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# ORBIT-TO-ORBIT SHUTTLE ENGINE DESIGN STUDY

BOOK 1

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**Air Force Rocket Propulsion Laboratory**  
**Edwards Air Force Base, California**

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FINAL REPORT

ORBIT-TO-ORBIT  
SHUTTLE ENGINE DESIGN STUDY

W. P. Luscher, et. al.  
Aerojet Liquid Rocket Company  
Sacramento, California

May 1972

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Headquarters, Air Force Flight Test Center  
Rocket Propulsion Laboratory  
Edwards Air Force Base, California

## FOREWORD

This report presents the work accomplished on Contract F04611-71-C004, the Orbit-to-Orbit Shuttle Engine Design Study (OOS) over the period from 1 March 71 to 1 December 1971. The program was administered by the Procurement Division of the Directorate of Material, Edwards Air Force Base, Edwards, California. The technical project manager at the Rocket Propulsion Laboratory, Edwards, California was Mr. L. Tepe. Mr. Werner P. Luscher directed the study effort for Aerojet Liquid Rocket Company.

This report is contained in 4 books described as follows:

- Book 1: Parametric Cycle Study
- Book 2: 25K lb Engine Design
- Book 3: 25K lb Engine Maintenance, Development Plans,  
Cost Estimates and 10K lb Engine Design
- Book 4: Appendices

This technical report has been reviewed and is approved.

L. E. Tepe  
Project Manager

## ABSTRACT

This report presents the analytical design of propulsion systems utilizing LOX/Hydrogen propellants to be used as the propulsion for the Orbit to Orbit Space Vehicle of 65,000 lb lift-off weight.

The report contains the evaluation of various engine cycles in the thrust range of 8,000 lb to 50,000 lb thrust for performance, weight and envelope culminating in the cycle selection and detail design of a 25,000 lb and 10,000 lb thrust engine. The engine concepts are described in sufficient detail to obtain reliable engine weight, performance, envelope information and methods of engine control. The impact of various engine design requirements were evaluated. The engines are designed to be reusable and capable of starting in the idle mode operation.

The technology requirements for meeting the engine design and operating requirements are identified.

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# NOMENCLATURE

## UNITS:

|                    |                        |
|--------------------|------------------------|
| $^{\circ}\text{F}$ | Degrees Farenheit      |
| ft                 | Feet                   |
| GPM                | Gallons per Minute     |
| hr                 | Hours                  |
| HP                 | Horsepower             |
| in.                | Inches                 |
| lb                 | Pounds                 |
| mm                 | Millimeters            |
| psi                | Pounds per Square Inch |
| rpm                | Revolutions per Minute |
| $^{\circ}\text{R}$ | Degrees Rankine        |
| sec                | Seconds                |

## SYMBOLS:

|             |                                  |
|-------------|----------------------------------|
| A/R         | Area Ratio                       |
| CR          | Contraction Ratio                |
| DN          | Bearing (Bore Diameter mm x rpm) |
| $\epsilon$  | Area Ratio                       |
| F           | Thrust                           |
| $I_s$       | Specific Impulse                 |
| $L'$        | Chamber Length                   |
| MR          | Mixture Ratio                    |
| M           | Mach Number                      |
| MRD         | Mixture Ratio Distribution       |
| $N_s$       | Specific Speed                   |
| $N_f$       | Number of Cycles                 |
| $P_c$       | Chamber Pressure                 |
| PVC         | Pressure Volume Compensated      |
| SF          | Safety Factor                    |
| S           | Suction Specific Speed           |
| $T_{T_i}$   | Turbine Inlet Temp               |
| $T_{FD}$    | Fuel Pump Discharge Temp         |
| $T$         | Chamber Hot Wall Temp            |
| $T_W$       | Chamber Wall Temp Gradient       |
| $T_B$       | Bulk Temperature                 |
| V           | Velocity                         |
| $\dot{W}$   | Weight Flow Rate                 |
| $\eta_{BO}$ | Burnout Weight Efficiency        |

## GLOSSARY:

|           |                                        |
|-----------|----------------------------------------|
| ALRC      | Aerojet Liquid Rocket Company          |
| AGCarb    | Carbon Cloth Material                  |
| CJKT      | Preburner & Turbine By-pass            |
| ERE       | Energy Release Efficiency              |
| FTPA      | Fuel Turbopump Assembly                |
| FDV       | Fuel Discharge Valve                   |
| FRHG      | Fuel Rich Hot Gas                      |
| FPBYV     | Fuel Preburner & Turbine By-Pass Valve |
| FFC       | Final Flight Configuration             |
| Hz        | Frequency                              |
| LRU       | Line Replaceable Unit                  |
| $N_{TF}$  | Fuel Turbine rpm                       |
| $N_{TO}$  | Oxidizer Turbine rpm                   |
| $N_{TFE}$ | Fuel Low Speed Inducer rpm             |
| $N_{TOE}$ | Ox Low Speed Inducer rpm               |
| NPSH      | Net Position Suction Head              |
| NPSP      | Net Positive Suction Pressure          |
| OTPA      | Oxidizer Turbopump Assembly            |
| OPBV      | Oxidizer Preburner Valve               |
| OSCV      | Oxidizer Mixture Ratio Control Valve   |
| PL        | Payload                                |
| PFC       | Preliminary Flight Configuration       |
| TCA       | Thrust Chamber Assembly                |
| TGJD      | Temp at FRHG Injector Inlet            |
| UTMO      | Max Oxidizer Turbine Tip Speed         |
| UTMF      | Max Fuel Turbine Tip Speed             |

## SECTION I

### INTRODUCTION

Contract F04611-71-C-0040, the Orbit-to-Orbit Shuttle Design Study (OOS), was awarded to the Aerojet Liquid Rocket Company (ALRC) on 1 March 1971. The program was administered by the Procurement Division of the Directorate of Material of the Edwards Air Force Base, Edwards, California. The technical direction originated at the Rocket Propulsion Laboratory, Edwards, California.

The basic objective of the OOS Program was to provide analytical design performance and cost data for advanced  $O_2/H_2$  engine systems that could be used in a variety of high energy, space maneuvering missions.

The near term application of the study was the main propulsion system of the Orbit-to-Orbit Shuttle or Space Tug. The Earth-to-Orbit (EOS) portion of the Space Transportation System will be able to place large payloads into low-earth orbits in the late 1970's. The vehicle payload carried by the EOS is the Orbit-to-Orbit Shuttle. The OOS must be capable of transferring payloads from the low-earth orbit of the EOS to other orbits. To perform these types of missions efficiently, the OOS vehicle system must be designed for high performance, multiple re-starts, long-term space storability, long life, reusability, low maintenance, and low cost.

The study program consisted of five discrete tasks which are described below:

1. Consideration of the impact of varying the maximum thrust level between 8,000 and 50,000 lb thrust, with the objective of selecting the optimum engine design and turbine drive cycle for each thrust regime. The turbine drive cycles to be considered included the gas generator, staged combustion, staged combustion bleed, expander, coolant gas top-off and combustion gas top-off cycles.
2. The analysis and preliminary design of a 25,000 lb thrust engine.
3. The effects of varying the engine mixture ratio and turbopump NPSH for 8,000, 15,000 and 25,000 lb thrust engine systems were determined.
4. Study of the effects of design variations on the 25,000 lb engine.
5. The development of plans and costs for a Demonstrator Engine Program, a development program, and production of three versions of the Task I engine. The three versions were ground based reusable, space based reusable and expandable.

The technical effort associated with the first five tasks was completed on 1 September 1971, coincident with the award of a contract extension for Phase VI studies.

## I, Introduction (cont.)

The studies were directed to the design of a 10,000 lb thrust engine utilizing the results of the previous five tasks to the maximum extent practicable.

## SECTION II

### SUMMARY

The scope of the OOS Engine Design Study included the selection of a basic engine cycle resulting in the largest payload capability from 8K to 50K thrust for the Orbit-to-Orbit Mission within the given envelope and life constraints. Based on the results of the study, the basic engine cycle and design point was selected which formed the basis for a 25K and 10K thrust engine design. The turbine drive cycles studied were: staged combustion, staged combustion bleed, expander, gas generator, coolant tap-off and hot gas tap-off. In arriving at the design concepts, only component technology which would be proven during an advanced development program was considered.

The 25K thrust engine design effort consisted of the definition of the engine concept and configuration for a reusable, throttleable space engine including the complete characterization of the operational characteristics, e.g., off-design, chillover, start transient, and interface definition. The interface definition included envelope, suction line size, gimbal actuator, purge requirement, autogenous pressurization system, and preconditioning requirements.

The basic engine design was evaluated with respect to the impact of changing design requirements, on engine configuration, performance, weight, and envelope.

For the purpose of establishing engine cost figures, a tentative engine development plan was established including a demonstrator engine phase and an engine development phase which preceded the engine production program. The cost study also treated the impact of engine thrust level, cycle, and design requirements.

The technical approach for the engine cycle selection was to establish the optimum chamber pressure for each engine cycle and for each thrust level. This chamber pressure had to satisfy simultaneously the 300 cycle engine life requirement, envelope restriction, and engine power balance requirement.

The baseline 10K thrust engine design is essentially a scaled version of the 25K engine with minor differences in the turbopump and autogenous systems for pump assisted idle mode operation. In addition an alternate in line design utilizing a LOX pump gear drive was established.

As the basic engine nozzle configuration, a minimum length Rao nozzle contour was assumed, and the corresponding thrust chamber and engine performance was determined utilizing the JANNAF thrust chamber performance prediction method. An injector performance efficiency of  $ERE = 99\%$  of theoretical was assumed.

## 11. Summary (cont.)

To obtain engine weights, a baseline engine design point was selected and appropriate layouts made for each cycle. The engine weights obtained from these layouts were selected as functions of engine thrust, chamber pressure mixture ratio, area ratio and NPSH.

### Conclusion and Recommendations

The practical maximum chamber pressure, meeting the 300 cycle life, was established utilizing existing material fatigue life test data for Zirconium Copper material. However, available data is very sketchy, forcing large safety factors in the thrust chamber design.

With the selected thrust chamber pressure and available stowed engine length, the payload capability for each cycle was determined in the thrust range from 8K to 50K lb thrust for both retractable and fixed nozzle configuration. The result of this analysis indicated that the staged combustion cycle results in the highest payload capability within the thrust range considered. Consequently, was selected as the engine cycle for the OOS 25K and 10K thrust engine designs.

The basic engine design for both engines features fixed minimum Rao nozzle configuration with hydrogen regeneratively cooled thrust chamber and nozzle extensions. The turbopumps are sidemounted to obtain the maximum fixed nozzle area ratio within the envelope constraints and the feed system is highly integrated to minimize weight and hot gas ducting. The turbopumps feature hydraulic driven low speed pumps to minimize turbopump weight.

The engine has a 10:1 throttle capability within the thrust range of  $MR = 5.5$  to  $MR = 6.5$  which is achieved by gas/gas injector concept in both the preburner and main injector. All hydrogen is vaporized in the regeneratively cooled thrust chamber assembly. The main injector oxidizer flow is vaporized in the main injector oxidizer vanes by the fuel rich turbine exhaust gases. The preburner oxidizer is vaporized in the preburner chamber, permitting a light weight design. The throttle capability may be used to increase the engine life and thermal cycle capability. Full engine thrust is usually only required during the first burn, and the subsequent burns are insensitive to thrust level. The off-design data indicate that throttling will significantly help the life capability of the critical components, since turbine temperature, turbine speed, and chamber wall temperature gradient rapidly decrease.

To control the engine, both two valve and a three valve control systems were considered. Poppet type valves with metallic seals were selected for all valve applications because of their inherent superior sealing capabilities over a wide range of temperatures. Electrical actuation was selected for all of the valves. Electrical actuation is desirable for systems which do not require fast response (as in the case of the OOS) because of the ease in check-out, long storage life, low maintenance and high reliability.

The two valve control system utilizes a liquid oxygen preburner valve for thrust control and the liquid oxygen pump discharge valve for mixture ratio control. Throttling is achieved by controlling the preburner mixture ratio. A three valve control system was used in the final design. In this system, an additional turbine and preburner bypass control valve was incorporated, because it provided superior engine design and operational features. The selected three valve control system also provides the engine with built-in idle capability for both the pressure fed and pump assisted idle mode.

## II, Summary (cont.)

The engine off-design and start transient characteristics were evaluated using the LETS II engine design computer program to verify that the engine concept met the operational requirements. This evaluation also led to the definition of idle mode and start transient valve sequencing requirements. The engine system control interface consists of a separate engine computer-controller and data storage translating and controlling the vehicle commands. The engine system control modifications for different applications were defined for manned, unmanned reusable, and expendable mission requirements.

Engine maintainability was considered in the design of each component to meet the cycle life, duration, maintenance, and refurbishing cost goals. Components of similar life capability were interfaced to obtain replaceable units.

The result of the engine study indicated that use of the retractable nozzle concept for high pressure engines (such as the stage combustion engine cycle) result in very marginal payload gains. Conversely, a retractable nozzle improves the capability of the low pressure cycle engines considerably. Therefore, a fixed nozzle engine concept was selected for both the 10K and 25K thrust engine configuration.

The driving design consideration was the requirement of engine reusability and life, particularly in the thrust chamber, and turbine design area. These requirements were met by adequately controlling the thermal condition in the thrust chamber (and throughout the engine) and the selection of proper turbine tip speeds.

The study also indicated that the small thrust engine results in higher payload capability due to the feasibility of larger nozzle expansion area ratios within the given envelope constraints. However, the smaller thrust engines resulted in lower payload capability when clustered in a multi engine system as compared to a single engine system of equal thrust level.

The engine nominal design data are summarized for the 25K and 10K engine in Tables I and II. Figures 1 and 2 show the baseline engine configuration for the 25K and 10K engines respectively.

