICATIONS, MODE 2

Thrust Split = 0.5

Engine	LOX/LH_2	
Vacuum Thrust, N (lb)	45,496	(10,228)
Vacuum Specific Impulse, sec	451.1	(451.1)
Total Flow Rate, kg/sec (lb/sec)	10.28	(22.67)
Mixture Ratio	7.0	(7.0)
Oxygen Flow Rate, kg/sec (lb/sec)	9.00	(19.84)
RP-1 Flow Rate, kg/sec (lb/sec)	--	(--)
Hydrogen Flow Rate, kg/sec (lb/sec)	1.28	(2.83)
Thrust Chamber		
Vacuum Thrust, N (lb)	45,496	(10,228)
Vacuum Specific Impulse, sec	451.1	(451.1)
Chamber Pressure, atm (psia)	37.4	(550)
Nozzle Area Ratio	300	(300)
Throat Area, cm^2 ($in.^2$)	58.90	(9.13)
Coolant Jacket LH_2 Flow Rate, kg/sec (lb/sec)	1.28	(2.83)
Coolant Inlet Temperature, °K (°R)	50	(90)
Coolant Exit Temperature, °K (°R)	481	(865)
Coolant Jacket ΔP, atm (psia)	8.16	(120)
Injector Flow Rates, kg/sec (lb-sec)		
Oxygen	--	(--)
RP-1	--	(--)
O_2/H_2 Fuel-Rich Gas	1.69	(3.72)
O_2/H_2 Ox-Rich Gas	8.59	(18.95)

TABLE XXVI. - BASELINE DUAL-EXPANDER ENGINE PRESSURE SCHEDULE, MODE 1
Thrust Split = 0.5
S.I. UNITS

Pressure, atm	Flow Circuit									
	Central Thrust Chamber		Fuel-Rich Preburner LH_2 Pump Turbine		Fuel-Rich Preburner RP-1 Pump Turbine		Ox-Rich Preburner LOX Pump Turbine		Ox-Rich Preburner LOX Pump Turbine LOX/RP-1 System	
	LOX	RP-1	LOX	LH_2	LOX	LH_2	LOX	LH_2	LOX	LH_2
Main Pump Discharge	94.5	94.5	63.3	75.9	63.3	75.9	63.3	75.9	63.3	75.9
ΔP Line	2.7	2.7	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Shutoff Valve Inlet	91.8	91.8	61.9	74.5	61.9	74.5	61.9	74.5	61.9	74.5
ΔP Shutoff Valve	1.0	1.0	0.6	0.8	0.6	0.8	0.6	0.8	0.6	0.8
Shutoff Valve Outlet	90.8	90.8	61.3	73.7	61.3	73.7	61.3	73.7	61.3	73.7
ΔP Line	2.7	2.7	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Coolant Jacket Inlet	--	--	--	72.3	--	72.3	--	72.3	--	72.3
ΔP Coolant Jacket	--	--	--	14.2	--	14.2	--	14.2	--	14.2
Coolant Jacket Outlet	--	--	--	58.1	--	58.1	--	58.1	--	58.1
ΔP Line	--	--	--	2.7	--	2.7	--	2.7	--	2.7
Preburner Control Inlet	--	--	59.9	55.4	59.9	55.4	--	--	--	--
ΔP Control	--	--	4.4	4.1	4.4	4.1	--	--	--	--
Preburner Inlet	--	--	55.5	51.3	55.5	51.3	59.9	55.4	59.9	55.4
ΔP Preburner	--	--	8.3	4.1	8.3	4.1	8.9	4.4	8.9	4.4
Hot Gas Control Valve Inlet	--	--	--		47.2		--		51.0	
ΔP Hot Gas Control Valve	--	--	--		4.7		--		5.1	
Turbine Inlet	--	--	47.2		42.5		51.0		45.9	
ΔP Turbine	--	--	6.5		1.4		10.3		4.8	
Check Valve Inlet	--	--	--		41.1		--		41.1	
ΔP Check Valve	--	--	--		0.4		--		0.4	
Main Injector Inlet	88.1	88.1	40.7		40.7		40.7		40.7	
ΔP Injector	13.3	13.3	3.3		3.3		3.3		3.3	
Chamber Pressure	74.8		37.4		37.4		37.4		37.4	

TABLE XXVI (cont.)

ENGLISH UNITS

	Flow Circuit									
	Central Thrust Chamber		Fuel-Rich Preburner LH_2 Pump Turbine		Fuel-Rich Preburner RP-1 Pump Turbine		Ox-Rich Preburner LOX Pump Turbine		Ox-Rich Preburner LOX Pump Turbine LOX/RP-1 System	
Pressure, psia	LOX	RP-1	LOX	LH_2	LOX	LH_2	LOX	LH_2	LOX	LH_2
Main Pump Discharge	1390	1390	930	1115	930	1115	930	1115	930	1115
ΔP Line	40	40	20	20	20	20	20	20	20	20
Shutoff Valve Inlet	1350	1350	910	1095	910	1095	910	1095	910	1095
ΔP Shutoff Valve	14	14	9	11	9	11	9	11	9	11
Shutoff Valve Outlet	1336	1336	901	1084	901	1084	901	1084	901	1084
ΔP Line	40	40	20	20	20	20	20	20	20	20
Coolant Jacket Inlet	--	--	--	1064	--	1064	--	1064	--	1064
ΔP Coolant Jacket	--	--	--	210	--	210	--	210	--	210
Coolant Jacket Outlet	--	--	--	854	--	854	--	854	--	854
ΔP Line	--	--	--	40	--	40	--	40	--	40
Preburner Control Inlet	--	--	881	814	881	814	--	--	--	--
ΔP Control	--	--	65	60	65	60	--	--	--	--
Preburner Inlet	--	--	816	754	816	754	881	814	881	814
ΔP Preburner	--	--	122	60	122	60	132	65	132	65
Hot Gas Control Valve Inlet	--	--	--		694		--		749	
ΔP Hot Gas Control Valve	--	--	--		69		--		75	
Turbine Inlet	--	--	694		625		749		674	
ΔP Turbine	--	--	96		21		151		70	
Check Valve Inlet	--	--	--		604		--		604	
ΔP Check Valve	--	--	--		6		--		6	
Main Injector Inlet	1296	1296	598		598		598		598	
ΔP Injector	196	196	48		48		48		48	
Chamber Pressure	1100		550		550		550		550	

Simplified plug cluster engine cycle schematics are shown on Figures 66 and 67 for Mode 1 and 2 operation, respectively. The plug cluster consists of five O_2/H_2 modules and five O_2/RP-1 modules. The O_2/H_2 modules are fed by a single turbopump assembly which employs an expander drive cycle. Hydrogen is first used to cool the plug base closure before cooling the O_2/H_2 modules. The heated hydrogen is then used to drive the O_2 and H_2 pumps. A small portion of the hydrogen, about 0.2% of the total engine flow, is used as base bleed and the rest is combusted with the liquid oxygen. The O_2/RP-1 modules are also fed by a single turbopump assembly which uses a gas generator drive cycle. The fuel-rich turbine exhaust products can be either dumped down the plug or out a 5:1 turbine exhaust nozzle. An individual turbine exhaust nozzle results in less hot gas manifolding because the "plug dump" must be evenly distributed over a large circumference. The individual turbine exhaust nozzle was assumed in this analysis. A zero length plug nozzle is used and the module area ratios are established as a function of overall area ratio for 10 touching modules. The zero length plug was selected on the basis of results from the Unconventional Nozzle Tradeoff Study (Ref. 3). The overall plug cluster area ratio is shown as a function of the module area ratio below.

No. of Touching Modules	Module Area Ratio	Overall Mode 1 Cluster Area Ratio
10	112	200
↓	200	358
	300	537
	350	626
	400	716

For the high module area ratios, the performance contribution from adding a truncated isentropic plug is small and the addition of the plug weight is not warranted. A plug base closure is added to obtain the base pressure benefits.

As discussed in Section IV, Cooling Evaluation, a chamber pressure of 20.4 atm (300 psia) was selected for this concept because of the problems associated with cooling the O_2/RP-1 module.

The coolant jacket pressure drop and coolant outlet temperature data required for the power balance analysis are summarized below:

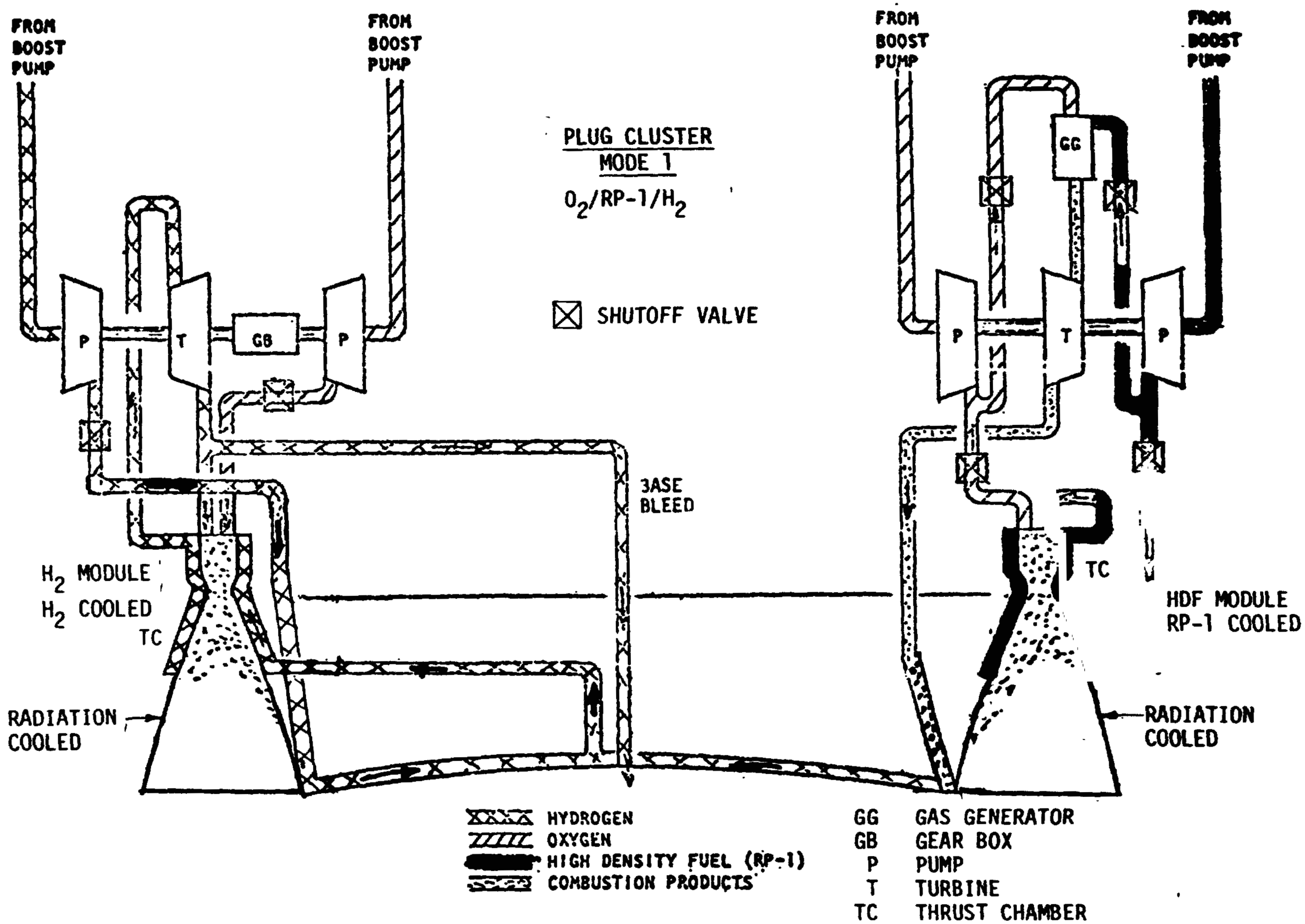

Figure 66. Mode 1 Plug Cluster Engine Schematic

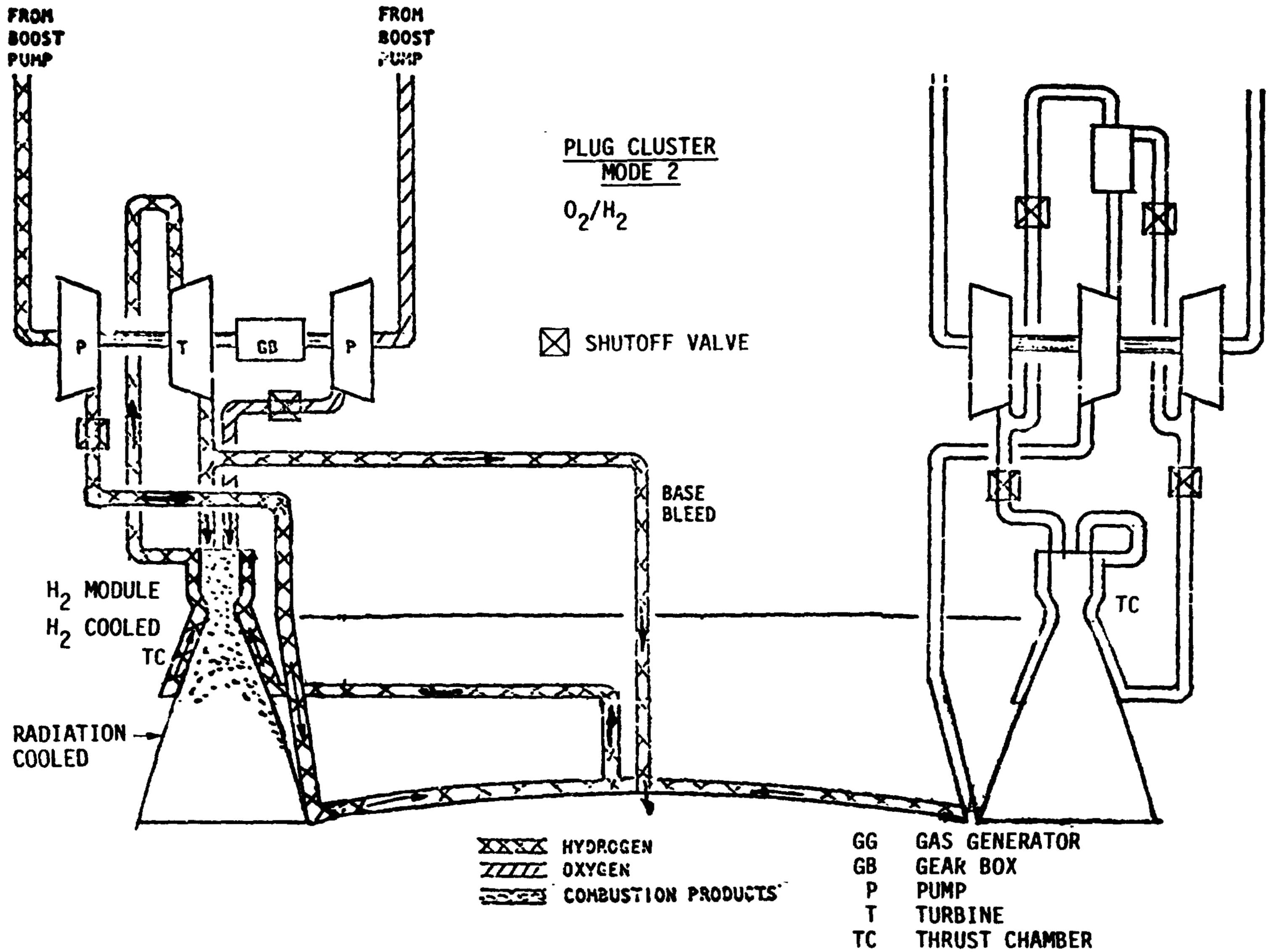

Figure 67. Mode 2 Plug Cluster Engine Schematic

Chamber Pressure, atm (psia)	Module	Total Coolant Pressure Drop, atm (psia)	Coolant Outlet Temp., °K (°R)
20.4 (300)	O_2/H_2	0.34 (5.0)	359 (647)
20.4 (300)	O_2/RP-1	40.8 (600)	809 (1456)

The hydrogen pressure drop and outlet temperature include the effect of cooling the plug base.

Based upon a review of RL-10 data, the analyses conducted for the Unconventional Nozzle Tradeoff Study (Ref. 3) and the tripropellant and dual-expander engine analyses performed for this contract, the following turbomachinery efficiencies were used in the power balance analyses:

LOX/LH_2	Efficiency
Oxygen Pump	63%
Hydrogen Pump	60%
Turbine	72%
LOX/RP-1	
Oxygen Pump	63%
RP-1 Pump	60%
Turbine	60%

Pump discharge pressure requirements for a module thrust chamber pressure of 20.4 atm (300 psia) are shown on Tables XXVII and XXVIII for the gas generator and expander cycles, respectively. These tables also show the pressure drop data for each of the system components.

Preliminary engine operating specifications for the established pressure requirements are shown on Table XXIX for Mode 1 operation. During Mode 2 operation the LOX/RP-1 modules are shutdown and the only major effect is that the gap between modules goes to one (1) with an attendant overall plug cluster area ratio amplification from 358:1 to 715:1. The O_2/H_2 component operating conditions remain about the same as in Mode 1.

Table XXIX also shows that for a single stage RP-1 pump, the operating speed is 90,000 RPM which is bearing DN limited. This speed is also significantly higher than the oxygen pump speed. If a single shaft, single turbine drive is desired for the LOX and RP-1 pumps, as shown on the cycle schematic, the RP-1 pump speed must be reduced. A possible operating

TABLE XXVII. - PLUG CLUSTER O_2/RP-1 GAS GENERATOR CYCLE PRESSURE SCHEDULE

S.I. UNITS

Module Thrust Chamber Flows

Pressure, atm	Propellant	
	Oxygen	RP-1
Main Pump Discharge	29.7	70.9
ΔP Line	2.7	2.7
Shutoff Valve Inlet	27.0	68.2
ΔP Shutoff Valve	0.3	0.7
Shutoff Valve Outlet	26.7	67.5
ΔP Line	2.7	2.7
Coolant Jacket Inlet	--	64.8
ΔP Coolant Jacket	--	40.8
Main Injector Inlet	24.0	24.0
ΔP Injector	3.6	3.6
Chamber Pressure	20.4	20.4

Gas Generator Flows

Pressure, atm	Oxygen	RP-1
Main Pump Discharge	29.7	70.9
ΔP Line	2.7	2.7
G.G. Valve Inlet	27.0	68.2
ΔP G.G. Valve	0.3	3.4
G.G. Injector Inlet	26.7	64.8
ΔP G.G. Injector	4.0	42.1
Turbine Inlet	22.7	22.7

TABLE XXVII (cont.)

ENGLISH UNITS

Module Thrust Chamber Flows

Pressure, psia	Propellant	
	Oxygen	RP-1
Main Pump Discharge	437	1043
ΔP Line	40	40
Shutoff Valve Inlet	397	1003
ΔP Shutoff Valve	4	10
Shutoff Valve Outlet	393	993
ΔP Line	40	40
Coolant Jacket Inlet	-	953
ΔP Coolant Jacket	-	600
Main Injector Inlet	353	353
ΔP Injector	53	53
Chamber Pressure	300	300

Gas Generator Flows

Pressure, psia	Oxygen	RP-1
Main Pump Discharge	437	1043
ΔP Line	40	40
G.G. Valve Inlet	397	1003
ΔP G.G. Valve	4	50
G.G. Injector Inlet	393	953
ΔP G.G. Injector	59	619
Turbine Inlet	334	334

TABLE XXVIII. - PLUG CLUSTER O_2/H_2 EXPANDER CYCLE PRESSURE SCHEDULE

S.I. UNITS

Pressure, atm	Propellant	
	Hydrogen	Oxygen
Main Pump Discharge	30.5	29.7
ΔP Line	1.4	2.7
Shutoff Valve Inlet	29.1	27.0
ΔP Shutoff Valve	0.3	0.3
Shutoff Valve Outlet	28.8	26.7
ΔP Line	1.4	2.7
Coolant Jacket Inlet	27.4	--
ΔP Coolant Jacket	0.3	--
Coolant Jacket Outlet	27.1	--
ΔP Line	2.7	--
Turbine Inlet	24.4	--
ΔP Turbine	2.2	--
Main Injector Inlet	22.2	24.0
ΔP Injector	1.8	3.6
Chamber Pressure	20.4	20.4

TABLE XXVIII (cont.)

ENGLISH UNITS

Pressure, psia	Propellant	
	Hydrogen	Oxygen
Main Pump Discharge	448	437
ΔP Line	20	40
Shutoff Valve Inlet	428	397
ΔP Shutoff Valve	4	4
Shutoff Valve Outlet	424	393
ΔP Line	20	40
Coolant Jacket Inlet	404	-
ΔP Coolant Jacket	5	-
Coolant Jacket Outlet	399	-
ΔP Line	40	-
Turbine Inlet	359	-
ΔP Turbine	33	-
Main Injector Inlet	326	353
ΔP Injector	26	53
Chamber Pressure	300	300

TABLE XXIX. - PLUG CLUSTER ENGINE PRELIMINARY OPERATING SPECIFICATIONS MODE 1

Thrust Split = 0.5

S.I. UNITS

Engine	LOX/RP-1	LOX/LH_2	COMBINED LOX/RP-1 & LH_2
Vacuum Thrust, N	44,482	44,482	88,964
Total Flow Rate, kg/sec	13.14	9.83	22.97
Mixture Ratio	3.1	7.0	4.18
Oxygen Flow Rate, kg/sec	9.94	8.60	18.54
RP-1 Flow Rate, kg/sec	3.20	--	3.20
Hydrogen Flow Rate, kg/sec	--	1.23	1.23
Modules			
Vacuum Thrust, N	8,896	8,896	
Chamber Pressure, atm	20.4	20.4	
Nozzle Area Ratio	200	200	
Throat Area, cm^2	21.25	21.29	
Throat Diameter, cm	5.20	5.207	
Nozzle Exit Area, cm^2	1,250	4,258	
Nozzle Exit Diameter, cm	73.56	73.63	
Plug Cluster			
Base Thrust, N	--	--	2,002
Number of Modules	5	5	10
Plug Cluster Area Ratio	--	--	358
Total Throat Area, cm^2	--	--	212.7
Total Exit Area(1), cm^2	--	--	76,161
Plug Cluster Diameter, cm	--	--	311.4
Gap	--	--	0

(1) Includes base.

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Main Pumps	O_2/RP-1 Module Feed System: RP-1 Pump	O_2/RP-1 Module Feed System: LOX/RP-1 LOX Pump	O_2/H_2 Module Feed System: LOX/LH_2 LOX Pump	O_2/H_2 Module Feed System: LH_2 Pump
Outlet Flow Rate, kg/sec	3.20	9.94	8.60	1.23
Volumetric Flow Rate, m^3/sec	.00401	.00874	.00756	.0174
NPSH, m	36.1	17.5	11.9	197
Suction Specific Speed $(RPM)(m^3/sec)^{1/2}/(m)^{3/4}$	387	387	387	155
Speed, RPM	90,000	27,600	28,490	61,560
Discharge Pressure, atm	70.9	29.7	29.7	30.5
Head Rise, m	883	258	258	4,270
Number of Stages	1	1	1	2
Specific Speed (N_s), $(RPM)(m^3/sec)^{1/2}/(m)^{3/4}$	35.2	40.1	38.5	25.9
Head Coefficient	0.483	0.46	0.46	0.525
Impeller Tip Speed, m/sec	134	74.1	74.1	200
Impeller Tip Diameter, cm	2.84	5.13	4.95	6.20
Horsepower, mHP	62.82	54.30	47.00	116.7
Efficiency, %	60	63	63	60

TABLE XXIX (cont.)

Gas Generator	LOX/RP-1 Fuel-Rich
RP-1 Inlet Temp., °K	809
Chamber Pressure, atm	23.4
Combustion Temp., °K	1089
Mixture Ratio	0.32
Ox. Flow Rate, kg/sec	0.042
RP-1 Flow Rate, kg/sec	0.130
Total Flow Rate, kg/sec	0.172

Turbines	RP-1 Turbopump	LOX Turbopump	Expander Cycle Turbine
Inlet Pressure, atm	23.4	23.4	24.4
Inlet Temperature, °K	.089	.089	359
Gas Flow Rate, kg/sec	0.092	0.080	1.23
Gas Properties			
C_p, Specific Heat at Constant Pressure, Cal/g°K	0.64	0.64	3.502
γ, Ratio of Specific Heats	1.132	1.132	1.394
Shaft Horsepower(1), mHP	64.7	55.9	168.6
Efficiency, %	60	60	72
Pressure Ratio (Total To Static)	20	20	1.10

(1) Includes 3% horsepower penalty for boost pump drive flow.

Turbine Exhaust Performance	O_2/RP-1 Fuel-Rich Gas
Turbine Exit Pressure, atm	1.17
Turbine Exit Total Temp., °K	896
Gas Molecular Weight	26.6
Ratio of Specific Heats	1.132
Characteristic Exhaust Velocity, m/sec	833
Nozzle Area Ratio	5:1
Nozzle Pressure Ratio	0.0364
Thrust Coefficient (Vacuum)	1.168
Vacuum Specific Impulse, sec	137.5
Vacuum Thrust, N	231

Engine Weight, Envelope and Performance

Engine Weight = 297 kg

Total Length = 154.4 cm

Total Diameter = 311.4 cm

Delivered Vacuum Specific Impulse:

Mode 1 = 395.0 sec

Mode 2 = 448.9 sec

TABLE XXIX (cont.)

ENGLISH UNITS

Engine	LOX/RP-1	LOX/LH_2	Combined LOX/RP-1 & LH_2
Vacuum Thrust, lb	10,000	10,000	20,000
Total Flow Rate, lb/sec	28.97	21.67	50.64
Mixture Ratio	3.1	7.0	4.18
Oxygen Flow Rate, lb/sec	21.91	18.96	40.87
RP-1 Flow Rate, lb/sec	7.06	--	7.06
Hydrogen Flow Rate, lb/sec	--	2.71	2.71
Modules			
Vacuum Thrust, lb	2,000	2,000	
Chamber Pressure, psia	300	300	
Nozzle Area Ratio	200	200	
Throat Area, in.^{2}	3.294	3.30	
Throat Diameter, in.	2.048	2.05	
Nozzle Exit Area, in.^{2}	658.8	660.0	
Nozzle Exit Diameter, in.	28.96	28.99	
Plug Cluster			
Base Thrust, lb	--	--	450
Number of Modules	5	5	10
Plug Cluster Area Ratio	--	--	358
Total Throat Area, in.^{2}	--	--	32.97
Total Exit Area$^{(1)}$, in.^{2}	--	--	11,805
Plug Cluster Diameter, in.	--	--	122.6
Gap	--	--	0

(1) Includes base.

	O_2/RP-1 Module Feed System		O_2/H_2 Module Feed System	
Main Pumps	RP-1 Pump	LOX/RP-1 LOX Pump	LOX/LH_2 LOX Pump	LH_2 Pump
Outlet Flow Rate, lb/sec	7.06	21.91	18.96	2.71
Volumetric Flow Rate, GPM	63.51	138.5	119.9	276.5
NPSH, ft	119.3	41.1	39.0	645
Suction Specific Speed, (RPM)(GPM)$^{1/2}$/(FT)$^{3/4}$	20,000	20,000	20,000	8,000
Speed, RPM	90,000	27,600	28,490	61,560
Discharge Pressure, psia	1,043	437	437	448
Head Rise, ft	2,896	847	847	14,010
Number of Stages	1	1	1	2
Specific Speed (N_S), (RPM)(GPM)$^{1/2}$/(FT)$^{3/4}$	1,817	2,069	1,987	1,337
Head Coefficient	0.483	0.46	0.46	0.525
Impeller Tip Speed, ft/sec	439	243	243	655
Impeller Tip Diameter, in.	1.12	2.02	1.95	2.44
Horsepower	61.96	53.56	46.35	115.1
Efficiency, %	60	63	63	60

TABLE XXIX (cont.)

Gas Generator	LOX/RP-1 Fuel-Rich
RP-1 Inlet Temp., °R	1456
Chamber Pressure, psia	344
Combustion Temp., °R	1960
Mixture Ratio	0.32
Ox. Flow Rate, lb/sec	0.092
RP-1 Flow Rate, lb/sec	0.287
Total Flow Rate, lb/sec	0.379

Turbines	RP-1 Turbopump	LOX Turbopump	Expander Cycle Turbine
Inlet Pressure, psia	344	344	359
Inlet Temperature, °R	1960	1960	647
Gas Flow Rate, lb/sec	0.203	0.176	2.71
Gas Properties			
C_p, Specific Heat at Constant Pressure, Btu/lb-°R	0.64	0.64	3.502
γ, Ratio of Specific Heats	1.132	1.132	1.394
Shaft Horsepower(1)	63.82	55.17	166.3
Efficiency, %	60	60	72
Pressure Ratio (Total to Static)	20	20	1.10

(1) Includes 3% horsepower penalty for boost pump drive flow.

Turbine Exhaust Performance	O_2/RP-1 Fuel-Rich Gas
Turbine Exit Pressure, psia	17.2
Turbine Exit Total Temp., °R	1613
Gas Molecular Weight	26.6
Ratio of Specific Heats	1.132
Characteristic Exhaust Velocity, ft/sec	2734
Nozzle Area Ratio	5:1
Nozzle Pressure Ratio	0.0364
Thrust Coefficient (Vacuum)	1.618
Vacuum Specific Impulse, sec	137.5
Vacuum Thrust, lb	52

Engine Weight, Envelope and Performance

Engine Weight = 655 lb

Total Length = 60.8 in.

Total Diameter = 122.6 in.

Delivered Vacuum Specific Impulse:

Mode 1 = 395.0 sec

Mode 2 = 448.9 sec

point is shown on Table XXX. The suction specific speed must be reduced and the number of pump stages increased from 1 to 2 in order to keep the RP-1 pump specific speed at a reasonable value. It is also estimated that the RP-1 pump performance will decrease from 60% to 57%. Because of these adverse effects, parallel, separate turbines were assumed for the gas generator cycle balance of Table XXIX.

TABLE XXX. - LOX/RP-1 PUMP PARAMETERS FOR SINGLE SHAFT, SINGLE TURBINE DRIVE

S.I. UNITS

Main Pumps	LOX/RP-1 Module Feed System RP-1 Pump	LOX Pump
Outlet Flow Rate, kg/sec	3.20	9.94
Volumetric Flow Rate, m^3/sec	.00401	.00874
NPSH, m	25.3	12.5
Suction Specific Speed, $(RPM)(m^3/sec)^{1/2}/(m)^{3/4}$	155	387
Speed, RPM	27,600	27,600
Discharge Pressure, atm	70.9	29.7
Head Rise, m	893	258
Number of Stages	2	1
Specific Speed (N_S), $(RPM)(m^3/sec)^{1/2}/(m)^{3/4}$	18.0	40.1
Head Coefficient	0.575	0.46
Impeller Tip Speed, m/sec	87.2	74.1
Impeller Tip Diameter, cm	6.02	5.13
Efficiency, %	57	63

ENGLISH UNITS

Outlet Flow Rate, lb/sec	7.06	21.91
Volumetric Flow Rate, GPM	63.51	138.5
NPSH, ft	83.0	41.1
Suction Specific Speed, $(RPM(GPM)^{1/2}/(FT)^{3/4}$	8000	20,000
Speed, RPM	27,600	27,600
Discharge Pressure, psia	1043	437
Head Rise, ft	2930	847
Number of Stages	2	1
Specific Speed (N_S), $(RPM)(GPM)^{1/2}/(FT)^{3/4}$	929	2069
Head Coefficient	0.575	0.46
Impeller Tip Speed, ft/sec	286	243
Impeller Tip Diameter, in.	2.37	2.02
Efficiency, %	57	63

SECTION VI

TASK IV - ENGINE PERFORMANCE, WEIGHT AND ENVELOPE PARAMETRICS

A. OBJECTIVES AND GUIDELINES

The objectives of this task were to provide parametric engine performance, weight and envelope data for the tripropellant, dual-expander and plug cluster engine concepts. The parametric analyses were conducted on each concept to determine the effects of varying design thrust level, thrust split and Mode 1 area ratio upon the engines dimensions, dry weight and delivered vacuum specific impulse. The analyses were conducted over the following ranges:

Engine Concept	Thrust Level, KN (K lb)	Thrust Split	Mode 1 Overall Area Ratio	Module Area Ratio
Tripropellant	66.7 to 400.3 (15 to 90)	0.4 to 0.8	200 to 600	-
Dual-Expander	66.7 to 400.3 (15 to 90)	0.4 to 0.8	200 to 600	-
Plug-Cluster	66.7 to 400.3 (15 to 90)	0.4 to 0.8	200 to 716	112 to 400

The thrust chamber pressures for each concept were established by engine cooling evaluations. The maximum operating chamber pressures for each engine concept are listed below as a function of thrust and thrust split.

Engine Concept	Thrust Level, KN (K lb)	Thrust Split	Mode 1 Thrust Chamber Pressure atm (psia)
Tripropellant	66.7 to 400.3 (15 to 90)	0.4	136 (2000)
	66.7 to 400.3 (15 to 90)	0.5	136 (2000)
	66.7 to 400.3 (15 to 90)	0.6	136 (2000)
	66.7 (15)	0.8	81.6 (1200)
	89 to 400.3 (20 to 90)	0.8	136 (2000)

Engine Concept	Thrust Level, KN (K lb)	Thrust Split	LOX/RP-1 Thrust Chamber Pressure, atm (psia)	LOX/LH_2 Thrust Chamber Pressure, atm (psia)
Dual-Expander	66.7 (15)	0.4	81.6 (1200)	40.8 (600)
		0.5	68.0 (1000)	34.0 (500)
		0.6	57.8 (850)	28.9 (425)
		0.8	12.9 (190)	6.46 (95)
	89 (20)	0.4	88.4 (1300)	44.2 (650)
		0.5	74.8 (1100)	37.4 (550)
		0.6	61.2 (900)	30.6 (450)
		0.8	13.6 (200)	6.8 (100)
	177.9 (40)	0.4	102.0 (1500)	51.0 (750)
		0.5	88.4 (1300)	44.2 (650)
		0.6	71.4 (1050)	55.7 (525)
		0.8	15.6 (230)	7.8 (115)
	266.9 (60)	0.4	112.2 (1650)	56.1 (825)
		0.5	95.2 (1400)	47.6 (700)
		0.6	78.2 (1150)	39.1 (575)
		0.8	17.7 (260)	8.84 (130)
	400.3 (90)	0.4	122.4 (1800)	61.2 (900)
		0.5	102.0 (1500)	51.0 (750)
		0.6	85.0 (1250)	42.5 (625)
		0.8	19.0 (280)	9.5 (140)
Plug Cluster	66.7 to 400.3 (15 to 90)	0.4 to 0.8	20.4 (300)	20.4 (300)

The maximum operating pressure for the dual-expander engine at a thrust split of 0.8 is below the 34 atm (500 psia) minimum value listed in the contract statement of work. However, these cases, 12.9 to 19.0 atm (190 to 280 psia), were evaluated to complete the study matrix.

The parametric data was generated for a LOX/RP-1 mixture ratio of 3.1 and a LOX/LH_2 mixture ratio of 7.0 per the study guidelines. Because the plug cluster operating pressure is low, the effect of operating the LOX/LH_2 modules at a mixture ratio of 6.0 rather than 7.0 was also investigated.

Other OTV engine requirements and guidelines were listed in Section II, Tables IV through VII.

B. PARAMETRIC DATA

1. Tripropellant Engine

The baseline operating conditions for this engine are a Mode 1 thrust of 88964N (20,000 lbs), thrust split = 0.5, a nozzle area ratio of 400:1, and LOX/RP-1 and LOX/LH_2 mixture ratios of 3.1 and 7.0, respectively. Baseline engine performance, weight and envelope data are presented on Table XXXI.

Performance, weight and envelope predictions for other study thrusts, thrust splits and area ratios are presented on Table XXXII. These data are shown for a Mode 1 operating thrust chamber pressure of 136 atm (2000 psia). However, as previously noted, at a thrust split of 0.8 and a thrust level of 66723N (15,000 lbs), the engine is cooling limited to a chamber pressure of 81.6 atm (1200 psia). This operating point and the resulting data are shown on Table XXXIII. This data should be used at this point instead of the 136 atm (2000 psia) data.

Plots of some of the parametric data have been prepared at P_c = 136 atm (2000 psia) to show the data trends. Mode 1 and 2 delivered performance is shown as a function of nozzle area ratio for various thrust splits at the baseline Mode 1 thrust of 88964N (20,000 lbs) on Figures 68 and 69, respectively. Mode 1 and 2 delivered performance as a function of thrust for various thrust splits at a baseline area ratio of 400:1 is shown on Figures 70 and 71, respectively. Performance increases with increasing thrust level because the kinetics loss is reduced. Mode 1 performance decreases with increasing thrust split because the amount of RP-1 used increases. Mode 2 performance decreases with increasing thrust split because the Mode 2 thrust and chamber pressure decrease which increase the kinetics loss.

Engine dry weight is shown as a function of nozzle area ratio and thrust split on Figure 72 for a baseline Mode 1 thrust of 88964N (20,000 lbs). Weight decreases with increasing thrust split because the LOX/RP-1 thrust contribution is greater which results in lighter engine components. The effect of Mode 1 thrust upon the engine dry weight is shown on Figure 73 for the baseline thrust split of 0.5.

TABLE XXXI. - BASELINE TRIPROFELLANT ENGINE DATA

S.I. UNITS

ENGINE PERFORMANCE

	MODE 1	MODE 2
1.THRUST (N)	88964.43	44105.73
2.THRUST SPLIT	.50	
3.CHAMBER PRESSURE (ATMS)	137.00	68.98
4.THRUST OF LOX/RP-1 (N)	44482.22	
5.THRUST OF LOX/LH2 (N)	44482.22	44105.70
6.FRACTION OF H2/TOTAL FUEL	.30	
7.OVERALL MIXTURE RATIO	4.25	7.00
8.ISP ODE (SECONDS)	436.37	483.30
9.TOTAL FLOW RATE (KGM/SEC)	21.67	9.76
10.FUEL FLOW RATE (KGM/SEC)	4.12	1.22
11.LOX FLOW RATE (KGM/SEC)	17.55	8.54
12.ENERGY RELEASE EFFICIENCY	.980	.980
13.NOZZLE EFFICIENCY	.996	.996
14.BOUNDARY LAYER THRUST DECREMENT (N)	1080.13	640.78
15.KINETIC EFFICIENCY	.991	.991
16.ISP DELIVERED (SECONDS)	418.63	460.63
17.THRUST TO WEIGHT RATIO	35.91	17.80

ENGINE SIZE (METERS)

1.AREA RATIO	400.00
2.PERCENT BELL	90.00
3.THROAT RADIUS	.03
4.AREA RATIO (COPPER)	8.00
5.AREA RATIO (TUBE BUNDLE)	156.75
6.GIMBAL LENGTH	.13
7.INJECTOR LENGTH	.10
8.CHAMBER LENGTH	.19
9.NOZZLE LENGTH	2.00
10.OVERALL STOWED ENGINE LENGTH	1.03
11.OVERALL DPLYED ENGINE LENGTH	2.42
12.ENGINE EXIT DIAMETER	1.25

ENGINE WEIGHTS (KGM)

1.GIMBAL	7.57	13.RP-1 VALVE	13.54
2.INJECTOR	9.14	14.LOW SPD O2 BOOST PUMP	5.31
3.COMB. CHAMBER	11.09	15.LOW SPEED H2 PUMP	1.00
4.COPPER NOZZLE	10.02	16.LOW SPD RP1 PUMP	.06
5.TUBE BUNDLE	19.90	17.HI SPEED O2 TPA	17.00
6.RAD.COOLED NOZZLE	15.02	18.HI SPD H2 TPA	11.04
7.NOZZLE DPLY SYS.	17.51	19.HI SPD RP TPA	3.60
8.FUEL RICH PREBRN(O2-H2)	6.19	20.MANIFLD	16.78
9.OX RICH PREBRN(O2-H2)	7.08	21.PRO LINES	14.97
10.FUEL RICH PREBRN(O2-RP)	3.40	22.IG SYS	12.70
11.HOT GAS VALVE	3.47	23.MISCELLANEOUS	19.50
12.H2+O2 VALVES-ACT	19.94	24.TOTAL ENG WT	252.60

TABLE XXXI (cont.)

ENGLISH UNITS

ENGINE PERFORMANCE

	MODE 1	MODE 2
1.THRUST (LBF)	20000.00	9915.35
2.THRUST SPLIT	.50	
3.CHAMBER PRESSURE (PSIA)	2000.00	1007.00
4.THRUST OF LOX/RP-1 (LBF)	10000.00	
5.THRUST OF LOX/LH2 (LBF)	10000.00	9915.35
6.FRACTION OF H2/TOTAL FUEL	.30	
7.OVERALL MIXTURE RATIO	4.25	7.00
8.ISP ODE (SECONDS)	438.37	483.30
9.TOTAL FLOW RATE (LBM/SEC)	47.78	21.53
10.FUEL FLOW RATE (LBM/SEC)	9.09	2.69
11.LOX FLOW RATE (LBM/SEC)	38.68	18.83
12.ENERGY RELEASE EFFICIENCY	.980	.980
13.NOZZLE EFFICIENCY	.996	.996
14.BOUNDARY LAYER THRUST DECREMENT (LBF)	242.03	144.05
15.KINETIC EFFICIENCY	.991	.991
16.ISP DELIVERED (SECONDS)	418.63	460.63
17.THRUST TO WEIGHT RATIO	35.91	17.80

ENGINE SIZE (IN)

1.AREA RATIO	490.00
2.PERCENT BELL	90.00
3.THROAT RADIUS	1.23
4.AREA RATIO (COPPER)	8.00
5.AREA RATIO (TUBE BUNDLE)	156.75
6.GIMBAL LENGTH	5.09
7.INJECTOR LENGTH	4.00
8.CHAMBER LENGTH	7.54
9.NOZZLE LENGTH	78.63
10.OVERALL STOWED ENGINE LENGTH	64.22
11.OVERALL DPLYED ENGINE LENGTH	95.18
12.ENGINE EXIT DIAMETER	49 29

ENGINE WEIGHTS (LBM)

1.GIMBAL	16.70	13.RP-1 VALVE	29.85
2.INJECTOR	20.16	14.LOW SPD O2 BOOST PUMP	11.70
3.COMB. CHAMBER	25.78	15.LOW SPEED H2 PUMP	2.20
4.COPPER NOZZLE	23.41	16.LOW SPD RP1 PUMP	1.90
5.TUBE BUNDLE	43.07	17.HI SPEED O2 TPA	37.67
6.RAD.COOLED NOZZLE	41.48	18.HI SPD H2 TPA	26.11
7.NOZZLE DPLY SYS.	38.01	19.HI SPD RP TPA	8.11
8.FUEL RICH PREBRN(O2-H2)	13.65	20.MANIFLD	37.00
9.OX RICH PREBRN(O2-H2)	15.60	21.PRO LINES	33.00
10.FUEL RICH PREBRN(O2-RP)	7.56	22.IG SYS	28.00
11.HOT GAS VALVE	7.65	23.MISCELLANEOUS	43.00
12.H2+O2 VALVES-ACT	43.95	24.TOTAL ENG WT	556.89

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TABLE XXXII. - TRIPROPELLANT ENGINE PARAMETRIC DATA, MODE 1 P_C = 137 atms (2000 psia)

S.I. UNITS

TRIPROPELLANT ENGINE MODEL

PROPELLANTS: LOX/LH2/RP-1

PROPELLANT	TEMP	ENTHALPY
LOX	90.18 K(162.3 R)	-3093.0 CAL/MOL
LH2	20.27 K(36.49 R)	-21.5 CAL/MOL
RP/1	298.15 K(536.7 R)	-6200.0 CAL/MOL

OVERALL MIXTURE RATIO	CORRESPONDING FRACTION OF H2 TO TOTAL FUEL
3.10	0.0 (LOX/RP-1 ONLY)
3.88	0.2
4.66	0.4
5.44	0.6
6.22	0.8
7.00	1.0 (LOX/LH2 ONLY)

MODE 1 THRUST (N)	MODE 2 THRUST (N)	THRUST SPLIT	MIX. RATIO	FRACTION H2/FUEL	MODE 1 PC (ATMS)	MODE 2 PC (ATMS)	AREA RATIO	THROAT RADIUS (M)	MODE1 ISP-T (SEC)	MODE1 ISP-D (SEC)	MODE2 ISP-T (SEC)	MODE2 ISP-D (SEC)	ENG ST LENGTH (M)	ENG DP LENGTH (M)	ENGINE DIA. (M)	ENGINE WEIGHT (KGM)
[illegible]6723.	39704.	.40	4.60	.39	137.	82.	200.	.027	438.4	420.0	474.7	453.9	1.47	1.59	.775	195.5
66723.	39685.	.40	4.61	.39	137.	83.	300.	.027	443.9	423.9	479.6	457.3	1.47	1.88	.984	203.8
66723.	39701.	.40	4.61	.39	137.	83.	400.	.027	447.4	427.1	483.4	460.8	1.46	2.12	1.080	211.7
66723.	39330.	.40	4.61	.39	137.	83.	600.	.027	451.9	434.8	487.8	464.0	1.45	2.51	1.319	226.9
66723.	33085.	.50	4.25	.30	137.	69.	200.	.027	429.3	410.9	474.5	453.3	1.46	1.59	.774	194.3
66723.	33070.	.50	4.25	.30	137.	69.	300.	.0[illegible]	434.8	414.9	479.5	456.7	1.45	1.88	.945	202.6
66723.	33082.	.50	4.25	.30	137.	69.	400.	.027	438.4	418.1	483.3	460.1	1.45	2.12	1.085	210.6
66723.	32763.	.50	4.26	.30	137.	69.	600.	.027	442.9	425.8	487.7	463.2	1.44	2.51	1.317	225.7
66723.	26401.	.60	3.95	.22	137.	55.	200.	.027	420.7	402.3	474.1	451.6	1.45	1.59	.773	193.0
66723.	26388.	.60	3.95	.22	137.	55.	300.	.027	426.1	406.3	479.1	454.9	1.44	1.87	.942	201.3
66723.	26397.	.60	3.95	.22	137.	55.	400.	.027	429.7	409.4	483.0	458.3	1.44	2.11	1.083	209.3
66723.	26200.	.60	3.96	.22	137.	55.	600.	.027	434.5	417.1	487.6	462.5	1.43	2.50	1.315	224.5
66723.	13146.	.80	3.47	.09	137.	28.	200.	.027	402.9	384.2	473.1	446.5	1.42	1.59	.772	188.9
66723.	13140.	.80	3.47	.09	137.	28.	300.	.027	408.4	388.1	478.2	449.6	1.41	1.87	.940	197.2
66723.	13138.	.80	3.47	.10	137.	28.	400.	.027	412.0	391.3	482.2	452.8	1.41	2.11	1.081	205.1
6672[illegible]	13002.	.80	3.47	.10	137.	28.	600.	.027	416.6	398.9	486.7	455.7	1.40	2.50	1.312	220.3
889[illegible].	52937.	.40	4.60	.39	137.	82.	200.	.032	438.4	420.5	474.7	454.5	1.66	1.82	.894	233.3
88[illegible].	52912.	.40	4.61	.39	137.	83.	300.	.031	443.9	424.4	479.6	457.9	1.65	2.14	1.090	244.0
88964.	52934.	.40	4.61	.39	137.	83.	400.	.031	447.4	427.7	483.4	461.3	1.65	2.42	1.254	254.2
88964.	52485.	.40	4.61	.39	137.	83.	600.	.031	451.9	435.0	487.8	464.5	1.64	2.87	1.523	273.8
88964.	44112.	.50	4.25	.30	137.	69.	200.	.032	429.3	411.4	474.5	453.8	1.64	1.81	.893	231.8
88964.	44093.	.50	4.25	.30	137.	69.	300.	.031	434.8	415.4	479.5	457.2	1.64	2.14	1.088	242.4
88964.	44109.	.50	4.25	.30	137.	69.	400.	.031	438.4	418.6	483.3	460.7	1.63	2.42	1.252	252.6
88964.	43686.	.50	4.26	.30	137.	69.	600.	.031	442.9	426.3	487.7	463.8	1.62	2.87	1.519	272.2
88964.	35200.	.60	3.95	.22	137.	55.	200.	.032	420.7	402.8	474.1	452.1	1.63	1.81	.892	230.0
88964.	35184.	.60	3.95	.22	137.	55.	300.	.031	426.1	406.8	479.1	455.4	1.62	2.14	1.087	240.7
88964.	35195.	.60	3.95	.22	137.	55.	400.	.031	429.7	409.9	483.0	458.8	1.62	2.41	1.250	250.9
88964.	34934.	.60	3.96	.22	137.	55.	600.	.031	434.3	417.7	487.6	463.0	1.60	2.86	1.517	270.5
88964.	17528.	.80	3.47	.09	137.	28.	200.	.031	402.9	384.7	473.1	447.1	1.60	1.81	.890	224.7
88964.	17520.	.80	3.47	.09	137.	28.	300.	.031	408.4	388.6	478.2	450.2	1.59	2.14	1.085	235.3

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TABLE XXXII (cont.)

S.I. UNITS

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88964.	17518.	.80	3.47	.10	137.	28.	400.	.031	412.0	391.8	482.2	453.4	1.59	2.41	1.248	245.5
88964.	47337.	.80	3.47	.10	137.	28.	600.	.031	416.6	399.4	486.7	456.5	1.57	2.86	1.514	265.1
177929.	105866.	.40	4.00	.39	137.	82.	200.	.045	438.4	421.6	474.7	455.7	2.21	2.50	1.2[illegible]2	368.3
177929.	105818.	.40	4.01	.39	137.	83.	300.	.044	443.9	425.6	479.6	459.1	2.21	2.97	1.539	387.9
177929.	105863.	.40	4.01	.39	137.	83.	400.	.044	447.4	428.9	483.4	462.6	2.20	3.36	1.770	406.8
177929.	105182.	.40	4.01	.39	137.	83.	600.	.044	451.9	435.3	487.8	465.9	2.19	4.08	2.152	443.0
177929.	88216.	.50	4.25	.30	137.	69.	200.	.045	429.3	412.6	474.5	455.1	2.19	2.50	1.261	365.2
177929.	88180.	.50	4.25	.30	137.	69.	300.	.044	434.8	416.6	479.5	458.5	2.18	2.96	1.537	384.7
177929.	88213.	.50	4.25	.30	137.	69.	400.	.044	438.4	419.8	483.3	462.0	2.16	3.35	1.766	403.7
177929.	87554.	.50	4.26	.30	137.	69.	600.	.044	442.9	426.7	487.7	465.2	2.16	3.99	2.146	440.5
177929.	70394.	.60	3.95	.22	137.	55.	200.	.045	420.7	403.9	474.1	453.3	2.17	2.50	1.259	361.9
177929.	70364.	.60	3.95	.22	137.	55.	300.	.044	426.1	408.0	479.1	456.7	2.16	2.96	1.535	381.5
177929.	70386.	.60	3.95	.22	137.	55.	400.	.044	429.7	411.1	483.0	460.1	2.16	3.35	1.766	400.4
177929.	69948.	.60	3.96	.22	137.	55.	600.	.044	434.3	418.6	487.6	464.4	2.14	3.98	2.144	437.2
177929.	35055.	.80	3.47	.09	137.	28.	200.	.044	402.9	385.8	473.1	448.4	2.13	2.49	1.257	352.2
177929.	35040.	.80	3.47	.09	137.	28.	300.	.044	408.4	389.8	478.2	451.5	2.12	2.96	1.532	371.8
177929.	35038.	.80	3.47	.10	137.	28.	400.	.044	412.0	392.9	482.2	454.8	2.12	3.34	1.762	390.8
177929.	34679.	.80	3.47	.10	137.	28.	600.	.044	416.6	399.7	486.7	457.8	2.10	3.97	2.137	427.5
266893.	158792.	.40	4.00	.39	137.	82.	200.	.055	438.4	422.3	474.7	456.4	2.63	3.03	1.545	489.8
266893.	158722.	.40	4.01	.39	137.	83.	300.	.054	443.9	425.3	479.6	459.9	2.62	3.60	1.883	516.1
266893.	158790.	.40	4.01	.39	137.	83.	400.	.054	447.4	429.6	483.4	463.4	2.61	4.07	2.166	545.5
266893.	157959.	.40	4.01	.39	137.	83.	600.	.054	451.9	435.6	487.8	466.7	2.60	4.86	2.635	599.1
266893.	132317.	.50	4.25	.30	137.	69.	200.	.055	429.3	413.2	474.5	455.8	2.60	3.02	1.545	485.3
266893.	132264.	.50	4.25	.30	137.	69.	300.	.054	434.8	417.3	479.5	459.2	2.60	3.59	1.861	513.[illegible]
266893.	132315.	.50	4.25	.30	137.	69.	400.	.054	438.4	420.5	483.3	462.7	2.59	4.07	2.163	541.0
266893.	131989.	.50	4.26	.30	137.	69.	600.	.054	442.9	426.9	487.7	466.0	2.57	4.85	2.630	594.5
266893.	105586.	.60	3.95	.22	137.	55.	200.	.054	420.7	404.6	474.1	454.1	2.58	3.02	1.541	480.6
266893.	105541.	.60	3.95	.22	137.	55.	300.	.054	426.1	408.6	479.1	457.4	2.57	3.59	1.878	508.8
266893.	105579.	.60	3.95	.22	137.	55.	400.	.054	429.7	411.8	483.0	460.9	2.56	4.06	2.161	536.3
266893.	105052.	.60	3.96	.22	137.	55.	600.	.054	434.3	418.6	487.6	465.2	2.55	4.84	2.625	589.8
266893.	52580.	.80	3.47	.09	137.	28.	200.	.054	402.9	386.5	473.1	449.1	2.53	3.02	1.539	467.1
266893.	52560.	.80	3.47	.09	137.	28.	300.	.054	408.4	390.5	478.2	452.3	2.52	3.58	1.875	495.4
266893.	52558.	.80	3.47	.10	137.	28.	400.	.054	412.0	393.6	482.2	455.6	2.51	4.04	2.156	522.8
266893.	52021.	.80	3.47	.10	137.	28.	600.	.053	416.6	401.4	486.7	458.6	2.49	4.83	2.615	576.4
400340.	238176.	.40	4.00	.39	137.	82.	200.	.067	438.4	422.9	474.7	457.1	3.13	3.67	1.891	659.5
400340.	238074.	.40	4.01	.39	137.	83.	300.	.067	443.9	427.0	479.6	460.5	3.12	4.37	2.305	700.5
400340.	238178.	.40	4.01	.39	137.	83.	400.	.066	447.4	430.3	483.4	464.1	3.11	4.95	2.651	740.5
400340.	237217.	.40	4.01	.39	137.	83.	600.	.066	451.9	435.8	487.8	467.4	3.09	5.92	3.227	814.8
400340.	198465.	.50	4.25	.30	137.	69.	200.	.067	429.3	413.9	474.5	456.5	3.10	3.67	1.888	653.0
400340.	198388.	.50	4.25	.30	137.	69.	300.	.066	434.8	418.0	479.5	459.9	3.09	4.36	2.302	693.9
400340.	198465.	.50	4.25	.30	137.	69.	400.	.066	438.4	421.2	483.3	463.5	3.08	4.94	2.647	734.0
400340.	197469.	.50	4.26	.30	137.	69.	600.	.066	442.9	427.1	487.7	466.8	3.06	5.91	3.220	812.3
400340.	158370.	.60	3.95	.22	137.	55.	200.	.067	420.7	405.2	474.1	454.8	3.07	3.66	1.886	646.4
400340.	158305.	.60	3.95	.22	137.	55.	300.	.066	426.1	409.3	479.1	458.2	3.06	4.36	2.299	687.3
400340.	158363.	.60	3.95	.22	137.	55.	400.	.066	429.7	412.5	483.0	461.7	3.05	4.94	2.644	727.3
400340.	157771.	.60	3.96	.22	137.	55.	600.	.066	434.3	418.8	487.6	466.0	3.03	5.90	3.214	805.7
400340.	78868.	.80	3.47	.09	137.	28.	200.	.067	402.9	387.1	473.1	449.8	3.01	3.66	1.883	627.7
400340.	78839.	.80	3.47	.09	137.	28.	300.	.066	408.4	391.1	478.2	453.1	3.00	4.35	2.294	668.6
400340.	78837.	.80	3.47	.10	137.	28.	400.	.066	412.0	394.3	482.2	456.4	2.99	4.93	2.630	708.6
400340.	78075.	.80	3.47	.10	137.	28.	600.	.065	416.6	401.8	486.7	459.4	2.97	5.88	3.201	780.9

TABLE XXXII (cont.)

ENGLISH UNITS

TRIPROPELLANT ENGINE MODEL

PROPELLANTS: LOX/LH2/RP-1

PROPELLANT	TEMP	ENTHALPY
LOX	90.18 K(162.3 R)	-3093.0 CAL/MOL
LH2	20.27 K(36.49 R)	-21.5 CAL/MOL
RP/1	298.15 K(536.7 R)	-6200.0 CAL/MOL

OVERALL MIXTURE RATIO	CORRESPONDING FRACTION OF H2 TO TOTAL FUEL
3.10	0.0 (LOX/RP-1 ONLY)
3.88	0.2
4.66	0.4
5.44	0.6
6.22	0.8
7.00	1.0 (LOX/LH2 ONLY)

MODE 1 THRUST (LBF)	MODE 2 THRUST (LBF)	THRUST SPLIT	MIX. RATIO	FRACTION H2/FUEL	MODE 1 PC (PSIA)	MODE 2 PC (PSIA)	AREA RATIO	THROAT RADIUS (IN)	MODE1 ISP-T (SEC)	MODE1 ISP-D (SEC)	MODE2 ISP-T (SEC)	MODE2 ISP-D (SEC)	ENG ST LENGTH (IN)	ENG CP LENGTH (IN)	ENGINE DIA. (IN)	ENGINE WEIGHT (LBM)
15000.	8920.	.40	4.60	.39	2000.	1203.	200.	1.078	438.4	420.0	474.7	453.9	57.99	62.74	30.495	430.9
15000.	8921.	.40	4.61	.39	2000.	1205.	300.	1.073	443.9	423.9	479.6	457.3	57.79	73.97	37.177	449.3
15000.	8925.	.40	4.61	.39	2000.	1206.	400.	1.069	447.4	427.1	483.4	460.8	57.63	83.37	42.766	466.8
15000.	8812.	.40	4.61	.39	2000.	1207.	600.	1.060	451.9	434.8	487.8	464.0	57.24	96.76	51.923	500.2
15000.	7438.	.50	4.25	.30	2000.	1004.	200.	1.077	429.3	410.9	474.5	453.3	57.47	62.66	30.459	428.4
15000.	7434.	.50	4.25	.30	2000.	1006.	300.	1.072	434.8	414.9	479.5	456.6	57.20	73.69	37.120	446.7
15000.	7437.	.50	4.25	.30	2000.	1007.	400.	1.066	438.4	418.1	483.3	460.1	57.10	83.27	42.709	464.2
15000.	7366.	.50	4.26	.30	2000.	1008.	600.	1.058	442.9	425.6	487.7	463.3	56.71	96.62	51.636	497.7
15000.	5935.	.60	3.95	.22	2000.	804.	200.	1.076	420.7	402.3	474.1	451.5	56.94	62.63	30.425	425.5
15000.	5932.	.60	3.95	.22	2000.	806.	300.	1.070	426.1	406.3	479.1	454.8	56.73	73.82	37.082	443.9
15000.	5934.	.60	3.95	.22	2000.	806.	400.	1.066	429.7	409.4	483.0	458.2	56.57	83.18	42.655	461.4
15000.	5890.	.60	3.96	.22	2000.	808.	600.	1.057	434.3	417.1	487.6	462.5	56.17	96.50	51.760	494.8
15000.	2955.	.60	3.47	.09	2000.	404.	200.	1.074	402.9	384.2	473.1	446.5	55.90	62.54	30.374	416.3
15000.	2954.	.60	3.47	.09	2000.	405.	300.	1.068	408.4	388.1	478.2	449.6	55.69	73.71	37.014	434.7
15000.	2953.	.60	3.47	.10	2000.	405.	400.	1.064	412.0	391.3	482.2	452.8	55.52	83.05	42.570	452.2
15000.	2923.	.60	3.47	.10	2000.	406.	600.	1.054	416.6	398.9	486.7	455.7	55.12	96.30	51.630	485.7
20000.	11901.	.40	4.60	.39	2000.	1203.	200.	1.244	438.4	420.5	474.7	454.4	65.24	71.48	35.192	514.4
20000.	11895.	.40	4.61	.39	2000.	1205.	300.	1.239	443.9	424.4	479.6	457.8	65.01	84.44	42.903	537.9
20000.	11899.	.40	4.61	.39	2000.	1206.	400.	1.234	447.4	427.7	483.4	461.3	64.82	95.29	49.355	560.4
20000.	11799.	.40	4.61	.39	2000.	1207.	600.	1.224	451.9	435.0	487.8	464.6	64.41	113.09	59.944	603.6
20000.	9917.	.50	4.25	.30	2000.	1004.	200.	1.243	429.3	411.4	474.5	453.8	64.64	71.42	35.151	510.9
20000.	9912.	.50	4.25	.30	2000.	1006.	300.	1.237	434.8	415.0	479.5	457.2	64.41	84.35	42.840	534.4
20000.	9915.	.50	4.25	.30	2000.	1007.	400.	1.232	438.4	418.6	483.3	460.6	64.22	95.18	49.287	556.9
20000.	9821.	.50	4.26	.30	2000.	1008.	600.	1.221	442.9	426.3	487.7	463.8	63.78	112.69	59.622	600.1
20000.	7913.	.60	3.95	.22	2000.	804.	200.	1.241	420.7	402.8	474.1	452.1	64.04	71.35	35.111	507.1
20000.	7909.	.60	3.95	.22	2000.	806.	300.	1.235	426.1	406.8	479.1	455.4	63.81	84.26	42.792	530.6
20000.	7912.	.60	3.95	.22	2000.	806.	400.	1.231	429.7	409.9	483.0	458.8	63.62	95.08	49.223	553.1
20000.	7854.	.60	3.96	.22	2000.	808.	600.	1.219	434.3	417.7	487.6	463.0	63.17	112.75	59.731	590.3
20000.	3940.	.60	3.47	.09	2000.	404.	200.	1.239	402.9	384.7	473.1	447.0	62.86	71.26	35.052	495.3
20000.	3938.	.60	3.47	.09	2000.	405.	300.	1.233	408.4	388.6	478.2	450.2	62.62	84.14	42.713	518.8

TABLE XXXII (cont.)

ENGLISH UNITS

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20000.	393[illegible].	.80	3.47	.10	2000.	405.	400.	1.228	412.0	391.8	482.2	453.4	62.43	94.91	49.125	541.3
20000.	3897.	.80	3.47	.10	2000.	406.	600.	1.216	416.6	399.4	486.7	456.3	61.97	112.51	59.588	584.5
40000.	23[illegible].	.40	4.00	.39	2000.	1203.	200.	1.757	438.4	421.6	474.7	455.7	87.14	98.50	49.701	811.9
40000.	23769.	.40	4.01	.39	2000.	1205.	300.	1.749	443.9	425.6	479.6	459.1	86.62	116.60	60.590	855.1
40000.	23799.	.40	4.01	.39	2000.	1206.	400.	1.742	447.4	428.9	483.4	462.6	86.57	132.11	69.699	896.9
40000.	23647.	.40	4.01	.39	2000.	1207.	600.	1.730	451.9	435.3	487.8	465.9	86.07	157.39	84.730	978.0
40000.	19832.	.50	4.25	.30	2000.	1004.	200.	1.755	429.3	412.6	474.5	455.1	86.32	98.40	49.641	805.0
40000.	19823.	.50	4.25	.30	2000.	1006.	300.	1.747	434.8	416.6	479.5	458.5	86.00	116.67	60.506	848.2
40000.	19836.	.50	4.25	.30	2000.	1007.	400.	1.740	438.4	419.8	483.3	462.0	85.74	131.95	69.601	890.0
40000.	1960[illegible].	.50	4.26	.30	2000.	1008.	600.	1.726	442.9	425.7	487.7	465.2	85.21	157.11	84.563	971.0
40000.	15625.	.00	3.95	.22	2000.	804.	200.	1.753	420.7	403.9	474.1	453.3	85.50	98.31	49.584	797.8
40000.	15813.	.00	3.95	.22	2000.	806.	300.	1.744	426.1	409.0	479.1	456.7	85.18	116.58	60.431	841.0
40000.	15823.	.00	3.95	.22	2000.	806.	400.	1.738	429.7	411.1	483.0	460.1	84.92	131.81	69.511	882.8
40000.	15720.	.00	3.96	.22	2000.	808.	600.	1.723	434.3	418.4	487.6	464.4	84.35	156.83	84.394	963.8
40000.	7880.	.80	3.47	.09	2000.	404.	200.	1.750	402.9	385.8	473.1	448.4	83.66	96.17	49.498	770.6
40000.	7877.	.80	3.47	.09	2000.	405.	300.	1.741	408.4	389.8	478.2	451.5	83.55	116.36	60.316	819.8
40000.	7870.	.80	3.47	.10	2000.	405.	400.	1.734	412.0	392.9	482.2	454.6	83.29	131.57	69.368	861.5
40000.	7790.	.60	3.47	.10	2000.	406.	600.	1.718	416.6	400.7	486.7	457.8	82.67	156.42	84.145	942.5
60000.	35699.	.40	4.00	.39	2000.	1203.	200.	2.150	438.4	422.3	474.7	456.4	103.54	119.21	60.823	1079.9
60000.	35682.	.40	4.01	.39	2000.	1205.	300.	2.140	443.9	426.3	479.6	459.8	103.16	141.60	74.147	1142.2
60000.	35694.	.40	4.01	.39	2000.	1206.	400.	2.132	447.4	429.6	483.4	463.4	102.85	160.34	85.294	1202.7
60000.	35512.	.40	4.01	.39	2000.	1207.	600.	2.118	451.9	435.6	487.8	466.7	102.30	191.37	103.754	1320.7
60000.	29747.	.50	4.25	.30	2000.	1004.	200.	2.148	429.3	413.2	474.5	455.8	102.56	119.49	60.749	1069.8
60000.	29734.	.50	4.25	.30	2000.	1006.	300.	2.138	434.8	417.3	479.5	459.2	102.17	141.44	74.087	1132.1
60000.	29745.	.50	4.25	.30	2000.	1007.	400.	2.129	438.4	420.5	483.3	462.7	101.86	160.15	85.173	1192.6
60000.	29501.	.50	4.26	.30	2000.	1008.	600.	2.114	442.9	426.9	487.7	466.0	101.27	191.03	103.543	1310.7
60000.	23737.	.00	3.95	.22	2000.	804.	200.	2.145	420.7	404.6	474.1	454.1	101.57	118.98	60.678	1059.5
60000.	23720.	.00	3.95	.22	2000.	806.	300.	2.135	426.1	408.6	479.1	457.4	101.18	141.29	73.951	1121.8
60000.	23735.	.00	3.95	.22	2000.	806.	400.	2.127	429.7	411.8	483.0	460.9	100.87	159.96	85.061	1182.3
60000.	23610.	.00	3.96	.22	2000.	808.	600.	2.109	434.3	418.6	487.6	465.2	100.23	190.69	103.337	1300.4
60000.	11820.	.80	3.47	.09	2000.	404.	200.	2.142	402.9	386.5	473.1	449.1	99.63	118.60	60.571	1029.9
60000.	11815.	.80	3.47	.09	2000.	405.	300.	2.131	408.4	390.5	478.2	452.3	99.23	141.06	73.609	1092.1
60000.	11815.	.80	3.47	.10	2000.	405.	400.	2.122	412.0	393.6	482.2	455.6	98.92	159.68	84.885	1152.7
60000.	11695.	.80	3.47	.10	2000.	406.	600.	2.102	416.6	401.4	486.7	458.6	98.18	190.08	102.965	1270.6
90000.	53547.	.40	4.00	.39	2000.	1203.	200.	2.632	438.4	422.9	474.7	457.1	123.26	144.56	74.434	1454.0
90000.	53522.	.40	4.01	.39	2000.	1205.	300.	2.619	443.9	427.0	479.6	460.6	122.60	171.96	90.739	1544.3
90000.	53546.	.40	4.01	.39	2000.	1206.	400.	2.609	447.4	430.3	483.4	464.1	122.43	194.89	104.370	1632.5
90000.	53331.	.40	4.01	.39	2000.	1207.	600.	2.593	451.9	435.8	487.8	467.5	121.83	232.49	127.042	1805.2
90000.	44618.	.50	4.25	.30	2000.	1004.	200.	2.628	429.3	413.9	474.5	456.5	122.08	144.41	74.342	1439.6
90000.	44600.	.50	4.25	.30	2000.	1006.	300.	2.616	434.8	418.0	479.5	459.9	121.02	171.76	90.615	1529.9
90000.	44617.	.50	4.25	.30	20[illegible].	1007.	400.	2.600	438.4	421.2	483.3	463.5	121.24	194.65	104.230	1618.1
90000.	44395.	.50	4.26	.30	0.	1008.	600.	2.588	442.9	427.1	487.7	466.8	120.59	232.57	126.784	1790.8
90000.	35604.	.00	3.95	.22	0.	804.	200.	2.625	420.7	405.2	474.1	454.8	120.90	144.27	74.255	1425.8
90000.	35589.	.00	3.95	.22	300.	806.	300.	2.612	426.1	409.3	479.1	458.2	120.43	171.57	90.497	1515.3
90000.	35601.	.00	3.95	.22	2000.	806.	400.	2.602	429.7	412.5	483.0	461.7	120.06	194.43	104.092	1603.5
90000.	35470.	.00	3.96	.22	2000.	808.	600.	2.583	434.3	418.8	487.6	466.0	119.35	232.15	126.531	1770.2
90000.	17730.	.80	3.47	.09	2000.	404.	200.	2.621	402.9	387.1	473.1	449.8	118.56	144.06	74.122	1383.7
90000.	17723.	.80	3.47	.09	2000.	405.	300.	2.607	408.4	391.1	478.2	453.1	118.09	171.29	90.321	1474.1
90000.	17722.	.80	3.47	.10	2000.	405.	400.	2.597	412.0	394.3	482.2	456.4	117.72	194.07	103.874	1562.3
90000.	17553.	.80	3.47	.10	2000.	406.	600.	2.573	416.6	401.8	486.7	459.4	116.85	231.33	126.027	1734.9

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TABLE XXXIII. - TRIPROPELLANT ENGINE DATA, MODE 1
THRUST = 66723N (15,000 lbs), THRUST SPLIT = 0.8

S.I. UNITS

TRIPROPELLANT ENGINE MODEL

PROPELLANTS: LOX/LH2/RP-1

PROPELLANT	TEMP	ENTHALPY
LOX	90.18 K(162.3 R)	-3093.0 CAL/MOL
LH2	20.27 K(36.49 R)	-21.5 CAL/MOL
RP/1	298.15 K(536.7 R)	-6200.0 CAL/MOL

OVERALL MIXTURE RATIO	CORRESPONDING FRACTION OF H2 TO TOTAL FUEL
3.10	0.0 (LOX/RP-1 ONLY)
3.88	0.2
4.66	0.4
5.44	0.6
6.22	0.8
7.00	1.0 (LOX/LH2 ONLY)

MODE 1 THRUST (N)	MODE 2 THRUST (N)	THRUST SPLIT	MIX. RATIO	FRACTION H2/FUEL	MODE 1 PC (ATMS)	MODE 2 PC (ATMS)	AREA RATIO	THROAT RADIUS (M)	MODE1 ISP-T (SEC)	MODE1 ISP-D (SEC)	MODE2 ISP-T (SEC)	MODE2 ISP-D (SEC)	ENG ST LENGTH (M)	ENG OP LENGTH (M)	ENGINE DIA. (M)	ENGINE WEIGHT (KGM)
66723.	13088.	.80	3.47	.09	82.	17.	200.	.035	401.6	381.4	472.3	443.6	1.40	1.95	.997	181.8
66723.	13090.	.80	3.47	.09	82.	17.	300.	.035	407.3	385.2	477.6	446.5	1.40	2.32	1.215	198.7
66723.	13090.	.80	3.47	.09	82.	17.	400.	.035	410.9	388.3	481.7	449.6	1.39	2.62	1.397	207.1
66723.	12943.	.80	3.47	.09	82.	17.	600.	.035	415.7	396.2	486.2	452.4	1.74	3.12	1.694	231.1

TABLE XXXIII (cont.)