The results of the engine cost analysis indicates that the engine cycle selection and thrust level selection have very little impact on engine development and engine production cost. For the engine cost estimates, the schedule shown in Figure 3 was baselined resulting in the costs summarized in Table III.

In the course of the OOS Engine Design Study, it became evident that in certain technology areas more information is required.

The engine performance presented for 99% ERE is conservative because of the JANNAF performance prediction method used. A new JANNAF interim method results in 1-1/2 to 2 sec higher performance at an engine mixture ratio (MR)

TABLE I

## 25K ENGINE DESIGN SUMMARY

|                                     |                                        |        |
|-------------------------------------|----------------------------------------|--------|
| <u>Cycle:</u>                       | Staged Combustion                      |        |
| <u>Turbines:</u>                    | Parallel - Split Shaft (OTPA and FTPA) |        |
| <u>Performance</u>                  |                                        |        |
| F, (lb)                             |                                        | 25,000 |
| MR                                  |                                        | 6.0    |
| I <sub>s</sub> (sec)                |                                        | 465.7  |
| P <sub>c</sub> , (psia)             |                                        | 1800   |
| F/P <sub>c</sub>                    |                                        | 13.88  |
| R <sub>t</sub> (in.)                |                                        | 1.51   |
| <u>Envelope</u>                     |                                        |        |
| ε <sub>o</sub>                      |                                        | 290    |
| ε <sub>trans</sub>                  |                                        | N/A    |
| Engine Overall Length (in.)         |                                        | 32.0   |
| (L' = 6 in.)                        |                                        |        |
| (L' Throat - Gimbals = 13.5 in.)    |                                        |        |
| Engine Stowed Length (in.)          |                                        | N/A    |
| Engine Exit dia (in.)               |                                        | 51.43  |
| Engine Weight, W <sub>BO</sub> (lb) |                                        | 459.3  |

TABLE II

## 10K ENGINE DESIGN SUMMARY

| <u>Cycle: Staged Combustion</u>     |                       | <u>Side Mounted Pumps</u> |  |
|-------------------------------------|-----------------------|---------------------------|--|
| <u>Performance</u>                  |                       | <u>Baseline</u>           |  |
| F, (lb)                             |                       | 10,000                    |  |
| MR                                  |                       | 6.0                       |  |
| I <sub>g</sub> (sec)                |                       | 465.5                     |  |
| P <sub>c</sub> , (psia)             |                       | 1250                      |  |
| F/P <sub>c</sub>                    |                       | 8.0                       |  |
| R <sub>t</sub> (in.)                |                       | 1.13                      |  |
| <u>Envelope</u>                     |                       |                           |  |
| ε <sub>o</sub>                      |                       | 400                       |  |
| ε <sub>TRANS</sub>                  |                       | 5.5:1                     |  |
| Engine Overall Length (in.)         |                       | 76                        |  |
| (L' = 6 in.)                        |                       |                           |  |
| (L' Throat - Gimbal = 13.0 in.)     |                       |                           |  |
| Engine Stowed Length (in.)          |                       | 76                        |  |
| Engine Exit dia (in.)               |                       | 45.20                     |  |
| Engine Weight, W <sub>BO</sub> (lb) |                       | 278.1                     |  |
| <u>Suction Lines</u>                |                       |                           |  |
| Diameter                            | LO <sub>2</sub> /Fuel | 2.41/2.77                 |  |
| Location Diameter                   | LO <sub>2</sub> /Fuel | 16.0/16.8                 |  |

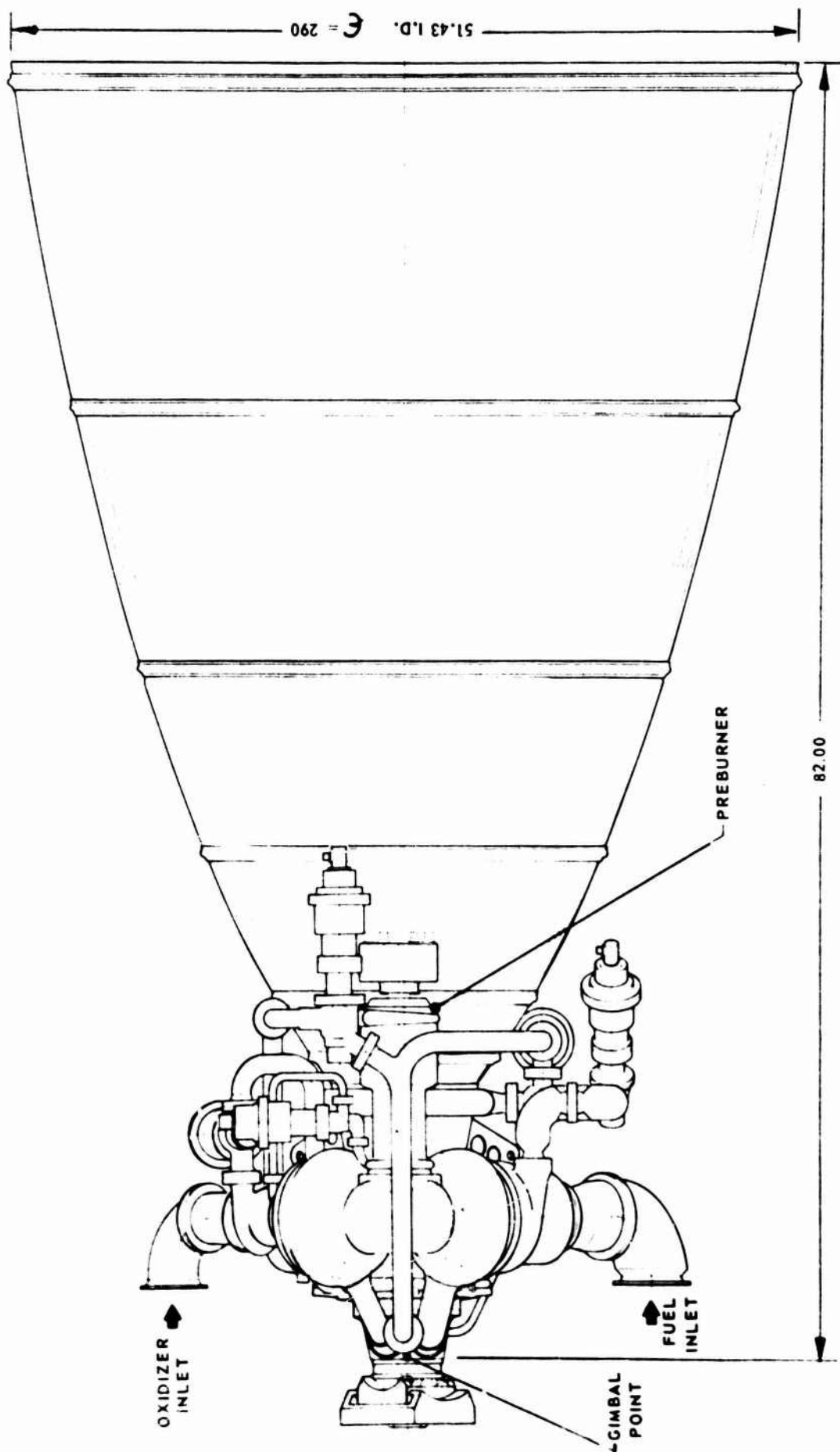


Figure 1. 25K Baseline Engine Configuration

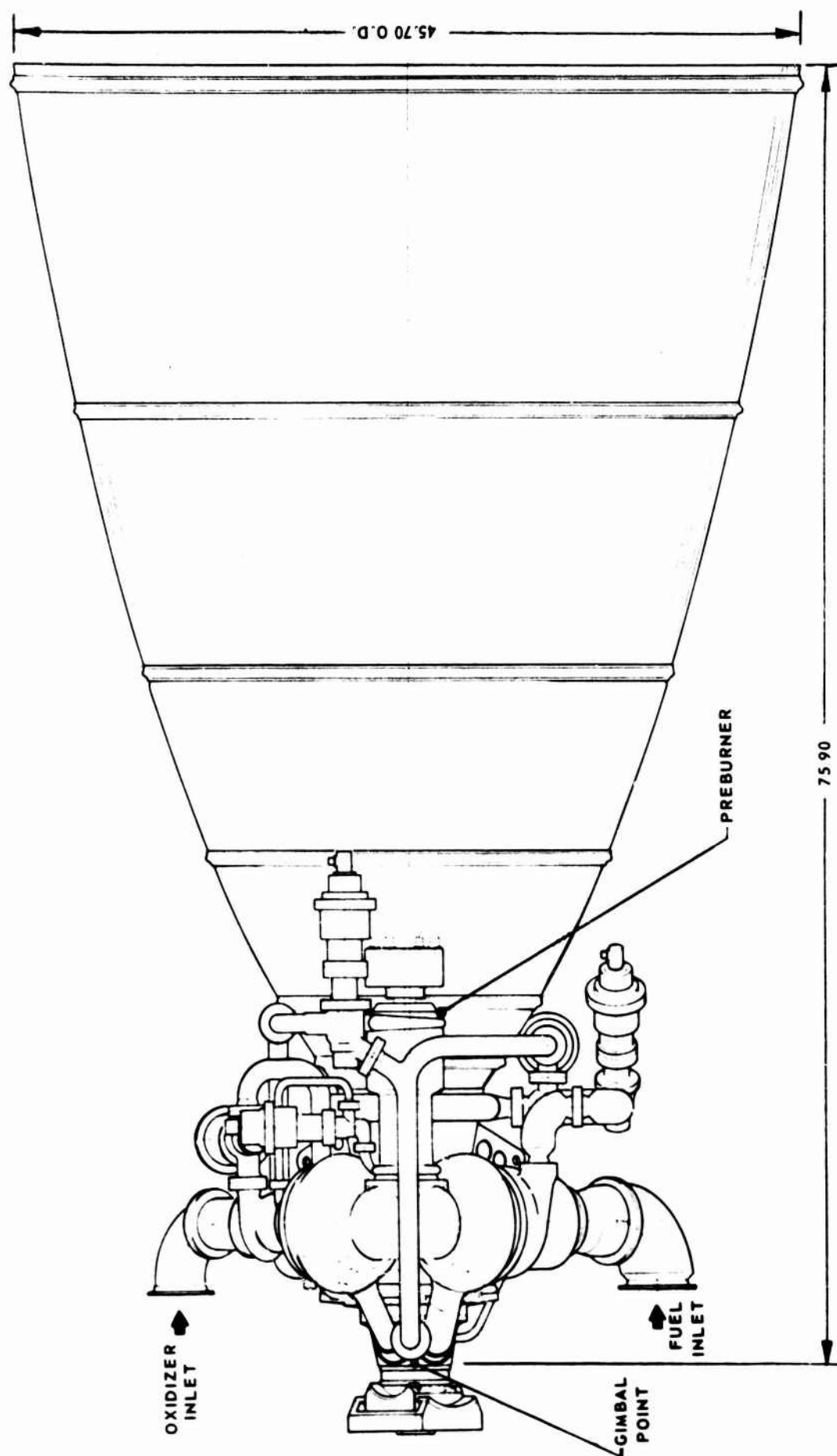


Figure 2. 10K Engine Baseline Engine Configuration

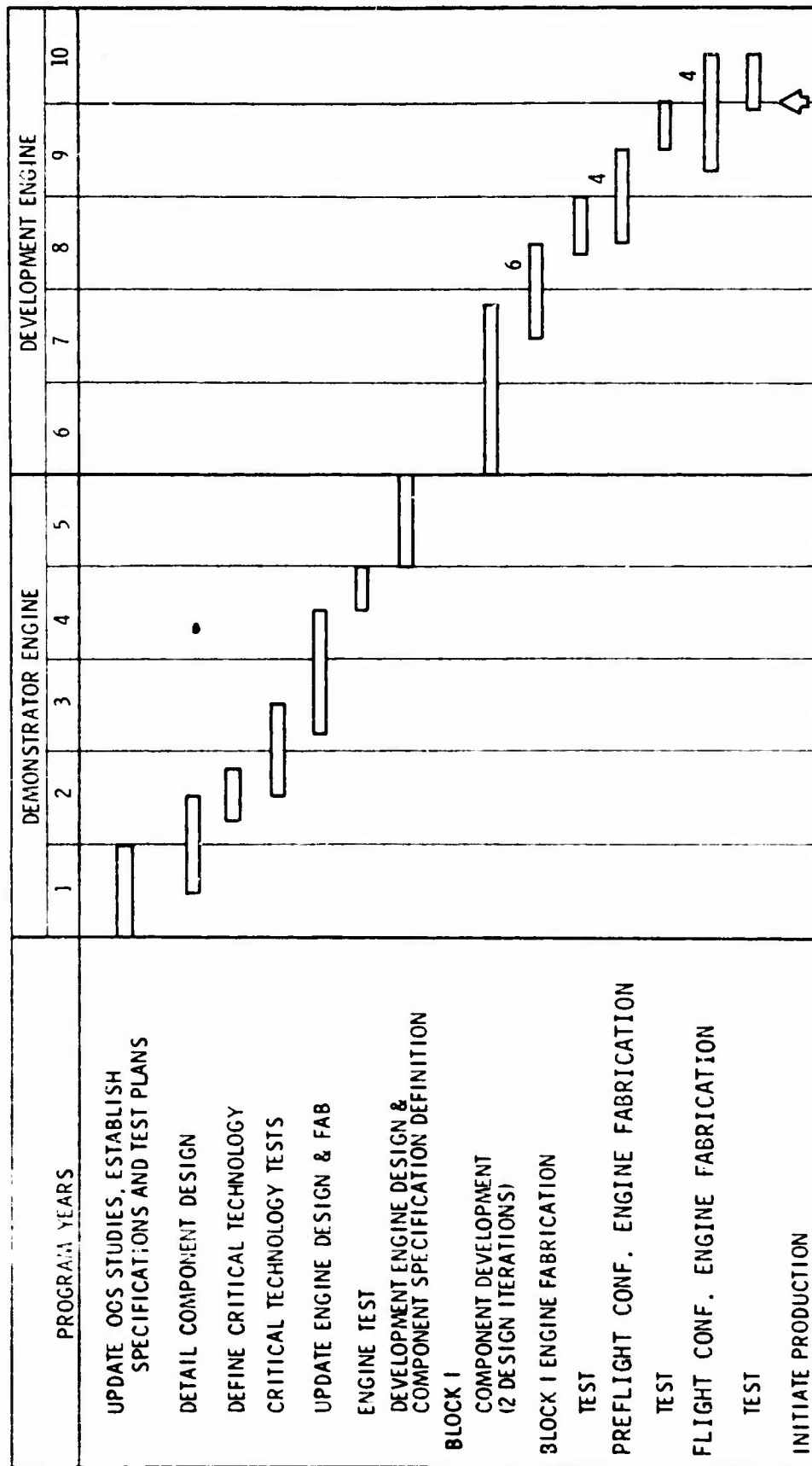


Figure 3. OOS Master Schedule

TABLE III

GROUND BASED REUSABLE 25K BASELINE ENGINE COST

DOLLARS

|                 | Demonstrator<br>Program | Development<br>Program | Production<br>Unit |
|-----------------|-------------------------|------------------------|--------------------|
| Manufacturing   | 2,900,304               | 10,576,125             | 620,500            |
| Quality Control | 1,410,735               | 3,824,205              | 107,700            |
| Test            | 6,407,000               | 15,194,000             | 40,600             |
| Engineering     | 7,500,000               | 15,131,662             | 62,500             |
|                 | 18,218,039              | 44,725,992             | 831,300            |

## 11. Summary (cont.)

of 6.0. Aerojet experience shows that at the higher chamber pressures 99.5% energy release efficiency (ERE) can be achieved. From this, it was concluded that the performance tolerance band is approximately 4 sec of specific impulse; the quoted performance presents the lower limit.

The high performance levels are obtained mostly through large nozzle expansion area ratios. (Much larger than the current TCA hot test experience covers). Therefore, it appears that large expansion ratio nozzles have to be investigated for their performance potential and deep throttling capability with LO<sub>2</sub>/LH<sub>2</sub> propellant (ice formation).

Envelope restricted engine performance is strongly affected by the thrust chamber length. Consequently, injector concepts resulting in short chamber length are the most beneficial for this application.

The engine weight in the reusable mission has a large payload effect. The engine design analysis indicates that most of the engine weight is in the nozzle of engines featuring large nozzle area ratios. Careful selection of nozzle regenerative coolant tube thickness or alternate materials can effect the engine weight by as much as 20%. A large fraction of the engine weight consists of the control valves subsystems, so it appears a fruitful area for new technology is light weight valve and actuator development (Table IV).

The greatest need for more technology information was found to exist in the determination of the thrust chamber material. Low cycle fatigue life, in particular the effect of the operating environment, appears to have an order of magnitude effect on the low cycle fatigue life of the considered chamber materials. This technology is particularly important for low thrust engines, since thrust chamber thermal cycle life largely effects the thrust chamber pressure selection as well as the coolant pressure drop requirements, fuel pump discharge pressure, and hence the engine cycle power balance.

The pump fed low thrust engine appears to have some difficulties with component miniturization; turbopump assembly performances (TPA) suffer from large internal leakage losses, which adversely affect the power balance and the efficiency potential of multi-stage, high speed pumps. The TPA rolling contact bearings are very small, and they operate at high DN values. The result is that they must operate at very light loads, relying on good thrust balancing for long life. Bearing retainers must be of low profile to permit adequate cooling and very limited experience is available in this area.

Small reusable engines require a considerable amount of instrumentation to permit efficient maintenance. Current instrumentation technique and sensors contribute greatly to overall engine weight. Sensor miniturization would greatly help to reduce engine weight.

Engine maintenance requires additional flight readiness instrumentation data recording, and failure or performance degradation analysis capability. An engine mounted computer forming an integral engine component should be developed in parallel with the engine.

TABLE IV

## 25K BASELINE ENGINE WEIGHT SUMMARY

STAGED COMBUSTION - PARALLEL TURBINE DRIVE

F = 25,000 LB      MR = 6.0  
 $c_{EXIT}$  = 290      NPSH (F) = 60 FT NOM  
 $P_C$  = 1800 PSIA      NPSH (O) = 16 FT

FIXED NOZZLE - TUBULAR - ALL  $H_2$  REGENERATIVELY COOLED

| <u>WEIGHT CATEGORY</u> |                                                                                    | <u>WEIGHT - LB</u> | <u>% TOTAL WEIGHT</u> |
|------------------------|------------------------------------------------------------------------------------|--------------------|-----------------------|
| I.                     | TCA                                                                                |                    |                       |
|                        | A. INJECTOR                                                                        | 21.7               |                       |
|                        | B. COPPER TC TO $\epsilon = 6:1$                                                   | 37.1               |                       |
|                        | C. TUBE REGEN TO EXIT $\epsilon = 290:1$                                           | 107.4              |                       |
|                        | D. IGNITER (INCLUDES IGNITER VALVE)                                                | 12.1               |                       |
|                        | SUBTOTAL                                                                           | 178.3              | 38.8                  |
| II.                    | TPA'S                                                                              |                    |                       |
|                        | A. FUEL (INCLUDING IN-LINE BOOST PUMP)                                             | 37.3               |                       |
|                        | B. OXIDIZER (INCLUDING IN-LINE BOOST PUMP)                                         | 30.2               |                       |
|                        | SUBTOTAL                                                                           | 67.5               | 14.7                  |
| III.                   | VALVES                                                                             | 43.1               | 9.4                   |
| IV.                    | GAS LINES, GAS MANIFOLDS, LIQUID LINES                                             | 78.3               | 17.0                  |
| V.                     | TURBINE DRIVE POWER - PREBURNER                                                    | 24.7               | 5.4                   |
| VI.                    | GIMBAL ASSY AND ACTUATOR SUPPORT STRUCTURE                                         | 9.9                | 2.2                   |
| VII.                   | ENGINE HARNESS, INSTRUMENTATION, SUPPORT STRUCTURE, BRACKETRY, AND ATTACH HARDWARE | 57.5               | 12.5                  |
|                        | TOTALS                                                                             | 459.3              | 100.0                 |

NOTE: ENGINE CONTROLLER WEIGHT NOT INCLUDED.

## II. Summary (cont.)

Another maintenance requirement is that the engine be ground checked duplicating actual engine operation. This is very problematic for large area ratio nozzle engines and may require new nozzle technology, in particular, separable, light weight, radiation cooled nozzle extensions, which can be removed at low area ratio for sea level testing, without altering significantly the engine fuel system parameters, and without decreasing flight engine performance.

The operational requirements for multi-restart engines desire chilldown through idle mode. High pressure engine idle mode thrust levels are rather low. This is caused by the small throat size of these engines. Pump assisted idle mode, would double the idle mode thrust level. Pump assisted idle modes may present mixture ratio control problems due to two phase flow and should be developed in an experimental program.

Engine dynamic stability was also considered. Injector baffles and acoustic dampers were, therefore included in both the main and preburner injectors. Both of these concepts are relatively new technology and need extension.

The requirement of autogenous tank pressurization during pump assisted idle mode was a new operating requirement and requires demonstration.

Engine start transients were kept slow to minimize the thermal shock on the turbine disks and blades. Technology could be developed to lower these transient stresses by special disk designs permitting faster starts and improved impulse capability for short impulse operation.

## SECTION III

### TECHNICAL DISCUSSION

#### A. ENGINE DESIGN PARAMETRIC STUDY

This section of the final report contains the results of the parametric engine design study including:

- . Generalized cycle descriptions in the range of 8K to 50K thrust level (excluding engine design constraint.) for mixture ratio = 6.0.
- . Comparison of the engine cycle payload capability considering envelope and engine design constraints at various thrust levels and MR = 6.0.
- . Identification of the best engine cycle at each thrust level between 8K and 50K at MR = 6.0.
- . Engine cycle description of the best engine cycle at discrete thrust levels of 8K, 15K, and 25K at MR = 6.0.

##### 1. Summary of Requirements

The operating characteristics requirements for the engine parametric study are summarized in Table V and the stowed envelope constraints in Table VI. The vehicle payload sensitivity to engine specific impulse and engine weight are given for two missions both the Orbit-to-Orbit Mission and the Lunar Lander Mission and are summarized in Table VII.

##### 2. Evaluation Criteria

The evaluation of the engine cycles consisted of three major elements.

- . Payload Capability
- . Operational Capability
- . Engine Cost

A more detailed breakdown of these characteristics is shown in Table VIII. For the parametric analysis the engine payload characteristics were evaluated with respect to satisfying the operational capabilities. The engine cost impact due to thrust size and cycle selection was found to be insignificant and was not used as a cycle evaluation criterion. The selection of the best engine cycle for a given thrust is based on the payload capability only.

TABLE V

8,000 TO 50,000-POUND THRUST ENGINE OPERATING CHARACTERISTICS

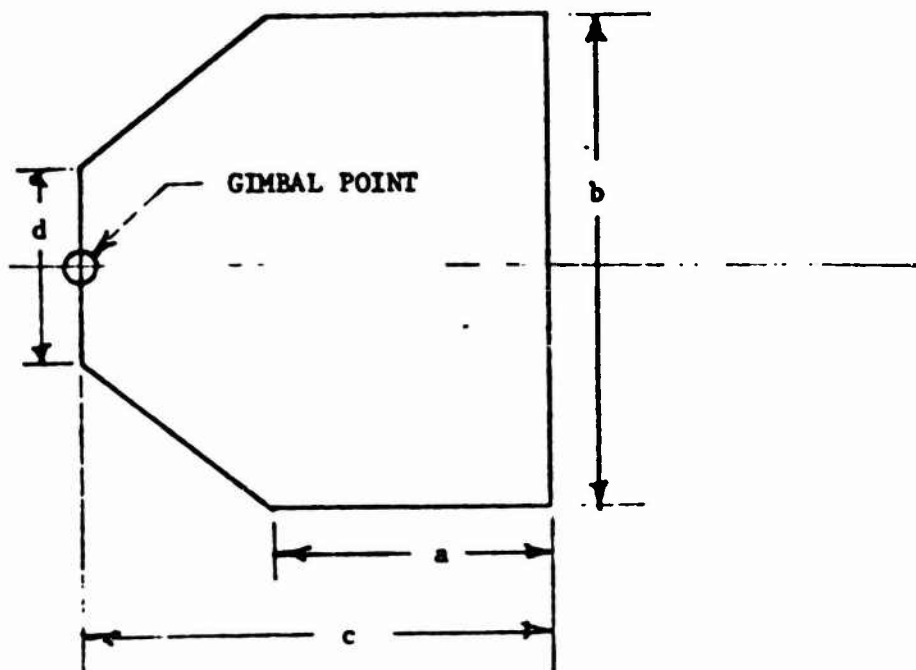
| Propellants                                        | Liquid Oxygen/Liquid Hydrogen |
|----------------------------------------------------|-------------------------------|
| Maximum Vacuum Thrust, pounds                      | 8,000 to 50,000               |
| Nominal Engine Mixture Ratio                       | 6.0:1                         |
| Engine Mixture Ratio Operating Range               | 5.5:1 to 6.5:1                |
| Vacuum Thrust Throttling Capability                | 5.0:1                         |
| Nozzle Configuration                               | *                             |
| Nozzle Expansion Ratio                             | *                             |
| Turbine Drive Cycle                                | *                             |
| Vacuum Specific Impulse, seconds                   | *                             |
| Engine System Weight, pounds                       | *                             |
| Number of Vacuum Starts                            | 60                            |
| Lifetime (Expendable Mode), thermal cycles         | 6                             |
| Lifetime (Reusable Mode), thermal cycles           | 300                           |
| Lifetime (Reusable Mode), hours                    | 10                            |
| Gimbal Angle (Square Pattern), degrees             | 7                             |
| Gimbal Acceleration, radians/(second) <sup>2</sup> | 20                            |
| Minimum Natural Frequency of Gimbal System, Hertz  | 10                            |
| Fuel Pump NPSH, feet of hydrogen                   | 60                            |
| Oxidizer Pump NPSH, feet of oxygen                 | 16                            |
| Maximum Single Run Duration, seconds               | 1000                          |
| Maximum Storage Time in Orbit (Dry), weeks         | 52                            |
| Maximum Time Between Firings (Coast Time), days    | 14                            |
| Minimum Time Between Firings (Coast Time), minutes | 10                            |
| Maintenance-Free Engine Run Time, hours            | 2                             |
| Maintenance-Free Engine Firing Cycles              | 60                            |

\*To Be Determined as a result of design and analysis.