ENGLISH UNITS

TRIPROPELLANT ENGINE MODEL

PROPELLANTS: LOX/LH2/RP-1

PROPELLANT	TEMP	ENTHALPY
LOX	90.18 K(162.3 R)	-3093.0 CAL/MOL
LH2	20.27 K(36.49 R)	-21.5 CAL/MOL
RP/1	298.15 K(536.7 R)	-6200.0 CAL/MOL

OVERALL MIXTURE RATIO	CORRESPONDING FRACTION OF H2 TO TOTAL FUEL
3.10	0.0 (LOX/RP-1 ONLY)
3.88	0.2
4.66	0.4
5.44	0.6
6.22	0.8
7.00	1.0 (LOX/LH2 ONLY)

MODE 1 THRUST (LBF)	MODE 2 THRUST (LBF)	THRUST SPLIT	MIX. RATIO	FRACTION H2/FUEL	MODE 1 PC (PSIA)	MODE 2 PC (PSIA)	AREA RATIO	THROAT RADIUS (IN)	MODE1 ISP-T (SEC)	MODE1 ISP-D (SEC)	MODE2 ISP-T (SEC)	MODE2 ISP-D (SEC)	ENG ST LENGTH (IN)	ENG OP LENGTH (IN)	ENGINE DIA. (IN)	ENGINE WEIGHT (LBM)
15000.	29424	.80	3.47	.09	1200.	241.	200.	1.387	401.6	381.4	472.3	443.3	55.17	76.77	39.240	400.8
15000.	29433	.80	3.47	.09	1200.	242.	300.	1.381	407.3	385.2	477.6	446.5	54.97	91.21	47.825	429.3
15000.	29439	.80	3.47	.09	1200.	242.	400.	1.375	410.9	388.3	481.7	449.6	56.80	103.27	55.083	456.7
15000.	29108	.80	3.47	.09	1200.	243.	600.	1.361	415.7	396.2	486.2	452.4	68.54	122.93	60.694	509.5

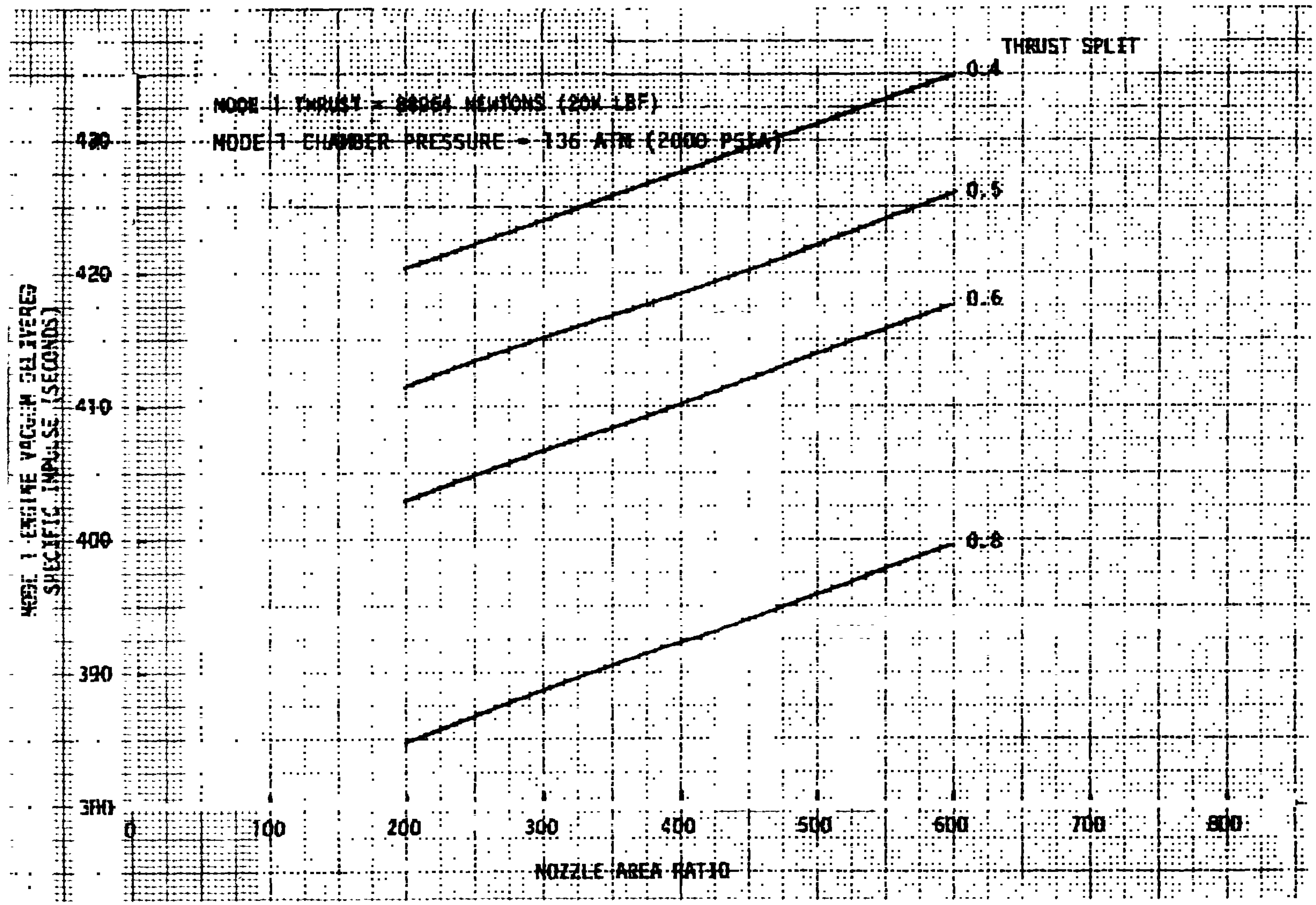

Figure 68. Effect of Nozzle Area Ratio on Tripropellant Engine Mode 1 Delivered Performance

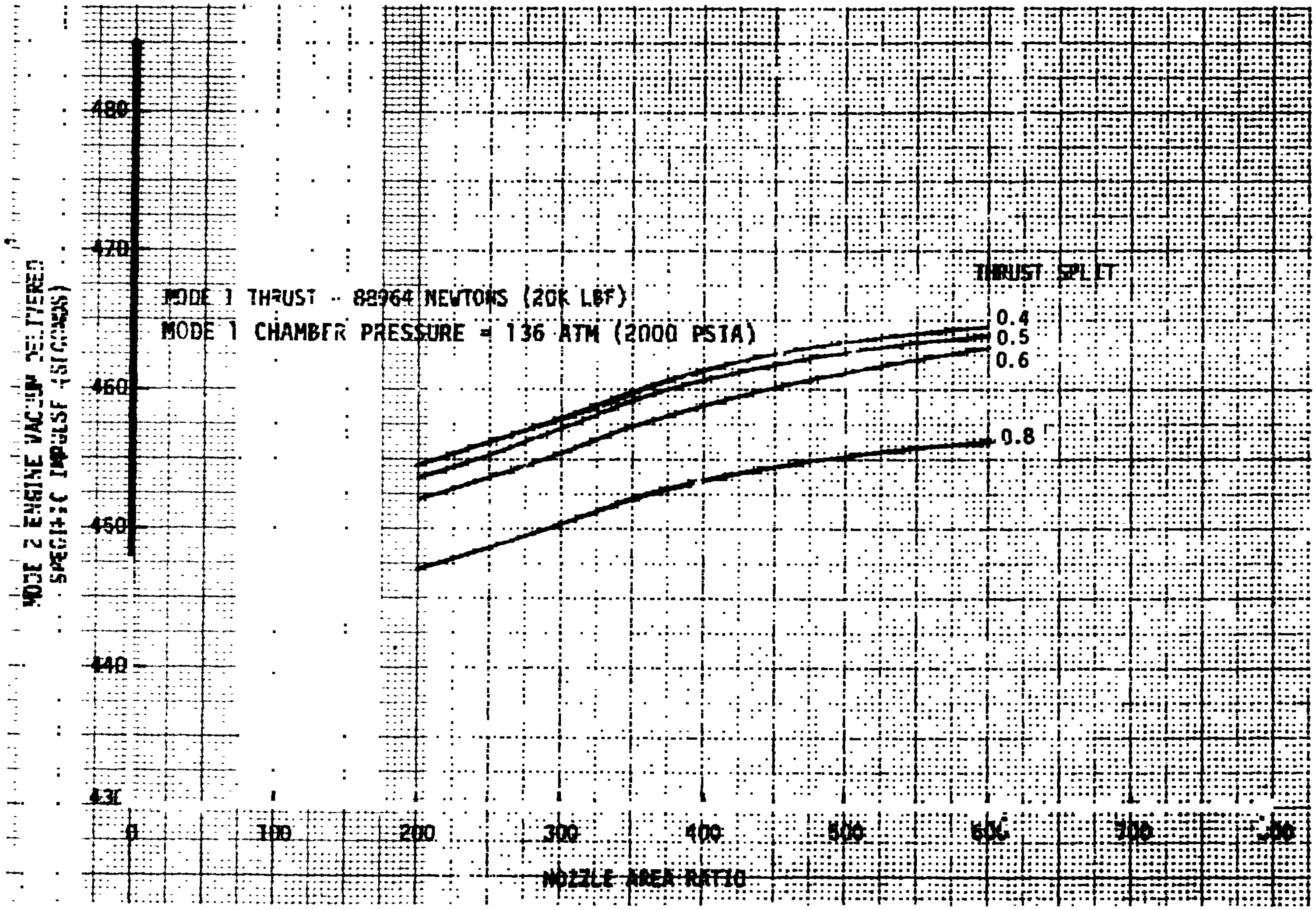

Figure 69. Effect of Nozzle Area Ratio on Tripropellant Engine Mode 2 Delivered Performance

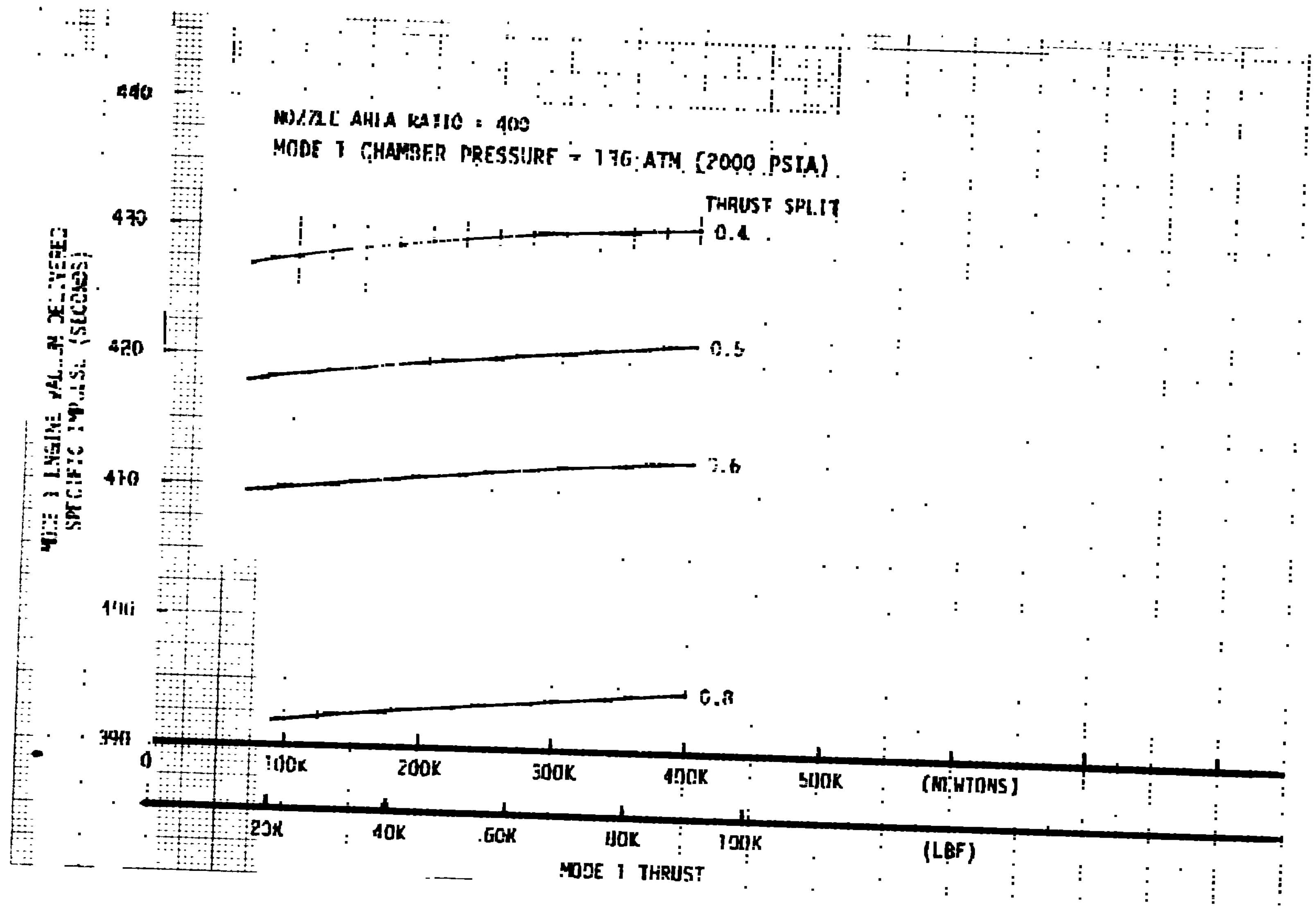

Figure 70. Effect of Thrust on Tripropellant Engine Mode 1 Delivered Performance

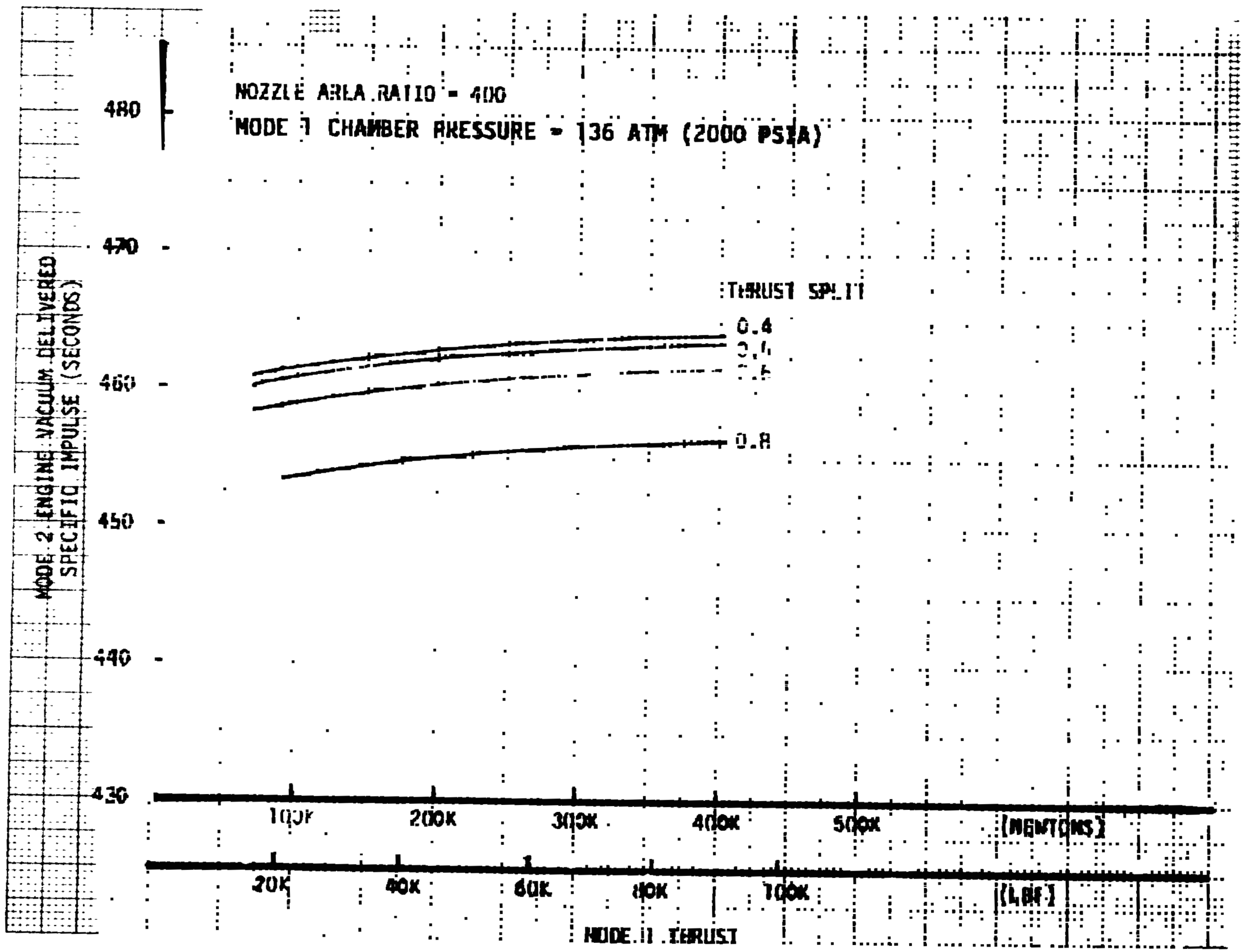

Figure 71. Effect of Thrust on Tripropellant Engine Mode 2 Delivered Performance

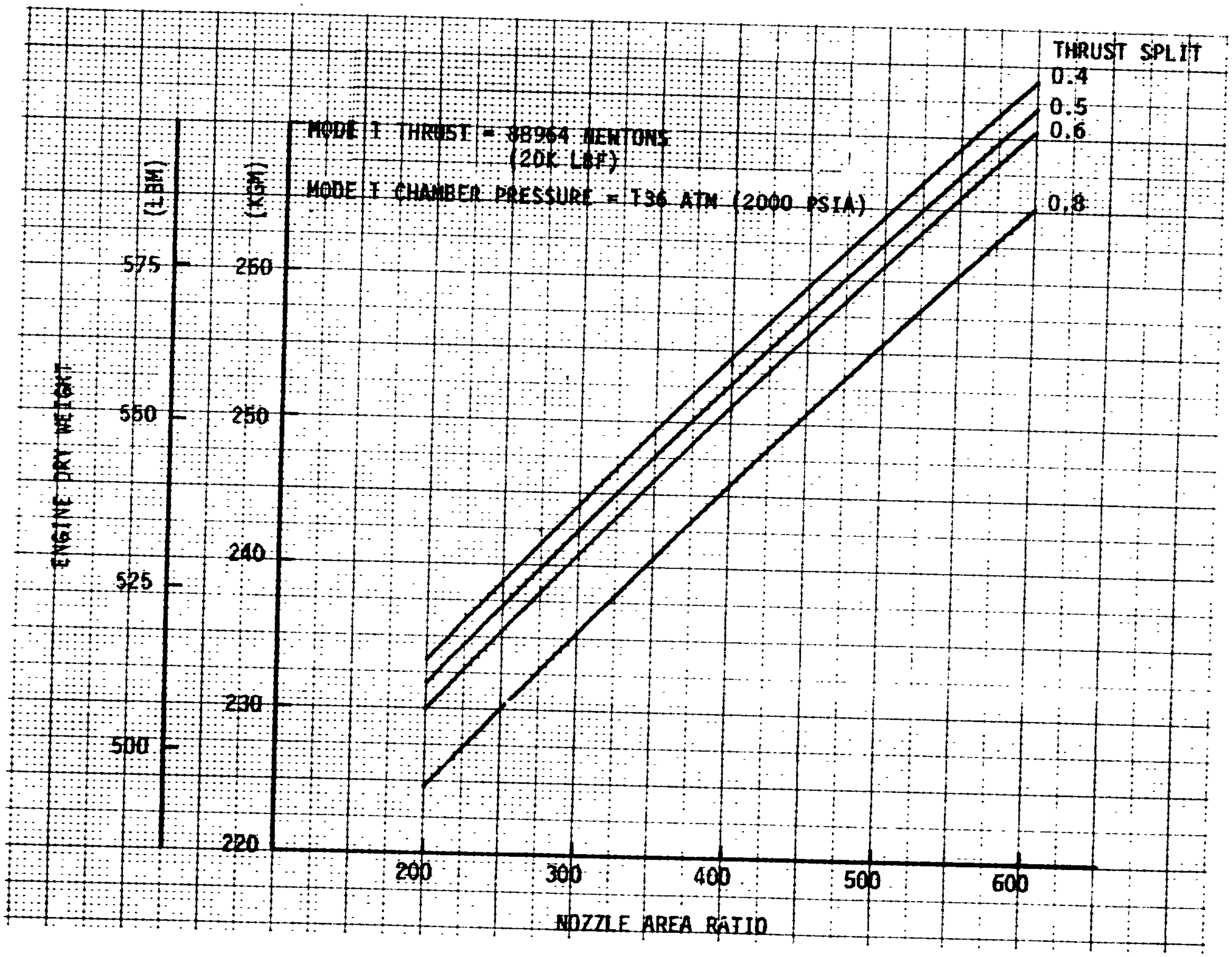

Figure 72. Effect of Area Ratio on Tripropellant Engine Weight

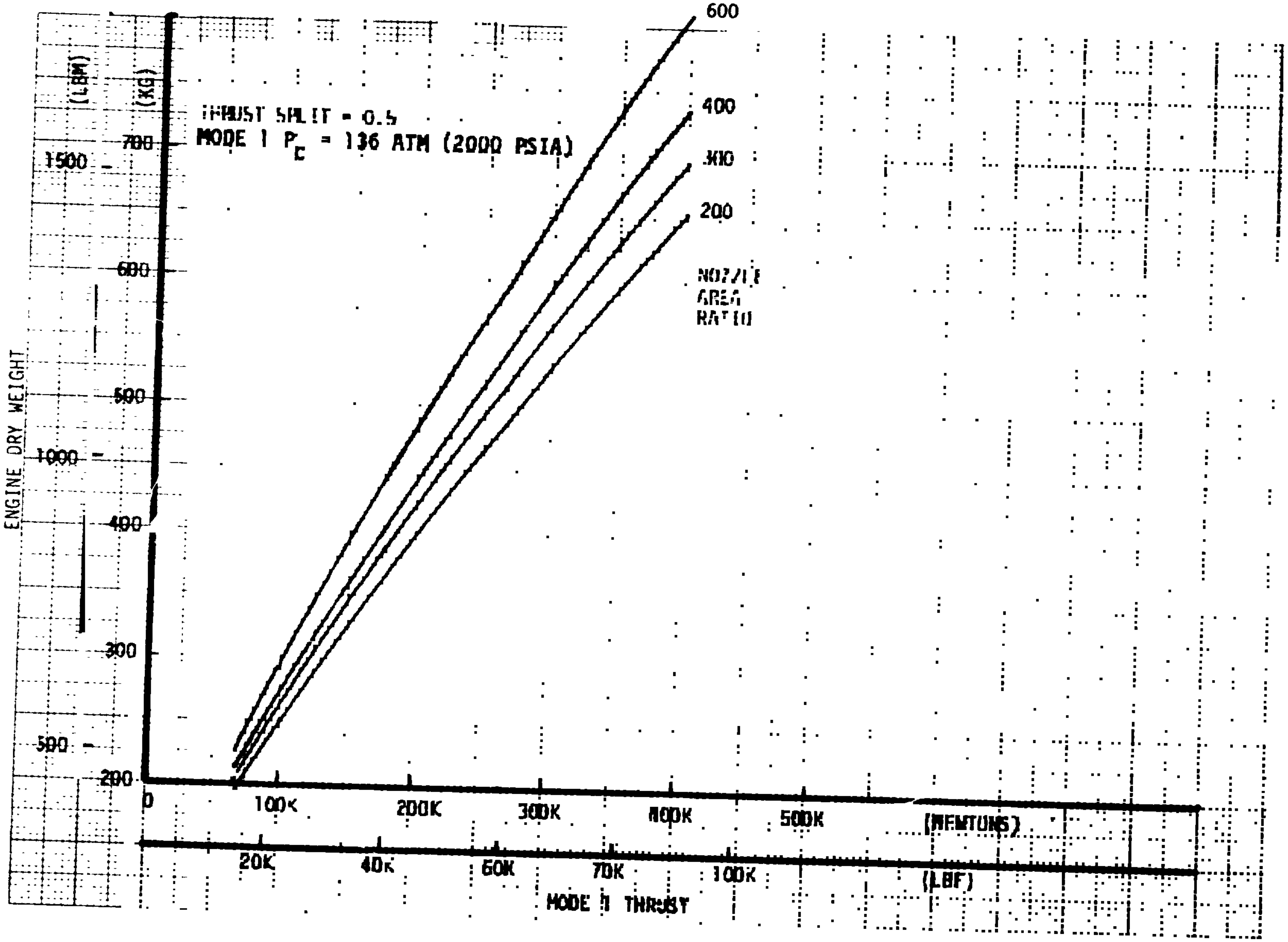

Figure 73. Effect of Thrust on Tripropellant Engine Weight

Engine envelope data is shown on Figures 74 and 75. Figure 74 shows the envelope data as a function of nozzle area ratio for the baseline Mode 1 thrust of 88964N (20,000 lbs) and thrust split of 0.5. Stowed length does not vary significantly with nozzle area ratio because the fixed nozzle length is always greater than the radiation cooled nozzle extension. Stowed length is calculated assuming that the radiation cooled nozzle extension can be retracted to the throat plane. The fixed nozzle length is based upon heat transfer analyses which established the minimum area ratio radiation cooled nozzle attachment points. Figure 75 presents the envelope data as a function of Mode 1 thrust at the baseline Mode 1 area ratio and thrust split values of 400:1 and 0.5, respectively.

2. Dual-Expander Engine

The baseline operating conditions for this engine are a Mode 1 thrust of 88964N (20,000 lbs), thrust split = 0.5, a Mode 1 nozzle area ratio of 200:1 and LOX/RP-1 and LOX/LH_2 engine mixture ratios of 3.1 and 7.0, respectively. Baseline engine performance, weight and envelope data are presented on Table XXXIV.

Performance, weight and envelope predictions for the other study thrusts, thrust splits and Mode 1 area ratios are presented on Table XXXV. The data were established for chamber pressure values resulting from cooling limitations previously listed and are shown on Figure 76.

Plots of some of the parametric data have been prepared to indicate the trends. Figures 77 and 78 show the Mode 1 and 2 delivered performance as functions of nozzle area ratio and thrust split for a baseline Mode 1 thrust of 88964N (20,000 lbs). The Mode 2 nozzle area ratios that are obtained for various Mode 1 area ratios are shown on Figure 79. Mode 1 delivered performance decreases with increasing thrust split because a greater contribution of the thrust is provided by LOX/RP-1 propellants. Mode 2 performance decreases with increasing thrust split because the Mode 2 thrust and chamber pressure are reduced significantly and this results in increased kinetics loss. The effect of Mode 1 thrust level upon the engine performance is shown on Figures 80 and 81 for the baseline Mode 1 overall area ratio of 200:1.

The Mode 1 performance of the dual-expander engine at a given overall Mode 1 area ratio is less than that of the tripropellant engine for two reasons. First, the lower operating chamber pressure results in increased kinetics loss. Second, the area ratio through which the LOX/LH_2 combustion products is expanded is less than the overall Mode 1 area ratio. This means that more of the performance contribution is obtained from the LOX/RP-1 propellants. For the tripropellant engine, all the

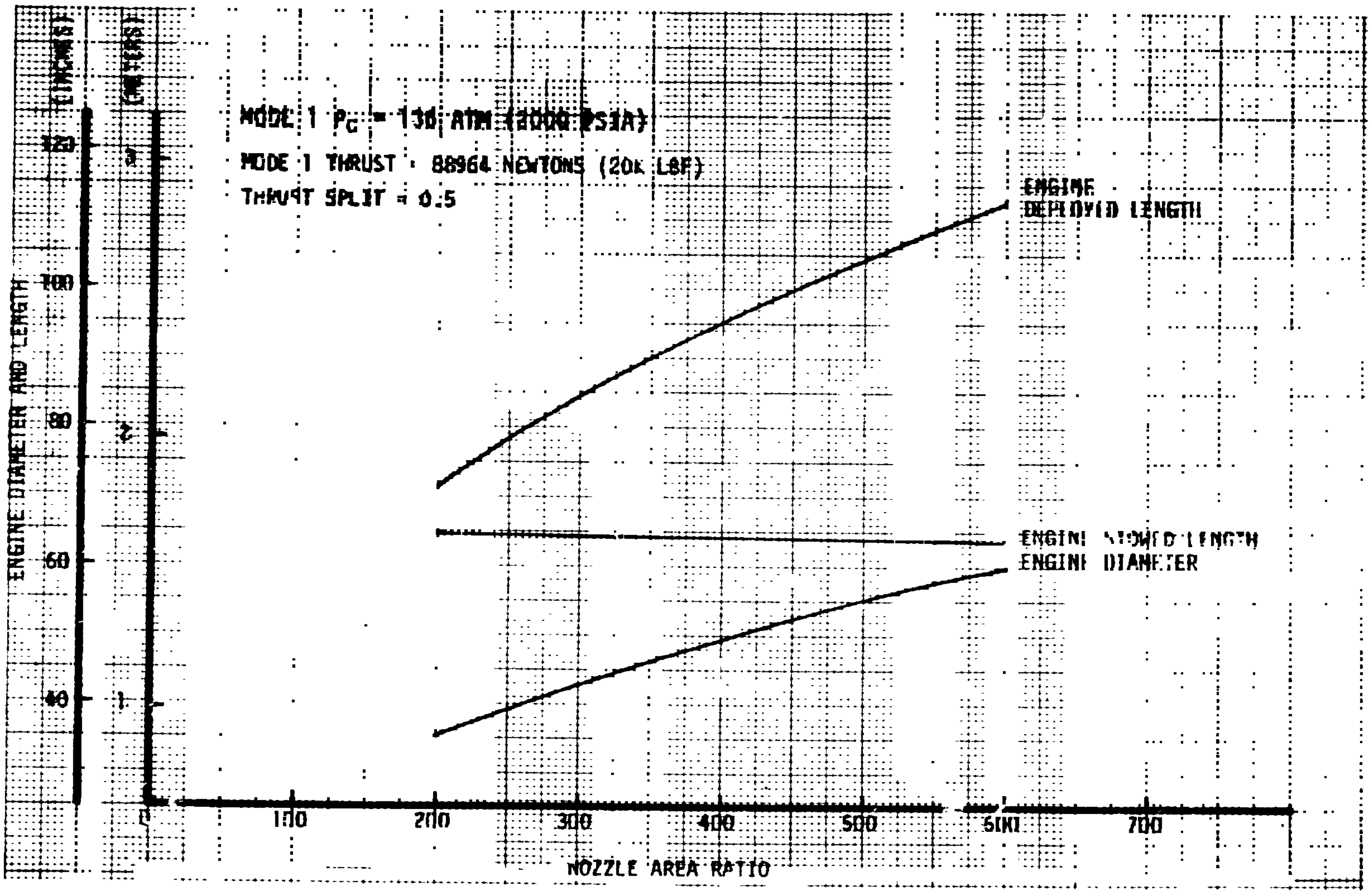

Figure 74. Effect of Nozzle Area Ratio on Tripropellant Engine Envelope

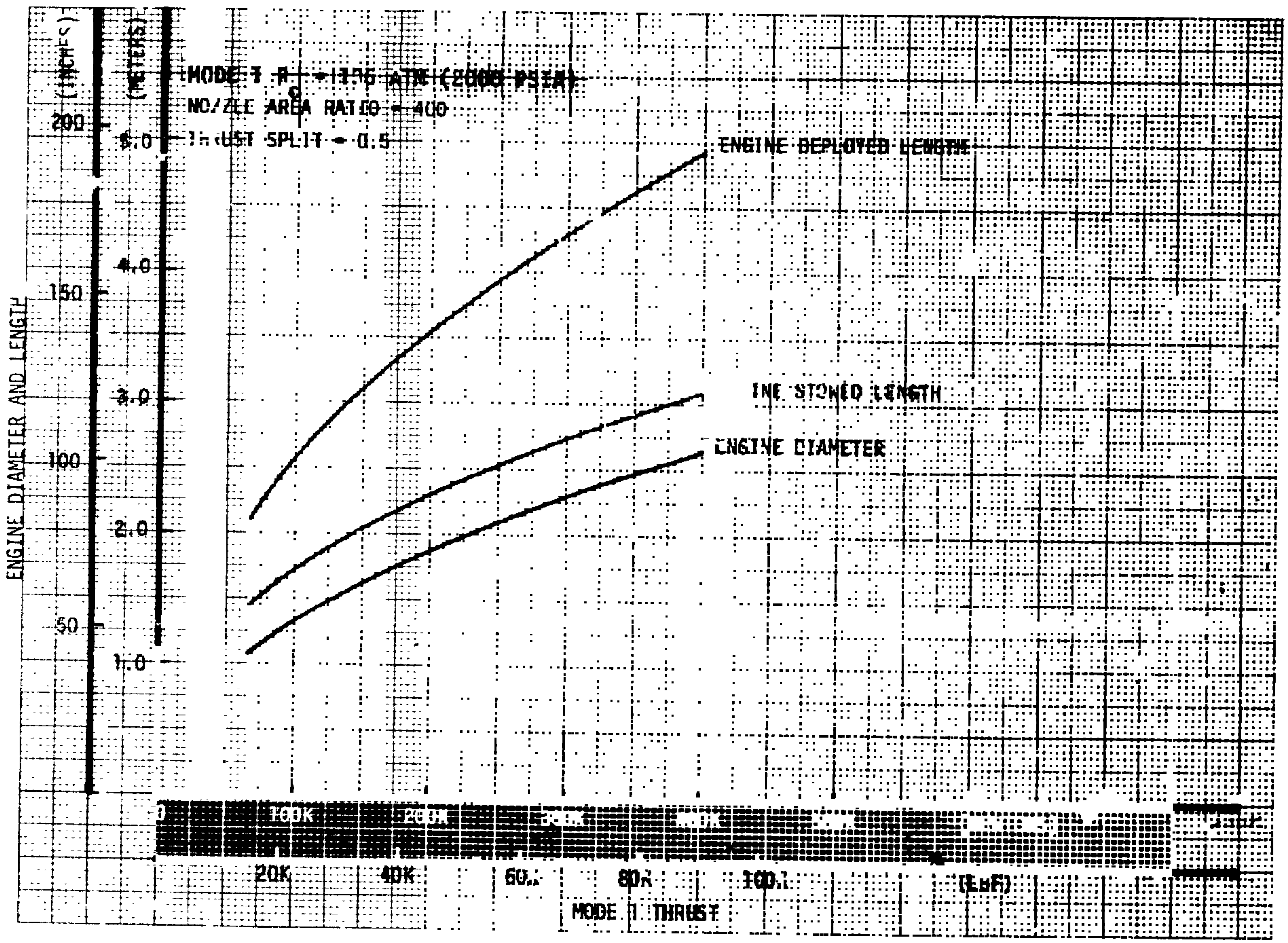

Figure 75. Effect of Thrust on Tripropellant Engine Envelope

TABLE XXXIV. - BASELINE DUAL-EXPANDER ENGINE DATA

S.I. UNITS

ENGINE PERFORMANCE

	MODE 1 LOX-RP	MODE 1 LOX-H2	MODE 2 (LOX-LH2)
1.THRUST(N)	44482.22	44482.22	45497.06
2.CHAMBER PRESSURE(ATM)	74.85	37.43	37.43
3.MIXTURE RATIO	3.19	7.00	7.00
4.TOTAL FLOWRATE (KG/SEC)	12.19	10.28	10.28
5.LOX FLOWRATE (KG/SEC)	9.22	9.00	9.00
6.FUEL FLOWRATE (KG/SEC)	2.97	1.29	1.29
7.ISP ODE (SECONDS)	391.19	467.15	478.09
8.ENERGY RELEASE EFFICIENCY	.980	.980	.980
9.KINETIC EFFICIENCY	.979	.985	.984
10.NOZZLE EFFICIENCY	.995	.996	.996
11.BOUND. LAYER THRUST LOSS (N)	132.97	806.62	806.62
12.ISP DELIVERED (SECONDS)	372.05	441.07	451.13

MODE 1 OVERALL PERFORMANCE

1.THRUST (N)	88964.43
2.ISP DELIVERED (SEC)	403.63
3.TOTAL FLOWRATE (KG/SEC)	22.48
4.THRUST SPLIT	.50
5.MIXTURE RATIO	4.28

ENGINE SIZE (M AND M**2)

1.GIMBAL LENGTH	.13	11.MODE 1 AREA RATIO	200.00
2.INJECTOR LENGTH	.10	12.LOXRP A RATIO	316.50
3.LOXRP TC LENGTH	.38	13.MODE1 LOXH2 RAT	141.75
4.LOXH2 TC LENG	.18	14.LOXRP CU AREA RAT	8.00
5.NOZZLE LENGTH	1.67	15.LOXH2 CU AREA RAT	8.00
6.TOTAL ENG LENG	2.28	16.LOXH2 TUBE A RAT	42.92
7.EXIT DIA	1.48	17.MODE 2(O2H2)AREA RATIO	300.00
8.THROAT RAD	.03	PER CENT BELL	90.00
9.LOXH2 THROAT AREA	.01		
10.LOXH2 THROAT WIDTH	.02		

ENGINE WEIGHTS (KG)

1.GIMBAL	7.57	15.LOW SPD O2 TPA(O2H2 SYS)	2.68
2.O2-RP1 INJECT	5.70	16.HI SPD O2 TPA(OH)	2.68
3.O2-H2 INJECT	11.18	17.LOW SPD LH2 TPA	1.00
4.O2-RP1 CC	14.73	18.LOW SPD RP-1 TPA	.86
5.O2-H2 CC	11.45	19.HI SPD O2 TPA(O2RPSYS)	8.16
6.O2-RP1 CU NOZ	6.43	20.HI SPD O2 TPA(OH)	6.90
7.FD CU NOZ	13.40	21.HI SPD LH2 TPA	8.34
8.FOR DEF TUBE NOZ	7.58	22.HI SPD RP1 TPA	3.11
9.FORCED DEF RAD COOLED NOZ	33.15	23.LINES	16.19
10.H2 RCH O2H2 PREBRN	3.24	24.H.GAS LINES	16.78
11.O2 RCH O2H2 PREBRN	7.76	25.IGN. SYSTEM	12.70
12.LOH2 VALVES-ACT.	13.95	26.MISCELLANEOUS	19.50
13.H.GAS VALVES	4.86	27.TOTAL ENG WEIGHT	249.39
14.RP1 VALVES	9.48	28.MODE1 F TO WT RATIO	36.38
		29.MODE2 F TO WT RATIO	18.60

TABLE XXXIV (cont.)