TABLE VI

MAXIMUM ENGINE DIMENSIONS (STOWED POSITION IN COS)

| <u>DIMENSION</u> | <u>MAXIMUM VALUE</u> |
|------------------|----------------------|
| a                | 50 inches            |
| b                | 87 inches            |
| c                | 82 inches            |
| d                | 40 inches            |



ENGINE CROSS-SECTION THROUGH THRUST CENTERLINE

TABLE VII

VEHICLE TRADEOFF FACTORS

Tradeoff factors based on Orbit-to-Orbit Missions:

$$\frac{\Delta PL}{\Delta Isp} = 157 \text{ lb/sec}$$

$$\frac{\Delta PL}{\Delta W_{\text{Burnout}}} = -3.68$$

Tradeoff factors for Lunar Lander (Based on 20,000 lbs to and return)

$$\frac{\Delta PL}{\Delta Isp} = 114 \text{ lb/sec}$$

$$\frac{\Delta PL}{\Delta W_{\text{Burnout}}} = -1$$

TABLE VIII

METHOD OF CYCLE EVALUATION

| <u>Payload Capability</u> | <u>Operational Capability</u> | <u>Cost</u>         |
|---------------------------|-------------------------------|---------------------|
| Specific Impulse          | Throttling                    | Demonstrator Engine |
| Engine Weight             | Chill Down                    | Flight Engine Dev.  |
| Mixture Ratio             | Propellant Utilization        | Production          |
| Envelope                  | Autogenous Pressurization     | Facilities          |
| NPSH                      | Engine Control (SS)           |                     |
|                           | Transient Control             |                     |
|                           | Engine Life                   |                     |

• Engine Payload Capability Primary OOS Engine Cycle Selection Criteria

### III. A. Engine Design Parametric Study (Task IV) (cont.)

#### 3. Engine Cycle Description

The basic engine cycles included the following six cycles (see Figures 4 and 5).

##### a. Bleed Cycles

The bleed cycles shown schematically in Figure 4, feature a series turbine drive, and for illustration, a separate turbine exhaust nozzle. These engine cycles are degraded in performance due to the turbine exhaust losses, and performance losses due to TCA-mixture ratio shift induced by the propellant bleed. The bleed cycles usually are operated at  $MR = 5.0$  to minimize these losses. At the mixture ratio 6.0 these losses increase. Consequently, bleed cycles are not competitive with the topping cycles.

The practical thrust chamber operating pressure of the bleed cycles is dependent on the TCA chamber life requirements and the available engine envelope.

Some basic assumptions were made in the evaluation of the bleed cycles. The turbine temperature of the gas generator cycles was assumed to be  $1860^{\circ}R$  for all thrust sizes and chamber pressures. For the chamber tap-off bleed cycle, the same turbine temperature of  $1860^{\circ}R$  was assumed at comparable mixture ratio as for the gas generator cycle.

For the coolant bleed cycle, the turbine temperature of  $1000^{\circ}R$  was assumed for all thrust sizes and chamber pressures.

##### b. Topping Engine Cycles

These cycles have high performance yielding engine performance approaching the thrust chamber performance because bleed losses are nonexistent or minimized. The basic schematic of these cycles is shown in Figure 5.

The expander cycle is inherently a low pressure cycle since the available energy for the feed system drive is the latent heat from the cooling jacket. The TCA pressure level attainable is strongly dependent on the thrust size and assumed thrust chamber length. It is also limited by the power balance requirement of the TPA feed system.

The staged combustion cycle have a fuel-rich preburner yielding a cycle somewhat more complex than the expander cycle. However, this addition permits the engine to operate at high chamber pressures and also makes the cycle less sensitive to feed system component efficiency. The turbine temperature was restricted to  $1860^{\circ}R$  for all thrust sizes and chamber pressures.

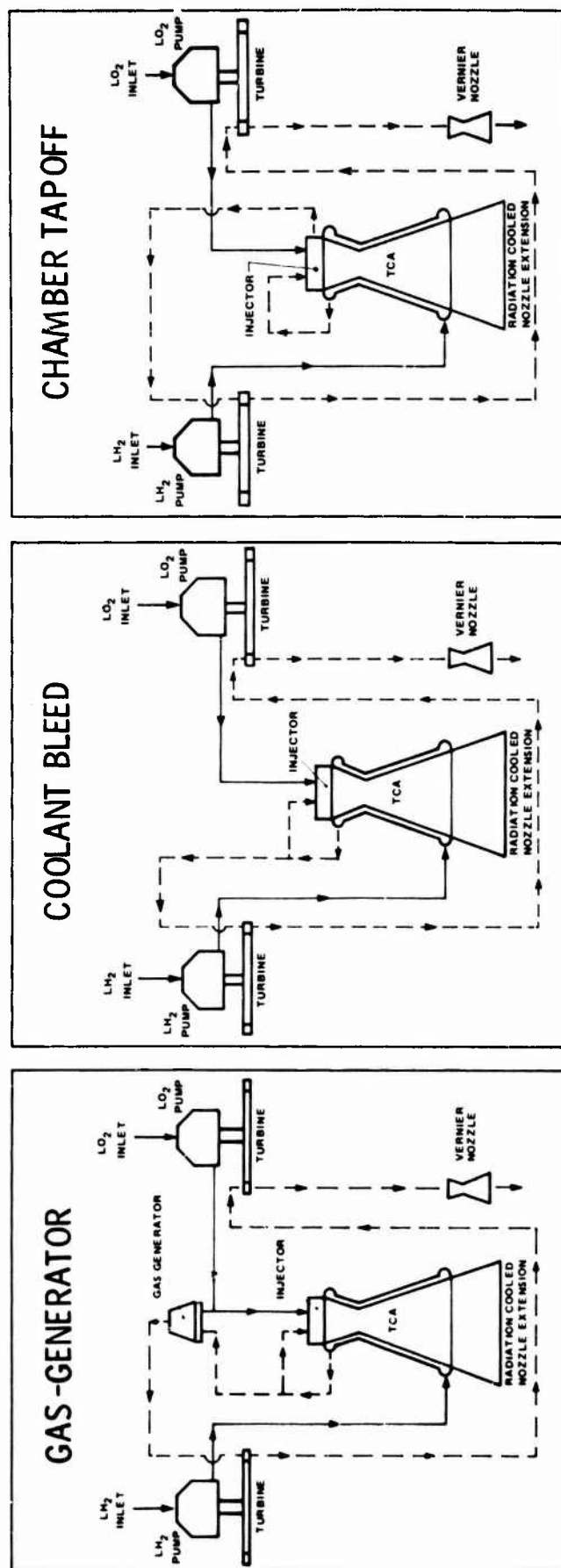


Figure 4. Engine Cycle Description - Bleed Cycles

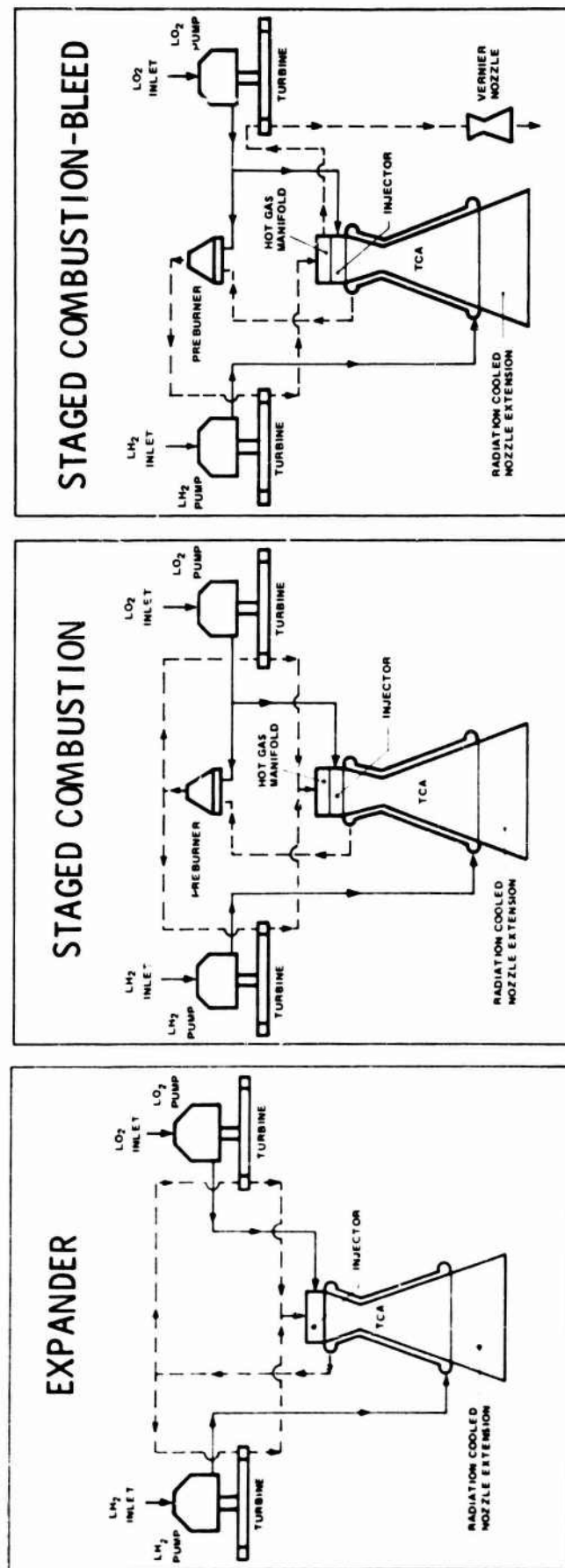


Figure 5. Engine Cycle Description - Topping Cycles

### III, A, Engine Design Parametric Study (Task IV) (cont.)

The staged combustion bleed cycle is a slight modification of the basic staged combustion cycle and has its application where power balance limits are encountered and bleed flow is desirable (i.e., dump-cooled nozzle extensions). All topping cycle feed systems are driven by parallel turbine drives to permit deep throttling without reverse pressure gradients at the tip of the oxidizer turbine, as would be the case for series turbine drives.

#### 4. Method of Approach

The general description of the six basic engine cycles at mixture ratio 6.0 and thrust levels between 8K and 50K involved the definition of the following parameters:

- Engine Delivered Vacuum Specific Impulse
- Engine Weight
- Engine Length
- Engine Maximum Diameter
- Suction Line Diameter
- Suction Line Orientation

All engines were designed to meet the 300 engine thermal cycle requirements, which in turn defined the coolant pressure drop requirements and bulk temperature rise. All engines were designed to operate at a nominal mixture ratio of 6.0, a mixture ratio range of 5.5 to 6.5, and a throttle capability of 5:1.

Additional analysis conducted to establish the engine thermal conditioning requirements and program cost is discussed in separate sections.

##### a. Thrust Chamber and Engine Performance

The contract specified that the engine delivered specific impulse be defined by the JANNAF method. A simplified performance summary is shown in Figure 6, describing TCA performance as a function of chamber pressure, expansion area ratio, mixture ratio and thrust level. There are currently two JANNAF performance prediction methods used. The interim method yields about 1.5 sec higher performance at  $MR = 6.0$  and considerably higher performance at the larger mixture ratios. For this study the official JANNAF performance prediction method was used yielding lower performance than the newer interim method. A detailed description of the engine performance is presented in Appendix A including both sets of data.

Engine performance was evaluated by utilizing existing computer programs for all six engine cycles. For this purpose thrust chamber cooling requirements and engine control systems were defined to establish feed system pressure drop requirements. A first set of cooling requirements were assumed for constant coolant Mach No. of the TCA throat  $Ma = 0.45$ . For the

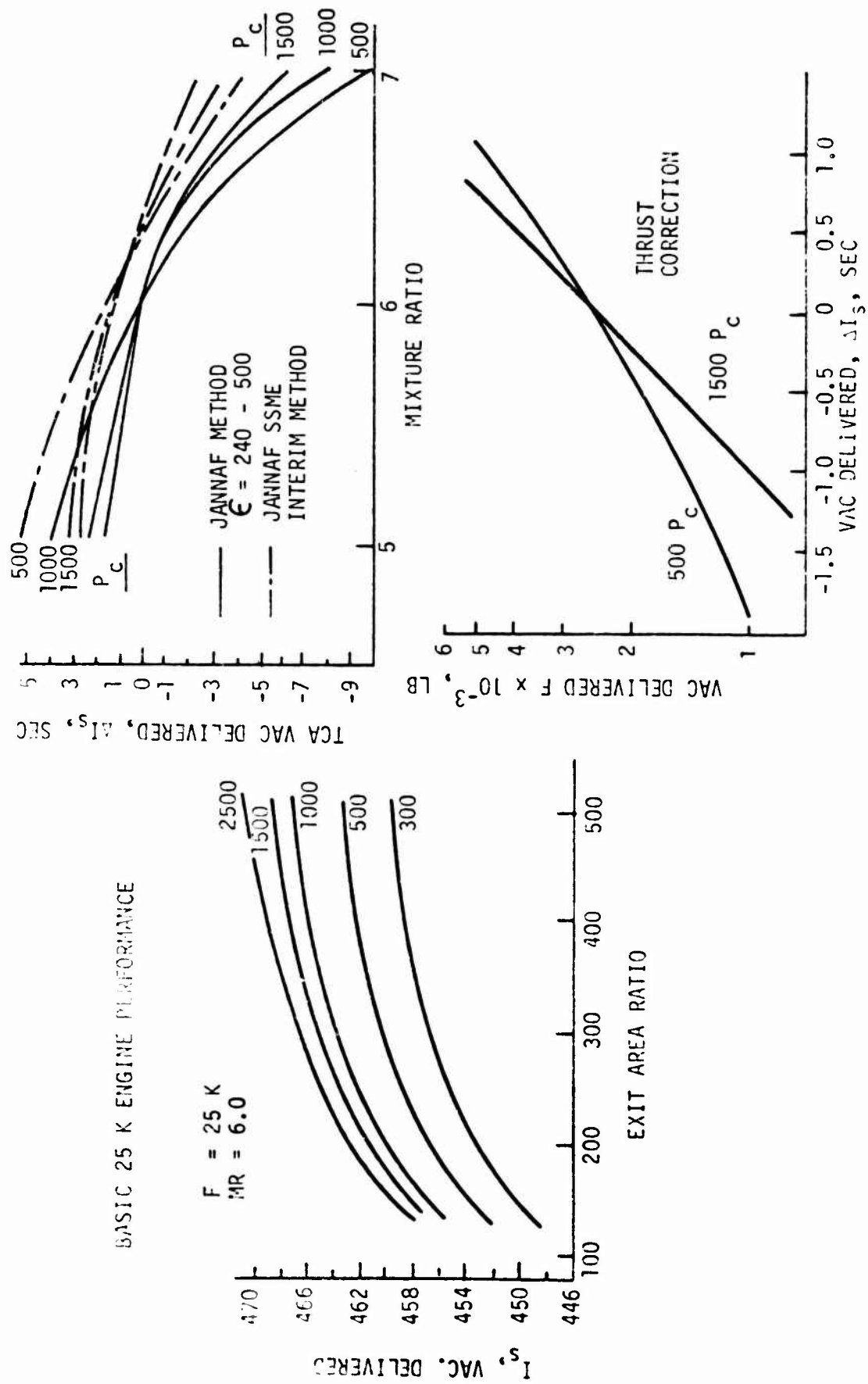


Figure 5. TCA Performance For Power Balance Analysis

### III, A, Engine Design Parametric Study (Task IV) (cont.)

staged combustion cycles and the expander cycle, the cooling requirements were later revised to adjust the coolant pressure drop requirement to meet the thrust chamber life requirements and the power balance simultaneous, for each thrust level and chamber pressure. This modification showed little effect on the staged combustion cycle.