ENGLISH UNITS

ENGINE PERFORMANCE

	MODE 1 LOX-RP	MODE 1 LOX-LH2	MODE 2 (LOX-LH2)
1.THRUST(LBF)	10000.00	10000.00	10228.15
2.CHAMBER PRESSURE(PSIA)	1100.00	550.00	550.00
3.MIXTURE RATIO	3.10	7.00	7.00
4.TOTAL FLOWRATE (LBM/SEC)	26.88	22.67	22.67
5.LOX FLOWRATE (LBM/SEC)	20.32	19.84	19.84
6.FUEL FLOWRATE (LBM/SEC)	6.56	2.83	2.83
7.ISP ODE (SECONDS)	391.19	467.15	478.09
8.ENERGY RELEASE EFFICIENCY	.980	.980	.980
9.KINETIC EFFICIENCY	.979	.985	.984
10.NOZZLE EFFICIENCY	.995	.996	.996
11.BOUND. LAYER THRUST LOSS (LBF)	29.89	181.33	181.33
12.ISP DELIVERED (SECONDS)	372.05	441.07	451.13

MODE 1 OVERALL PERFORMANCE

1.THRUST (LBF)	20000.00
2.ISP DELIVERED (SEC)	403.63
3.TOTAL FLOW RATE (LBM/SEC)	49.55
4.THRUST SPLIT	.50
5.MIXTURE RATIO	4.28

ENGINE SIZE (IN AND IN**2)

1.GIMBAL LENGTH	5.00	11.MODE 1 AREA RATIO	200.00
2.INJECTOR LENGTH	4.00	12.LOXRP A RATIO	316.50
3.LOXRP TC LENGTH	15.04	13.MODE1 LOXH2 RAT	141.75
4.LOXH2 TC LENG	6.94	14.LOXRP CU AREA RAT	8.00
5.NOZZLE LENGTH	65.73	15.LOXH2 CU AREA RAT	8.00
6.TOTAL ENG LENG	89.77	16.LOXH2 TUBE A RAT	42.92
7.EXIT DIA	58.46	17.MODE 2(O2H2)AREA RATIO	300.00
8.THROAT RAD	1.17	18.PER CENT BELL	90.00
9.LOXH2 THROAT AREA	4.13		
10.LOXH2 THROAT WIDTH	.90		

ENGINE WEIGHTS (LBM)

1.GIMBAL	10.70	15.LOW SPD O2 TPA(O2H2 SYS)	5.90
2.O2-RP1 INJECT	12.57	16.HI SPD O2 TPA(OH)	5.90
3.O2-H2 INJECT	24.64	17.LOW SPD LH2 TPA	2.20
4.O2-RP1 CC	32.48	18.LOW SPD RP-1 TPA	1.90
5.O2-H2 CC	25.25	19.HI SPD O2 TPA(O2RPSYS)	18.00
6.O2-RP1 CU NOZ	14.17	20.HI SPD O2 TPA(OH)	15.21
7.FD CU NOZ	29.54	21.HI SPD LH2 TPA	10.39
8.FOR DEF TUBE NOZ	16.71	22.HI SPD RP1 TPA	6.85
9.FORCED DEF RAD COOLED NOZ	73.08	23.LINES	35.70
10.H2 RCH O2H2 PREBRN	7.14	24.H.GAS LINES	37.00
11.O2 RCH O2H2 PREBRN	17.11	25.IGN. SYSTEM	28.00
12.O2H2 VALVES-ACT.	30.76	26.MISCELLANEOUS	43.00
13.H.GAS VALVES	10.71	27.TOTAL ENG WEIGHT	549.81
14.RP1 VALVES	20.89	28.MODE1 F TO WT RATIO	36.38
		29.MODE2 F TO WT RATIO	18.60

TABLE XXXV. - DUAL-EXPANDER ENGINE PARAMETRIC DATA

S.I. UNITS

DUAL EXPANDER ENGINE MODEL

PROPELLANTS: LOX/LH2/RP-1

PROPELLANT	TEMP	ENTHALPY
LOX	90.18 K(162.3 R)	-3093.0 CAL/MOL
LH2	20.27 K(36.49 R)	-21.5 CAL/MOL
RP-1	298.15 K(536.7 R)	-6200.0 CAL/MOL

LOX/RP-1 MIXTURE RATIO: 3.1
LOX/LH2 MIXTURE RATIO: 7.0

TOTAL MODE 1 THRUST (N)	THRUST SPLIT	TOTAL MODE 2 THRUST (N)	MODE 1 OVERALL MIX.	LOX-RP PC (ATMS)	LOX-H2 PC (ATMS)	MODE 1 OVERALL AREA RATIO	MODE1 LOXRP AREA RATIO	MODE1 LOXH2 AREA RATIO	MODE2 AREA RATIO	LOX-RP THROAT RADIUS (M)	LOX-H2 THROAT AREA (M**2)	MODE 1 LOX-RP ISP-D (SEC)	MODE 1 LOX-H2 ISP-D (SEC)	MODE 1 ISP-D (SEC)	MODE 2 LOX-H2 ISP-D (SEC)	ENGINE LENGTH (M)	ENGINE DIA. (M)	ENGINE WEIGHT (KG)
66723.	.40	40718.	4.63	82.	41.	200.	341.	153.	267.	.02	.00	372.23	443.33	411.86	450.90	1.85	1.27	202.
66723.	.40	40665.	4.63	82.	41.	300.	513.	229.	400.	.02	.00	376.57	447.78	416.29	454.84	2.15	1.55	221.
66723.	.40	40621.	4.63	82.	41.	400.	684.	305.	533.	.02	.00	379.32	450.53	419.06	457.14	2.40	1.79	236.
66723.	.40	40521.	4.63	82.	41.	600.	1027.	458.	800.	.02	.00	383.70	454.49	423.25	460.02	2.82	2.18	267.
66723.	.50	34123.	4.28	68.	34.	200.	317.	142.	300.	.03	.00	370.68	440.17	402.45	450.21	2.09	1.35	206.
66723.	.50	34015.	4.28	68.	34.	300.	475.	212.	450.	.03	.00	375.14	444.91	407.06	453.63	2.44	1.64	223.
66723.	.50	34021.	4.28	68.	34.	400.	634.	283.	600.	.03	.00	378.01	447.32	409.75	456.15	2.74	1.89	241.
66723.	.50	33884.	4.28	68.	34.	600.	952.	424.	900.	.03	.00	382.04	451.37	413.82	458.44	3.23	2.31	276.
66723.	.60	27469.	3.97	58.	29.	200.	292.	131.	350.	.03	.00	368.25	435.80	392.59	448.85	2.32	1.42	208.
66723.	.60	27358.	3.97	58.	29.	300.	439.	196.	525.	.03	.00	372.63	440.48	397.09	451.52	2.72	1.72	227.
66723.	.60	27349.	3.98	58.	29.	400.	585.	261.	700.	.03	.00	375.44	442.73	399.74	453.66	3.06	1.98	246.
66723.	.60	27223.	3.98	58.	29	600.	878.	391.	1050.	.03	.00	379.29	446.60	403.62	455.51	3.62	2.42	284.
66723.	.80	13987.	3.49	13.	6.	200.	245.	110.	600.	.08	.01	364.29	418.87	374.08	439.03	4.55	2.76	344.
66723.	.80	13920.	3.49	13.	6.	300.	368.	165.	900.	.08	.01	369.33	421.23	378.66	439.39	5.44	3.36	417.
66723.	.80	13846.	3.49	13.	6.	400.	490.	219.	1200.	.08	.01	372.60	423.79	381.82	439.70	6.18	3.86	490.
66723.	.80	13797.	3.50	13.	6.	600.	736.	328.	1800.	.08	.01	376.78	425.60	385.63	440.03	7.43	4.71	637.
88964.	.40	54290.	4.63	88.	44.	200.	341.	153.	267.	.02	.01	373.72	444.21	413.05	451.80	2.03	1.41	249.
88964.	.40	54220.	4.63	88.	44.	300.	513.	229.	400.	.02	.01	376.15	448.70	417.54	455.77	2.36	1.72	268.
88964.	.40	54162.	4.63	88.	44.	400.	684.	305.	533.	.02	.01	380.92	451.48	420.34	458.10	2.63	1.98	287.
88964.	.40	54327.	4.64	88.	44.	600.	1027.	458.	800.	.02	.01	385.39	455.48	424.59	461.02	3.10	2.41	325.
88964.	.50	45497.	4.28	75.	37.	200.	317.	142.	300.	.03	.01	372.05	441.07	405.63	451.13	2.28	1.48	249.
88964.	.50	45354.	4.28	75.	37.	300.	475.	212.	450.	.03	.01	376.61	445.86	408.32	454.60	2.67	1.81	270.
88964.	.50	45361.	4.28	75.	37.	400.	634.	283.	600.	.03	.01	379.49	448.30	411.04	457.16	2.99	2.08	292.
88964.	.50	45179.	4.28	75.	37.	600.	952.	424.	900.	.03	.01	383.60	452.40	415.17	459.49	3.53	2.54	334.
88964.	.60	36653.	3.97	61.	31.	200.	292.	131.	350.	.04	.01	369.49	436.87	393.74	449.97	2.57	1.59	252.
88964.	.60	36478.	3.98	61.	31.	300.	439.	196.	525.	.04	.01	373.97	441.61	398.37	452.68	3.02	1.93	276.
88964.	.60	36466.	3.98	61.	31.	400.	585.	261.	700.	.04	.01	376.82	443.89	401.06	454.87	3.40	2.22	300.
88964.	.60	36299.	3.98	61.	31.	600.	878.	391.	1050.	.04	.01	380.74	447.82	405.01	456.79	4.03	2.71	348.
88964.	.80	18648.	3.49	14.	7.	200.	245.	110.	600.	.09	.01	365.21	419.84	374.97	440.01	5.08	3.10	425.
88964.	.80	18559.	3.49	14.	7.	300.	368.	165.	900.	.09	.01	370.31	422.26	379.65	440.44	6.08	3.78	517.
88964.	.80	18460.	3.49	14.	7.	400.	490.	219.	1200.	.09	.01	373.61	424.88	382.85	440.81	6.92	4.34	610.
88964.	.80	18395.	3.50	14.	7.	600.	736.	328.	1800.	.09	.01	377.86	426.77	386.72	441.20	8.33	5.30	796.
177929.	.40	108579.	4.63	102.	51.	200.	341.	153.	267.	.03	.01	376.64	446.18	415.49	453.79	2.59	1.85	408.
177929.	.40	108440.	4.64	102.	51.	300.	513.	229.	400.	.03	.01	381.25	450.75	420.11	457.85	3.02	2.26	441.
177929.	.40	108323.	4.64	102.	51.	400.	684.	305.	533.	.03	.01	384.07	453.59	422.97	460.25	3.39	2.60	474.
177929.	.40	108050.	4.64	102.	51.	600.	1027.	458.	800.	.03	.01	388.66	457.69	427.33	463.24	3.99	3.17	540.

TABLE XXXV (cont.)

S.I. UNITS

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177929.	.50	90993.	4.28	88.	44.	200.	317.	142.	300.	.04	.01	374.81	443.09	406.10	453.19	2.90	1.95	408.
177929.	.50	90707.	4.28	88.	44.	300.	475.	212.	450.	.04	.01	379.56	447.98	410.94	456.75	3.40	2.35	443.
177929.	.50	90721.	4.28	88.	44.	400.	634.	283.	600.	.04	.01	382.48	450.49	413.71	459.38	3.82	2.70	479.
177929.	.50	90355.	4.28	88.	44.	600.	952.	424.	900.	.04	.01	386.70	454.69	417.95	461.80	4.52	3.29	550.
177929.	.60	73312.	3.98	71.	36.	200.	292.	131.	350.	.05	.01	372.85	439.36	396.89	452.59	3.28	2.07	412.
177929.	.60	72957.	3.98	71.	36.	300.	439.	196.	525.	.05	.01	377.60	444.26	401.71	455.41	3.87	2.52	453.
177929.	.60	72935.	3.98	71.	36.	400.	585.	261.	700.	.05	.01	380.57	446.65	404.51	457.71	4.36	2.90	494.
177929.	.60	72601.	3.98	71.	36.	600.	878.	391.	1050.	.05	.01	384.67	450.70	408.61	459.75	5.19	3.54	576.
177929.	.80	37289.	3.49	16.	8.	200.	245.	110.	600.	.12	.02	367.15	422.17	376.97	442.38	6.61	4.06	710.
177929.	.80	37112.	3.49	16.	8.	300.	368.	165.	900.	.11	.02	372.36	424.74	381.77	442.96	7.92	4.97	872.
177929.	.80	36914.	3.49	16.	8.	400.	490.	219.	1200.	.11	.02	375.73	427.50	385.06	443.46	9.03	5.71	1033.
177929.	.80	36784.	3.50	16.	8.	600.	736.	328.	1800.	.11	.02	380.09	429.55	389.05	444.01	10.86	6.97	1356.
266893.	.40	102869.	4.64	112.	56.	200.	341.	153.	267.	.04	.01	378.35	447.42	416.97	455.06	2.99	2.16	553.
266893.	.40	102561.	4.64	112.	56.	300.	513.	229.	400.	.04	.01	383.05	452.04	421.66	459.17	3.49	2.64	598.
266893.	.40	102485.	4.64	112.	56.	400.	684.	305.	533.	.04	.01	385.89	454.93	424.55	461.60	3.92	3.03	643.
266893.	.40	102072.	4.64	112.	56.	600.	1027.	458.	800.	.04	.01	390.52	459.06	428.96	464.63	4.63	3.70	733.
266893.	.50	136487.	4.28	95.	48.	200.	317.	142.	300.	.05	.01	376.13	444.21	407.35	454.33	3.38	2.27	553.
266893.	.50	136059.	4.28	95.	48.	300.	475.	212.	450.	.05	.01	380.96	449.14	412.25	457.95	3.96	2.71	602.
266893.	.50	136080.	4.28	95.	48.	400.	634.	283.	600.	.04	.01	383.92	451.69	415.06	460.60	4.46	3.19	652.
266893.	.50	135530.	4.28	95.	48.	600.	952.	424.	900.	.04	.01	388.17	455.95	419.34	463.06	5.29	3.86	752.
266893.	.60	109965.	3.98	78.	39.	200.	292.	131.	350.	.05	.01	374.12	440.54	398.13	453.78	3.81	2.42	557.
266893.	.60	109434.	3.98	78.	39.	300.	439.	196.	525.	.05	.01	378.95	445.48	403.03	456.65	4.49	2.95	613.
266893.	.60	109399.	3.98	78.	39.	400.	585.	261.	700.	.05	.01	381.95	447.91	405.86	459.00	5.07	3.39	670.
266893.	.60	108900.	3.98	78.	39.	600.	878.	391.	1050.	.05	.01	386.09	452.02	410.01	461.10	6.03	4.14	763.
266893.	.80	55931.	3.49	18.	9.	200.	245.	110.	600.	.13	.03	368.17	423.60	378.06	443.86	7.58	4.69	944.
266893.	.80	55664.	3.49	18.	9.	300.	368.	165.	900.	.13	.03	373.41	426.26	382.91	444.53	9.10	5.72	1158.
266893.	.80	55367.	3.49	18.	9.	400.	490.	219.	1200.	.13	.03	376.81	429.12	386.23	445.11	10.37	6.57	1372.
266893.	.80	55172.	3.50	18.	9.	600.	736.	328.	1800.	.13	.03	381.21	431.27	390.27	445.76	12.50	8.01	1800.
400340.	.40	244304.	4.64	122.	61.	200.	341.	153.	267.	.04	.02	379.89	448.66	418.37	455.32	3.47	2.54	759.
400340.	.40	243992.	4.64	122.	61.	300.	513.	229.	400.	.04	.02	384.67	453.33	423.12	460.48	4.06	3.09	621.
400340.	.40	243728.	4.64	122.	61.	400.	684.	305.	533.	.04	.02	387.54	456.26	426.04	462.95	4.56	3.55	683.
400340.	.40	243104.	4.64	122.	61.	600.	1027.	458.	800.	.04	.02	392.19	460.46	430.46	466.02	5.39	4.33	1007.
400340.	.50	204727.	4.28	102.	51.	200.	317.	142.	300.	.05	.02	377.33	445.31	406.51	455.45	3.95	2.69	758.
400340.	.50	204087.	4.28	102.	51.	300.	475.	212.	450.	.05	.02	382.23	450.29	413.48	459.10	4.65	3.27	828.
400340.	.50	204117.	4.28	102.	51.	400.	634.	283.	600.	.05	.02	385.21	452.88	416.31	461.81	5.24	3.77	897.
400340.	.50	203291.	4.29	102.	51.	600.	952.	424.	900.	.05	.02	389.48	457.19	420.63	464.31	6.22	4.59	1036.
400340.	.60	164985.	3.98	85.	43.	200.	292.	131.	350.	.06	.02	375.28	441.69	399.29	454.95	4.43	2.84	762.
400340.	.60	164149.	3.98	85.	43.	300.	439.	196.	525.	.06	.02	380.19	446.69	404.26	457.88	5.24	3.46	840.
400340.	.60	164095.	3.98	85.	43.	400.	585.	261.	700.	.06	.02	383.21	449.16	407.12	460.26	5.92	3.98	918.
400340.	.60	163347.	3.98	85.	43.	600.	878.	391.	1050.	.06	.02	387.37	453.33	411.31	462.82	7.05	4.85	1073.
400340.	.80	83890.	3.49	19.	10.	200.	245.	110.	600.	.16	.04	369.06	424.90	379.03	445.18	8.91	5.53	1300.
400340.	.80	83490.	3.49	19.	10.	300.	368.	165.	900.	.16	.04	374.36	427.66	383.93	445.74	10.69	6.74	1598.
400340.	.80	83045.	3.49	19.	10.	400.	490.	219.	1200.	.16	.04	377.78	430.58	387.28	446.59	12.19	7.75	1896.
400340.	.80	82753.	3.50	19.	10.	600.	736.	328.	1800.	.15	.04	382.22	432.81	391.37	447.33	14.70	9.45	2493.

TABLE XXXV (cont.)

ENGLISH UNITS

DUAL EXPANDER ENGINE MODEL

PROPELLANTS: LOX/LH2/RP-1

PROPELLANT	TEMP	ENTHALPY
LOX	90.18 K(162.3 R)	-3093.0 CAL/MOL
LH2	20.27 K(36.49 R)	-21.5 CAL/MOL
RP-1	298.15 K(536.7 F)	-6200.0 CAL/MOL

LOX/RP-1 MIXTURE RATIO: 3.1
LOX/LH2 MIXTURE RATIO: 7.0

TOTAL MODE 1 THRUST (LBF)	THRUST SPLIT	TOTAL MODE 2 THRUST (LBF)	MODE 1 OVERALL MIX. RATIO	LOX-RP PC (PSIA)	LOX-H2 PC (PSIA)	MODE 1 OVERALL AREA RATIO	MODE1 LOXRP AREA RATIO	MODE1 LOXH2 AREA RATIO	MODE2 AREA RATIO	LOX-RP THROAT RADIUS (IN)	LOX-H2 THROAT AREA (IN**2)	MODE 1 LOX-RP ISP-D (SEC)	MODE 1 LOX-H2 ISP-D (SEC)	MODE 1 ISP-D (SEC)	MODE 2 LOX-H2 ISP-D (SEC)	ENGINE LENGTH (IN)	ENGINE DIA. (IN)	ENGINE WEIGHT (LBM)
15000.	.40	9154.	4.63	1200.	600.	200.	341.	153.	267.	.87	7.50	372.23	443.33	411.66	450.90	72.83	50.11	452.
15000.	.40	9142.	4.63	1200.	600.	300.	513.	229.	400.	.86	7.42	376.57	447.[illegible]	416.29	454.86	84.56	61.00	486.
15000.	.40	9132.	4.63	1200.	600.	400.	684.	305.	533.	.86	7.36	379.32	450.53	419.06	457.14	94.44	7[illegible].26	520.
15000.	.40	9109.	4.63	1200.	600.	600.	1027.	458.	800.	.85	7.31	383.70	454.49	423.25	460.02	116.87	65.67	588.
15000.	.50	7671.	4.28	1000.	500.	200.	317.	142.	300.	1.06	7.54	370.68	440.17	402.45	450.21	82.32	53.14	454.
15000.	.50	7647.	4.28	1000.	500.	300.	475.	212.	450.	1.06	7.46	375.14	444.91	407.06	453.63	96.14	64.72	49[illegible].
15000.	.50	7648.	4.28	1000.	500.	400.	634.	283.	600.	1.05	7.42	378.01	447.32	409.75	456.15	107.77	78.50	53[illegible].
15000.	.50	7618.	4.28	1000.	500.	600.	952.	424.	900.	1.05	7.35	382.04	451.37	413.82	458.44	127.18	90.81	608.
15000.	.60	6180.	3.97	850.	425.	200.	292.	131.	350.	1.27	7.15	368.25	435.80	392.59	448.85	91.31	55.71	458.
15000.	.60	6150.	3.97	850.	425.	300.	439.	196.	525.	1.26	7.08	372.63	440.48	397.69	451.52	107.12	67.85	500.
15000.	.60	6148.	3.98	850.	425.	400.	585.	261.	700.	1.25	7.04	375.44	442.73	399.74	453.06	120.43	78.11	542.
15000.	.60	6123.	3.98	850.	425.	600.	878.	391.	1050.	1.25	6.98	379.29	446.60	403.62	455.54	142.66	95.22	626.
15000.	.80	3144.	3.49	190.	95.	200.	245.	110.	600.	3.08	16.46	364.29	418.87	374.04	439.03	178.96	108.58	758.
15000.	.80	3129.	3.49	190.	95.	300.	368.	165.	900.	3.06	16.39	369.33	421.23	378.56	439.39	213.98	132.26	920.
15000.	.80	3113.	3.49	190.	95.	400.	490.	219.	1200.	3.05	16.29	372.60	423.79	381.92	439.70	243.42	152.15	1081.
15000.	.80	3102.	3.50	190.	95.	600.	736.	328.	1800.	3.03	16.22	376.78	425.60	385.63	440.03	292.71	185.51	1404.
20000.	.40	12205.	4.63	1300.	650.	200.	341.	153.	267.	.96	9.22	373.72	444.21	413.05	451.80	79.77	55.56	549.
20000.	.40	12189.	4.63	1300.	650.	300.	513.	229.	400.	.96	9.13	376.15	448.70	417.34	455.77	92.77	67.69	590.
20000.	.40	12176.	4.63	1300.	650.	400.	684.	305.	533.	.95	9.07	380.92	451.48	420.34	458.10	103.71	77.91	632.
20000.	.40	12146.	4.64	1300.	650.	600.	1027.	458.	800.	.95	8.99	385.39	455.48	424.59	461.02	121.91	94.97	716.
20000.	.50	10228.	4.28	1100.	550.	200.	317.	142.	300.	1.17	9.13	372.05	441.07	403.63	451.13	89.77	58.46	550.
20000.	.50	10196.	4.28	1100.	550.	300.	475.	212.	450.	1.16	9.03	376.61	445.86	406.32	454.68	104.96	71.29	596.
20000.	.50	10196.	4.28	1100.	550.	400.	634.	283.	600.	1.16	8.98	379.49	448.30	411.04	457.16	117.75	81.96	643.
20000.	.50	10157.	4.28	1100.	550.	600.	952.	424.	900.	1.15	8.90	383.60	452.40	415.17	459.49	139.09	99.96	736.
20000.	.60	8240.	3.97	900.	450.	200.	292.	131.	350.	1.42	8.99	369.49	436.87	393.78	449.97	101.14	62.45	556.
20000.	.60	8201.	3.98	900.	450.	300.	439.	196.	525.	1.41	8.89	373.97	441.61	396.37	452.68	118.65	76.05	608.
20000.	.60	8198.	3.98	900.	450.	400.	585.	261.	700.	1.40	8.85	376.82	443.89	401.06	454.87	133.76	87.55	661.
20000.	.60	8160.	3.98	900.	450.	600.	878.	391.	1050.	1.40	8.77	380.74	447.82	405.01	456.79	158.66	106.72	768.
20000.	.80	4192.	3.49	200.	100.	200.	245.	110.	600.	3.46	20.83	365.21	419.84	374.97	440.01	199.94	122.07	936.
20000.	.80	4172.	3.49	200.	100.	300.	368.	165.	900.	3.44	20.71	370.31	422.26	379.65	440.44	239.30	148.68	1141.
20000.	.80	4150.	3.49	200.	100.	400.	490.	219.	1200.	3.42	20.59	373.61	424.88	382.85	440.81	272.39	171.01	1345.
20000.	.80	4135.	3.50	200.	100.	600.	736.	328.	1800.	3.40	[illegible]	377.86	426.77	386.72	441.20	327.77	208.52	1754.
40000.	.40	24410.	4.63	1500.	750.	200.	341.	153.	267.	1.26	15.93	376.64	446.18	415.49	453.79	101.94	73.03	899.
40000.	.40	24378.	4.64	1500.	750.	300.	513.	229.	400.	1.26	15.77	381.25	450.75	420.11	457.85	119.00	88.97	972.
40000.	.40	24352.	4.64	1500.	750.	400.	684.	305.	533.	1.25	15.67	384.07	453.59	422.97	460.25	133.37	102.39	1045.
40000.	.40	24291.	4.64	1500.	750.	600.	1027.	458.	800.	1.24	15.53	388.66	457.69	427.33	463.24	157.26	124.80	1198.

TABLE XXXV (cont.)

ENGLISH UNITS

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40000.	.50	20456.	4.28	1300.	650.	200.	317.	142.	300.	1.52	15.40	374.81	443.09	400.10	453.19	114.02	75.95	898.
40000.	.50	20392.	4.28	1300.	650.	300.	475.	212.	450.	1.51	15.23	379.56	447.98	410.94	456.75	133.72	92.46	977.
40000.	.50	20395.	4.28	1300.	650.	400.	634.	283.	600.	1.50	15.15	382.48	450.49	413.71	459.38	150.32	105.43	1056.
40000.	.50	20313.	4.28	1300.	650.	600.	952.	424.	900.	1.49	15.01	386.70	454.69	417.95	461.80	178.00	129.71	1213.
40000.	.60	16481.	3.98	1050.	525.	200.	292.	131.	350.	1.85	15.35	372.85	439.38	395.89	452.59	129.27	81.55	907.
40000.	.60	16401.	3.98	1050.	525.	300.	439.	196.	525.	1.84	15.18	377.60	444.26	401.71	455.41	152.34	99.29	998.
40000.	.60	16396.	3.98	1050.	525.	400.	585.	261.	700.	1.83	15.10	380.57	446.65	404.51	457.71	171.76	114.26	1089.
40000.	.60	16321.	3.98	1050.	525.	600.	878.	391.	1050.	1.82	14.97	384.67	450.70	408.61	459.75	204.20	139.29	1271.
40000.	.80	8383.	3.49	230.	115.	200.	245.	110.	600.	4.56	36.05	367.15	422.17	376.97	442.38	260.21	160.61	1566.
40000.	.80	8343.	3.49	230.	115.	300.	368.	165.	900.	4.53	35.83	372.36	426.74	381.77	442.96	311.96	195.61	1921.
40000.	.80	8299.	3.49	230.	115.	400.	490.	219.	1200.	4.51	35.60	375.73	427.50	385.06	443.46	355.48	224.95	2277.
40000.	.80	8269.	3.50	230.	115.	600.	736.	328.	1800.	4.48	35.43	380.09	429.55	389.65	444.01	426.31	274.26	2989.
60000.	.40	36614.	4.64	1650.	825.	200.	341.	153.	267.	1.47	21.69	378.35	447.42	416.97	455.06	117.67	85.21	1220.
60000.	.40	36568.	4.64	1650.	825.	300.	513.	229.	400.	1.46	21.47	383.05	452.04	421.66	459.17	137.56	103.60	1319.
60000.	.40	36526.	4.64	1650.	825.	400.	684.	305.	533.	1.46	21.33	385.69	454.93	424.55	461.60	154.32	119.46	1418.
60000.	.40	36435.	4.64	1650.	825.	600.	1027.	458.	800.	1.45	21.14	390.52	459.08	428.96	464.63	182.18	145.59	1617.
60000.	.50	30683.	4.28	1400.	700.	200.	317.	142.	300.	1.79	21.42	376.13	444.21	407.35	454.33	132.67	89.53	1219.
60000.	.50	30587.	4.28	1400.	700.	300.	475.	212.	450.	1.78	21.18	380.96	449.14	412.25	457.93	156.10	109.02	1328.
60000.	.50	30592.	4.28	1400.	700.	400.	634.	283.	600.	1.77	21.06	383.92	451.69	415.06	460.60	175.66	125.49	1438.
60000.	.50	30468.	4.28	1400.	700.	600.	952.	424.	900.	1.76	20.87	388.17	455.95	419.34	[illegible]	208.30	152.93	1657.
60000.	.60	24721.	3.98	1150.	575.	200.	292.	131.	350.	2.16	20.99	374.12	440.54	398.13	453.78	149.64	95.35	1228.
60000.	.60	24602.	3.98	1150.	575.	300.	439.	196.	525.	2.15	20.76	378.95	445.48	403.03	456.65	176.00	116.09	1352.
60000.	.60	24594.	3.98	1150.	575.	400.	585.	261.	700.	2.14	20.64	381.95	447.91	405.86	459.06	199.50	133.62	1476.
60000.	.60	24482.	3.98	1150.	575.	600.	878.	391.	1050.	2.13	20.46	386.09	452.02	410.01	461.10	237.42	162.85	1725.
60000.	.80	12574.	3.49	260.	130.	200.	245.	110.	600.	5.25	47.69	368.17	423.00	379.06	443.86	298.01	184.81	2061.
60000.	.80	12514.	3.49	260.	130.	300.	368.	165.	900.	5.21	47.39	373.41	426.28	382.91	444.53	358.17	225.07	2553.
60000.	.80	12447.	3.49	260.	130.	400.	490.	219.	1200.	5.18	47.06	376.81	429.12	386.23	445.11	406.25	258.82	3025.
60000.	.80	12403.	3.50	260.	130.	600.	736.	328.	1800.	5.15	46.84	381.21	431.27	390.27	445.76	492.04	315.53	3969.
90000.	.40	54922.	4.64	1800.	900.	200.	341.	153.	267.	1.73	29.77	379.89	448.66	418.37	456.32	130.64	99.83	1674.
90000.	.40	54852.	4.64	1800.	900.	300.	513.	229.	400.	1.72	29.47	384.67	453.33	423.12	460.48	159.94	121.66	1610.
90000.	.40	54792.	4.64	1800.	900.	400.	684.	305.	533.	1.71	29.26	387.54	456.26	426.04	462.95	179.58	139.95	1949.
90000.	.40	54652.	4.64	1800.	900.	600.	1027.	458.	800.	1.70	29.01	392.19	460.46	430.48	466.02	212.22	170.56	2219.
90000.	.50	46024.	4.28	1500.	750.	200.	317.	142.	300.	2.12	29.93	377.33	445.31	408.51	455.45	155.58	105.85	1672.
90000.	.50	45881.	4.28	1500.	750.	300.	475.	212.	450.	2.10	29.60	382.23	450.29	413.48	459.10	183.03	128.89	1825.
90000.	.50	45887.	4.28	1500.	750.	400.	634.	283.	600.	2.09	29.43	385.21	452.88	416.31	461.81	206.16	148.35	1978.
90000.	.50	45702.	4.29	1500.	750.	600.	952.	424.	900.	2.08	29.15	389.48	457.19	420.63	464.31	244.74	180.79	2205.
90000.	.60	37081.	3.98	1250.	625.	200.	292.	131.	350.	2.54	28.91	375.28	441.69	399.29	454.95	174.00	111.92	1680.
90000.	.60	36902.	3.98	1250.	625.	300.	439.	196.	525.	2.52	28.59	380.19	446.69	404.26	457.88	206.24	136.26	1851.
90000.	.60	36890.	3.98	1250.	625.	400.	585.	261.	700.	2.51	28.43	383.21	449.16	407.12	460.26	232.69	156.83	2023.
90000.	.60	36722.	3.98	1250.	625.	600.	878.	391.	1050.	2.50	28.17	387.37	453.33	411.31	462.42	277.40	191.13	2306.
90000.	.80	18859.	3.49	280.	140.	200.	245.	110.	600.	6.19	66.24	369.06	424.90	379.03	445.18	350.67	217.86	2867.
90000.	.80	18769.	3.49	280.	140.	300.	368.	165.	900.	6.14	65.82	374.36	427.66	383.93	445.94	426.68	265.33	3523.
90000.	.80	18669.	3.49	280.	140.	400.	490.	219.	1200.	6.11	65.37	377.78	430.56	387.28	446.59	479.92	305.11	4181.
90000.	.80	18604.	3.50	280.	140.	600.	736.	328.	1800.	6.08	65.03	382.22	432.81	391.37	447.33	576.70	371.94	5498.

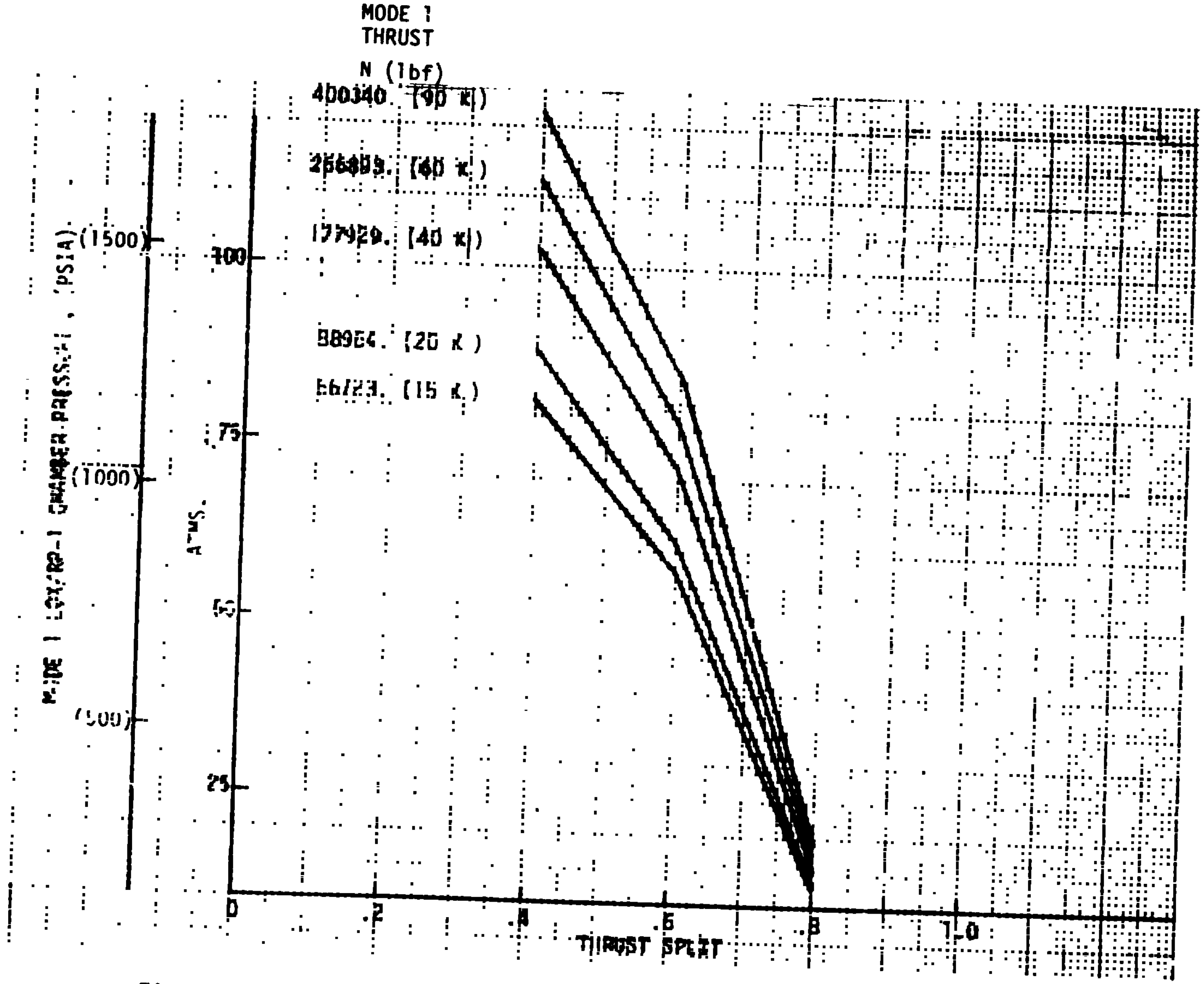

Figure 76. Dual-Expander Engine Mode 1 LOX/RP-1 Chamber Pressure

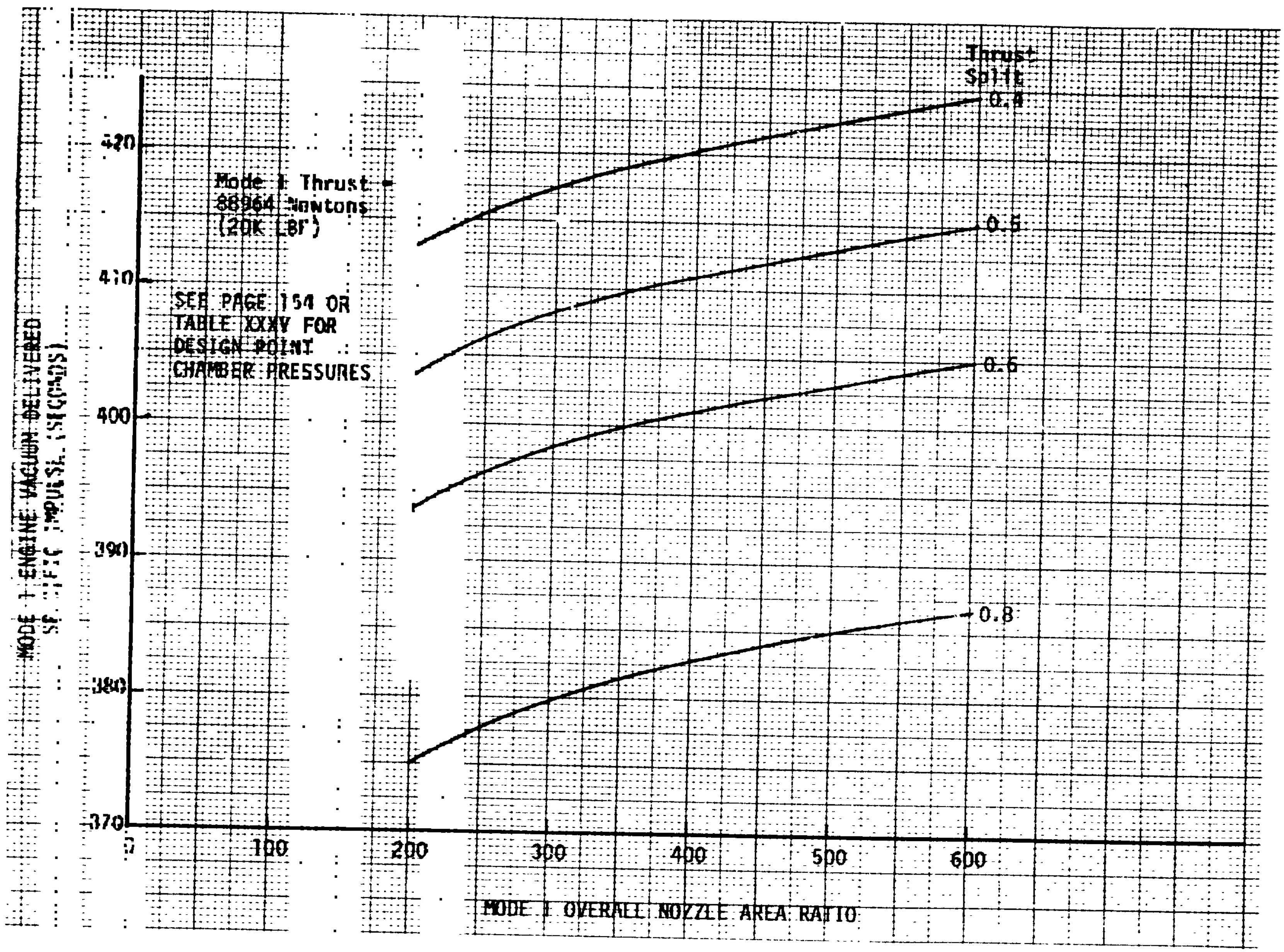

Figure 77. Effect of Mode 1 Overall Area Ratio on Dual-Expander Engine Mode 1 Delivered Performance

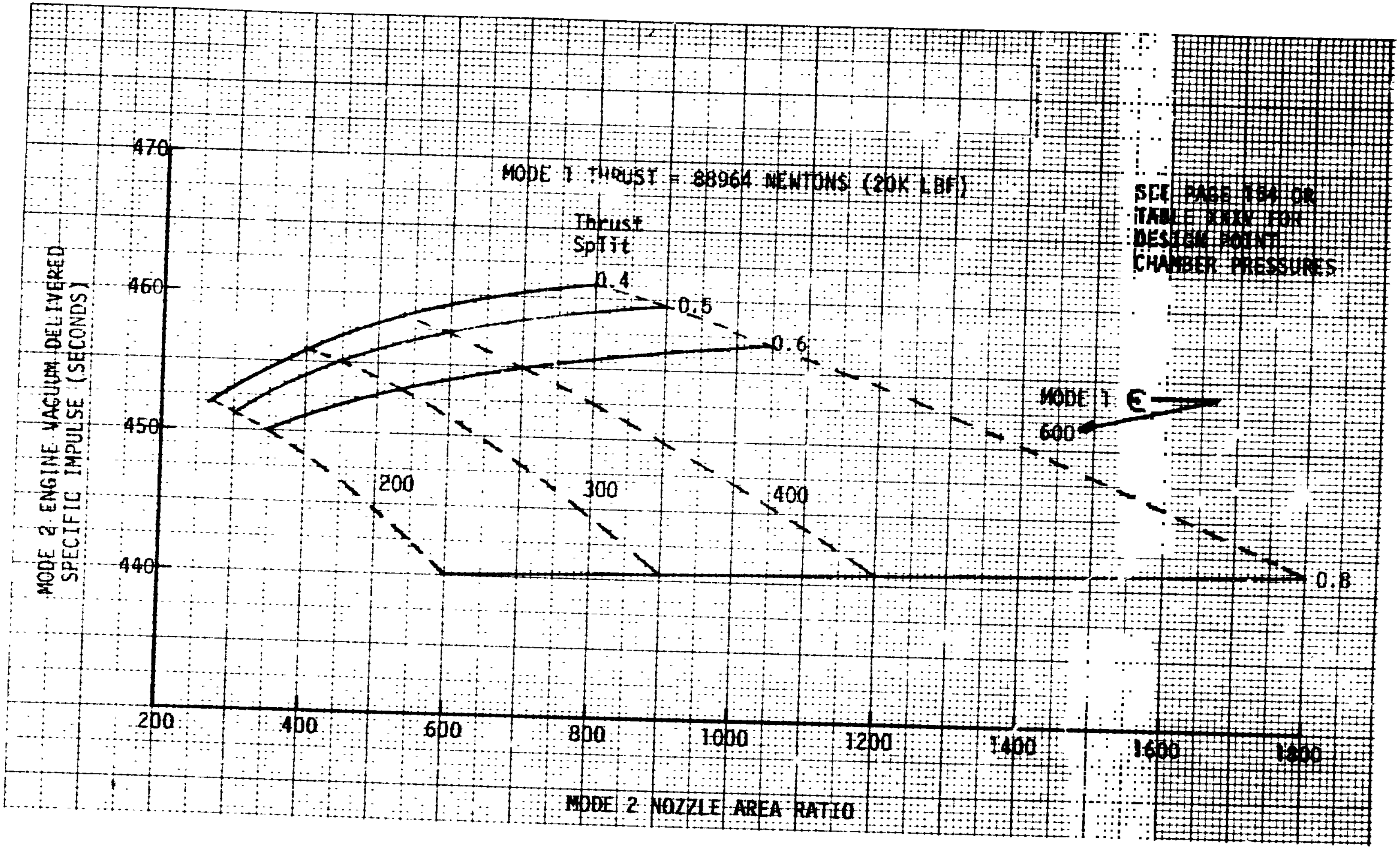

Figure 78. Effect of Mode 2 Nozzle Area Ratio on Dual-Expander Engine Mode 2 Delivered Performance