A further basic assumption for the performance evaluation was made in the selection of the nozzle contour. As the basic contour for all thrust levels, chamber pressure, and mixture ratios, the minimum length Rao contour was assumed as the optimum contour. The injector energy release efficiency was assumed to be  $ERE = 99\%$  by agreement with the customer. ALRC experience has shown this assumption is well within the existing state-of-the-art.

#### b. Engine Weight and Envelope

No standard methods are in existence to determine engine weights as a function of engine cycle, thrust level, and chamber pressure. Consequently, a new procedure had to be developed.

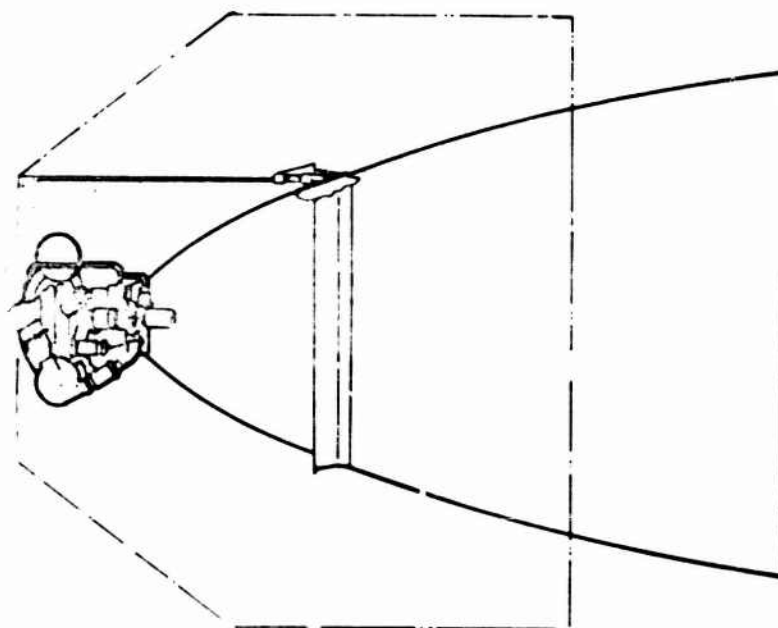
The first step in this procedure was to define common technology, design, and materials, for all engine cycles. All assumptions made for this purpose are documented in Section III,A,5 and are summarized in Figure 7.

Both fixed and retractable bell nozzle engine configurations were considered. For the retractable nozzle concept certain groundrules were imposed to define the manner of retracting the nozzle extension. As shown in Figure 8, both minimum weight and length nozzles were investigated.

The minimum weight concept retracts the nozzle just enough to clear the 82-in. interface and has the transition area ratio at the minimum area ratio. The minimum length retractable nozzle retracts the nozzle in such a manner as to obtain the minimum stowed engine length. The decision was made to consider the minimum weight retractable nozzle concept only, since no payload tradeoff factors were available to investigate the desirability or benefits of the reduced stowed engine length.

Based on these groundrules the procedure for the engine weight analysis was as follows:

- . For each engine cycle, a baseline engine layout was prepared indicating the most desirable engine configuration at design, thrust, and chamber pressure.
- . For each cycle every component was scaled analytically as functions of:



# CHAMBER

MATERIAL: ZrCu  
 COOLING: SINGLE UP-PASS  
 L': 8 INCHES (14 INCHES)  
 CONFIG: MILLED SLOTS  
 T<sub>w</sub> MAX: 1000° F

# NOZZLE

MATERIAL: ARMCO 22-13-5  
 TYPE: BRAZED TUBE  
 COOLING: DOWN & UP-PASS  
 ATTACHMENT: BRAZED  
 T<sub>w</sub> MAX: 1200° F  
 CONTOUR MIN LENGTH RAO

# SKIRT:

MATERIAL: AGCrb-101  
 TYPE: RADIATION COOLED  
 ATTACHMENT: FLANGE & SEAL

FIXED & RETRACTABLE

# MAIN INJECTOR

PROPELLANT: GH<sub>2</sub> / LO<sub>2</sub>  
 TYPE: PLATELETS - VANE  
 MATERIAL: ARMCO 22-13-5 &  
 CRES 347  
 ERE 99%

# GAS GENERATOR & PREBURNER

PROPELLANT: GH<sub>2</sub> / LO<sub>2</sub>  
 TYPE: PLATELET, DUAL  
 OX CIRCUIT  
 MATERIAL: INCONEL 718  
 T<sub>Ti</sub> = 1860° R

# TURBOPUMPS

DRIVE INDIVIDUAL TURBINES  
 BOOST PUMPS: MIN TPA WEIGHT

Figure 7. Main Assumptions for Parametric Study

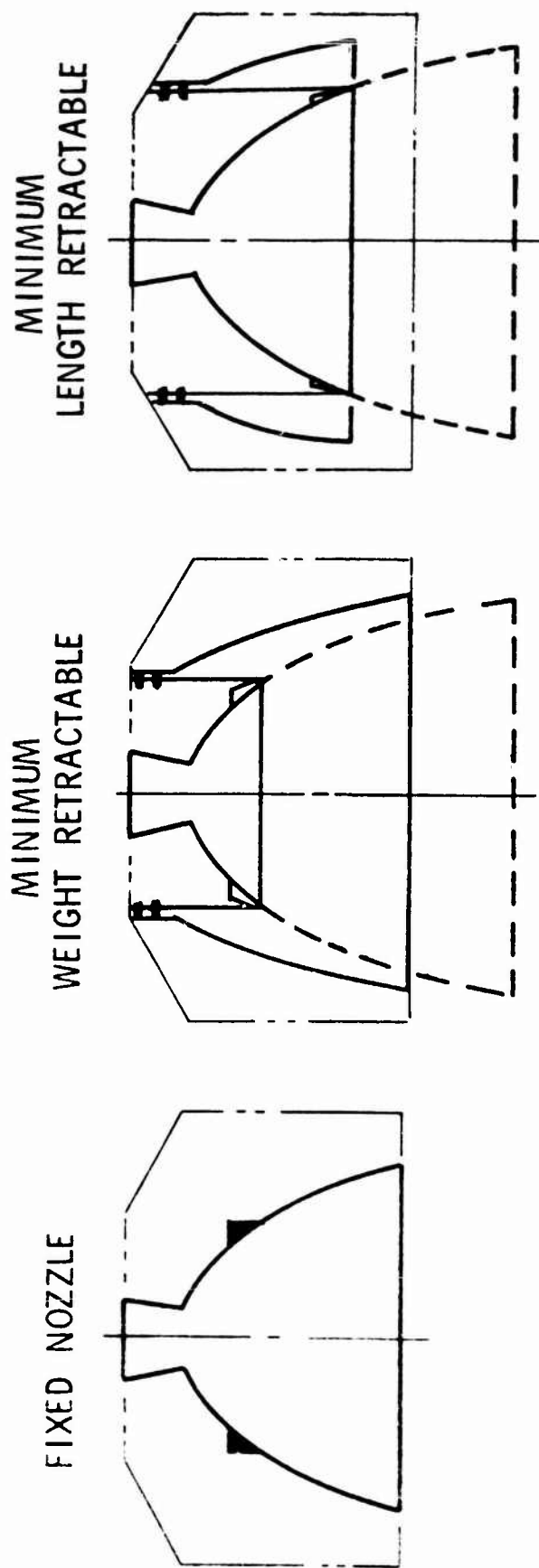


Figure 3. Nozzle Configuration

### III. A, Engine Design Parametric Study (Task IV) (cont.)

Thrust

Chamber Pressure

Mixture Ratio

Expansion Area Ratio

NPSH

- . The engine weights were computed as a function of the scaling parameter for each engine cycle and nozzle concept.

For the selected baseline design points the component weights were calculated based on the engine layout drawings and are presented in Table IX through Table XIV. These weights form the base for the analytical weight allocation.

#### c. Engine Envelope Dimensions

The engine envelope dimensions are presented as the study total engine length and the maximum nozzle extension diameter. It was assumed that the engine length from the chamber throat to the gimbal point is constant for all cycles, except the expander cycle, and for all thrust levels and chamber pressures.

For the expander cycle a thrust chamber length of 14-in. was assumed as compared to 8-in. for all other cycles. This improves the drive capability of the cycle since it will result in increased coolant temperatures. Consequently, engine length variations are equal to the minimum length Rao Contour Nozzle length variation.

#### d. Suction Line Diameter and Orientation

The suction line orientation was scaled from the engine layout drawings for each engine cycle. The orientation is expressed in terms of suction line center diameter from the thrust chamber axis.

#### e. Thrust Chamber Cooling Requirements

For the evaluation of the engine performance and weight, it is necessary to establish the thrust chamber cooling requirement since it affects the turbine bleed losses, power balance capability, and pump discharge requirement.

The objective of the thrust chamber cooling system is to provide a reusable chamber capable of 300 thermal cycles. For this purpose a aluminum copper regenerative cooled chamber with machined cooling passages was selected.

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TABLE IX

## WEIGHT BREAKDOWN

SUMMIT ENGINE CYCLEGAS GENERATOR BLEED - SERIES TURBINE DRIVE

F = 10,000 LBS.

MR = 6.0

 $\epsilon_{EXIT}$  = 450 $\epsilon_{TRANS}$  = 150 $P_c$  = 1250 PSIA

NPSH(F) = 60 FT. NOMINAL

NPSH(O) = 16 FT.

FIXED

AG CARB

Radiation Cooled Nozzle Extension

NOTE: Engine Controller Unit not included

| <u>WEIGHT CATEGORY</u>                                                    | <u>WEIGHT- LBS.</u> | <u>% TOTAL WEIGHT</u> |
|---------------------------------------------------------------------------|---------------------|-----------------------|
| I. TCA                                                                    |                     |                       |
| A. Injector                                                               | 24.0                |                       |
| B. Copper TC to $\epsilon$ = 6:1                                          | 29.5                |                       |
| C. Tube Regen to $\epsilon$ = 150:1                                       | 17.4                |                       |
| D. Rad. Cooled Nozzle to $\epsilon$ = 450:1<br>+ Fixed Flange             | 39.7<br>8.0         |                       |
| E. Igniter                                                                | 8.4                 |                       |
| F. Including Nozzle Retraction (None)                                     | 127.0               | 43.0%                 |
| II. TPA's                                                                 |                     |                       |
| A. Fuel                                                                   | 17.0                |                       |
| B. Ox                                                                     | 24.0                |                       |
| C. Including Boost Pumps (None)                                           | 41.0                | 13.9%                 |
| III. Valves                                                               | 50.2                | 16.9%                 |
| IV. Gas Lines, Gas Manifolds,<br>Liquid Lines                             | 18.2                | 6.2%                  |
| V. Turbine Drive Power - (GG & Igniter)                                   | 20.6                | 6.9%                  |
| VI. Harness, Instrumentation<br>- Structure, Bracketry<br>- Miscellaneous | 38.6                | 13.1%                 |
|                                                                           | 295.6               | 100.0%                |

TABLE X  
WEIGHT BREAKDOWN

SUBJECT ENGINE CYCLE

COOLANT TAPOFF - SERIES TURBINE

F = 10,000 LBS.

MR = 6.0

$\epsilon_{EXIT}$  = 450

$\epsilon_{TRANS}$  = 150

P<sub>c</sub> = 1250 PSIA

NPSH(F) = 60 FT. NOMINAL

NPSH(O) = 16 FT.

FIXED

AG CARB

Radiation Cooled Nozzle Extension

NOTE: Engine Controller unit not included

| <u>WEIGHT CATEGORY</u>                                        | <u>WEIGHT- LBS.</u> | <u>% TOTAL WEIGHT</u> |
|---------------------------------------------------------------|---------------------|-----------------------|
| 1. TCA                                                        |                     |                       |
| A. Injector                                                   | 24.0                |                       |
| B. Copper TC to $\epsilon$ = 6:1                              | 29.5                |                       |
| C. Tube Regen to $\epsilon$ = 150:1                           | 17.4                |                       |
| D. Rad. Cooled Nozzle to $\epsilon$ = 450:1<br>+ Fixed Flange | 39.7<br>8.0         |                       |
| E. Igniter                                                    | 8.4                 |                       |
| 1. Including Nozzle Retraction (None)                         | 127.0               | 46.7%                 |
| 2. TFA's                                                      |                     |                       |
| A. Fuel                                                       | 17.0                |                       |
| B. Ox                                                         | 24.0                |                       |
| 2. Including Boost Pumps (None)                               | 41.0                | 15.1%                 |
| 3. TFA's                                                      | 46.9                | 17.2%                 |
| 4. Gas Lines, Gas Manifolds,<br>Heads Lines                   | 18.6                | 6.8%                  |
| 5. Turbine Drive Power - (TCA)                                | -                   | -                     |
| 6. Instrumentation<br>Wiring, Bracketry<br>Sensors            | 38.6                | 14.2%                 |
|                                                               | 272.1               | 100.0%                |

TABLE XI  
WEIGHT BREAKDOWN

SUBJECT ENGINE CYCLE

CHAMBER TAPOFF - SERIES TURBINE

F = 10,000 lbs

MR = 6.0

$\epsilon_{EXIT}$  = 450

$\epsilon_{TRANS}$  = 150

P<sub>C</sub> = 1250 PSIA

NPSH(F) = 60 FT. NOMINAL

NPSH(O) = 16 FT.