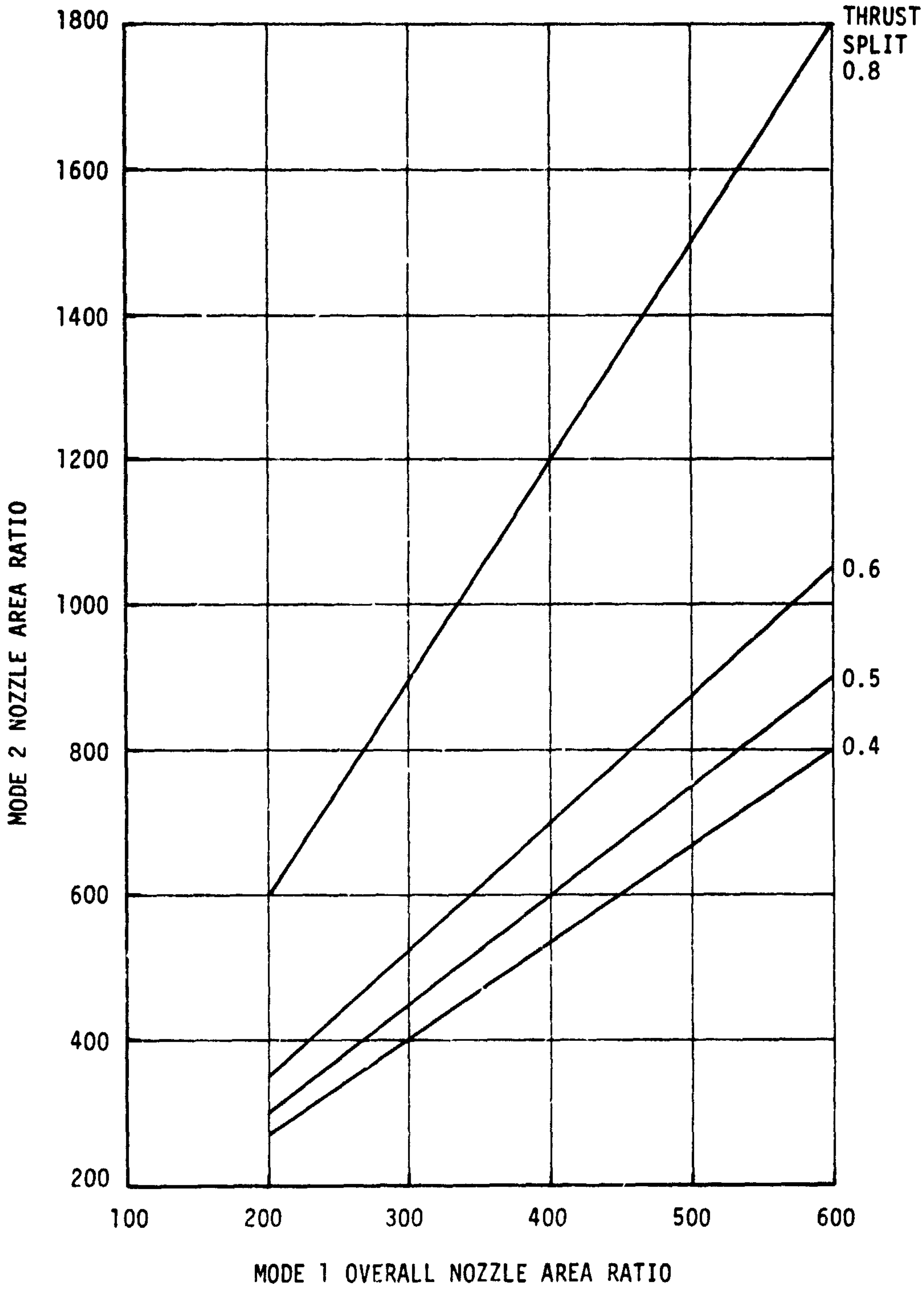

Figure 79. Dual-Expander Engine Mode 2 Nozzle Area Ratio

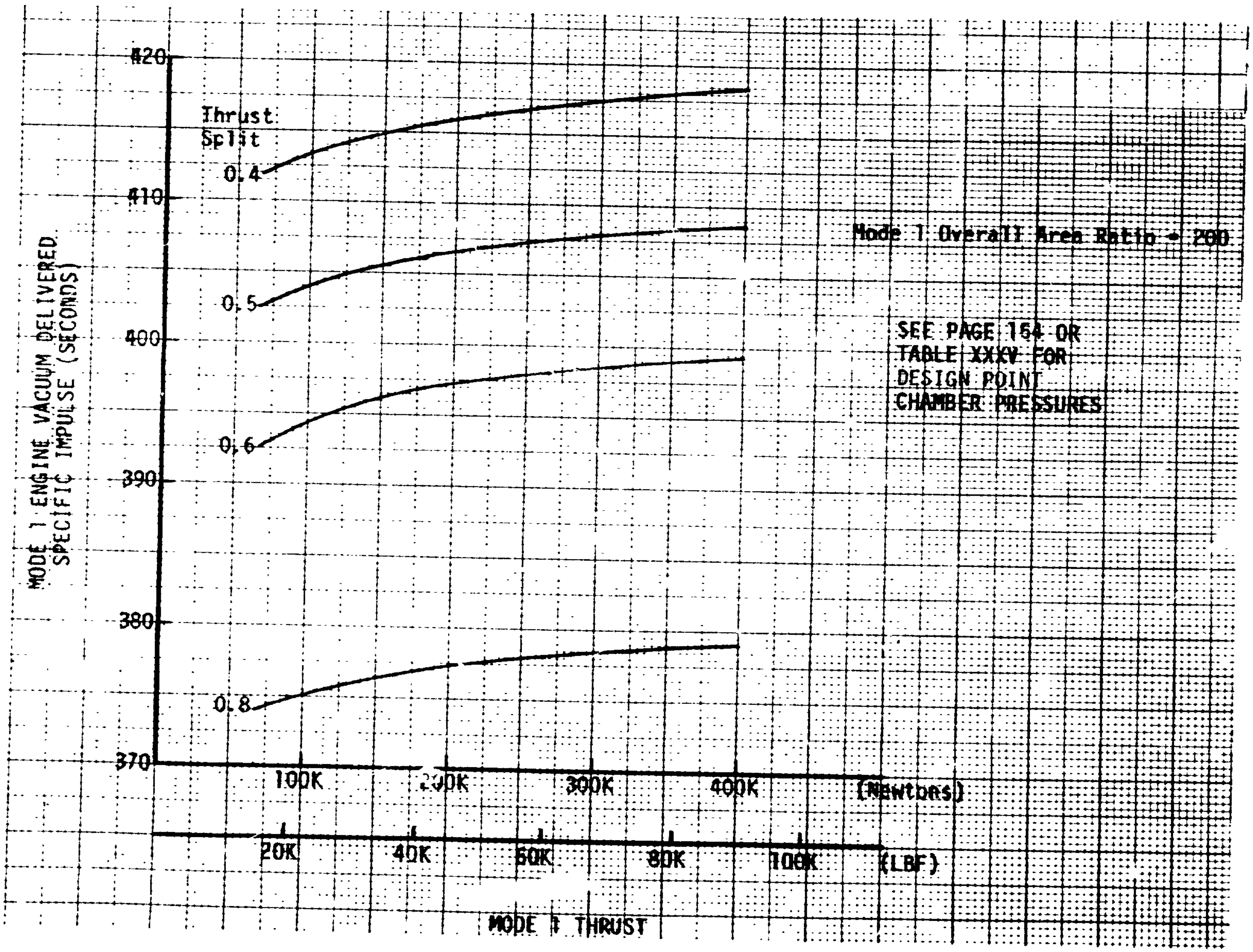

Figure 80. Effect of Thrust on Dual-Expander Engine Mode 1 Delivered Performance

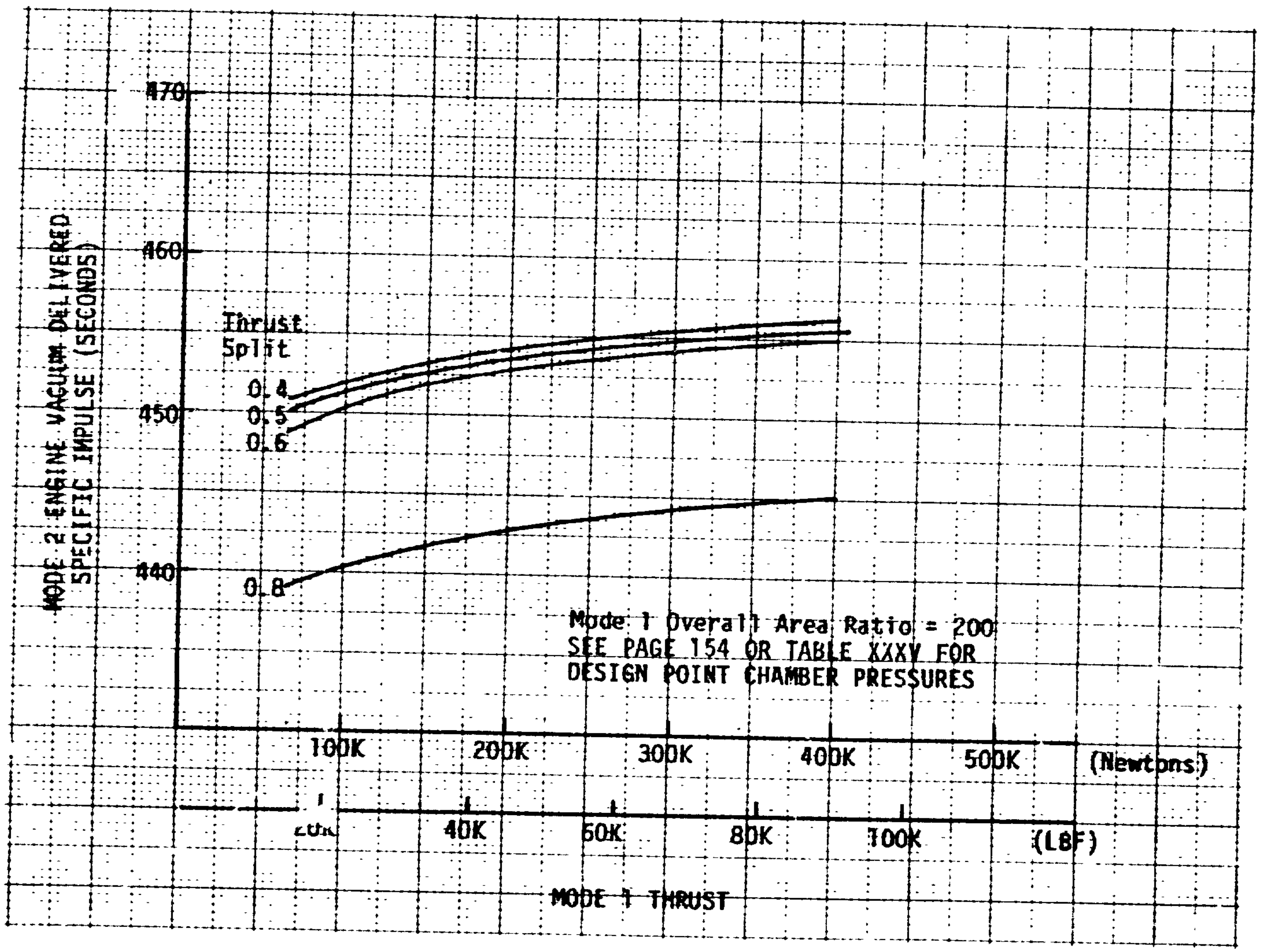

Figure 81. Effect of Thrust on Dual Expander Engine Mode 2 Delivered Performance

products of combustion are expanded through the full area ratio. The Mode 2 performance is a little lower than the tripropellant engine because of higher kinetics losses associated with lower chamber pressure operation.

Engine dry weight is shown on Figure 82 as a function of Mode 1 overall nozzle area ratio and thrust split at the baseline Mode 1 thrust of 88964N (20,000 lbs). Engine weight increases with increasing thrust split because the operating chamber pressure decreases. This results in very heavy nozzles for the high required area ratios (Figure 79). As discussed previously, the chamber pressures at a thrust split of 0.8 are below practical operating pressures for pump-fed engines. The data is included only to complete the study matrix and to indicate the danger of extrapolating the study results. For example, a linear extrapolation of the weight data obtained at thrust splits of 0.4, 0.5 and 0.6 would result in an obviously significant error at a thrust split of 0.8.

The effect of Mode 1 thrust on the dual-expander engine dry weight is shown on Figure 83 for the baseline thrust split of 0.5 and various Mode 1 overall nozzle area ratios.

The dual-expander engine envelope data is shown on Figures 84 and 85. Figure 84 shows the envelope data as a function of the Mode 1 overall area ratio for the baseline Mode 1 thrust and thrust split values of 88964N (20,000 lbs) and 0.5, respectively. Figure 85 shows the envelope data as a function of the Mode 1 thrust for the baseline thrust split of 0.5 and an overall Mode 1 area ratio of 200:1.

3. Plug Cluster Engine

The baseline operating conditions for this engine are a Mode 1 thrust level of 88964N (20,000 lbs), thrust split = 0.5, and overall Mode 1 geometric area ratio of 358:1 (module area ratio = 200:1) and LOX/RP-1 and LOX/LH_2 engine mixture ratios of 3.1 and 7.0, respectively. In addition, based upon the results of Contract NAS3-20109, Unconventional Nozzle Tradeoff Study (Ref 3), all the modules are assumed to touch (zero gap) in Mode 1 and a zero length plug and 10 modules are used. Baseline engine performance, weight and envelope data are presented on Table XXXVI.

Performance, weight and envelope predictions for the other study Mode 1 thrusts, thrust splits and overall Mode 1 area ratios are presented on Table XXXVII. All of these data were established for a thrust chamber pressure of 20.4 atm (300 psia). This low chamber pressure value was selected because of problems associated with cooling the LOX/RP-1 modules

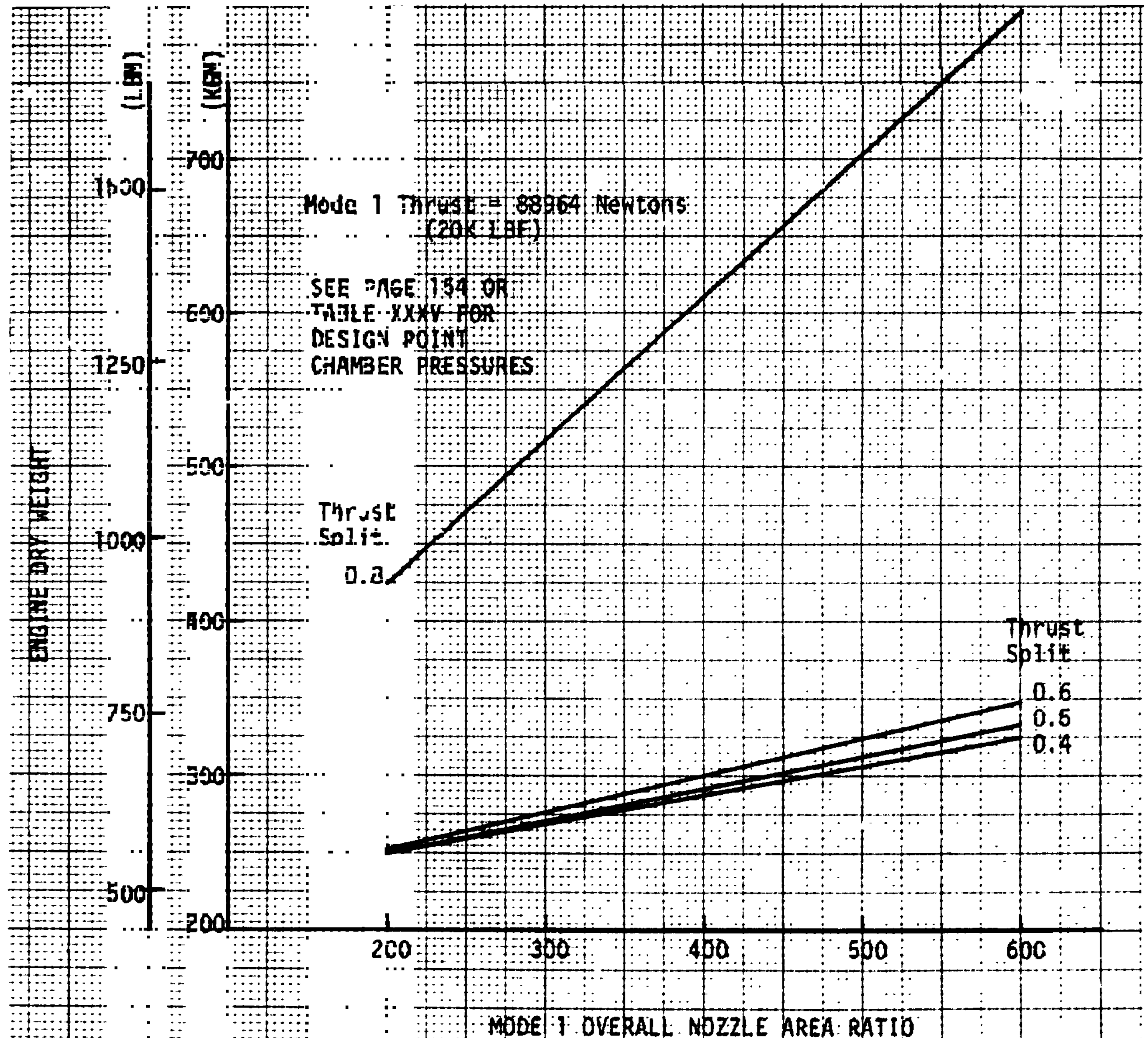

Figure 82. Effect of Mode 1 Overall Nozzle Area Ratio on Dual-Expander Engine Weight

C-3

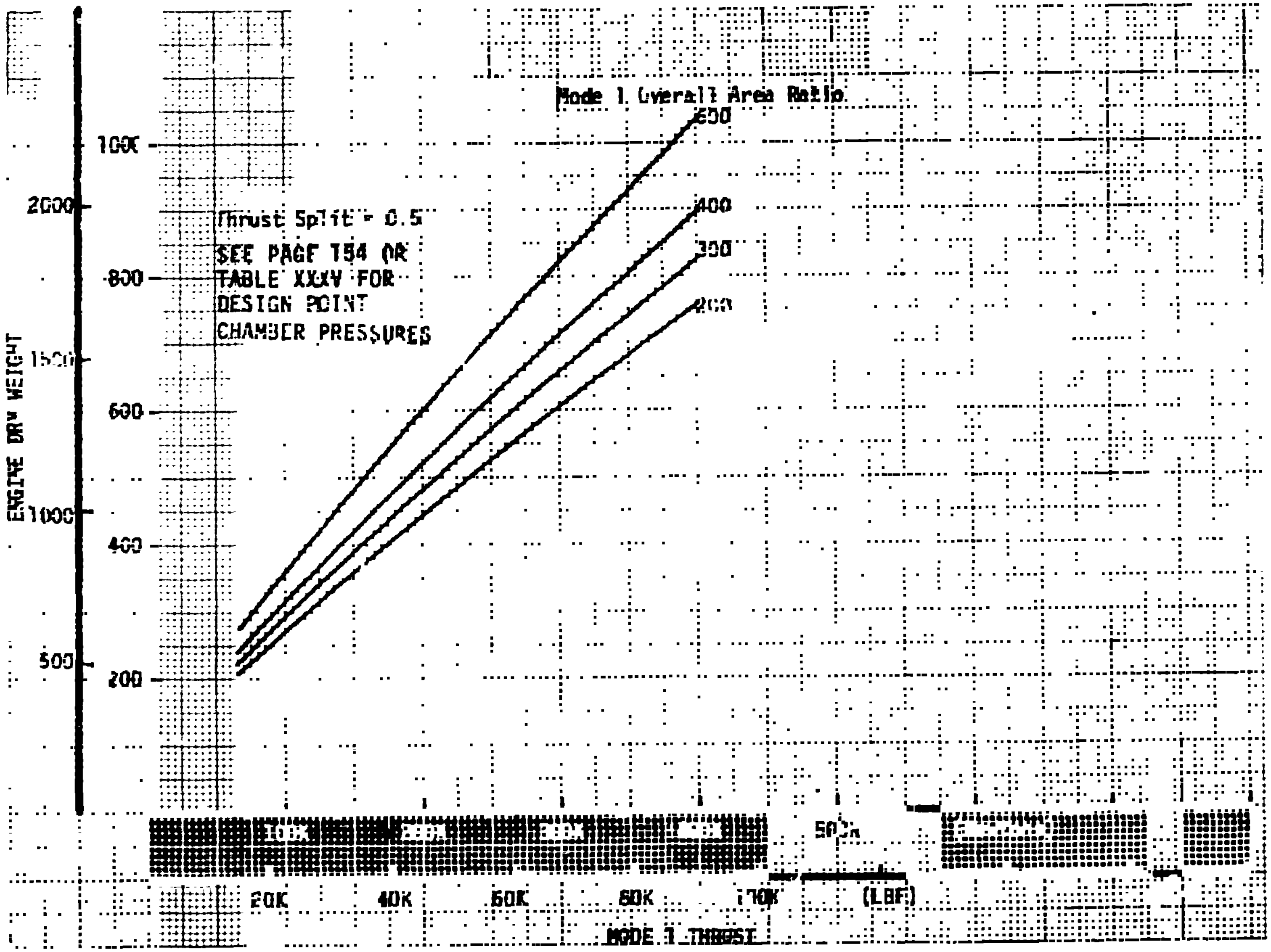

Figure 83. Effect of Thrust on Dual-Expander Engine Weight

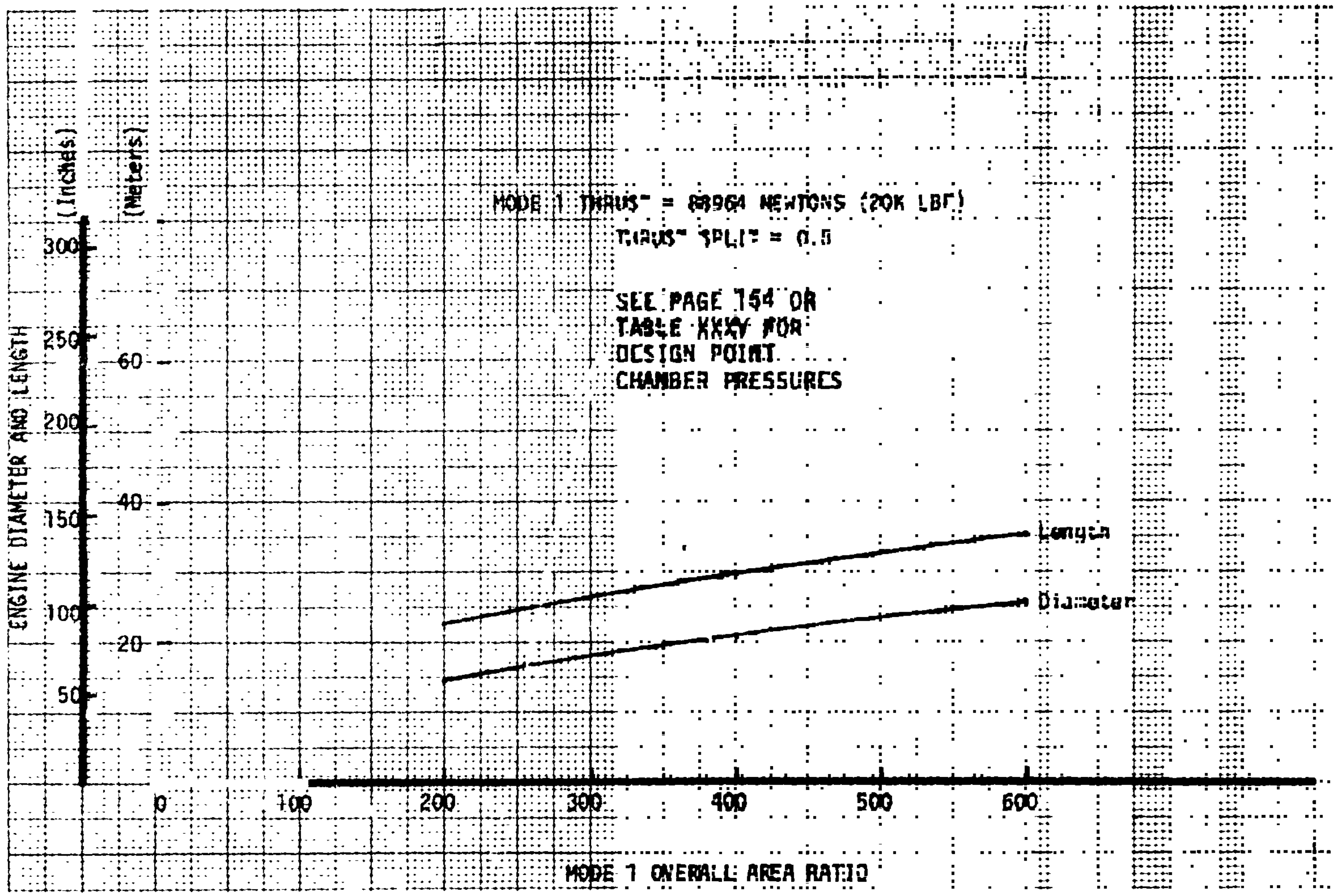

Figure 84. Effect of Mode 1 Overall Area Ratio on Dual-Expander Engine Envelope

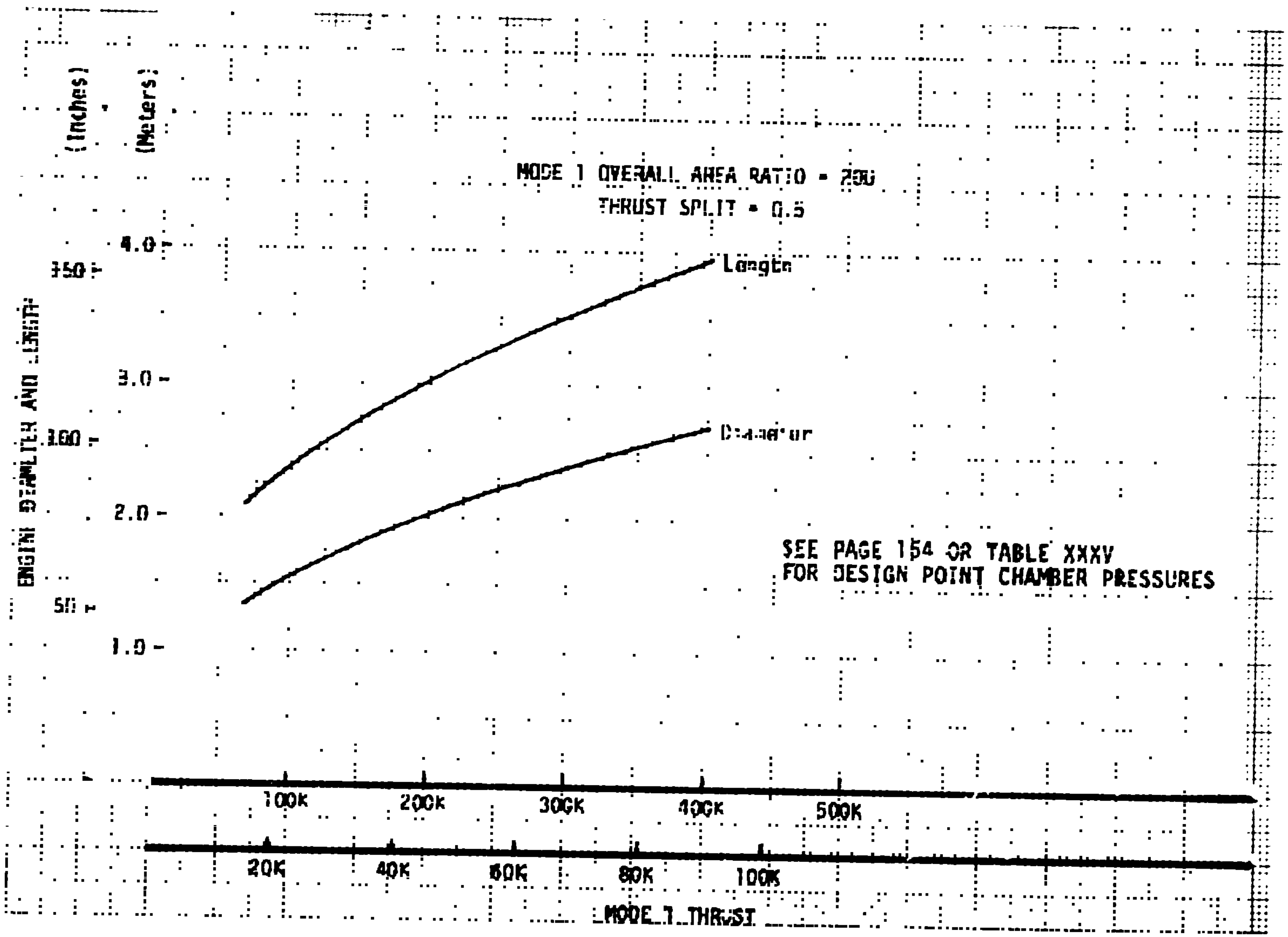

Figure 85. Effect of Thrust on Dual-Expander Engine Envelope

TABLE XXXVI. - BASELINE PLUG CLUSTER ENGINE DATA

S.I. UNITS

MODULE PARAMETERS

PC (ATMS)	AREA RATIO	PCNT. BELL	LOX/RP MR	LOX/LH2 MR	LOX/RP RT (M)	LOX/LH2 RT (M)	LOX/RP ISP-D (SEC)	LOX/LH2 ISP-D (SEC)
20.415	200.000	40.000	3.160	7.000	.026	.026	347.749	443.984

PLUG CLUSTER ENGINE PERFORMANCE

1.MODE 1 F (N)	68984.432	15.MODE 2 F (N)	43254.132
2.MOD1 BASE F(N)	2004.735	16.MD2 BASE F (N)	698.249
3.MOD-PLUG F (N)	80773.225	17.MOD-PLUG F (N)	42555.884
4.THRUST SPLIT	.500	18.MODE 2 GAP	1.000
5.MODE 1 GAP	.000	19.MD2 FLW (KG/S)	9.026
6.MD1 FLOW(KG/S)	22.469	20.FUELFLOW(KG/S)	1.228
7.FUELFLOW(KG/S)	4.430	21.OX FLOW (KG/S)	8.598
8.LOX FLOW(KG/S)	18.039	22.TILT ANG(RADS)	.103
9.GG-BASE (KG/S)	.356	23.MD2 ISPD (SEC)	448.086
10.GG FLOW(KG/S)	.136		
11.BSSFLOW(KG/S)	.023		
12.GAS GEN MR	.320		
13.GG ISP (SECS)	137.500		
14.MD1 ISPD(SEC)	394.900		

PLUG CLUSTER ENGINE DIMENSIONS (M AND M**2)

MODE 1 AREA RATIO	MODE 2 AREA RATIO	NUMBER OF MODULES	NO.OF LOX-RP MODULES	NO.OF LOX-LH2 MODULES	PERCENT PLUG	PLUG LENGTH (M)	BASE AREA (M**2)	EQUIV.ENG LENGTH (M)	ENGINE LENGTH (M)	ENGINE DIAMETER (M)
357.716	714.074	10	5.000	5.000	.000	8.456	2.152	.956	1.545	3.110

PLUG CLUSTER ENGINE WEIGHTS (KGM)

1.F VECTOR CNTRL	.757	13.INJECTRS (ALL)	25.038
2.LOX/LH2 TCA	15.054	14.LOX/RP TCA	33.031
3.LOX/LH2 RG NOZ	17.463	15.LOX/RP RG NOZS	13.759
4.LOX RP RAD NOZ	44.804	16.LOX/LH2 RG NOZ	43.059
5.LOX/RP GAS GEN	1.093	17.LOX/LH2 VALVES	7.017
6.LOX/RP VALVES	5.007	18.LOX/RP LOX TPA	2.076
7.LOX/LH2 LO TPA	2.076	19.LH2 LO SPD TPA	.998
8.RP1 LO SPD TPA	.002	20.LOX/RP HI TPA	5.908
9.LOX/LH2 HI TPA	4.908	21.LH2 HI SPD TPA	7.006
10.RP1 HI SP TPA	2.249	22.LINES	22.052
11.LOX/RP IGN SY	7.711	23.LOX/LH2 IGN SY	4.090
12.BASE CLOSURE	6.542	24.MISCELLANEOUS	19.504
		25.TOTAL ENGINE WT	297.012

TABLE XXXVI (cont.)

ENGLISH UNITS

MODULE PARAMETERS

PC (PSIA)		PCNT. BELL	LOX/HP MR	LOX/LH2 MR	LOX/HP WT (IN)	LOX/LH2 WT (IN)	LOX/HP ISP-D (SEC)	LOX/LH2 ISP-D (SEC)
300.00	.000	90.000	5.160	7.000	1.020	1.045	347.749	443.984

PLUG CLUSTER ENGINE PERFORMANCE

1.MODE 1 F (LBF)	20000.000	15.MODE 2 F (LBF)	9723.900
2.MO1 BASE F(LB)	450.000	16.MO2 BASE F(LB)	156.972
3.MOD-PLUG F(LB)	19507.378	17.MOD-PLUG F(LB)	9566.934
4.THRUST SPLIT	.500	18.MODE 2 GAP	1.000
5.MODE 1 GAP	.000	19.MO2 FLW (LB/S)	21.662
6.MO1 FLOW(LB/S)	50.656	20.FUELFLOW(LB/S)	2.708
7.FUELFLOW(LB/S)	9.767	21.OX FLOW (LB/S)	18.955
8.OX FLOW(LB/S)	40.871	22.TILT ANG(DEGR)	5.091
9.GG+BASE (LB/S)	.356	23.MO2 ISPD(SEC)	448.800
10.GG FLOW(LB/S)	.305		
11.BASFLOW(LB/S)	.051		
12.GAS GEN MR	.320		
13.GG ISP (SECS)	137.500		
14.MO1 ISPD(SEC)	394.980		

PLUG CLUSTER ENGINE DIMENSIONS (IN AND IN**2)

MODE 1 AREA RATIO	MODE 2 AREA RATIO	NUMBER OF MODULES	NO. OF LOX-HP MODULES	NO. OF LOX-LH2 MODULES	PERCENT PLUG	PLUG LENGTH (IN)	BASE AREA (IN**2)	EQUIV.ENG LENGTH (IN)	ENGINE LENGTH (IN)	ENGINE DIAMETER (IN)
357.716	714.674	10	5.000	5.000	.000	332.046	3335.475	37.700	60.820	122.590

PLUG CLUSTER ENGINE WEIGHTS (LBM)

1.F VECTOR CNTRL	1.070	13.INJECTRS (ALL)	55.200
2.LOX/LH2 TCA	33.200	14.LOX/HP TCA	74.143
3.LOX/LH2 RG NOZ	38.500	15.LOX/HP RG NOZS	30.333
4.LOX/HP RAD NOZ	96.409	16.LOX/LH2 RD NOZ	94.936
5.LOX/HP GAS GEN	3.733	17.LOX/LH2 VALVES	15.409
6.LOX/HP VALVES	12.935	18.LOX/HP LOW TPA	5.900
7.LOX/LH2 LO TPA	5.900	19.LH2 LO SPD TPA	2.205
8.HP1 LO SPD TPA	1.900	20.LOX/HP HI TPA	13.425
9.LOX/LH2 HI TPA	10.953	21.LH2 HI SPD TPA	15.578
10.HP1 HI SP TPA	4.759	22.LINES	49.918
11.LOX/HP IGN SY	17.000	23.LOX/LH2 IGN SY	11.000
12.BASE CLOSURE	14.422	24.MISCELLANEOUS	43.000
		25.TOTAL ENGINE WT	654.799

TABLE XXXVII. - PLUG CLUSTER ENGINE PARAMETRIC DATA

S.I. UNITS

NO. OF MODS	F SPLIT	MODE 1 TOTAL THRUST (N)	MODE 1 BASE THRUST (N)	MODE 1 MODULE-PLUG F (N)	MODE 1 ISP D (SEC)	MODE 2 TOTAL THRUST (N)	MODE 2 BASE THRUST (N)	MODE 2 ISPD (SEC)	CHAMBER PRESSURE (ATMS)	MODULE AREA RATIO	MODE 1 AREA RATIO	MODE 2 AREA RAT	GAS GEN FLOW (KG/S)	% BELL	MODE 2 GAP (AV)	% FULL PLUG	ENGINE EQUIV. PLUG LENGTH (M)	ENGINE LENGTH (M)	ENGINE DIAM. (M)	TOTAL ENG WGT. (KGM)
10	.4	66723.	1702.	64909.	397.7	39227.	768.	442.4	20.	112.	200.	334.	.1	90.	.7	0.	.80	1.12	2.0	195.
10	.4	66723.	1458.	65154.	403.3	39251.	663.	448.7	20.	200.	358.	597.	.1	90.	.7	0.	.86	1.38	2.7	232.
10	.4	66723.	1158.	65455.	404.9	39280.	520.	451.0	20.	300.	537.	896.	.1	90.	.7	0.	1.01	1.62	3.3	275.
10	.4	66723.	1108.	65503.	405.9	39289.	495.	452.1	20.	350.	626.	1045.	.1	90.	.7	0.	1.07	1.72	3.6	294.
10	.4	66723.	1067.	65544.	407.1	39298.	475.	453.2	20.	400.	716.	1195.	.1	90.	.7	0.	1.12	1.82	3.6	314.
10	.5	66723.	1753.	64831.	387.6	32379.	622.	442.0	20.	112.	200.	401.	.1	90.	1.0	0.	.80	1.12	2.0	198.
10	.5	66723.	1509.	65075.	393.3	32406.	524.	448.3	20.	200.	358.	717.	.1	90.	1.0	0.	.85	1.36	2.7	235.
10	.5	66723.	1203.	65380.	394.7	32436.	411.	450.6	20.	300.	537.	1076.	.1	90.	1.0	0.	1.01	1.62	3.3	277.
10	.5	66723.	1152.	65431.	395.8	32440.	391.	451.8	20.	350.	626.	1255.	.1	90.	1.0	0.	1.07	1.72	3.6	297.
10	.5	66723.	1111.	65473.	396.9	32450.	376.	453.0	20.	400.	716.	1434.	.1	90.	1.0	0.	1.12	1.82	3.8	318.
10	.6	66723.	1830.	64750.	378.4	25608.	400.	441.5	20.	112.	200.	502.	.1	90.	1.5	0.	.80	1.12	2.0	261.
10	.6	66723.	1563.	64993.	383.6	25630.	392.	447.9	20.	200.	358.	840.	.1	90.	1.5	0.	.85	1.38	2.7	238.
10	.6	66723.	1252.	65304.	385.1	25664.	308.	450.5	20.	300.	537.	1346.	.1	90.	1.5	0.	1.01	1.62	3.3	280.
10	.6	66723.	1200.	65356.	386.1	25675.	293.	451.6	20.	350.	626.	1569.	.1	90.	1.5	0.	1.06	1.72	3.6	303.
10	.6	66723.	1158.	65398.	387.3	25686.	281.	452.7	20.	400.	716.	1793.	.1	90.	1.5	0.	1.12	1.82	3.8	321.
10	.8	66723.	1924.	64579.	361.4	12307.	0.	436.3	20.	112.	200.	112.	.2	90.	4.0	0.	.80	1.12	2.0	260.
10	.8	66723.	1685.	64818.	366.0	12347.	0.	443.4	20.	200.	358.	200.	.2	90.	4.0	0.	.85	1.36	2.7	244.
10	.8	66723.	1362.	65141.	367.6	12393.	0.	447.1	20.	300.	537.	300.	.2	90.	4.0	0.	1.01	1.62	3.3	285.
10	.8	66723.	1309.	65193.	368.7	12409.	0.	448.4	20.	350.	626.	350.	.2	90.	4.0	0.	1.06	1.72	3.6	306.
10	.8	66723.	1267.	65235.	369.6	12417.	0.	449.5	20.	400.	716.	400.	.2	90.	4.0	0.	1.12	1.82	3.8	326.
10	.4	88904.	2268.	86547.	394.0	52332.	1052.	442.9	20.	112.	200.	334.	.1	90.	.7	0.	.75	1.24	2.3	244.
10	.4	88904.	1939.	86876.	404.8	52371.	884.	449.2	20.	200.	358.	596.	.1	90.	.7	0.	.90	1.54	3.1	293.
10	.4	88904.	1542.	87273.	406.6	52414.	694.	451.0	20.	300.	537.	894.	.1	90.	.7	0.	1.11	1.82	3.8	349.
10	.4	88904.	1473.	87342.	407.6	52427.	661.	452.7	20.	350.	626.	1043.	.1	90.	.7	0.	1.16	1.93	4.1	376.
10	.4	88904.	1417.	87397.	408.8	52439.	634.	453.6	20.	400.	716.	1192.	.1	90.	.7	0.	1.21	2.04	4.4	403.
10	.5	88904.	2334.	86445.	389.2	43210.	831.	442.5	20.	112.	200.	400.	.1	90.	1.0	0.	.75	1.24	2.3	267.
10	.5	88904.	2005.	86773.	395.0	[illegible]	691.	448.9	20.	200.	358.	715.	.1	90.	1.0	0.	.90	1.54	3.1	297.
10	.5	88904.	1600.	87178.	396.6	43299.	546.	451.4	20.	300.	537.	1073.	.1	90.	1.0	0.	1.11	1.82	3.8	352.
10	.5	88904.	1530.	87248.	397.7	43315.	522.	452.4	20.	350.	626.	1251.	.1	90.	1.0	0.	1.16	1.93	4.1	380.
10	.5	88904.	1474.	87304.	398.9	43329.	500.	453.6	20.	400.	716.	1429.	.1	90.	1.0	0.	1.21	2.04	4.4	467.
10	.6	88964.	2403.	86339.	379.4	34188.	622.	442.1	20.	112.	200.	500.	.2	90.	1.5	0.	.75	1.24	2.3	251.
10	.6	88904.	2075.	86606.	385.6	34234.	523.	448.5	20.	200.	358.	693.	.2	90.	1.5	0.	.90	1.54	3.1	300.
10	.6	88904.	1602.	87079.	387.1	34278.	411.	451.1	20.	300.	537.	1341.	.2	90.	1.5	0.	1.11	1.62	3.8	356.
10	.6	88904.	1592.	87144.	388.2	34294.	391.	452.1	20.	350.	626.	1503.	.2	90.	1.5	0.	1.16	1.93	4.1	385.
10	.6	88904.	1535.	87206.	389.4	34310.	375.	453.3	20.	400.	716.	1750.	.2	90.	1.5	0.	1.21	2.04	4.4	410.
10	.8	88904.	2556.	86114.	363.2	16448.	0.	436.8	20.	112.	200.	112.	.2	90.	4.0	0.	.75	1.24	2.3	257.
10	.8	88904.	2232.	86437.	366.6	16510.	0.	444.0	20.	200.	358.	200.	.2	90.	4.0	0.	.90	1.54	3.1	306.
10	.8	88904.	1804.	86865.	369.9	16577.	0.	447.0	20.	300.	537.	300.	.2	90.	4.0	0.	1.11	1.82	3.8	361.
10	.8	88904.	1752.	86937.	371.1	16599.	0.	449.0	20.	350.	626.	350.	.2	90.	4.0	0.	1.16	1.93	4.1	369.
10	.8	88904.	1675.	86944.	372.2	16611.	0.	450.1	20.	400.	716.	400.	.2	90.	4.0	0.	1.21	2.04	4.4	416.
10	.4	177929.	4495.	173135.	401.6	104774.	2094.	444.1	20.	112.	200.	333.	.2	90.	.7	0.	.99	1.62	3.3	432.
10	.4	177929.	3837.	173792.	407.4	104872.	1759.	450.5	20.	200.	358.	593.	.2	90.	.7	0.	1.19	2.05	4.4	531.
10	.4	177929.	3047.	174582.	409.9	104973.	1381.	453.0	20.	300.	537.	890.	.2	90.	.7	0.	1.19	2.43	5.4	642.
10	.4	177929.	2910.	174719.	411.1	105000.	1314.	454.1	20.	350.	626.	1038.	.2	90.	.7	0.	.96	2.59	5.8	690.
10	.4	177929.	2799.	174829.	412.4	105020.	1260.	455.2	20.	400.	716.	1186.	.2	90.	.7	0.	1.12	2.75	6.2	751.
10	.5	177929.	4018.	172939.	392.1	86581.	1652.	443.7	20.	112.	200.	399.	.3	90.	1.0	0.	.99	1.62	3.3	437.
10	.5	177929.	3959.	173596.	398.3	86676.	1388.	450.2	20.	200.	358.	711.	.3	90.	1.0	0.	1.19	2.05	4.4	536.
10	.5	177929.	3155.	174400.	400.3	86786.	1089.	452.7	20.	300.	537.	1066.	.3	90.	1.0	0.	1.19	2.43	5.3	640.
10	.5	177929.	3017.	174538.	401.5	86819.	1036.	453.6	20.	350.	626.	1243.	.3	90.	1.0	0.	.96	2.59	5.8	701.
10	.5	177929.	2904.	174650.	402.8	86850.	994.	455.0	20.	400.	716.	1420.	.3	90.	1.0	0.	1.12	2.75	6.2	755.
10	.6	177929.	4748.	172735.	383.0	68536.	1237.	443.3	20.	112.	200.	498.	.3	90.	1.5	0.	.99	1.62	3.3	441.
10	.6	177929.	4091.	173392.	389.3	68659.	1039.	449.6	20.	200.	358.	888.	.3	90.	1.5	0.	1.19	2.05	4.4	540.
10	.6	177929.	3272.	174210.	391.2	68771.	815.	452.4	20.	300.	537.	1331.	.3	90.	1.5	0.	1.20	2.43	5.3	651.

TABLE XXXVII (cont.)

S.I. UNITS

10	.6	177929.	3132.	174350.	392.4	68867.	776.	453.5	20.	350.	626.	1552.	.3	90.	1.5	0.	.96	2.59	5.8	705.
10	.6	177929.	3018.	174463.	393.7	68891.	744.	454.7	20.	400.	716.	1773.	.3	90.	1.5	0.	1.12	2.75	6.2	759.
10	.6	177929.	5034.	172305.	366.6	33040.	0.	438.1	20.	112.	200.	112.	.4	90.	4.0	0.	1.00	1.62	3.3	449.
10	.8	177929.	4363.	172954.	372.8	33194.	0.	445.3	20.	200.	358.	200.	.4	90.	4.0	0.	1.19	2.05	4.4	548.
10	.8	177929.	3535.	173862.	374.6	33349.	0.	449.0	20.	300.	537.	300.	.4	90.	4.0	0.	1.20	2.43	5.3	658.
10	.8	177929.	3343.	173943.	375.8	33396.	0.	450.4	20.	350.	626.	350.	.4	90.	4.0	0.	.96	2.59	5.6	712.
10	.8	177929.	3278.	174058.	377.1	33423.	0.	451.5	20.	400.	716.	400.	.4	90.	4.0	0.	1.12	2.75	6.1	767.
10	.4	266893.	6713.	259732.	402.9	157229.	3132.	444.9	20.	112.	200.	332.	.3	90.	.7	0.	1.13	1.92	4.1	614.
10	.4	266893.	5726.	260717.	409.4	157388.	2631.	451.3	20.	200.	358.	592.	.3	90.	.7	0.	1.13	2.43	5.4	763.
10	.4	266893.	4545.	261898.	411.6	157507.	2065.	453.8	20.	300.	537.	666.	.3	90.	.7	0.	1.27	2.90	6.5	920.
10	.4	266893.	4340.	262102.	412.8	157589.	1964.	454.9	20.	350.	626.	1035.	.3	90.	.7	0.	1.47	3.10	7.1	1010.
10	.4	266893.	4175.	262268.	414.1	157628.	1863.	456.0	20.	400.	716.	1183.	.3	90.	.7	0.	1.66	3.26	7.5	1091.
10	.5	266893.	[illegible]	259442.	395.5	129924.	2472.	444.5	20.	112.	200.	398.	.4	90.	1.0	0.	1.13	1.92	4.0	620.
10	.5	266893.	5964.	260429.	400.0	130119.	2076.	450.9	20.	200.	358.	709.	.4	90.	1.0	0.	1.14	2.43	5.4	768.
10	.5	266893.	4762.	261631.	402.2	130295.	1629.	453.5	20.	300.	537.	1068.	.4	90.	1.0	0.	1.27	2.90	6.5	933.
10	.5	266893.	4495.	261837.	403.4	130346.	1549.	454.6	20.	350.	626.	1240.	.4	90.	1.0	0.	1.47	3.10	7.0	1015.
10	.5	266893.	4727.	262005.	404.8	130394.	1485.	455.8	20.	400.	716.	1416.	.4	90.	1.0	0.	1.66	3.26	7.5	1097.
10	.6	266893.	7382.	259143.	384.5	102904.	1850.	444.0	20.	112.	200.	497.	.5	90.	1.5	0.	1.13	1.92	4.0	625.
10	.6	266893.	6095.	260128.	391.6	103110.	1553.	450.5	20.	200.	358.	885.	.5	90.	1.5	0.	1.15	2.43	5.4	773.
10	.6	266893.	4871.	261352.	393.2	103291.	1219.	453.2	20.	300.	537.	1327.	.5	90.	1.5	0.	1.27	2.90	6.5	938.
10	.6	266893.	4602.	261560.	394.5	103347.	1159.	454.3	20.	350.	626.	1547.	.5	90.	1.5	0.	1.47	3.10	7.0	1020.
10	.6	266893.	4492.	261729.	395.6	103400.	1111.	455.5	20.	400.	716.	1767.	.5	90.	1.5	0.	1.66	3.28	7.5	1101.
10	.8	266893.	7467.	258511.	366.2	49652.	0.	436.8	20.	112.	200.	112.	.7	90.	4.0	0.	1.13	1.92	4.0	633.
10	.8	266893.	6526.	259486.	374.6	49961.	0.	446.1	20.	200.	358.	200.	.7	90.	4.0	0.	1.16	2.43	5.3	761.
10	.8	266893.	5252.	260752.	376.8	50146.	0.	449.8	20.	300.	537.	300.	.7	90.	4.0	0.	1.27	2.90	6.5	946.
10	.8	266893.	5041.	260963.	378.1	50219.	0.	451.2	20.	350.	626.	350.	.7	90.	4.0	0.	1.47	3.10	7.0	1028.
10	.8	266893.	4869.	261134.	379.5	50262.	0.	452.4	20.	400.	716.	400.	.7	90.	4.0	0.	1.66	3.28	7.5	1110.
10	.4	400340.	*****	389635.	404.1	235922.	4667.	445.6	20.	112.	200.	332.	.5	90.	.7	0.	1.17	2.28	5.0	882.
10	.4	400340.	9552.	391113.	410.8	236175.	3936.	452.0	20.	200.	358.	591.	.5	90.	.7	0.	1.28	2.90	6.6	1104.
10	.4	400340.	6765.	392879.	413.1	236423.	3089.	454.5	20.	300.	537.	887.	.5	90.	.7	0.	1.84	3.47	8.0	1351.
10	.4	400340.	6479.	393185.	414.4	236487.	2938.	455.6	20.	350.	626.	1034.	.5	90.	.7	0.	2.09	3.71	8.6	1474.
10	.4	400340.	6231.	393433.	415.7	236546.	2817.	456.6	20.	400.	716.	1181.	.5	90.	.7	0.	2.31	3.94	9.2	1596.
10	.5	400340.	*****	389208.	394.7	194996.	3698.	445.2	20.	112.	200.	397.	.6	90.	1.0	0.	1.18	2.26	5.0	868.
10	.5	400340.	8811.	390687.	401.5	195300.	3165.	451.7	20.	200.	358.	706.	.6	90.	1.0	0.	1.28	2.90	6.6	1110.
10	.5	400340.	7013.	392485.	403.8	195578.	2436.	454.2	20.	300.	537.	1061.	.6	90.	1.0	0.	1.84	3.47	8.0	1357.
10	.5	400340.	6704.	392794.	405.1	195656.	2317.	455.4	20.	350.	626.	1237.	.6	90.	1.0	0.	2.09	3.71	8.6	1480.
10	.5	400340.	6453.	393044.	406.5	195724.	2221.	456.6	20.	400.	716.	1413.	.6	90.	1.0	0.	2.31	3.94	9.2	1602.
10	.6	400340.	*****	[illegible]	385.8	154474.	2768.	444.7	20.	112.	200.	496.	.7	90.	1.5	0.	1.18	2.28	4.9	893.
10	.6	400340.	9090.	390244.	392.6	154805.	2322.	451.2	20.	200.	358.	863.	.7	90.	1.5	0.	1.28	2.90	6.5	1116.
10	.6	400340.	7259.	392073.	394.9	155094.	1822.	453.9	20.	300.	537.	1324	.7	90.	1.5	0.	1.84	3.47	8.0	1363.
10	.6	400340.	6947.	392385.	396.2	155179.	1733.	455.1	20.	350.	626.	1543.	.7	90.	1.5	0.	2.09	3.71	8.6	1486.
10	.6	400340.	6694.	[illegible]	397.6	155261.	1661.	456.3	20.	400.	716.	1762.	.7	90.	1.5	0.	2.31	3.94	9.2	1608.
10	.8	400340.	*****	367832.	369.7	74587.	0.	439.5	20.	112.	200.	112.	1.0	90.	4.0	0.	1.19	2.26	4.9	902.
10	.8	400340.	9710.	389297.	376.5	74981.	0.	446.8	20.	200.	358.	200.	1.0	90.	4.0	0.	1.28	2.90	6.5	1125.
10	.8	400340.	7816.	391189.	378.7	75364.	0.	450.6	20.	300.	537.	300.	1.0	90.	4.0	0.	1.84	3.47	8.0	1372.
10	.8	400340.	7500.	391504.	380.1	75475.	0.	452.0	20.	350.	626.	350.	1.0	90.	4.0	0.	2.09	3.71	8.6	1494.
10	.8	400340.	7243.	391761.	381.5	75542.	0.	453.2	20.	400.	716.	400.	1.0	90.	4.0	0.	2.31	3.94	9.2	1616.

TABLE XXXVII (cont.)

ENGLISH UNITS

NO. OF MODS	F SPLIT	MODE1 TOTAL THRUST (LBF)	MODE1 BASE THRUST (LBF)	MODE 1 MODULE-PLUG F (LBF)	MODE 1 ISP D (SEC)	MODE 2 TOTAL THRUST (LBF)	MODE2 BASE THRUST (LBF)	MODE2 ISPD (SEC)	CHAMBER PRESSURE (PSIA)	MODULE AREA RATIO	MODE1 AREA RATIO	MODE2 AREA RAT	GAS GEN FLOW (LB/S)	%BELL	MODE2 GAP (AV)	% FULL PLUG	ENGINE EQUIV. LENGTH (IN)	ENGINE LENGTH (IN)	ENGINE DIAM. (IN)	TOTAL ENG WGT. (LBM)
10	.4	15000.	383.	14592.	397.7	8818.	177.	442.4	300.	112.	200.	334.	.2	90.	.7	0.	26.14	44.04	80.2	429.
10	.4	15000.	328.	14647.	403.3	8624.	149.	448.7	300.	200.	358.	597.	.2	90.	.7	0.	33.66	54.41	106.4	511.
10	.4	15000.	266.	14714.	404.9	8831.	117.	451.0	300.	300.	537.	896.	.2	90.	.7	0.	39.75	63.74	129.8	603.
10	.4	15000.	249.	14726.	405.9	8833.	111.	452.1	300.	350.	626.	1045.	.2	90.	.7	0.	41.94	67.75	140.0	648.
10	.4	15000.	240.	14735.	407.1	8834.	107.	455.2	300.	400.	716.	1195.	.2	90.	.7	0.	44.12	71.51	149.4	695.
10	.5	15000.	394.	14575.	387.8	7279.	140.	442.0	300.	112.	200.	401.	.2	90.	1.0	0.	26.14	44.04	80.2	436.
10	.5	15000.	339.	14629.	393.3	7285.	118.	448.3	300.	200.	358.	717.	.2	90.	1.0	0.	33.66	54.41	106.4	518.
10	.5	15000.	271.	14698.	394.7	7292.	92.	450.8	300.	300.	537.	1076.	.2	90.	1.0	0.	39.74	63.74	129.8	610.
10	.5	15000.	259.	14710.	395.8	7294.	88.	451.8	300.	350.	626.	1255.	.2	90.	1.0	0.	41.93	67.75	140.0	655.
10	.5	15000.	250.	14719.	396.9	7296.	84.	453.0	300.	400.	716.	1434.	.2	90.	1.0	0.	44.12	71.51	149.5	700.
10	.6	15000.	406.	14556.	378.4	5757.	105.	441.5	300.	112.	200.	502.	.3	90.	1.5	0.	26.13	44.04	80.3	443.
10	.6	15000.	351.	14611.	383.6	5763.	88.	447.9	300.	200.	358.	896.	.3	90.	1.5	0.	33.65	54.41	106.4	525.
10	.6	15000.	281.	14681.	385.1	5769.	69.	450.5	300.	300.	537.	1346.	.3	90.	1.5	0.	39.73	63.74	129.9	617.
10	.6	15000.	270.	14693.	386.1	5772.	66.	451.6	300.	350.	626.	1569.	.3	90.	1.5	0.	41.92	67.75	140.0	662.
10	.6	15000.	260.	14702.	387.3	5774.	63.	452.7	300.	400.	716.	1793.	.3	90.	1.5	0.	44.11	71.51	149.5	707.
10	.8	15000.	433.	14518.	361.4	2767.	0.	436.3	300.	112.	200.	112.	.4	90.	4.0	0.	26.13	44.04	80.3	455.
10	.8	15000.	379.	14572.	366.6	2776.	0.	443.4	300.	200.	358.	200.	.4	90.	4.0	0.	33.65	54.41	106.4	537.
10	.8	15000.	306.	14644.	367.6	2786.	0.	447.1	300.	300.	537.	300.	.4	90.	4.0	0.	39.72	63.74	129.9	628.
10	.8	15000.	294.	14656.	368.7	2790.	0.	448.4	300.	350.	626.	350.	.4	90.	4.0	0.	41.91	67.75	140.1	674.
10	.8	15000.	285.	14665.	369.8	2791.	0.	449.5	300.	400.	716.	400.	.4	90.	4.0	0.	44.10	71.51	149.5	719.
10	.4	20000.	510.	19457.	399.0	11765.	236.	442.9	300.	112.	200.	334.	.2	90.	.7	0.	29.65	48.91	92.5	537.
10	.4	20000.	436.	19530.	404.8	11773.	199.	449.2	300.	200.	358.	596.	.2	90.	.7	0.	37.70	60.82	122.6	647.
10	.4	20000.	347.	19620.	406.6	11783.	156.	451.6	300.	300.	537.	894.	.2	90.	.7	0.	43.82	71.53	149.6	769.
10	.4	20000.	331.	19635.	407.6	11786.	149.	452.7	300.	350.	626.	1043.	.2	90.	.7	0.	45.78	76.13	161.3	829.
10	.4	20000.	319.	19648.	408.8	11789.	142.	453.8	300.	400.	716.	1192.	.2	90.	.7	0.	47.73	80.45	172.2	889.
10	.5	20000.	525.	19434.	389.2	9714.	167.	442.5	300.	112.	200.	400.	.3	90.	1.0	0.	29.65	48.91	92.5	545.
10	.5	20000.	451.	19507.	395.0	9724.	157.	448.9	300.	200.	358.	715.	.3	90.	1.0	0.	37.70	60.82	122.6	655.
10	.5	20000.	360.	19598.	396.6	9734.	123.	451.4	300.	300.	537.	1073.	.3	90.	1.0	0.	43.83	71.53	149.6	777.
10	.5	20000.	344.	19614.	397.7	9737.	117.	452.4	300.	350.	626.	1251.	.3	90.	1.0	0.	45.79	76.13	161.3	837.
10	.5	20000.	331.	19627.	398.9	9741.	112.	453.6	300.	400.	716.	1429.	.3	90.	.0	0.	47.75	80.45	172.2	897.
10	.6	20000.	540.	19410.	379.9	7680.	140.	442.1	300.	112.	200.	500.	.4	90.	1.5	0.	29.65	48.91	92.5	553.
10	.6	20000.	467.	19483.	385.6	7696.	118.	446.5	300.	200.	358.	893.	.4	90.	1.5	0.	37.70	60.82	122.6	662.
10	.6	20000.	374.	19576.	387.1	7706.	92.	451.1	300.	300.	537.	1341.	.4	90.	1.5	0.	43.83	71.53	149.6	764.
10	.6	20000.	356.	19592.	388.2	7710.	88.	452.1	300.	350.	626.	1563.	.4	90.	1.5	0.	45.80	76.13	161.3	844.
10	.6	20000.	345.	19605.	389.4	7713.	84.	453.3	300.	400.	716.	1786.	.4	90.	1.5	0.	47.76	80.45	172.1	904.
10	.8	20000.	575.	19359.	363.2	3698.	0.	436.6	300.	112.	200.	112.	.5	90.	4.0	0.	29.65	48.91	92.5	566.
10	.8	20000.	502.	19432.	366.6	3712.	0.	444.0	300.	200.	358.	200.	.5	90.	4.0	0.	37.71	60.82	122.6	675.
10	.8	20000.	406.	19528.	369.9	3727.	0.	447.6	300.	300.	537.	300.	.5	90.	4.0	0.	43.84	71.53	149.5	797.
10	.8	20000.	369.	19544.	371.1	3732.	0.	449.0	300.	350.	626.	350.	.5	90.	4.0	0.	45.82	76.13	161.2	857.
10	.8	20000.	376.	19557.	372.2	3734.	0.	450.1	300.	400.	716.	400.	.5	90.	4.0	0.	47.79	80.45	172.1	917.
10	.4	40000.	1010.	38922.	401.6	23554.	471.	444.1	300.	112.	200.	333.	.5	90.	.7	0.	39.13	63.94	130.4	953.
10	.4	40000.	863.	39070.	407.9	23576.	395.	450.5	300.	200.	358.	593.	.5	90.	.7	0.	[illegible].72	80.61	172.8	1172.
10	.4	40000.	685.	39247.	409.9	23594.	310.	453.0	300.	300.	537.	890.	.5	90.	.7	0.	[illegible]	95.59	210.7	1415.
10	.4	40000.	654.	39278.	411.1	23605.	295.	454.1	300.	350.	626.	1038.	.5	90.	.7	0.	37.94	102.04	227.2	1535.
10	.4	40000.	629.	39303.	412.4	23611.	283.	455.2	300.	400.	716.	1186.	.5	90.	.7	0.	43.98	108.08	242.6	1655.
10	.5	40000.	1038.	38878.	392.1	19460.	371.	443.7	300.	112.	200.	399.	.6	90.	1.0	0.	39.14	63.94	130.4	963.
10	.5	40000.	890.	39026.	398.3	19486.	312.	450.2	300.	200.	358.	711.	.6	90.	1.0	0.	46.77	80.61	172.7	1182.
10	.5	40000.	709.	39207.	400.3	19510.	245.	452.7	300.	300.	537.	1066.	.6	90.	1.0	0.	46.93	95.59	210.6	1425.
10	.5	40000.	678.	39238.	401.5	19518.	233.	453.6	300.	350.	626.	1243.	.6	90.	1.0	0.	37.94	102.04	227.0	1545.
10	.5	40000.	653.	39263.	402.6	19525.	223.	455.0	300.	400.	716.	1420.	.6	90.	1.0	0.	43.98	108.08	242.4	1665.
10	.6	40000.	1067.	38832.	383.0	15407.	278.	443.3	300.	112.	200.	498.	.7	90.	1.5	0.	39.16	63.94	130.3	973.
10	.6	40000.	920.	38980.	389.3	15435.	234.	449.6	300.	200.	358.	888.	.7	90.	1.5	0.	46.82	80.61	172.5	1191.
10	.6	40000.	735.	39164.	391.2	15460.	185.	452.4	300.	300.	537.	1331.	.7	90.	1.5	0.	47.09	95.59	210.4	1434.

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TABLE XXXVII (cont.)

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10	.6	40000.	704.	39195.	392.4	15468.	174.	453.5	300.	350.	626.	1552.	.7	90.	1.5	0.	37.94	102.04	220.9	1555.
10	.6	40000.	679.	39221.	395.7	15476.	167.	454.7	300.	400.	716.	1773.	.7	90.	1.5	0.	43.98	108.08	242.2	1674.
10	.8	40000.	1132.	38736.	366.6	7428.	0.	436.1	300.	112.	200.	112.	1.0	90.	4.0	0.	39.19	63.94	130.2	989.
10	.8	40000.	935.	38882.	372.8	7462.	0.	445.3	300.	200.	358.	200.	1.0	90.	4.0	0.	40.92	80.61	172.3	1207.
10	.8	40000.	795.	39072.	374.6	7497.	0.	449.0	300.	300.	537.	300.	1.0	90.	4.0	0.	47.40	95.59	210.2	1450.
10	.8	40000.	763.	39164.	375.8	7508.	0.	450.4	300.	350.	626.	350.	1.0	90.	4.0	0.	37.94	102.04	220.5	1571.
10	.8	40000.	737.	39130.	377.1	7514.	0.	451.5	300.	400.	716.	400.	1.0	90.	4.0	0.	43.98	108.08	241.8	1690.
10	.4	60000.	1569.	58390.	402.9	35346.	704.	444.9	300.	112.	200.	332.	.7	90.	.7	0.	44.41	75.47	159.5	1355.
10	.4	60000.	1287.	58611.	409.4	35382.	591.	451.3	300.	200.	358.	592.	.7	90.	.7	0.	44.61	95.79	211.2	1682.
10	.4	60000.	1022.	58877.	411.6	35410.	464.	453.8	300.	300.	537.	888.	.7	90.	.7	0.	49.94	114.04	257.6	2046.
10	.4	60000.	976.	58923.	412.8	35427.	442.	454.9	300.	350.	626.	1035.	.7	90.	.7	0.	57.80	121.90	277.7	2226.
10	.4	60000.	939.	58966.	414.1	35436.	423.	456.0	300.	400.	716.	1183.	.7	90.	.7	0.	65.16	129.26	290.5	2466.
10	.5	60000.	1549.	58325.	393.5	29209.	550.	444.5	300.	112.	200.	398.	.9	90.	1.0	0.	44.45	75.47	159.4	1366.
10	.5	60000.	1327.	58547.	400.0	29252.	467.	450.9	300.	200.	358.	709.	.9	90.	1.0	0.	44.86	95.79	211.0	1694.
10	.5	60000.	1057.	58817.	402.2	29292.	366.	453.5	300.	300.	537.	1064.	.9	90.	1.0	0.	49.94	114.04	257.3	2058.
10	.5	60000.	1010.	58863.	403.4	29303.	348.	454.6	300.	350.	626.	1240.	.9	90.	1.0	0.	57.80	121.90	277.4	2238.
10	.5	60000.	973.	58901.	404.8	29314.	334.	455.8	300.	400.	716.	1416.	.9	90.	1.0	0.	65.16	129.26	290.1	2417.
10	.6	60000.	1592.	58258.	384.5	23134.	416.	444.0	300.	112.	200.	497.	1.1	90.	1.5	0.	44.49	75.47	159.3	1377.
10	.6	60000.	1370.	58479.	391.0	[illegible]	349.	[illegible]	300.	200.	358.	865.	1.1	90.	1.5	0.	45.09	95.79	210.9	1764.
10	.6	60000.	1095.	58754.	393.2	23221.	274.	[illegible]	300.	300.	537.	1327.	1.1	90.	1.5	0.	49.94	114.04	257.1	2049.
10	.6	60000.	1048.	58801.	394.5	23233.	261.	454.3	300.	350.	626.	1547.	1.1	90.	1.5	0.	57.80	121.90	277.1	2249.
10	.6	60000.	1010.	58839.	395.8	23245.	250.	455.5	300.	400.	716.	1767.	1.1	90.	1.5	0.	65.16	129.26	295.8	2428.
10	.8	60000.	1685.	58115.	368.2	11162.	0.	436.8	300.	112.	200.	112.	1.4	90.	4.0	0.	44.57	75.47	159.1	1395.
10	.8	60000.	1469.	58335.	374.8	11218.	0.	446.1	300.	200.	358.	200.	1.5	90.	4.0	0.	45.56	95.79	210.5	1722.
10	.8	60000.	1181.	58619.	376.6	11273.	0.	449.8	300.	300.	537.	300.	1.5	90.	4.0	0.	49.94	114.04	256.6	2086.
10	.8	60000.	1153.	58667.	378.1	11290.	0.	451.2	300.	350.	626.	350.	1.5	90.	4.0	0.	57.80	121.96	270.6	[illegible]
10	.8	60000.	1095.	58705.	379.5	11294.	[illegible]	452.4	300.	400.	716.	400.	1.5	90.	4.0	0.	65.16	129.26	295.2	[illegible]
10	.4	90000.	2255.	87593.	404.1	53037.	1054.	445.6	300.	112.	200.	332.	1.1	90.	.7	0.	40.21	69.58	195.0	1944.
10	.4	90000.	1923.	87926.	410.8	53094.	865.	452.0	300.	200.	358.	591.	1.1	90.	.7	0.	50.27	114.37	258.3	2458.
10	.4	90000.	1525.	88323.	413.1	53150.	694.	454.5	300.	300.	537.	887.	1.1	90.	.7	0.	72.51	136.61	314.9	2979.
10	.4	90000.	1456.	88391.	414.4	53164.	661.	455.6	300.	350.	626.	1034.	1.1	90.	.7	0.	82.10	146.20	339.5	3249.
10	.4	90000.	1401.	88447.	415.7	53178.	633.	456.8	300.	400.	716.	1181.	1.1	90.	.7	0.	91.08	155.18	362.5	3518.
10	.5	90000.	2314.	87497.	394.7	43837.	831.	445.2	300.	112.	200.	397.	1.4	90.	1.0	0.	40.33	69.56	194.9	1957.
10	.5	90000.	1981.	87830.	401.5	43905.	698.	451.7	300.	200.	358.	708.	1.4	90.	1.0	0.	50.27	114.37	256.0	2447.
10	.5	90000.	1577.	88234.	403.8	43966.	548.	454.2	300.	300.	537.	1061.	1.4	90.	1.0	0.	72.51	136.61	314.6	2993.
10	.5	90000.	1507.	88303.	405.1	43985.	521.	455.4	300.	350.	626.	1237.	1.4	90.	1.0	0.	82.10	146.20	339.1	3263.
10	.5	90000.	1451.	88360.	406.5	44002.	499.	456.6	300.	400.	716.	1413.	1.4	90.	1.0	0.	91.08	155.18	362.0	3532.
10	.6	90000.	2376.	87398.	385.8	34727.	822.	444.7	300.	112.	200.	496.	1.6	90.	1.5	0.	40.45	69.58	194.7	1970.
10	.6	90000.	2043.	87730.	392.6	34802.	522.	451.2	300.	200.	358.	883.	1.6	90.	1.5	0.	50.27	114.37	257.7	2460.
10	.6	90000.	1632.	88141.	394.9	34867.	410.	453.9	300.	300.	537.	1324.	1.6	90.	1.5	0.	72.51	136.61	314.2	3005.
10	.6	90000.	1562.	88212.	396.2	34886.	390.	455.1	300.	350.	626.	1543.	1.6	90.	1.5	0.	82.10	146.20	336.7	3275.
10	.6	90000.	1505.	88268.	397.6	34904.	373.	456.3	300.	400.	716.	1762.	1.6	90.	1.5	0.	91.08	155.18	361.5	3544.
10	.8	90000.	2513.	87188.	369.7	16766.	0.	439.5	300.	112.	200.	112.	2.2	90.	4.0	0.	40.68	89.56	194.4	1989.
10	.8	90000.	2183.	87517.	376.5	16856.	0.	446.8	300.	200.	358.	200.	2.2	90.	4.0	0.	50.27	114.37	257.2	2479.
10	.8	90000.	1757.	87943.	378.7	16942.	0.	450.6	300.	300.	537.	300.	2.2	90.	4.0	0.	72.51	136.61	313.5	3025.
10	.8	90000.	1686.	88014.	380.1	16968.	0.	452.0	300.	350.	626.	350.	2.2	90.	4.0	0.	82.10	146.20	337.8	3295.
10	.8	90000.	1628.	88071.	381.5	16983.	0.	453.2	300.	400.	716.	400.	2.2	90.	4.0	0.	91.08	155.18	360.5	3564.

with either LOX or RP-1. The data has been generated for RP-1 cooled LOX/RP-1 modules. Cooling with RP-1 assumes that some of the impurities are removed from this propellant to increase the bulk temperature limit that is normally imposed to avoid cracking, gumming and coking of the RP-1. It should be noted that the cooling problems would be much less severe if other hydrocarbons such as, methane or propane were used in the mixed-mode plug cluster. Investigation of the propellants were beyond this contract scope of work.

Plots of some of these parametric data have also been prepared to show the trends. Figures 86 and 87 show the Mode 1 and 2 delivered performance as functions of Mode 1 overall area ratio and thrust split for the baseline Mode 1 thrust of 88964N (20,000 lbs). Overall Mode 1 area ratio was selected as the abscissa for the plots in accordance with the statement of work and relates to overall engine size. For a zero length plug with zero gap, the overall geometric area ratio is not really a meaningful parameter in the performance calculations. Module area ratio is more indicative of the system performance potential. Therefore, the module area ratios that are obtained with 10 touching modules are plotted as a function of overall Mode 1 area ratio on Figure 88. In Mode 2 operation, the LOX/RP-1 modules are inactive and the cluster (or geometric) area ratio increases and gaps are created between the modules. However, for the zero length plug, only the module area ratio is again of any real importance in the performance calculations. In other words, this plug cluster performance is based upon the module performance corrected for the module tilt angle and the base pressure contribution. Because only two modules are operating in Mode 2 at a thrust split of 0.8, the base pressure effects are expected to be negligible and Mode 2 performance for these cases is based entirely upon the module performance with a tilt angle correction. This is why the overall Mode 2 area ratio and module area ratios are shown as equal for these cases in the tabular data. Mode 1 performance (Figure 86) decreases with increasing thrust split because the LOX/RP-1 thrust contribution is greater. Mode 2 performance (Figure 87) also decreases with increasing thrust split because the base pressure contribution is reduced as the gap between modules increases.

The effect of Mode 1 thrust level upon Mode 1 and 2 performance is shown on Figures 89 and 90, respectively. These data are presented for the baseline overall area ratio of 358 and module area ratio of 200.

The plug cluster engine performance is relatively low because the low thrust and low operating chamber pressure of the modules results in larger kinetics losses than high thrust, high pressure engines such as the tripropellant concept.