FIXED AG CARB Radiation Cooled Nozzle Extension

NOTE: ENGINE CONTROLLER UNIT NOT INCLUDED

| <u>WEIGHT CATEGORY</u>                                                      | <u>WEIGHT- LBS.</u> | <u>% TOTAL WEIGHT</u> |
|-----------------------------------------------------------------------------|---------------------|-----------------------|
| I. TCA                                                                      |                     |                       |
| A. Injector                                                                 | 24.0                |                       |
| B. Copper TC to $\epsilon$ = 6:1                                            | 29.5                |                       |
| C. Tube Regen to $\epsilon$ = 150:1                                         | 17.4                |                       |
| D. Rad. Cooled Nozzle to $\epsilon$ = 450:1<br>+ Fixed Flange               | 39.7<br>8.0         |                       |
| E. Igniter                                                                  | 8.4                 |                       |
| F. Including Nozzle Retraction (None)                                       | 127.0               | 46.7%                 |
| II. TPA's                                                                   |                     |                       |
| A. Fuel                                                                     | 17.0                |                       |
| B. Ox                                                                       | 24.0                |                       |
| C. Including Boost Pumps (None)                                             | 41.0                | 15.1%                 |
| III. Valves                                                                 | 46.9                | 17.2%                 |
| IV. Gas Lines, Gas Manifolds,<br>Liquid Lines                               | 18.6                | 6.8%                  |
| V. Turbine Drive Power -(TCA)                                               | -                   | -                     |
| VI. Engine Harness, Instrumentation<br>Structure, Bracketry<br>and Hardware | 38.6                | 14.2%                 |
|                                                                             | 272.1               | 100.0%                |

TABLE XII

## WEIGHT BREAKDOWN - EXPANDER

ENGINE CYCLEEXPANDER - PARALLEL TURBINE DRIVE

F = 10000 lbs.

MR = 6.0

 $\epsilon_{EXIT} = 450$  $\epsilon_{TRANS} = 145$  $P_C = 600$  PSIA

NPSH(F) = 60 FT. NOM.

NPSH(O) = 16 FT.

RETRACTABLE

AG CARB

Radiation Cooled Nozzle Extension

NOTE: ENGINE CONTROLLER UNIT NOT INCLUDED

| <u>WEIGHT CATEGORY</u>                           | <u>WEIGHT- LBS.</u> | <u>% TOTAL WEIGHT</u> |
|--------------------------------------------------|---------------------|-----------------------|
| I. TCA                                           |                     |                       |
| A. Injector                                      | 17.8                |                       |
| B. Copper TC to $\epsilon = 6:1$                 | 40.5                |                       |
| C. Tube Regen to $\epsilon = 145:1$              | 40.4                |                       |
| D. Rad. Cooled Nozzle to $\epsilon = 450:1$      | 83.9                |                       |
| E. Igniter                                       | 8.4                 |                       |
| F. Including Nozzle Retraction                   | 71.1 + 191 = 262.1  | 62.8%                 |
| II. TPA's                                        |                     |                       |
| A. Fuel                                          | 17.0                |                       |
| B. Ox                                            | 24.0                |                       |
| C. Including Boost Pumps (none)                  | 41.0                | 9.8%                  |
| III. Valves                                      | 47.3                | 11.3%                 |
| IV. Gas Lines, Gas Manifolds, Liquid Lines       | 28.1                | 6.8%                  |
| V. Turbine Drive Power - (TCA)                   | -                   |                       |
| VI. Wires, Instrumentation, Structure, Bracketry | 38.6                | 9.3%                  |
|                                                  | 417.1               | 100.0%                |

TABLE XIII

## WEIGHT BREAKDOWN

SUBJECT ENGINE CYCLESTAGED COMBUSTION - PARALLEL TURBINE DRIVE

F = 25000 lbs.

MR = 6.0

 $\epsilon_{EXIT} = 450$  $\epsilon_{TRANS} = 145$  $P_c = 1500$  PSIA

NPSH(F) = 60 FT. NOM.

NPSH(O) = 16 FT.

RETRACTABLE

AG CARB

Radiation Cooled Nozzle Extension

NOTE: ENGINE CONTROLLER UNIT NOT INCLUDED

| <u>WEIGHT CATEGORY</u>                                                      | <u>WEIGHT- LBS.</u>  | <u>% TOTAL WEIGHT</u> |
|-----------------------------------------------------------------------------|----------------------|-----------------------|
| I. TCA                                                                      |                      |                       |
| A. Injector                                                                 | 17.8                 |                       |
| B. Copper TC to $\epsilon = 6:1$                                            | 33.3                 |                       |
| C. Tube Regen to $\epsilon = 145$                                           | 40.4                 |                       |
| D. Rad. Cooled Nozzle to $\epsilon = 450:1$                                 | 83.9                 |                       |
| E. Igniter                                                                  | 8.4                  |                       |
| F. Including Nozzle retraction                                              | $70.6+183.8 = 254.4$ | 53.6%                 |
| II. TPA's                                                                   |                      |                       |
| A. Fuel                                                                     | 36.0                 |                       |
| B. Ox                                                                       | 20.0                 |                       |
| C. Including Boost Pumps                                                    | $20 + 56.0 = 76.0$   | 16.0%                 |
| III. Valves                                                                 | 48.1                 | 10.1%                 |
| IV. Gas Lines, Gas Manifolds,<br>Liquid Lines                               | 39.8                 | 8.4%                  |
| V. Turbine Drive Power - Preburner<br>(Includes Igniter)                    | 18.1                 | 3.8%                  |
| VI. Wires, Harness, Instrumentation<br>Support Structure, Bracketry<br>etc. | 38.6                 | 8.1%                  |
|                                                                             | 475.0                | 100.0%                |

TABLE XIV  
WEIGHT BREAKDOWN

SUBJECT ENGINE CYCLE

STAGED COMBUSTION - BLEED

SERIES TURBINE DRIVE

F = 25000 LBS.

MR = 6.0

$\epsilon_{EXIT}$  = 450

$\epsilon_{TRANS}$  = 145

P<sub>C</sub> = 1500 PSIA

NPSH(F) = 60 FT. NOM.

NPSH(O) = 16 FT.

RETRACTABLE

AG CARB

Radiation Cooled Nozzle Extension

NOTE: ENGINE CONTROLLER UNIT NOT INCLUDED

| <u>WEIGHT CATEGORY</u>                                                   | <u>WEIGHT- LBS.</u> | <u>% TOTAL WEIGHT</u> |
|--------------------------------------------------------------------------|---------------------|-----------------------|
| I. TCA                                                                   |                     |                       |
| A. Injector                                                              | 17.8                |                       |
| B. Copper TC to $\epsilon$ = 6:1                                         | 33.3                |                       |
| C. Tube Regen to $\epsilon$ = 145:1                                      | 40.4                |                       |
| D. Rad. Cooled Nozzle to $\epsilon$ = 450:1                              | 83.9                |                       |
| E. Igniter                                                               | 8.4                 |                       |
| F. Including Nozzle Retraction                                           | 70.6+183.8 = 254.4  | 51.4%                 |
| II. TPA's                                                                |                     |                       |
| A. Fuel                                                                  | 36.0                |                       |
| B. Ox                                                                    | 20.0                |                       |
| C. Including Boost Pumps                                                 | 20.0+56.0 = 76.0    | 15.4%                 |
| III. Drives                                                              | 63.7                | 12.8%                 |
| IV. Gas Lines, Gas Manifolds,<br>Liquid Lines                            | 41.7                | 8.4%                  |
| V. Turbine Drive Power - Preburner<br>(includes Igniter)                 | 20.6                | 4.2%                  |
| VI. Harness, Instrumentation<br>and Structure, Bracketry<br>and Hardware | 38.6                | 7.8%                  |
|                                                                          | 495.0               | 100.0%                |

### III, A, Engine Design Parametric Study (Task IV) (cont.)

The requirement for 300 thermal cycles imposed severe design restraints on the thrust chamber because all temperature gradients must be maintained below certain limits.

Aerojet test data on low cycle fatigue characteristics of Zirconium Copper was used as bases for these limits. This data lead to the design requirement of a maximum wall temperature of 935°F. See Figure 9.

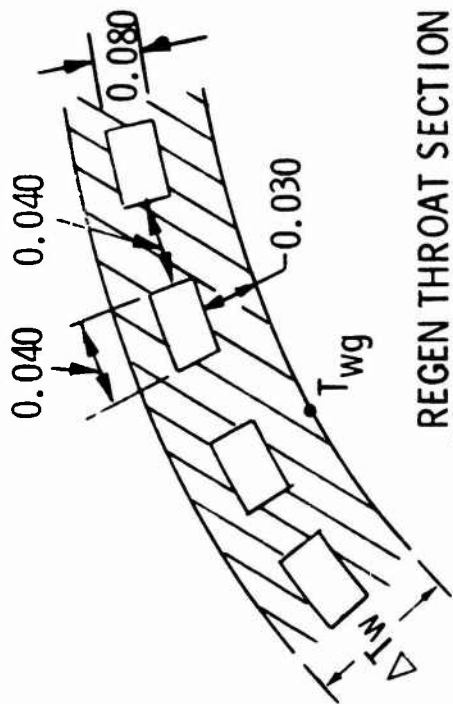
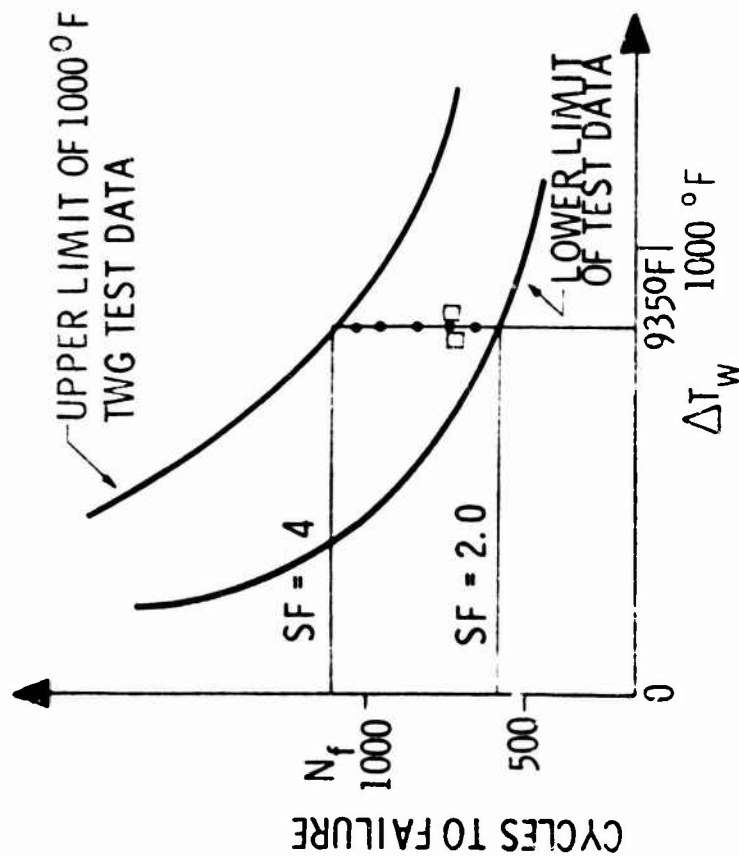
Figures 10 and 11 present the coolant bulk temperature rise and coolant pressure drop as a function of chamber pressure, thrust size and pump discharge pressure. Correction curves are shown for varying combustion chamber lengths and mixture ratios.

These coolant requirements were used for the generalized set of data. However, for the payload comparison analysis in which engine design constraints are important the coolant requirements were based on the heat transfer analysis (Appendix B) to meet 300 thermal cycles.

#### 5. Assumptions

A complete listing of the engine technology and design assumptions made for parametric engine design study (Task IV) is included in Table XV which is self explanatory.