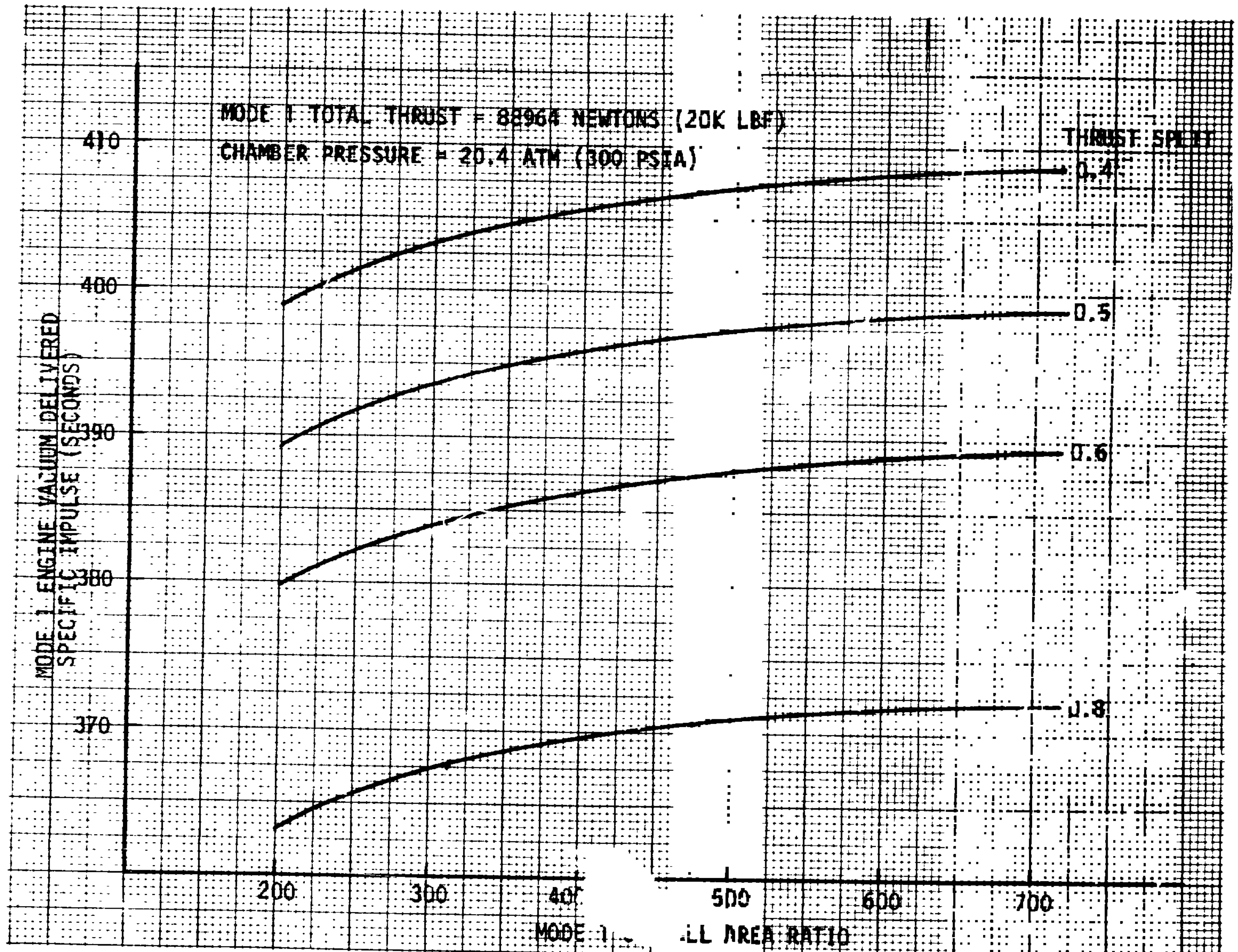

Figure 86. Effect of Mode 1 Overall Area Ratio on Plug Cluster Engine Mode 1 Delivered Performance

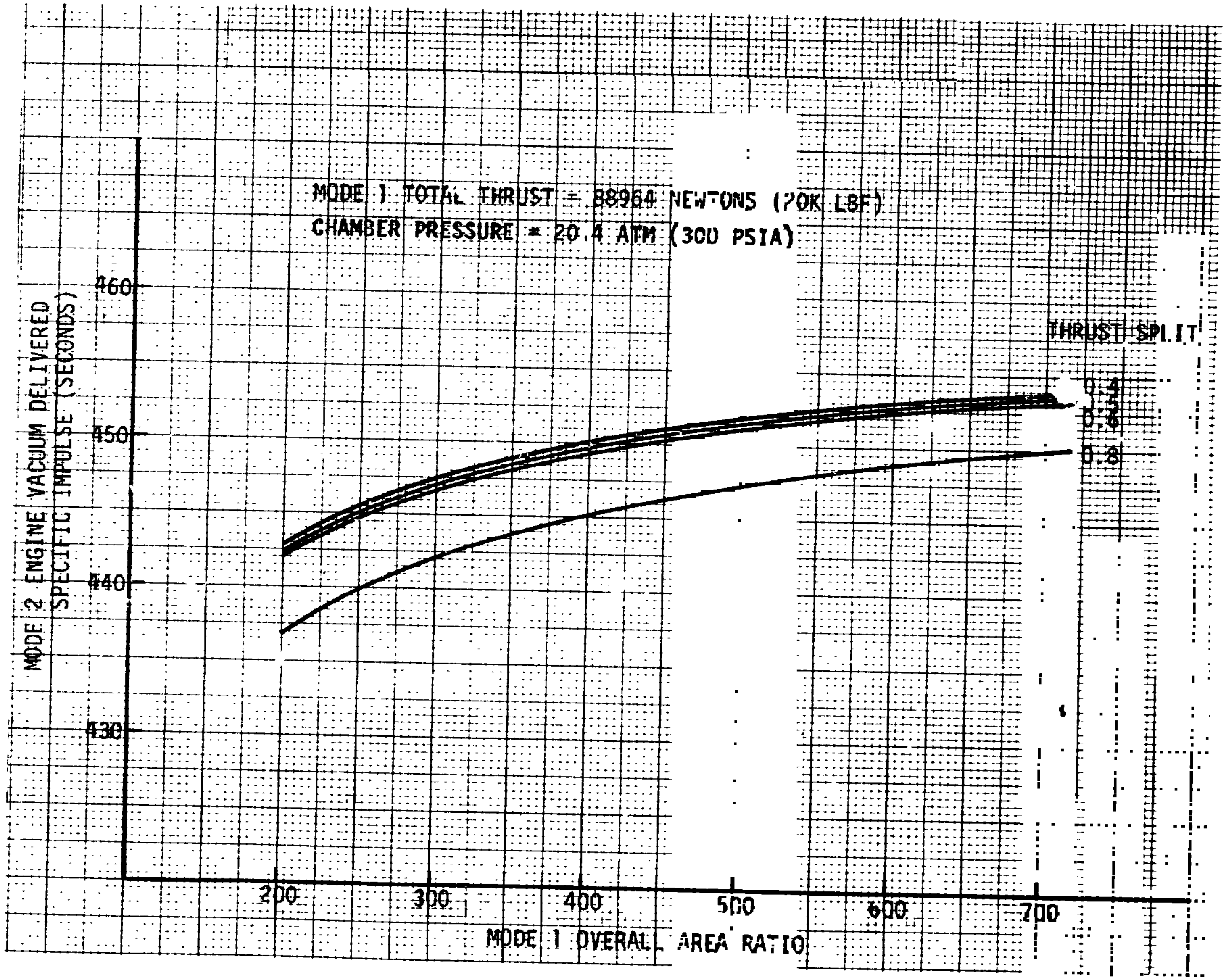

Figure 87. Effect of Mode 1 Overall Area Ratio on Plug Cluster Engine Mode 2 Delivered Performance

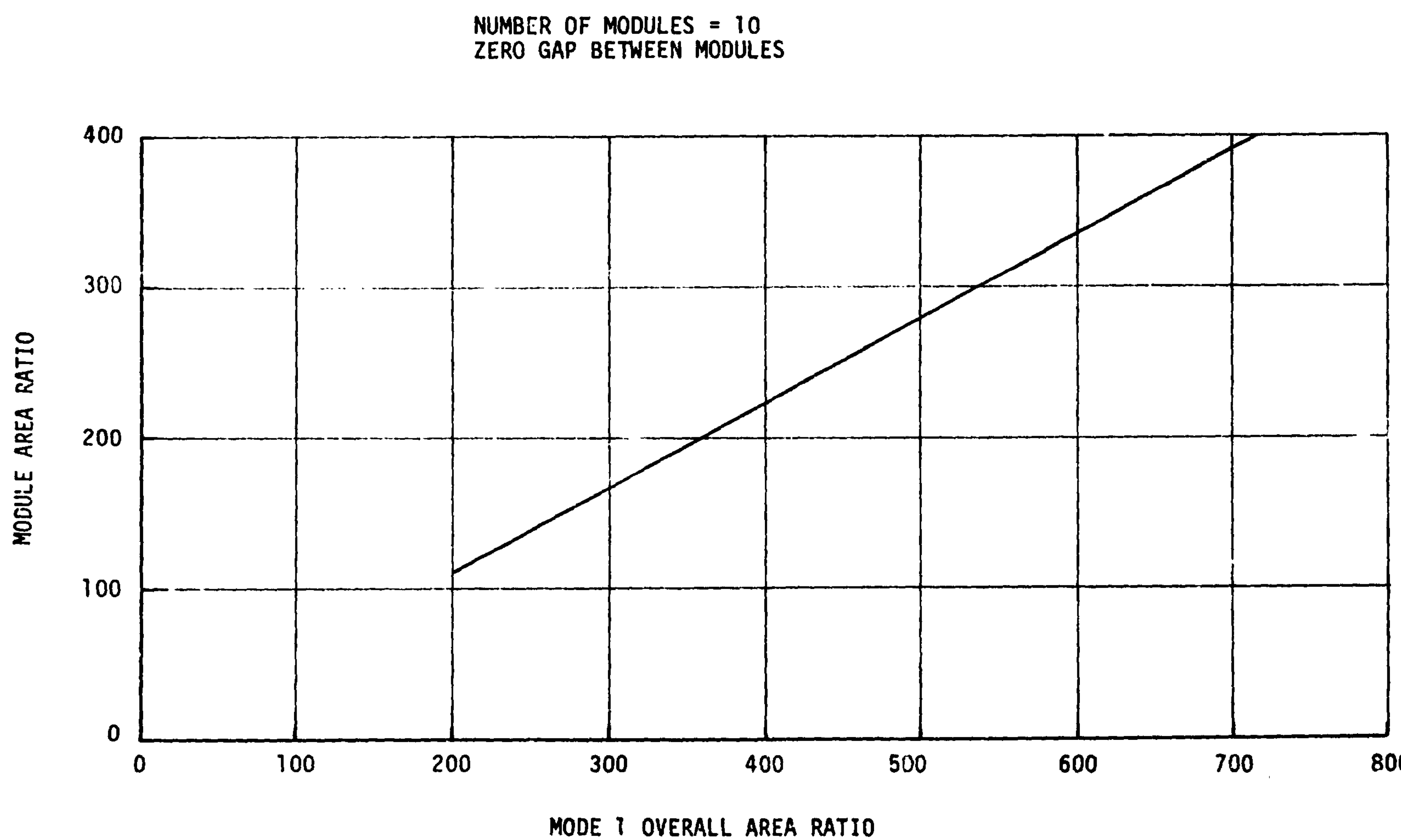

Figure 88. Plug Cluster Module Area Ratio Requirements

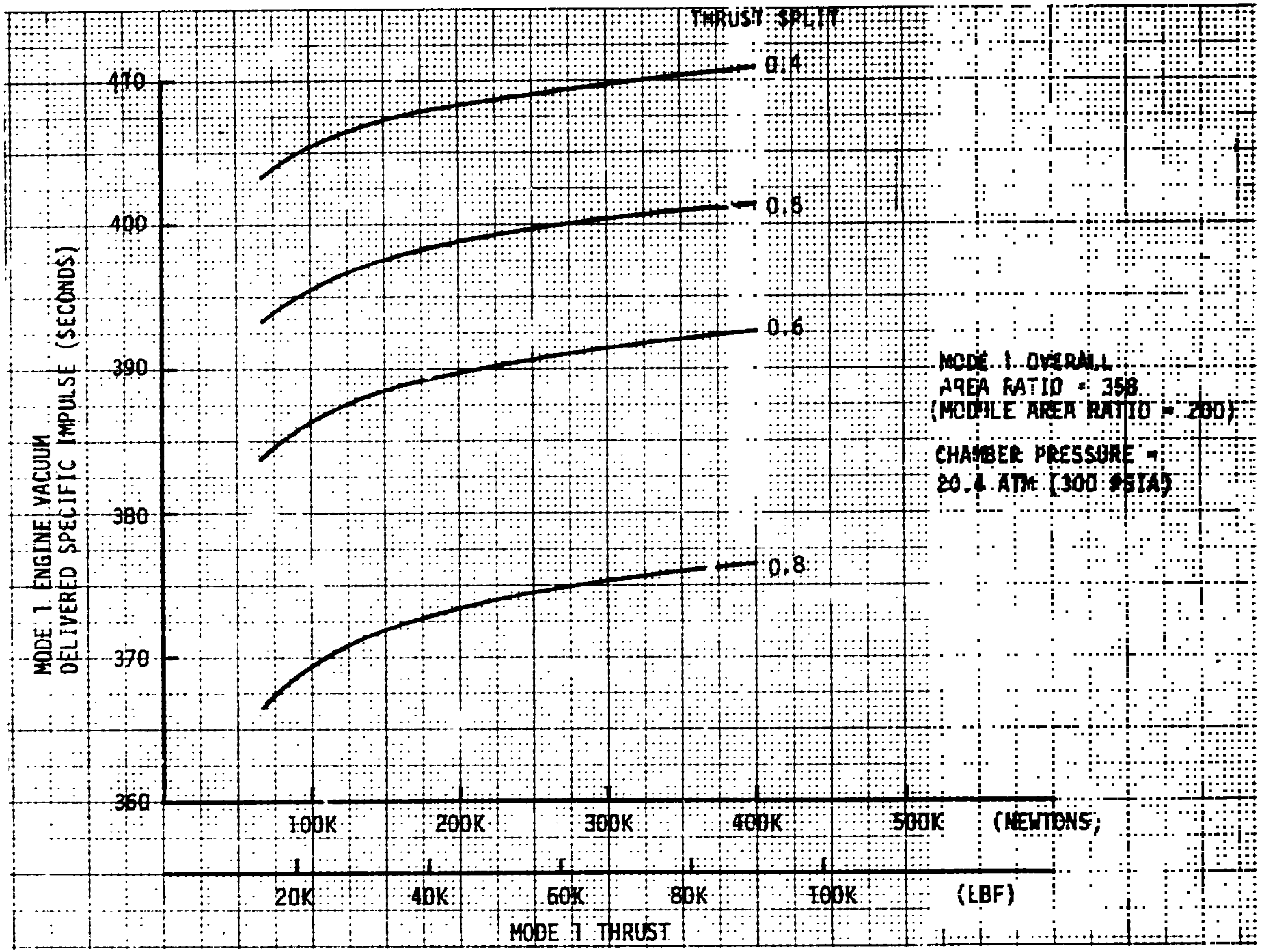

Figure 89. Effect of Thrust on Plug Cluster Engine Mode 1 Delivered Performance

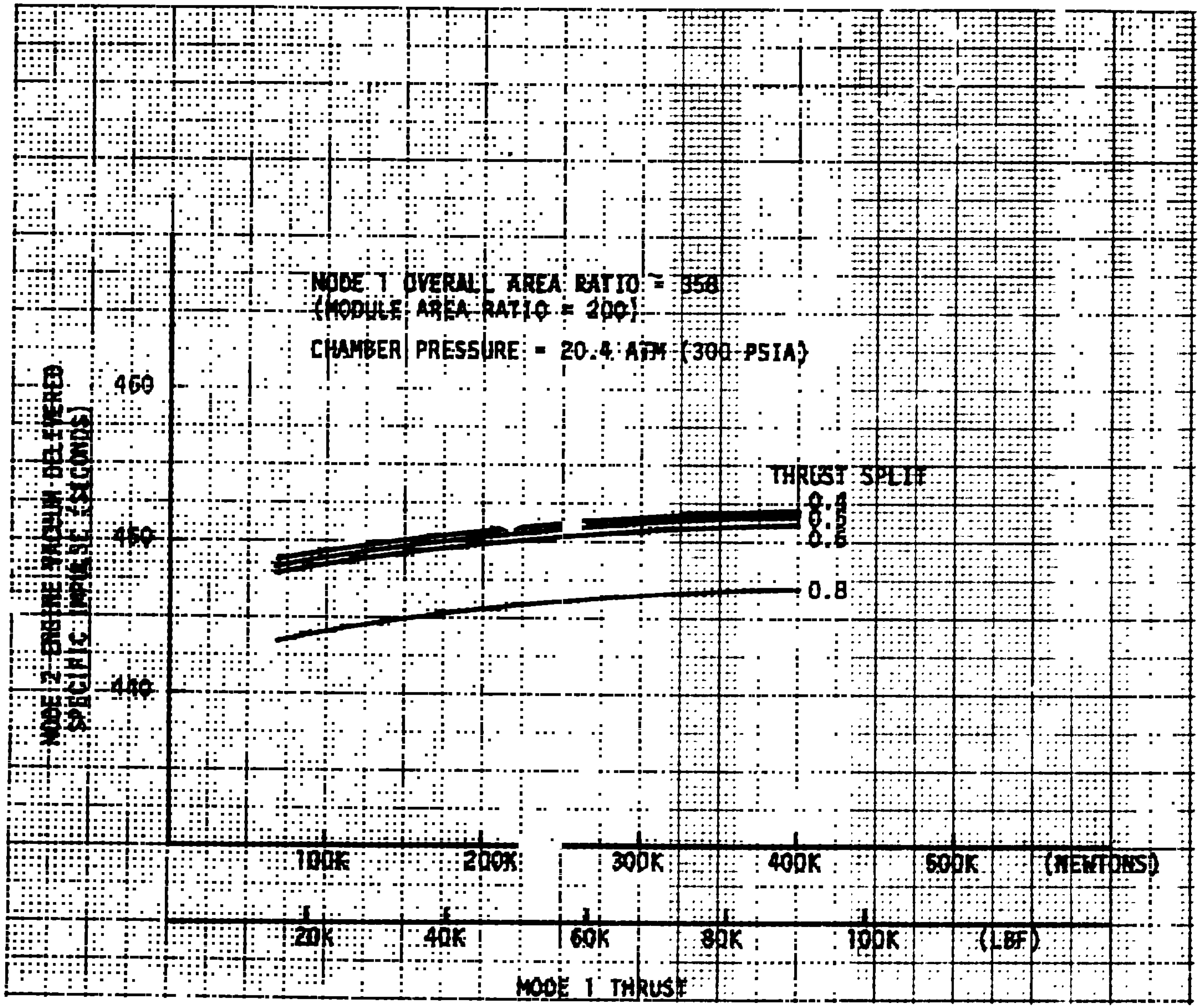

Figure 90. Effect of Thrust on Plug Cluster Engine Mode 2 Delivered Performance

Engine dry weight is shown on Figure 91 as a function of Mode 1 overall area ratio for various thrust splits at the baseline Mode 1 thrust level of 88964N (20,000 lbs). Engine weight increases with increasing thrust split because the LOX/RP-1 thrust chamber modules are heavier than the LOX/LH_2 modules and this more than makes up for lighter turbomachinery weights. The LOX/RP-1 module chambers are longer (liquid-liquid injection) than the LOX/LH_2 module chambers (liquid-gas injection) to meet the 98% combustion efficiency requirement and this results in heavier weights.

The effect of Mode 1 thrust on the plug cluster engine dry weight is shown on Figure 92 for the baseline thrust split of 0.5 and various Mode 1 overall area ratios.

The plug cluster engine envelope data is shown on Figure 93 and 94. Figure 93 shows the envelope data as a function of the overall Mode 1 area ratio for the baseline thrust of 88964N (20,000 lbs) and thrust split of 0.5. The equivalent engine length is defined as the length from the conventional engine mounting plane to the module exits. The engine length is defined as the length from the top of the modules to the module exits (see the sketch on Figure 93). The equivalent length parameter is introduced because some of the propellant tank can fit in the plug recess which is not possible with other engine types like a single bell nozzle. Figure 94 shows the envelope data as a function of Mode 1 thrust for baseline thrust split, overall area ratio and module area ratio values of 0.5, 358 and 200, respectively. The plot and the tabular data show that the plug cluster engine diameter exceeds the 447 cm (176") diameter limitation at the majority of the overall nozzle area ratios at thrust levels greater than 177.9 KN (40,000 lbs). All the data was calculated to complete the study matrix but it should be recognized that engines with diameters greater than 447 cm (176") will not fit within the current shuttle payload bay.

The effect of the module operating chamber pressure and LOX/LH_2 module mixture ratio upon the engine performance was also investigated. This was done to aid in comparing the data generated under this contract with that established for the Unconventional Nozzle Tradeoff Study (Ref. 3) and to show the sensitivities. This peripheral study was conducted at the baseline thrust level of 88964N (20,000 lb).

Tables XXXVIII and XXXIX can be used to compare the plug cluster engine characteristics for LOX/LH_2 module mixture ratios of 6.0 and 7.0 with the modules operating at 20 atm (300 psia) chamber pressure. The LOX/RP-1 module mixture ratios for all cases is 3.1. Table XXXVIII shows that a 6 to 7 sec performance gain is achieved in Mode 2 if the LOX/LH_2 module mixture ratio is reduced from 7.0 to 6.0.

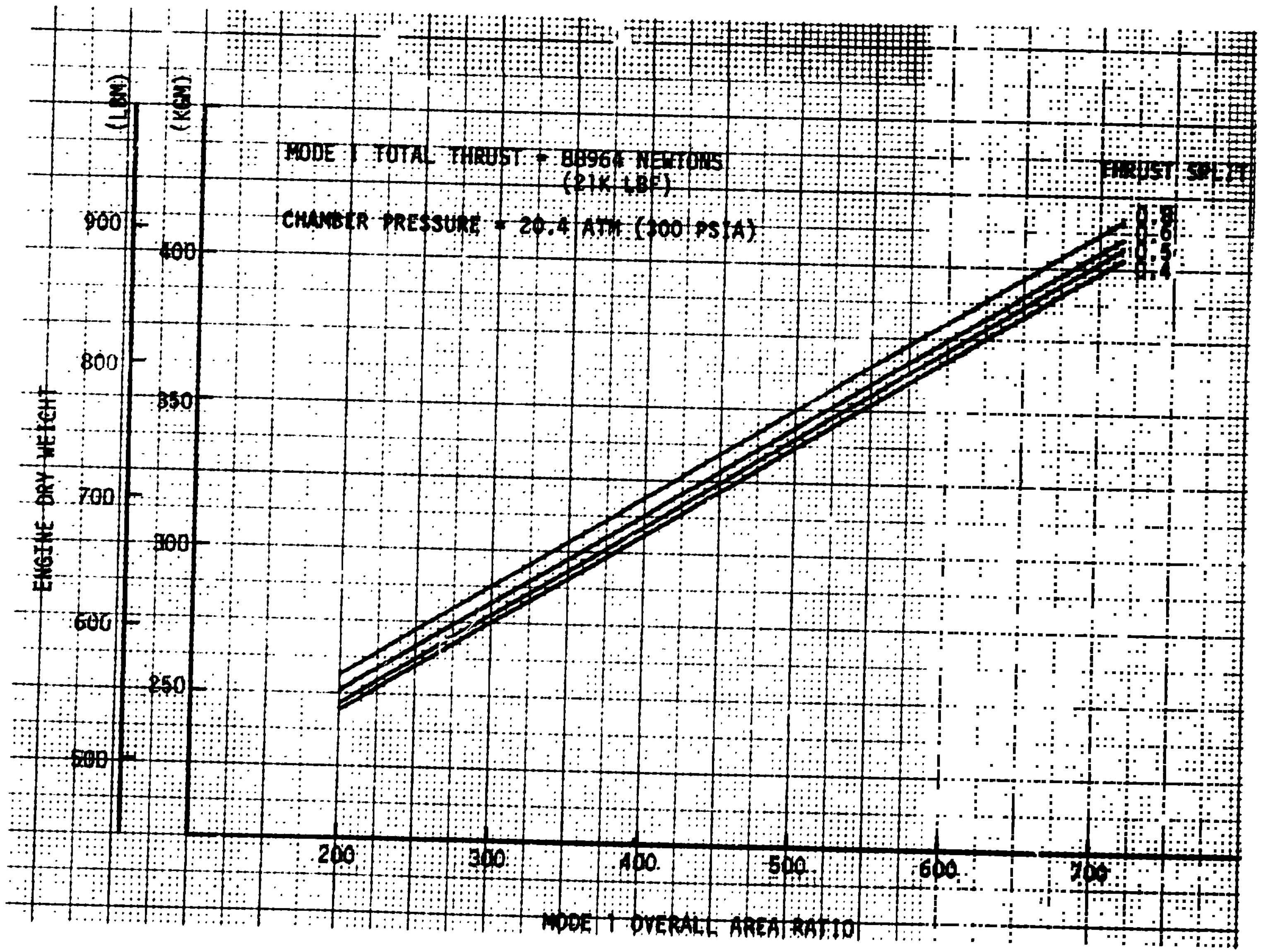

Figure 91. Effect of Mode 1 Overall Area Ratio on Plug Cluster Engine Weight

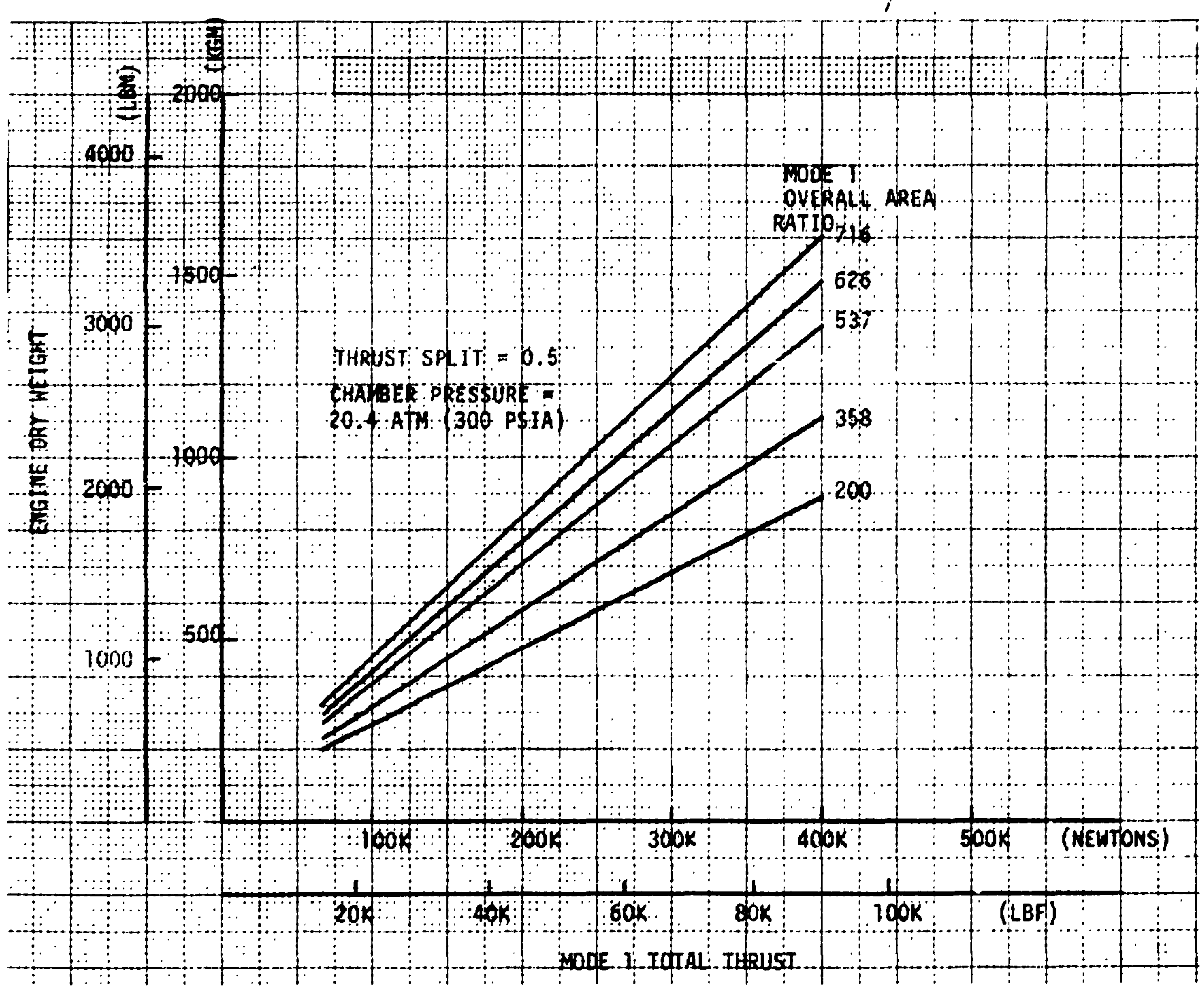

Figure 92. Effect of Thrust on Plug Cluster Engine Weight

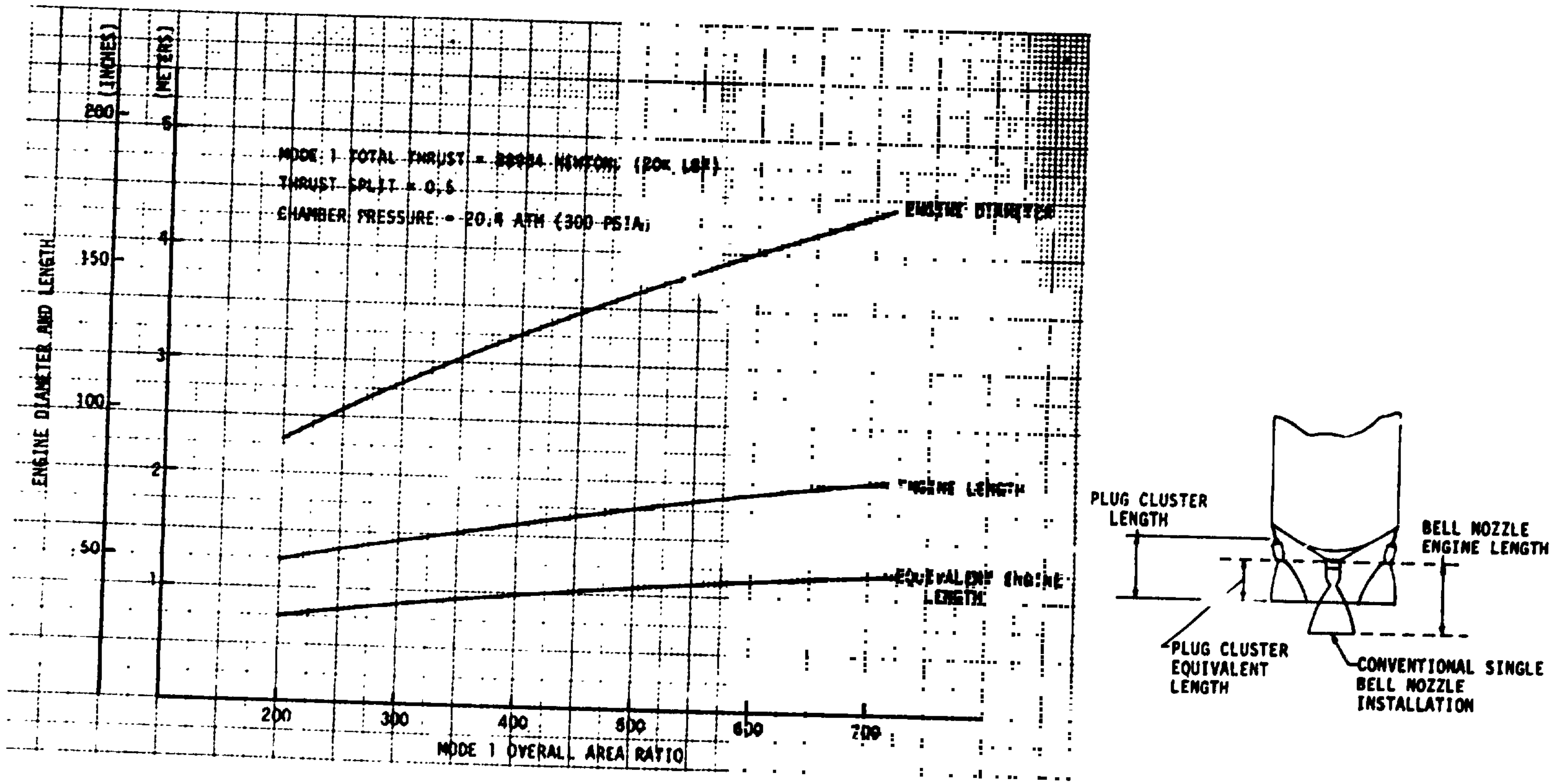

Figure 93. Effect of Mode 1 Overall Area Ratio on Plug Cluster Engine Envelope

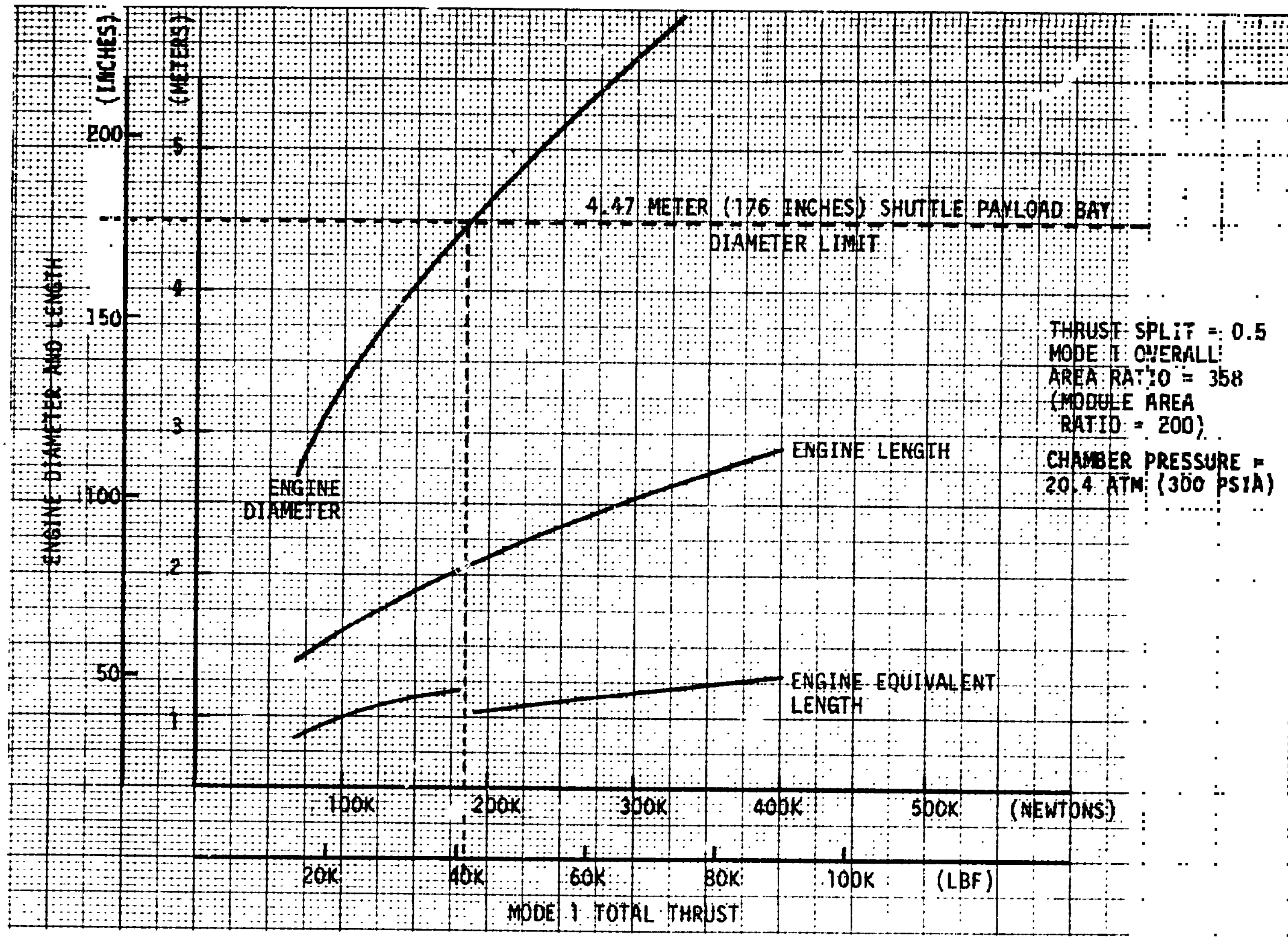

Figure 94. Effect of Thrust on Plug Cluster Engine Envelope

TABLE XXXVIII. - PLUG CLUSTER ENGINE PARAMETRIC DATA, MR = 6.0, P_c = 20.4 atm (300 psia)

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NO. OF MODS	% SPLIT	MODE1 TOTAL THRUST (N)	MODE1 BASE THRUST (N)	MODE 1 MODULE-PLUG F (N)	MODE 1 ISP D (SEC)	MODE 2 TOTAL THRUST (N)	MODE2 BASE THRUST (N)	MODE2 ISPD (SEC)	CHAMBER PRESSURE (ATMS)	MODULE AREA RATIO	MODE1 AREA RATIO	MODE2 AREA RAT	GAS GEN FLOW (KG/S)	%BELL	MODE2 GAP (AV)	% FULL PLUG	ENGINE EQUIV. LENGTH (M)	ENGINE LENGTH (M)	ENGINE DIAM. (M)	TOTAL ENG WGT. (KGM)
10	.4	88964.	1982.	86833.	401.7	52185.	857.	449.6	20.	112.	200.	331.	.1	90.	.7	0.	.75	1.24	2.4	244.
10	.4	88964.	1667.	87147.	407.3	52245.	708.	455.3	20.	200.	358.	591.	.1	90.	.7	0.	.96	1.54	3.1	293.
10	.4	88964.	1311.	87504.	408.9	52303.	549.	457.3	20.	300.	537.	886.	.1	90.	.7	0.	1.11	1.82	3.8	349.
10	.4	88964.	1195.	87620.	411.0	52336.	496.	459.2	20.	400.	716.	1181.	.1	90.	.7	0.	1.21	2.04	4.4	403.
10	.4	88964.	1033.	87782.	412.2	52368.	426.	460.5	20.	500.	896.	1477.	.1	90.	.7	0.	1.30	2.25	4.9	457.
10	.5	88964.	2070.	86708.	391.2	43028.	672.	449.2	20.	112.	200.	397.	.1	90.	1.0	0.	.75	1.24	2.4	247.
10	.5	88964.	1752.	87026.	396.7	43094.	555.	454.9	20.	200.	358.	707.	.1	90.	1.0	0.	.96	1.54	3.1	297.
10	.5	88964.	1383.	87394.	398.3	43158.	430.	457.1	20.	300.	537.	1061.	.1	90.	1.0	0.	1.11	1.82	3.8	352.
10	.5	88964.	1260.	87513.	400.5	43198.	389.	459.0	20.	400.	716.	1413.	.1	90.	1.0	0.	1.21	2.04	4.4	407.
10	.5	88964.	1095.	87682.	401.6	43234.	334.	460.3	20.	500.	896.	1767.	.1	90.	1.0	0.	1.30	2.25	4.9	461.
10	.6	88964.	2168.	86574.	381.3	33977.	499.	448.8	20.	112.	200.	495.	.2	90.	1.5	0.	.75	1.24	2.4	251.
10	.6	88964.	1847.	86894.	386.8	34052.	412.	454.6	20.	200.	358.	882.	.2	90.	1.5	0.	.96	1.54	3.1	300.
10	.6	88964.	1465.	87276.	388.3	34117.	319.	456.8	20.	300.	537.	1323.	.2	90.	1.5	0.	1.11	1.82	3.8	356.
10	.6	88964.	1343.	87398.	390.5	34160.	289.	458.7	20.	400.	716.	1762.	.2	90.	1.5	0.	1.21	2.04	4.4	410.
10	.6	88964.	1166.	87575.	391.6	34198.	248.	460.1	20.	500.	896.	2203.	.2	90.	1.5	0.	1.30	2.25	4.9	464.
10	.8	88964.	2397.	86273.	363.6	16321.	0.	445.1	20.	112.	200.	112.	.2	90.	4.0	0.	.75	1.24	2.4	257.
10	.8	88964.	2074.	86595.	369.0	16401.	0.	451.5	20.	200.	358.	200.	.2	90.	4.0	0.	.96	1.54	3.1	306.
10	.8	88964.	1665.	87004.	370.3	16476.	0.	454.5	20.	300.	537.	300.	.2	90.	4.0	0.	1.12	1.82	3.8	362.
10	.8	88964.	1538.	87131.	372.5	16516.	0.	456.7	20.	400.	716.	400.	.2	90.	4.0	0.	1.22	2.04	4.4	416.
10	.8	88964.	1344.	87325.	373.5	16536.	0.	457.9	20.	500.	896.	500.	.2	90.	4.0	0.	1.31	2.25	4.9	470.

ENGLISH UNITS

NO. OF MODS	% SPLIT	MODE1 TOTAL THRUST (LBF)	MODE1 BASE THRUST (LBF)	MODE 1 MODULE-PLUG F (LBF)	MODE 1 ISP D (SEC)	MODE 2 TOTAL THRUST (LBF)	MODE2 BASE THRUST (LBF)	MODE2 ISPD (SEC)	CHAMBER PRESSURE (PSIA)	MODULE AREA RATIO	MODE1 AREA RATIO	MODE2 AREA RAT	GAS GEN FLOW (LB/S)	%BELL	MODE2 GAP (AV)	% FULL PLUG	ENGINE EQUIV. LENGTH (IN)	ENGINE LENGTH (IN)	ENGINE DIAM. (IN)	TOTAL ENG WGT. (LBM)
10	.4	20000.	445.	19521.	401.7	11732.	193.	449.6	300.	112.	200.	331.	.2	90.	.7	0.	29.63	48.91	93.0	537.
10	.4	20000.	375.	19591.	407.3	11745.	159.	455.3	300.	200.	358.	591.	.2	90.	.7	0.	37.65	60.02	123.4	647.
10	.4	20000.	295.	19672.	408.9	11758.	123.	457.3	300.	300.	537.	886.	.2	90.	.7	0.	43.75	71.53	150.6	769.
10	.4	20000.	269.	19698.	411.0	11766.	112.	459.2	300.	400.	716.	1181.	.2	90.	.7	0.	47.62	80.45	173.4	889.
10	.4	20000.	232.	19734.	412.2	11773.	96.	460.5	300.	500.	896.	1477.	.2	90.	.7	0.	51.03	88.45	193.6	1008.
10	.5	20000.	465.	19493.	391.2	9672.	151.	449.2	300.	112.	200.	397.	.3	90.	1.0	0.	29.65	48.91	92.9	545.
10	.5	20000.	394.	19564.	396.7	9688.	125.	454.9	300.	200.	358.	707.	.3	90.	1.0	0.	37.69	60.02	123.2	655.
10	.5	20000.	311.	19647.	398.3	9702.	97.	457.1	300.	300.	537.	1061.	.3	90.	1.0	0.	43.41	71.53	150.4	777.
10	.5	20000.	284.	19674.	400.5	9711.	87.	459.0	300.	400.	716.	1413.	.3	90.	1.0	0.	47.72	80.45	173.2	897.
10	.5	20000.	246.	19712.	401.6	9719.	75.	460.3	300.	500.	896.	1767.	.3	90.	1.0	0.	51.18	88.45	193.4	1016.
10	.6	20000.	487.	19463.	381.3	7630.	112.	448.8	300.	112.	200.	495.	.4	90.	1.5	0.	29.66	48.91	92.8	553.
10	.6	20000.	415.	19535.	386.8	7655.	93.	454.6	300.	200.	358.	882.	.4	90.	1.5	0.	37.73	60.02	123.1	662.
10	.6	20000.	329.	19620.	388.3	7670.	72.	456.8	300.	300.	537.	1323.	.4	90.	1.5	0.	43.87	71.53	150.2	784.
10	.6	20000.	302.	19648.	390.5	7680.	65.	458.7	300.	400.	716.	1762.	.4	90.	1.5	0.	47.82	80.45	172.9	904.
10	.6	20000.	262.	19688.	391.6	7688.	56.	460.1	300.	500.	896.	2203.	.4	90.	1.5	0.	51.33	88.45	193.1	1024.
10	.8	20000.	539.	19395.	363.6	3669.	0.	445.1	300.	112.	200.	112.	.5	90.	4.0	0.	29.70	48.91	92.7	566.
10	.8	20000.	466.	19467.	369.0	3687.	0.	451.5	300.	200.	358.	200.	.5	90.	4.0	0.	37.80	60.02	122.8	675.
10	.8	20000.	374.	19559.	370.3	3704.	0.	454.5	300.	300.	537.	300.	.5	90.	4.0	0.	43.99	71.53	149.9	[illegible]
10	.8	20000.	346.	19588.	372.5	3713.	0.	456.7	300.	400.	716.	400.	.5	90.	4.0	0.	48.03	80.45	172.5	917.
10	.8	20000.	302.	19631.	373.5	3720.	0.	457.9	300.	500.	896.	500.	.5	90.	4.0	0.	51.63	88.45	198.6	1037.

TABLE XXXIX. - PLUG CLUSTER ENGINE PARAMETRIC DATA, MR = 7.0, P_c = 20.4 atm (300 psia)

S.I. UNITS

NO.OF MODS	F SPLIT	MODE1 TOTAL THRUST (N)	MODE1 BASE THRUST (N)	MODE 1 MODULE-PLUG F (N)	MODE 1 ISP D (SEC)	MODE 2 TOTAL THRUST (N)	MODE2 BASE THRUST (N)	MODE2 ISPD (SEC)	CHAMBER PRESSURE (ATMS)	MODULE AREA RATIO	MODE1 AREA RATIO	MODE2 AREA RAT	GAS GEN FLOW (KG/S)	%BELL	MODE2 GAP (AV)	% FULL PLUG	ENGINE EQUIV. LENGTH (M)	ENGINE LENGTH (M)	ENGINE DIAM. (M)	TOTAL ENG WGT. (KGM)
10	.4	88964.	2268.	86547.	399.0	52332.	1052.	442.9	20.	112.	200.	334.	.1	90.	.7	0.	.75	1.24	2.3	244.
10	.4	88964.	1939.	86876.	404.8	52371.	884.	449.2	20.	200.	358.	596.	.1	90.	.7	0.	.96	1.54	3.1	293.
10	.4	88964.	1542.	87273.	406.6	52414.	694.	451.6	20.	300.	537.	894.	.1	90.	.7	0.	1.11	1.82	3.8	349.
10	.4	88964.	1417.	87397.	408.8	52439.	634.	453.8	20.	400.	716.	1192.	.1	90.	.7	0.	1.21	2.04	4.4	403.
10	.4	88964.	1233.	87582.	410.0	52465.	544.	455.3	20.	500.	896.	1490.	.1	90.	.7	0.	1.30	2.28	4.9	457.
10	.5	88964.	2334.	86445.	389.2	43210.	831.	442.5	20.	112.	200.	400.	.1	90.	1.0	0.	.75	1.24	2.3	247.
10	.5	88964.	2005.	86773.	395.0	43254.	698.	448.9	20.	200.	358.	715.	.1	90.	1.0	0.	.96	1.54	3.1	297.
10	.5	88964.	1600.	87178.	396.6	43299.	548.	451.4	20.	300.	537.	1073.	.1	90.	1.0	0.	1.11	1.82	3.8	352.
10	.5	88964.	1474.	87304.	398.9	43329.	500.	453.6	20.	400.	716.	1429.	.1	90.	1.0	0.	1.21	2.04	4.4	407.
10	.5	88964.	1284.	87493.	400.0	43358.	432.	455.0	20.	500.	896.	1788.	.1	90.	1.0	0.	1.30	2.25	4.9	461.
10	.6	88964.	2403.	86339.	379.9	34188.	622.	442.1	20.	112.	200.	500.	.2	90.	1.5	0.	.75	1.24	2.3	251.
10	.6	88964.	2075.	86666.	385.6	34234.	523.	448.5	20.	200.	358.	893.	.2	90.	1.5	0.	.96	1.54	3.1	300.
10	.6	88964.	1662.	87079.	387.1	34278.	411.	451.1	20.	300.	537.	1341.	.2	90.	1.5	0.	1.11	1.82	3.8	356.
10	.6	88964.	1535.	87206.	389.4	34310.	375.	453.3	20.	400.	716.	1786.	.2	90.	1.5	0.	1.21	2.04	4.4	410.
10	.6	88964.	1340.	87401.	390.5	34339.	324.	454.8	20.	500.	896.	2234.	.2	90.	1.5	0.	1.30	2.25	4.9	464.
10	.8	88964.	2556.	86115.	363.2	16448.	0.	436.8	20.	112.	200.	112.	.2	90.	4.0	0.	.75	1.24	2.3	257.
10	.8	88964.	2232.	86437.	368.6	16510.	0.	444.0	20.	200.	358.	200.	.2	90.	4.0	0.	.96	1.58	3.1	306.
10	.8	88964.	1804.	86865.	369.9	16577.	0.	447.6	20.	300.	537.	300.	.2	90.	4.0	0.	1.11	1.82	3.8	361.
10	.8	88964.	1675.	86994.	372.2	16611.	0.	450.1	20.	400.	716.	400.	.2	90.	4.0	0.	1.21	2.04	4.4	416.
10	.8	88964.	1469.	87200.	373.2	16636.	0.	451.7	20.	500.	896.	500.	.2	90.	4.0	0.	1.30	2.28	4.9	470.

ENGLISH UNITS

NO.OF MODS	F SPLIT	MODE1 TOTAL THRUST (LBF)	MODE1 BASE THRUST (LBF)	MODE 1 MODULE-PLUG F (LBF)	MODE 1 ISP D (SEC)	MODE 2 TOTAL THRUST (LBF)	MODE2 BASE THRUST (LBF)	MODE2 ISPD (SEC)	CHAMBER PRESSURE (PSIA)	MODULE AREA RATIO	MODE1 AREA RATIO	MODE2 AREA RAT	GAS GEN FLOW (LB/S)	%BELL	MODE2 GAP (AV)	% FULL PLUG	ENGINE EQUIV. LENGTH (IN)	ENGINE LENGTH (IN)	ENGINE DIAM. (IN)	TOTAL ENG WGT. (LBM)
10	.4	20000.	510.	19457.	399.0	11765.	236.	442.9	300.	112.	200.	334.	.2	90.	.7	0.	29.65	48.91	92.5	537.
10	.4	20000.	436.	19530.	404.8	11773.	199.	449.2	300.	200.	358.	596.	.2	90.	.7	0.	37.70	60.82	122.6	647.
10	.4	20000.	347.	19620.	406.6	11783.	156.	451.6	300.	300.	537.	894.	.2	90.	.7	0.	43.82	71.53	149.6	769.
10	.4	20000.	319.	19648.	408.8	11789.	142.	453.8	300.	400.	716.	1192.	.2	90.	.7	0.	47.73	80.45	172.2	889.
10	.4	20000.	277.	19689.	410.0	11795.	123.	455.3	300.	500.	896.	1490.	.2	90.	.7	0.	51.20	88.45	192.3	1008.
10	.5	20000.	525.	19434.	389.2	9714.	187.	442.5	300.	112.	200.	400.	.3	90.	1.0	0.	29.65	48.91	92.5	545.
10	.5	20000.	451.	19507.	395.0	9724.	157.	448.9	300.	200.	358.	715.	.3	90.	1.0	0.	37.70	60.82	122.6	655.
10	.5	20000.	360.	19598.	396.6	9734.	123.	451.4	300.	300.	537.	1073.	.3	90.	1.0	0.	43.83	71.53	149.6	777.
10	.5	20000.	331.	19627.	398.9	9741.	112.	453.6	300.	400.	716.	1429.	.3	90.	1.0	0.	47.75	80.45	172.2	897.
10	.5	20000.	289.	19669.	400.0	9747.	97.	455.0	300.	500.	896.	1788.	.3	90.	1.0	0.	51.22	88.45	192.2	1016.
10	.6	20000.	540.	19410.	379.9	7686.	140.	442.1	300.	112.	200.	500.	.4	90.	1.5	0.	29.65	48.91	92.5	553.
10	.6	20000.	467.	19483.	385.6	7696.	118.	448.5	300.	200.	358.	893.	.4	90.	1.5	0.	37.70	60.82	122.6	662.
10	.6	20000.	374.	19576.	387.1	7706.	92.	451.1	300.	300.	537.	1341.	.4	90.	1.5	0.	43.83	71.53	149.6	774.
10	.6	20000.	345.	19605.	389.4	7713.	84.	453.3	300.	400.	716.	1786.	.4	90.	1.5	0.	47.76	80.45	172.1	904.
10	.6	20000.	301.	19648.	390.5	7720.	73.	454.8	300.	500.	896.	2234.	.4	90.	1.5	0.	51.24	88.45	192.2	1024.
10	.8	20000.	579.	19359.	363.2	3698.	0.	436.8	300.	112.	200.	112.	.5	90.	4.0	0.	29.65	48.91	92.5	566.
10	.8	20000.	502.	19432.	368.6	3712.	0.	444.0	300.	200.	358.	200.	.5	90.	4.0	0.	37.71	60.82	122.6	675.
10	.8	20000.	406.	19528.	369.9	3727.	0.	447.6	300.	300.	537.	300.	.5	90.	4.0	0.	43.84	71.53	149.5	797.
10	.8	20000.	376.	19557.	372.2	3734.	0.	450.1	300.	400.	716.	400.	.5	90.	4.0	0.	47.79	80.45	172.1	917.
10	.8	20000.	330.	19603.	373.2	3740.	0.	451.7	300.	500.	896.	500.	.5	90.	4.0	0.	51.29	88.43	192.1	1037.

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Tables XL and XLI present the plug cluster characteristics for module operating chamber pressures of 34 atm (500 psia) and LOX/LH_2 module mixture ratios of 6.0 and 7.0, respectively. These tables show that the plug cluster performance can be increased approximately another 2 to 3 secs if the module operating pressure can be increased. As noted in previous sections, the LOX/RP-1 and not the LOX/LH_2 module limits the plug cluster operating pressure. The Mode 2 performance generated for a mixture of 6.0 at 34 atm (500 psia) is comparable to the Ref. 3 data.

A comparison of all data on Tables XXXVIII through XLI indicates that both the low operating pressure of the modules and low module thrust would seem to drive the "optimum" operating mixture ratio of the LOX/LH_2 modules from 7.0 to 6.0.

TABLE XL. - PLUG CLUSTER ENGINE PARAMETRIC DATA,
MR = 6.0, P_c = 34 atm (500 psia)

S.I. UNITS

NO.OF MODS	F SPLIT	MODE1 TOTAL THRUST (N)	MODE1 BASE THRUST (N)	MODE 1 MODULE-PLUG F (N)	MODE 1 ISP D (SEC)	MODE 2 TOTAL THRUST (N)	MODE2 BASE THRUST (N)	MODE2 ISPD (SEC)	CHAMBER PRESSURE (ATMS)	MODULE AREA RATIO	MODE1 AREA RATIO	MODE2 AREA RAT	GAS GEN FLOW (KG/S)	%BELL	MODE2 GAP (AV)	% FULL PLUG	ENGINE EQUIV. LENGTH (M)	ENGINE LENGTH (M)	ENGINE DIAM. (M)	TOTAL ENG WGT. (KGM)
10	.4	88964.	1947.	86867.	404.8	52231.	842.	451.5	34.	112.	200.	331.	.1	90.	.7	0.	.60	1.04	1.8	209.
10	.4	88964.	1638.	87176.	410.3	52291.	695.	457.3	34.	200.	358.	590.	.1	90.	.7	0.	.78	1.27	2.4	240.
10	.4	88964.	1287.	87528.	412.1	52350.	539.	459.4	34.	300.	537.	884.	.1	90.	.7	0.	.92	1.48	3.0	274.
10	.4	88964.	1178.	87640.	414.1	52376.	488.	461.4	34.	400.	716.	1179.	.1	90.	.7	0.	1.04	1.66	3.4	308.
10	.4	88964.	1014.	87800.	415.4	52407.	419.	462.7	34.	500.	896.	1474.	.1	90.	.7	0.	1.14	1.81	3.8	341.
10	.5	88964.	2034.	86744.	394.3	43083.	660.	451.1	34.	112.	200.	396.	.1	90.	1.0	0.	.60	1.04	1.8	213.
10	.5	88964.	1721.	87057.	400.0	43154.	545.	456.9	34.	200.	358.	706.	.1	90.	1.0	0.	.78	1.27	2.4	244.
10	.5	88964.	1358.	87420.	401.8	43220.	422.	459.2	34.	300.	537.	1058.	.1	90.	1.0	0.	.93	1.48	3.0	278.
10		88964.	1242.	87535.	403.8	43250.	382.	461.2	34.	400.	716.	1410.	.1	90.	1.0	0.	1.04	1.66	3.4	311.
10		88964.	1076.	87702.	405.0	43286.	328.	462.5	34.	500.	896.	1763.	.1	90.	1.0	0.	1.14	1.81	3.8	344.
10	.6	88964.	2130.	86611.	384.5	34046.	490.	450.7	34.	112.	200.	493.	.2	90.	1.5	0.	.60	1.04	1.8	216.
10	.6	88964.	1814.	86927.	390.2	34121.	404.	456.6	34.	200.	358.	880.	.2	90.	1.5	0.	.76	1.27	2.4	247.
10	.6	88964.	1438.	87303.	392.0	34189.	313.	458.9	34.	300.	537.	1319.	.2	90.	1.5	0.	.93	1.48	3.0	281.
10	.6	88964.	1319.	87421.	394.0	34220.	283.	460.9	34.	400.	716.	1757.	.2	90.	1.5	0.	1.04	1.66	3.8	314.
10	.6	88964.	1145.	87595.	395.1	34259.	243.	462.3	34.	500.	896.	2196.	.2	90.	1.5	0.	1.14	1.81	3.8	347.
10	.8	88964.	2355.	86314.	367.1	16386.	0.	447.1	34.	112.	200.	112.	.2	90.	4.0	0.	.60	1.04	1.8	221.
10	.8	88964.	2037.	86632.	372.7	16466.	0.	453.6	34.	200.	358.	200.	.2	90.	4.0	0.	.78	1.27	2.4	252.
10	.8	88964.	1634.	87035.	374.2	16543.	0.	456.7	34.	300.	537.	300.	.2	90.	4.0	0.	.93	1.08	2.9	286.
10	.8	88964.	1511.	87157.	376.2	16574.	0.	458.9	34.	400.	716.	400.	.2	90.	4.0	0.	1.04	1.66	3.4	319.
10	.8	88964.	1321.	87348.	377.2	16603.	0.	460.2	34.	500.	896.	500.	.2	90.	4.0	0.	1.15	1.81	3.8	353.

ENGLISH UNITS

NO.OF MODS	F SPLIT	MODE1 TOTAL THRUST (LBF)	MODE1 BASE THRUST (LBF)	MODE 1 MODULE-PLUG F (LBF)	MODE 1 ISP D (SEC)	MODE 2 TOTAL THRUST (LBF)	MODE2 BASE THRUST (LBF)	MODE2 ISPD (SEC)	CHAMBER PRESSURE (PSIA)	MODULE AREA RATIO	MODE1 AREA RATIO	MODE2 AREA RAT	GAS GEN FLOW (LB/S)	%BELL	MODE2 GAP (AV)	% FULL PLUG	ENGINE EQUIV. LENGTH (IN)	ENGINE LENGTH (IN)	ENGINE DIAM. (IN)	TOTAL ENG WGT. (LBM)
10	.4	20000.	438.	19529.	404.6	11742.	189.	451.5	500.	112.	200.	331.	.2	90.	.7	0.	23.70	40.79	72.0	462.
10	.4	20000.	368.	19598.	410.3	11755.	156.	457.3	500.	200.	358.	590.	.2	90.	.7	0.	30.65	49.99	95.5	529.
10	.4	20000.	289.	19677.	412.1	11769.	121.	459.4	500.	300.	537.	884.	.2	90.	.7	0.	36.40	58.25	116.5	604.
10	.4	20000.	264.	19702.	414.1	11774.	110.	461.4	500.	400.	716.	1179.	.2	90.	.7	0.	40.75	65.18	134.[illegible]	678.
10	.4	20000.	228.	19738.	415.4	11782.	94.	462.7	500.	500.	896.	1474.	.2	90.	.7	0.	44.86	71.36	149.6	751.
10	.5	20000.	457.	19501.	394.3	9685.	148.	451.1	500.	112.	200.	396.	.3	90.	1.0	0.	23.71	40.79	71.9	469.
10	.5	20000.	387.	19571.	400.0	9701.	122.	456.9	500.	200.	358.	706.	.3	90.	1.0	0.	30.67	49.99	95.3	537.
10	.5	20000.	305.	19653.	401.8	9716.	95.	459.2	500.	300.	537.	1058.	.3	90.	1.0	0.	36.44	58.25	116.3	612.
10	.5	20000.	279.	19679.	403.8	9723.	86.	461.2	500.	400.	716.	1410.	.3	90.	1.0	0.	40.81	65.18	134.0	686.
10	.5	20000.	242.	19716.	405.0	9731.	74.	462.5	500.	500.	896.	1763.	.3	90.	1.0	0.	44.94	71.36	149.6	758.
10	.6	20000.	479.	19471.	384.5	7654.	110.	450.7	500.	112.	200.	493.	.4	90.	1.5	0.	23.72	40.79	71.8	476.
10	.6	20000.	408.	19542.	390.2	7671.	91.	456.6	500.	200.	358.	880.	.4	90.	1.5	0.	30.70	49.99	95.2	544.
10	.6	20000.	323.	19627.	392.0	7686.	70.	458.9	500.	300.	537.	1319.	.4	90.	1.5	0.	36.48	58.25	116.2	619.
10	.6	20000.	297.	19653.	394.0	7693.	64.	460.9	500.	400.	716.	1757.	.4	90.	1.5	0.	40.87	65.18	133.8	693.
10	.6	20000.	258.	19692.	395.1	7702.	55.	462.3	500.	500.	896.	2196.	.4	90.	1.5	0.	45.02	71.36	149.4	765.
10	.8	20000.	530.	19404.	367.1	3684.	0.	447.1	500.	112.	200.	112.	.5	90.	4.0	0.	23.75	40.79	71.7	488.
10	.8	20000.	458.	19476.	372.7	3702.	0.	453.6	500.	200.	358.	200.	.5	90.	4.0	0.	30.75	49.99	94.9	556.
10	.8	20000.	367.	19566.	374.2	3719.	0.	456.7	500.	300.	537.	300.	.5	90.	4.0	0.	36.56	58.25	115.8	631.
10	.8	20000.	340.	19594.	376.2	3726.	0.	458.9	500.	400.	716.	400.	.5	90.	4.0	0.	40.99	65.18	133.4	704.
10	.8	20000.	297.	19636.	377.8	3732.	0.	460.2	500.	500.	896.	500.	.5	90.	4.0	0.	45.17	71.36	148.9	777.

TABLE XLI. - PLUG CLUSTER ENGINE PARAMETRIC DATA, MR = 7.0, P_c = 34 atm (500 psia)

S.I. UNITS

NO.OF MODS	F SPLIT	MODE1 TOTAL THRUST (N)	MODE1 BASE THRUST (N)	MODE 1 MODULE-PLUG F (N)	MODE 1 ISP D (SEC)	MODE 2 TOTAL THRUST (N)	MODE2 BASE THRUST (N)	MODE2 ISPD (SEC)	CHAMBER PRESSURE (ATMS)	MODULE AREA RATIO	MODE1 AREA RATIO	MODE2 AREA RAT	GAS GEN FLOW (KG/S)	%BELL	MODE2 GAP (AV)	% FULL PLUG	ENGINE EQUIV. LENGTH (M)	ENGINE LENGTH (M)	ENGINE DIAM. (M)	TOTAL ENG WGT. (KGM)
10	.4	88964.	2220.	86595.	402.4	52356.	1026.	446.0	34.	112.	200.	333.	.1	90.	.7	0.	.60	1.04	1.8	209.
10	.4	88964.	1897.	86917.	408.6	52393.	862.	452.7	34.	200.	358.	595.	.1	90.	.7	0.	.78	1.27	2.4	240.
10	.4	88964.	1507.	87307.	410.5	52438.	677.	455.3	34.	300.	537.	893.	.1	90.	.7	0.	.93	1.48	2.9	274.
10	.4	88964.	1386.	87428.	412.6	52456.	618.	457.6	34.	400.	716.	1191.	.1	90.	.7	0.	1.04	1.66	3.4	307.
10	.4	88964.	1206.	87608.	413.9	52482.	534.	459.1	34.	500.	896.	1489.	.1	90.	.7	0.	1.14	1.81	3.8	341.
10	.5	88964.	2287.	86492.	392.7	43241.	810.	445.6	34.	112.	200.	400.	.1	90.	1.0	0.	.60	1.04	1.8	213.
10	.5	88964.	1963.	86815.	398.7	43283.	681.	452.4	34.	200.	358.	714.	.1	90.	1.0	0.	.78	1.27	2.4	244.
10	.5	88964.	1569.	87212.	400.6	43330.	534.	455.0	34.	300.	537.	1071.	.1	90.	1.0	0.	.93	1.48	2.9	278.
10	.5	88964.	1443.	87334.	402.7	43351.	488.	457.3	34.	400.	716.	1428.	.1	90.	1.0	0.	1.04	1.66	3.4	311.
10	.5	88964.	1257.	87520.	403.9	43380.	422.	458.9	34.	500.	896.	1786.	.1	90.	1.0	0.	1.14	1.81	3.8	344.
10	.6	88964.	2357.	86385.	383.4	34222.	607.	445.1	34.	112.	200.	500.	.2	90.	1.5	0.	.60	1.04	1.8	216.
10	.6	88964.	2038.	86707.	389.4	34266.	510.	452.0	34.	200.	358.	892.	.2	90.	1.5	0.	.78	1.27	2.4	247.
10	.6	88964.	1628.	87113.	391.2	34313.	400.	454.7	34.	300.	537.	1338.	.2	90.	1.5	0.	.93	1.48	2.9	281.
10	.6	88964.	1505.	87236.	393.3	34334.	365.	457.1	34.	400.	716.	1784.	.2	90.	1.5	0.	1.04	1.66	3.4	314.
10	.6	88964.	1314.	87427.	394.4	34364.	314.	458.6	34.	500.	896.	2231.	.2	90.	1.5	0.	1.14	1.81	3.8	347.
10	.8	88964.	2512.	86158.	366.8	16485.	0.	440.1	34.	112.	200.	112.	.2	90.	4.0	0.	.60	1.04	1.8	221.
10	.8	88964.	2193.	86476.	372.5	16544.	0.	447.6	34.	200.	358.	200.	.2	90.	4.0	0.	.78	1.27	2.4	252.
10	.8	88964.	1771.	86898.	374.1	16612.	0.	451.4	34.	300.	537.	300.	.2	90.	4.0	0.	.93	1.48	2.9	286.
10	.8	88964.	1646.	87022.	376.1	16637.	0.	454.0	34.	400.	716.	400.	.2	90.	4.0	0.	1.04	1.66	3.4	319.
10	.8	88964.	1444.	87224.	377.1	16662.	0.	455.6	34.	500.	896.	500.	.2	90.	4.0	0.	1.14	1.81	3.8	353.

ENGLISH UNITS

NO.OF MODS	F SPLIT	MODE1 TOTAL THRUST (LBF)	MODE1 BASE THRUST (LBF)	MODE 1 MODULE-PLUG F (LBF)	MODE 1 ISP D (SEC)	MODE 2 TOTAL THRUST (LBF)	MODE2 BASE THRUST (LBF)	MODE2 ISPD (SEC)	CHAMBER PRESSURE (PSIA)	MODULE AREA RATIO	MODE1 AREA RATIO	MODE2 AREA RAT	GAS GEN FLOW (LB/S)	%BELL	MODE2 GAP (AV)	% FULL PLUG	ENGINE EQUIV. LENGTH (IN)	ENGINE LENGTH (IN)	ENGINE DIAM. (IN)	TOTAL ENG WGT. (LBM)
10	.4	20000.	499.	19467.	402.4	11770.	231.	446.0	500.	112.	200.	333.	.2	90.	.7	[illegible]	[illegible]	[illegible]	71.6	461.
10	.4	20000.	426.	19540.	408.6	11779.	194.	452.7	500.	200.	358.	595.	.2	90.	.7	0.	30.68	49.99	94.8	529.
10	.4	20000.	339.	19627.	410.5	11789.	152.	455.3	500.	300.	537.	893.	.2	90.	.7	0.	[illegible]	58.25	115.7	604.
10	.4	20000.	312.	19655.	412.6	11793.	139.	457.6	500.	400.	716.	1191.	.2	90.	.7	0.	40.82	[illegible]	133.2	478.
10	.4	20000.	271.	19695.	413.9	11799.	120.	459.1	500.	500.	896.	1489.	.2	90.	.7	0.	44.94	71.36	148.7	751.
10	.5	20000.	514.	19444.	392.7	9721.	182.	445.6	500.	112.	200.	400.	.3	90.	1.0	0.	23.71	40.79	71.5	469.
10	.5	20000.	141.	19517.	398.7	9730.	153.	452.4	500.	200.	358.	714.	.3	90.	1.0	0.	30.68	49.99	94.8	537.
10	.5	20000.	352.	19606.	400.6	9741.	120.	455.0	500.	300.	537.	1071.	.3	90.	1.0	0.	36.45	58.25	115.6	612.
10	.5	20000.	324.	19633.	402.7	9746.	110.	457.3	500.	400.	716.	1428.	.3	90.	1.0	0.	40.83	65.18	133.1	685.
10	.5	20000.	283.	19675.	403.9	9752.	95.	458.9	500.	500.	896.	1786.	.3	90.	1.0	0.	44.96	71.36	148.6	758.
10	.6	20000.	530.	19420.	383.4	7694.	136.	445.1	500.	[illegible]	200.	500.	.4	90.	1.5	[illegible]	23.72	40.79	71.5	476.
10	.6	20000.	457.	19493.	389.4	7703.	115.	452.0	500.	[illegible]	358.	892.	.4	90.	1.5	0.	[illegible]	49.99	94.8	544.
10	.6	20000.	366.	19561.	391.2	7714.	90.	454.7	500.	300.	537.	1338.	.4	90.	1.5	0.	36.45	58.25	115.6	619.
10	.6	20000.	338.	19611.	393.3	7719.	82.	457.1	500.	400.	716.	1784.	.4	90.	1.5	0.	40.84	65.18	133.1	692.
10	.6	20000.	295.	19654.	394.4	7725.	71.	458.6	500.	500.	896.	2231.	.4	90.	1.5	0.	44.97	71.36	148.6	765.
10	.8	20000.	565.	19369.	366.8	3706.	0.	440.1	500.	112.	200.	112.	.5	90.	4.0	0.	23.72	40.79	71.5	488.
10	.8	20000.	493.	19441.	372.5	3719.	0.	447.6	500.	200.	358.	200.	.5	90.	4.0	0.	30.69	49.99	94.7	556.
10	.8	20000.	[illegible]	19535.	374.1	3735.	0.	451.4	500.	300.	537.	300.	.5	90.	4.0	0.	36.47	58.25	115.8	631.
10	.8	20000.	[illegible]	19563.	376.1	3740.	0.	454.0	500.	400.	716.	400.	.5	90.	4.0	0.	40.86	65.18	133.8	704.
10	.8	20000.	325.	19609.	377.1	3748.	0.	455.6	500.	500.	896.	500.	.5	90.	4.0	0.	45.00	71.30	148.9	777.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The conclusions which were derived from the results of this study are discussed herein. These conclusions cover the results of all study tasks and are discussed for each engine concept investigated.

1. Tripropellant Engine

Hydrogen cooled tripropellant engines are practical to at least 136 atm (2000 psia) for ranges of thrust from 66.7 to 400.3 KN (15K to 90K lbf) and thrust split from 0.4 to 0.6. At a thrust split of 0.8 and 66.7 KN (15K lbf), the tripropellant engine is cooling limited to about 81.6 atm (1200 psia). However, at other thrust levels, a cooling limit was not reached for this thrust split of 0.8.

The tripropellant engine is not power balance limited and reasonable pump discharge pressures were achieved at all thrust splits investigated. Operation of the tripropellant engine components at both the Mode 1 and Mode 2 design conditions was also determined to be practical.

2. Dual-Expander Engine

Hydrogen cooling of the dual-expander engine with a parallel flow path for cooling of the inner and outer chambers is recommended. This engine concept proved to be cooling limited and the maximum chamber pressure is a function of both thrust and thrust split. The following chamber pressures were established at a baseline thrust of 88964N (20,000 lbf):

Thrust Split	Central LOX/RP-1 Chamber Pressure, atm (psia)	Annular LOX/LH2 Chamber Pressure, atm (psia)
0.4	88.4 (1300)	44.2 (650)
0.5	74.8 (1100)	37.4 (550)
0.6	61.2 (900)	30.6 (450)
0.8	13.6 (200)	6.8 (100)

Maximum operating pressures increase with increasing thrust level. At the upper end of the thrust range, 400.3KN (90K lb), the chamber pressures are:

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Thrust Split	Central LOX/RP-1 Chamber Pressure, atm (psia)	Annular LOX/LH_2 Chamber Pressure, atm (psia)
0.4	122.4 (1800)	61.2 (900)
0.5	102.0 (1500)	51.0 (750)
0.6	85.0 (1250)	42.5 (625)
0.8	19.0 (280)	9.5 (140)

The above tables show that a thrust split of 0.8 appears to be impractical for a pump-fed dual-expander system.

The dual-expander engine is not power balance limited and the design operating conditions for components in both modes of operation is practical.

3. Plug Cluster Engine

Cooling of the LOX/LH_2 module of the plug cluster engine is practical over the entire chamber pressure range of 20.4 to 68 atm (300 to 1000 psia) investigated. However, oxygen cooling of the LOX/RP-1 module was found to be impractical over the entire chamber pressure range and RP-1 cooling at 20.4 atm (300 psia) is feasible only if the coolant bulk temperature limit of 589°K (600°F) can be exceeded. This holds true over the entire thrust range of 66.7 to 400.3 KN (15 to 90K lbf) investigated.

Because of the low design module chamber pressures, 20.4 atm (300 psia), operating the LOX/LH_2 module at a mixture ratio 7.0 results in a significant Mode 2 performance penalty compared to a mixture ratio of 6.0.

The plug cluster exceeds the shuttle diameter constraint of 447 cm (176 in.) at a thrust level of about 177.9 KN (40K lbf).

B. RECOMMENDATIONS

The recommendations for advanced technology and further study efforts that were identified during the course of this study program are summarized in the following paragraphs. Items of general nature pertaining to all three engines and items peculiar to a particular engine concept are identified.

1. General

° Conduct a preliminary design study of the three baseline engine concepts and their components to provide engine and component layout drawings.

° Conduct an engine study to evaluate the use of methane and/or propane as fuels for each of the engine concepts.

° Design, fabricate and test a small, high speed hydrocarbon turbopump to add to the data base obtained under Contracts NAS 3-17794 and NAS 3-17800 for hydrogen and oxygen turbopumps suitable for the OTV application.

° Evaluate, design, fabricate, and test bearing and seal packages for use in long life, small, high speed cryogenic and hydrocarbon turbopump designs.

° Conduct an experimental study to evaluate the economic feasibility of making "pure" RP-1 to avoid gumming, cracking and coking problems in reuseable hydrocarbon engines.

2. Tripropellant Engine

° Design, fabricate and test a tripropellant injector using fuel-rich LOX/LH_2, oxidizer-rich LOX/LH_2, and fuel-rich LOX/RP-1 gases as the propellants.

3. Dual-Expander Engine

° Conduct a cold flow experimental program to evaluate the dual-expander aerodynamic performance and nozzle design criteria.

° Conduct a design analysis study on a combined regenerative and transpiration cooled chamber concept to determine the feasibility of increasing the operating thrust chamber pressure.

° Conduct a design study of the central chamber to evaluate the feasibility of manufacturing a dual-wall mill-slotted copper chamber.

4. Plug Cluster Engine

° Conduct a study to establish the feasibility and system design impacts associated with hydrogen cooling of the LOX/RP-1 modules.

° Design, fabricate and test long life, low thrust, regeneratively cooled thrust chamber modules for both LOX/LH_2 and LOX/RP-1 propellants.

° Extend the plug cluster cold flow experimental data base to improve performance prediction techniques.

° Conduct a hot-fire demonstration of a plug cluster engine to evaluate ignition of multiple chambers, hydraulics and interactions of multiple modules and to verify performance.

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