# THRUST CHAMBER LOW CYCLE FATIGUE LIFE $\Delta T_w$ AT THROAT (ZrCu)



- DESIGN SAFETY FACTOR ON FATIGUE LIFE
- SF = 4.0 ON THEORETICAL CURVE
- SF = 2.0 ON LOWER DATA BOUNDARY

- FOR ZrCu CHAMBER AND  $N_f = 300$  A THROAT  $\Delta T_w = 9350^\circ\text{F}$  IS REQUIRED
- COOLANT MACH NO. MUST MEET THE REQUIREMENT OF  $\Delta T_w = 9350^\circ\text{F}$
- CHAMBER PRESSURES MUST BE LIMITED TO MEET  $\Delta T_w = 9350^\circ\text{F}$   
 $T_w = 10000^\circ\text{F}$

Figure 3. Chamber Cooling Requirement

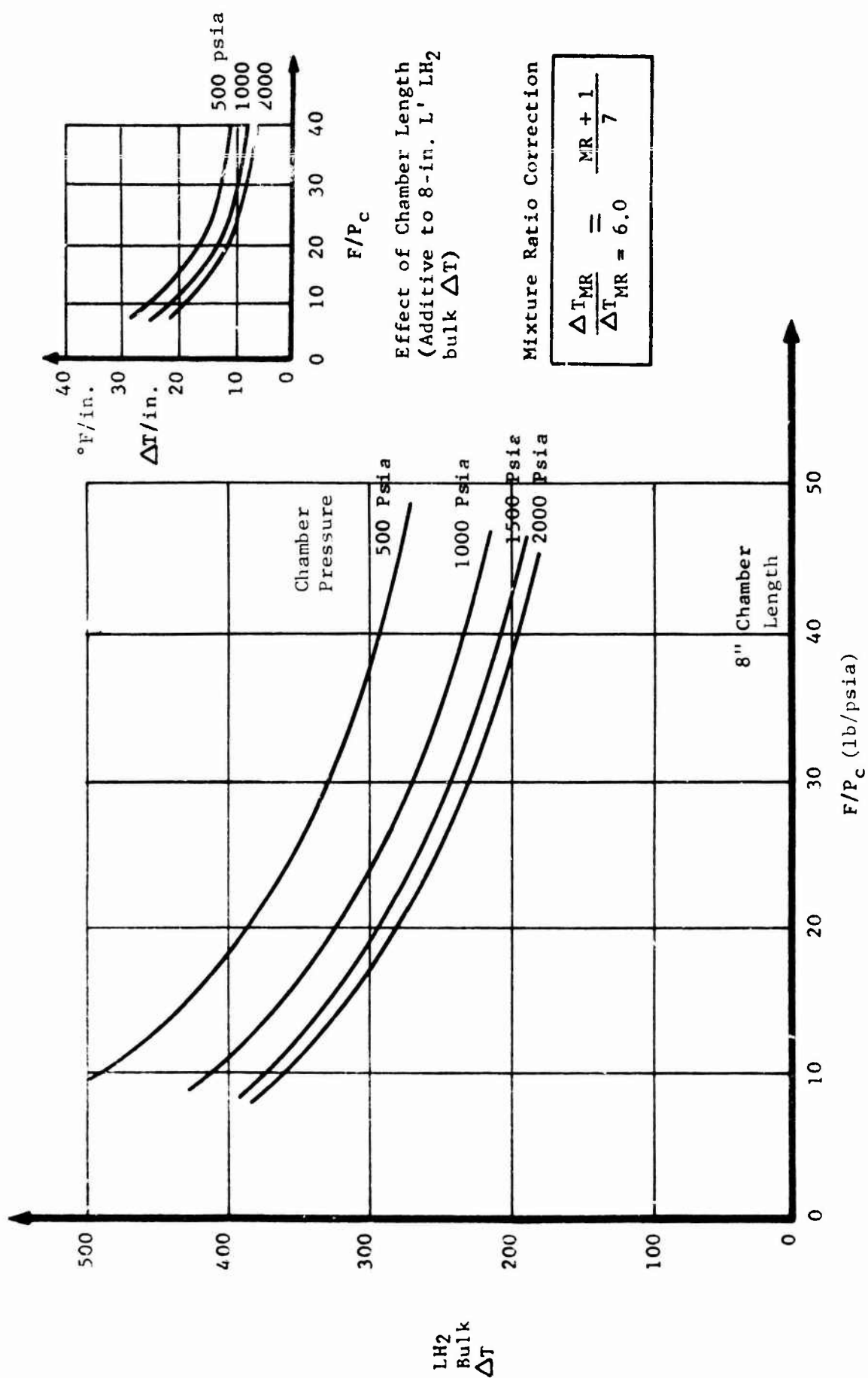
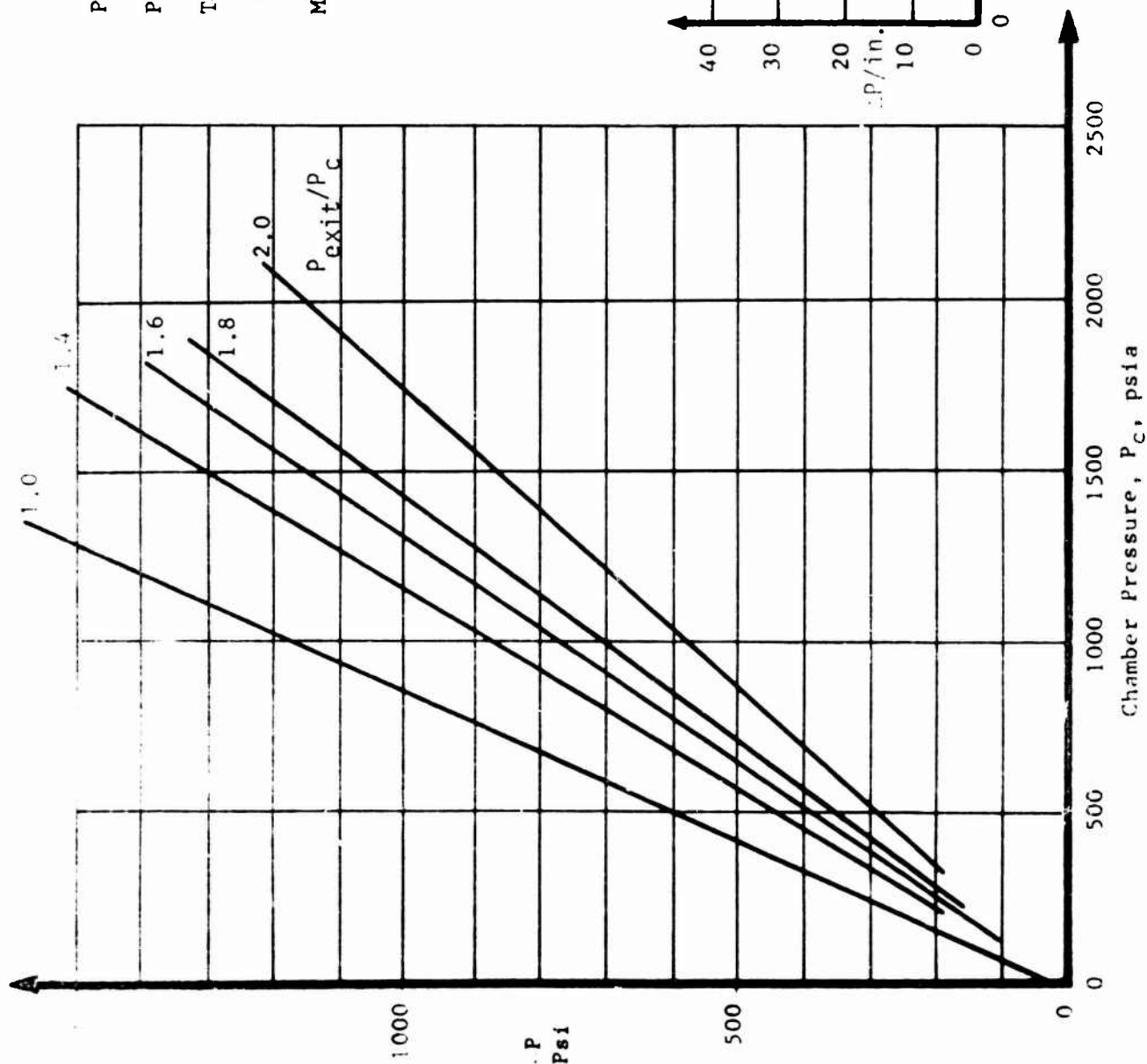


Figure 10. Chamber Coolant Bulk Temperature Rise



$P_{ex}$  = Tube Outlet Pressure  
 $P_c$  = Chamber Pressure  
 $T_{wj}$  = 1000°F  
 $T_w$  = 930°F  
 $MR$  = Const. = 6.0

Correction for chamber length  
(Additive to 8-in.  $L' P$ )

Figure 11. Chamber Coolant Pressure Drop

TABLE XV

## OOS COMPONENT ASSUMPTIONS AND JUSTIFICATION

## I. CHAMBER

| <u>ITEM</u>                             | <u>ASSUMPTIONS</u>                                                                                    | <u>JUSTIFICATIONS</u>                                                                                                               |
|-----------------------------------------|-------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| 1. Type                                 | H <sub>2</sub> Regen. - Single "Up" Pass, Rectangular Channels                                        | Best Coolant Properties; Less Expensive for Less than 10 Units than Tubular Design                                                  |
| 2. Material                             | ZrCu                                                                                                  | Good Low Cycle Fatigue Prop., High Heat Flux Capability, Good LCF Data                                                              |
| 3. Configuration                        | Conical, with Short Cylindrical Section @ Injector End, & Long Cylindrical Section for Expander Cycle | Least Wt, Good Perf., Low Heat Transfer Area (Except for Expander Cycle)                                                            |
| 4. Film Cooling                         | None                                                                                                  | Good Performance, Compatible Small P/E                                                                                              |
| 5. T Wall Max                           | 1000°F                                                                                                | Good Low Cycle Fatigue and Strength Properties                                                                                      |
| 6. L' Chamber Length                    | 8.0 in. (Except Expander Cycle)                                                                       | Good Perf. Est. for Gas/Liquid Injector                                                                                             |
| 7. Expander Cycle Chamber               | Add Cylindrical Section                                                                               | Need HOT H <sub>2</sub> to Run Cycle (See Graph for $\Delta P/\text{in.}$ & $\Delta T/\text{in.}$ Estimates)                        |
| 8. Contraction Ratio                    | $(R_j/R_t)^2 = 2.0$ ( $\Delta P_{ch} = 3.0\%$ for S.C. Cycles & 5.0% for non-S.C. Cycles)             | Max. Performance in Short L', Min. Heat Transfer Area and Chamber Weight                                                            |
| 9. Chamber Area Ratio                   | $(R_{exit}/R_t) = \xi_1 =$ (See Chart) (Minimize to Reduce Weight)                                    | See "Nozzle" Justifications                                                                                                         |
| 10. Channel Configuration               | Axial Milled Slots, Stepped Width                                                                     | State-of-the-Art Fabrication; Smooth Inner Wall, Several Closure Techniques, Optimize Cost vs $\Delta P$ and $\Delta \text{Weight}$ |
| a. Land Width/Slot Width Ratio @ Throat | 1.0 to 1.1                                                                                            | Per E-D Nozzle Proposal LR711618 and Other Chamber Fab & Testing                                                                    |
| b. Slot Width, in. @                    | .040 in.                                                                                              | Per E-D Nozzle Proposal LR711618 and Other Chamber Fab & Testing                                                                    |

ITEMASSUMPTIONSJUSTIFICATIONS

|                                                  |                                                                                                            |  |                                                                                                    |
|--------------------------------------------------|------------------------------------------------------------------------------------------------------------|--|----------------------------------------------------------------------------------------------------|
| c. Land Width @ Throat:                          | .040 in.                                                                                                   |  | Per E-D Nozzle Proposal LR711618 and O Chamber Fab & Testing                                       |
| d. Channel Depth                                 | As Required for Cooling (Minimize to Reduce Wall Weight)                                                   |  | Per E-D Nozzle Proposal LR711618 and O Chamber Fab & Testing                                       |
| e. Gas Side Wall Thickness                       | .030 in. at Throat                                                                                         |  | Per E-D Nozzle Proposal LR711618 and O Chamber Fab & Testing                                       |
| 11. Method of Attachment to Injector             | Bolted Flange with Metal Seal.                                                                             |  | Desirable for Component Inspection and Refurbishment Coats                                         |
| 12. Method of Attachment to Nozzle               | Braze                                                                                                      |  | Least Wt., Reliable Seal, N.F. Chamber N.F. Nozzle                                                 |
| 13. P <sub>chamb.</sub> Inlet/P <sub>c</sub>     | 2.0 or 2.4                                                                                                 |  | Pressure Schedule Requirement (Turbine Inj + Coolant $\Delta P_s$ )                                |
| 14. LCP Safety Factor (Design to Unmanned reqmt) | 4.0 (Manned)<br>2.0 (Unmanned)                                                                             |  | SSE Data, Historical Data, SF Strain = $SF_{NF} = (1.4)^2 = 2.0$<br>Additional SF = 2.0 for manned |
| 15. NF Design (Design to Unmanned Reqmt)         | 1200 (Manned)<br>600 (Unmanned)                                                                            |  | 300 Cycle Requirement + Item 14.                                                                   |
| 16. Static Safety Factors                        | See Table                                                                                                  |  | Historical Determination                                                                           |
| 17. Wall Thermal Gradients                       | $\Delta T_{wall} = 630^{\circ}F$ for N.F.S.F. = 4.0<br>$\Delta T_{wall} = 930^{\circ}F$ for N.F.S.F. = 2.0 |  | See LCF NF vs $\Delta T_{wall}$ Graph                                                              |

TABLE XV (cont.)

## II. NOZZLE

| ITEM                                | ASSUMPTIONS                                                                                         | JUSTIFICATIONS                                                                                               |
|-------------------------------------|-----------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|
| 1. Type                             | Fuel Regen. Brazed Tube Bundle Two Passes                                                           | Prelim. Study, Design Flexibility, Low TCA Wt.                                                               |
| 2. Material                         | ARMCO 22-13-5                                                                                       | Data from SSE Studies - Good LCP vs Hold Time Above 1100°F, Lower $P_c$ Than SSE; Can Repair & Braze         |
| 3. Tube Configuration               | All Identical Tapered Tubes, Tapered Wall, Round Tubes, (Unflattened)                               | Good Heat Transfer Prop., State-of-the-Art, Least Wt. for Max. Strength                                      |
| 4. Tube Bifurcations                | As Required for Cooling                                                                             | Design Flexibility for Study, No Fab Difficulties                                                            |
| 5. Nozzle Inlet, $\zeta_1$          | To be determined                                                                                    | Limited by LCP life, Material Strength @ Temp., and Heat Flux, e.g., $P_c$ & $\Delta P$ & $\Delta T$ Coolant |
| 6. Coolant Inlet (Torus), $\zeta_3$ | To be determined                                                                                    | Limited by Low Heat Flux Capability of Cold $H_2$ Inlet and One Tube Design                                  |
| 7. Nozzle Exit, $\zeta_2$           | @ $\frac{1}{2}$ Engine Length, or $\frac{1}{2}$ Nozzle Length for Larger Thrust Engines (see Graph) | Preliminary Tradeoff Study Results for Max. Payload (Low Weight & Min. Stowed Length)                        |
| 8. Chamber Attachment Method        | Brazed                                                                                              | Least Wt., Reliable Seal                                                                                     |
| 9. Method of Attachment             | Flange & Seal with Provision for Hot Gas Dump                                                       | Must Accept Retractable Nozzle with Cooled Flange                                                            |
| 10. Coolant Turn Around at Aft End  | Copper                                                                                              | Low Weight Manifold - Integral with Skirt Flange, Well Cooled @ Tip                                          |
| 11. LCP Life                        | 300 with 4.0 = 1200 Predicted (Manned) and 300 x 2.0 = 600 (Unmanned) (Design to Unmanned Cond.)    | Reqmt. + See Chamber Justification                                                                           |

| <u>ITEM</u>                                  | <u>ASSUMPTIONS</u>                            | <u>JUSTIFICATIONS</u>                                  |
|----------------------------------------------|-----------------------------------------------|--------------------------------------------------------|
| 12. Tube Strain at Crown (Max.)              | 1.3% @ NF = 1200 & 1.45% @ NF = 600           | Based on SSE & Prelim. OOS Calcs, & NF (See #17 & #18) |
| 13. Gas Side Wall Temperature                | 1200°F for NF = 1200 &<br>1400°F for NF = 600 | Based on SSE & Prelim. OOS Calcs, & NF (See #17 & #18) |
| 14. Minimum Wall Thickness                   | .015 in.                                      | Assumed Fab. Limit                                     |
| 15. Single Tube Section Wall Thickness Range | 2.0/1                                         | Fab Experience                                         |
| 16. Single Tube Section Diameter Range       | 3.5/1                                         | Fab. Experience                                        |
| 17. Coolant Outlet Temp                      | -150°F                                        | Heat Transfer Analysis                                 |
| 18. $\Delta T_{wall}$                        | 600°F                                         | Heat Transfer Analysis                                 |

TABLE XV (cont.)

## III. SKIRT

| <u>ITEM</u>                     | <u>ASSUMPTIONS</u>                 | <u>JUSTIFICATIONS</u>                                                                   |
|---------------------------------|------------------------------------|-----------------------------------------------------------------------------------------|
| 1. Type                         | Extendable/Retractable*            | Packaging Requirement & High $I_g$ goal                                                 |
| 2. Primary Cooling              | Radiation                          | Simplicity, Low Weight                                                                  |
| 3. Supplemental Cooling         | Maintain Flange Temp @ 1500°F      | Maintain Material Structural Properties in Flange to Reduce Weight                      |
| 4. Material**                   | AGCarb-101                         | Apollo Data, SSE Data, Nerva Data, Flexibility of $\xi_2$ for Study, Same Wt. as Cb-103 |
| 5. Wall Thickness               | Variable $\leq .20$ in.            | Min. Wt, Adequate Structural Stiffness and Strength, Min. Fab. Thickness                |
| 6. Contour                      | Rao Min. Length Contour Is Optimum | Max. Engine Dimensions Limit & Max Performance                                          |
| 7. Entrance Area Ratio, $\xi_2$ | Same as for Nozzle Exit            | Same as for Nozzle Exit                                                                 |
| 8. Support Brackets             | Three Min.                         | Attachments for Extend/Retract Mechanism                                                |
| 9. Stiffening Rings             | Two Min.                           | One for Attachment of Support Bracket and One at Aft End to Prevent Buckling            |

\* Stowed Position in OOS (Retracted) of Skirt Length is 82 in. from Gimbal Point; 15 in. Length Assumed for Gimbal to Throat Length for parameter analysis.

\*\* Alternate Material: Cb-103 where Engine Cycle Coolant &  $P_c$  and  $\xi_2$  Allows Use.  $T_w \text{ max} = 2300^\circ\text{F}$ .

TABLE XV (cont.)

## IV. MAIN INJECTOR

| ITEM                                    | ASSUMPTIONS                                                                        | JUSTIFICATIONS                                                                                                                              |
|-----------------------------------------|------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| 1. State of Propellants                 | Gaseous Fuel/Liquid Oxidizer                                                       | No O <sub>2</sub> Heat Exchanger Required. Good Idle Mode MR Control. Good for Staged Combustion Cycle, Short L'.                           |
| 2. Type                                 | Platelet Vane                                                                      | Low Blockage Ratio Best for Gas/Liquid With Staged Combustion; Ref SSE, Ares & See #4.                                                      |
| 3. Material                             | Body ARMCO 22-13-5, Vanes CRES 347, NI 200                                         | High Strength, Brazable, Thermal Cond. Control                                                                                              |
| 4. Injection Pattern                    | Impinging Oxid. Doublets, Shower Head Fuel                                         | Short L' Because of Impinging Elements & Small F/E.                                                                                         |
| 5. $\Delta P/P_c$ @ Full Thrust         | Oxid = .65, Fuel = .06 (Min. Ox. $\Delta P$ = 400 psia)                            | Min. for 5/1 Throttling Stability* SSE Data                                                                                                 |
| 6. Manifolding                          | Oxid Torus ( $\Delta P$ man = .05 P <sub>c</sub> or 30 psia, Whichever is Greater) | Distribute Oxid. Around O.D. to Vanes, Weight $\Delta P$ Tradeoff                                                                           |
| 7. Blockage Ratio (Vane Area/Open Area) | .42 for S.C. Cycles, Larger for Other Cycles depending on Injector Concept         | SSE Ratio, Gives Desired Fuel Injection Velocities                                                                                          |
| 8. Attachment to Chamber                | Bolted Flange                                                                      | Desirable for Component Inspection and Refurbishment. Very Small Loads for high $\zeta_0$ Nozzle                                            |
| 9. Attachment to Hot Gas Manifold       | Bolted Flange                                                                      | Same as Above Except Large Loads. Large, Bulky, Awkward HGM to Handle if Injector Were Welded to and Machined from HGM During Refurbishment |
| 10. Gas Distribution Device             | Separately Located Upstream at HGM Interface                                       | Required for Optimum Gas Distribution and Injector $\Delta P$                                                                               |

\* For 10:1 Throttling, Staged Combustion Cycle Use Same Oxid. System and Let  $\Delta P$  Go Up.  
(Check Strength of Vanes at Increased  $\Delta P$ .)

TABLE XV (cont.)

## V. PRE-BURNER

| <u>ITEM</u>                              | <u>ASSUMPTIONS</u>           | <u>JUSTIFICATIONS</u>                                                   |
|------------------------------------------|------------------------------|-------------------------------------------------------------------------|
| 1. Injector Type                         | Platelet, Dual Oxid. Circuit | High Perf., Throttability, Short Length                                 |
| 2. Injector Material                     | Ni-200 Platelets             | Good Thermal Conduction at Face                                         |
| 3. Chamber Material                      | Inconel 718                  | High Strength @ Elevated Temp                                           |
| 4. L' <sub>gg</sub> (in.) Length         | 6 in.                        | SSE Data                                                                |
| 5. T' <sub>ti</sub> Turbine Inlet Temp.  | 1860°R                       | Material Limit for Cycle Life Reg.                                      |
| 6. C.R. <sub>gg</sub> Contraction Retro. | 3.5/1 (to Turbine Nozzle)    | $\Delta P_{ch} = 2.0\%$ of P <sub>cgg</sub> (Chamber Pressure Drawings) |

TABLE XV (cont.)

## VI. IGNITERS

MAIN INJECTOR & PREBURNER/GAS GENERATOR

| <u>ITEM</u>           | <u>ASSUMPTIONS</u>                         | <u>JUSTIFICATIONS</u>                             |
|-----------------------|--------------------------------------------|---------------------------------------------------|
| 1. Type               | Electric Torch                             | Reliable, Demonstrated                            |
| 2. Initiator          | Spark                                      | Reliable, Demonstrated                            |
| 3. Materials          | Electrode Ni 200; Chamber Ni 200           | APS Ignition Program                              |
| 4. Seal               | Electrode Housing Brazed Metal to Ceramic  | Has Been Demonstrated (J-2 Plugs)                 |
| 5. Spark Energy       | 5 Modules/Spark                            | APS Data                                          |
| 6. Spark Rate         | 100 Sparks/sec $\approx$ 10 Mil Ign. Delay | Test Data Available @ 50 & 500 Sparks/Sec         |
| 7. Spark Voltage      | 20KV                                       | APS Experience                                    |
| 8. $W_t$ Torch Flow   | .065 $W_o$ ; .0125 $W_f$                   | APS Experience                                    |
| 9. Min. Temp of Torch | 1100° F                                    | Auto Ignit. Temp of H <sub>2</sub> O <sub>2</sub> |
| 10. Electrode         | O <sub>2</sub> Cooled, Submerged           | APS + Main Engine Ignit. Experience               |

TABLE XV (cont.)

## VII. TURBOPUMPS

| ITEM                           | ASSUMPTIONS                                                                                                                                                 | JUSTIFICATION                                                                                                                                                                                                    |
|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1. Type                        | Each pump driven by its own turbine                                                                                                                         | Turbopump envelope and space availability speed incompatibility.                                                                                                                                                 |
| 2. Low Speed Pumps             | Hydraulic Drive                                                                                                                                             | Specified NPSH (60 and 16 feet for LH <sub>2</sub> and LO <sub>2</sub> respectively).                                                                                                                            |
| 3. Bearing                     | Rolling element, propellant lubricated bearings. DN equal approximately 1.5 x 10 <sup>6</sup> and 1.0 for LH <sub>2</sub> and LO <sub>2</sub> respectively. | Demonstrated 23 hours with LH <sub>2</sub> ball bearings at 1.8 x 10 <sup>6</sup> DN. Demonstrated 15 hours with LO <sub>2</sub> ball bearings at 1.12 x 10 <sup>6</sup> DN. (Above times were without failure.) |
| 4. Pump Suction Specific Speed | Design S = 45000 corresponding to induce cavitating to non-cavitating head ratio equals 20%.                                                                | Current Design Point for Rocket Engines. Technology demonstrated at S = 55000 with water.                                                                                                                        |
| 5. Pump Suction Safety Factor  | Safety factor = 1.1.                                                                                                                                        | Pump design shaft speeds are reduced by dividing the available effective NPSH by the safety factor. (Effective NPSH equals NPSH + Thermodynamic suppression head.)                                               |
| 6. Pump Stages                 | One stage, LO <sub>2</sub> pump.<br>Two stage, LH <sub>2</sub> pump.                                                                                        | Current Rocket Engine design approach.                                                                                                                                                                           |
| 7. Pump Recirculation Flow     | Allocated 5% in each pump stage.                                                                                                                            |                                                                                                                                                                                                                  |
| 8. Pump Efficiency             | Computed values from curve fit.                                                                                                                             | Pump Efficiency Curve fit depicts rocket engine pump efficiency values as function of specific speed and flow values.                                                                                            |
| 9. Pump Material               | Aluminum impeller and housings.                                                                                                                             | Light Weight, high strength to weight ratio.                                                                                                                                                                     |

FN

ASSUMPTIONS

JUSTIFICATION

Turbine Temperature 1860°R (1400°F)

Typical turbine material (waspaloy) retains strength properties to this value. Turbine temperature increases to 2000°R will increase delivered specific power approximately 3% while reducing low cycle fatigue life by a factor of 10.

11. Turbine Rotor nozzle cooling. None

Turbine gas temperature selected sufficiently low to eliminate requirement.

12. Turbine Stages

|                                     | Expander - Parallel Turbine | Oxid. Turb. | Fuel Turb. |
|-------------------------------------|-----------------------------|-------------|------------|
| Stage Combustion Parallel Turbine   | 1                           | 1           | 2          |
| Stage Combustion Bleed              | 1                           | 1           | 2          |
| Gas Gen. - Series Turbine           | 2                           | 2           | 2          |
| Combustion Gas Topoff - Series Turb | 2                           | 2           | 2          |
| Coolant Tapoff - Series Turbine     | 2                           | 2           | 2          |

Acceptable Rocket Engine Design approach.

13. Turbine Pressure Ratio

Computed for topping cycles as required to satisfy power balance except for stage combustion bleed where oxidizer turbine pressure was set equal to 20:1. Bleed cycle pressure ratios were 4:1 and 15:1, LO<sub>2</sub> and LH<sub>2</sub> turbines respectively.

Oxidizer Turbine Flow are typically low and result in partial admission which in turn suggests the use of a single stage turbine. A pressure ratio of 4 was selected. This value does not affect turbine flow in the series turbine bleed cycle systems.

14. Turbine Mean Blade Speed

Fuel Turbine, 1500 ft/sec.  
Oxidizer Turbine, 1000 ft/sec.

Acceptable Rocket Engine Mean Blade speed on hydrogen turbine. Oxidizer turbine mean blade speed reduced to reduce turbine rotor diameter and polar moment of inertia to equalize pump spin up times.

15. Turbine Nozzle Angle

15°

Minimum practice angle from mechanical design considerations. Small angle selected to achieve maximum efficiency.

TABLE XV (cont.)

JUSTIFICATION

Turbine Rotor Hub to Tip Diameter Ratio selected at 0.8 maximum to limit tip leakage losses. Turbines with low flow will be partial admission to maintain this hub ratio.

Material selected for its high ductility characteristics coupled with adequate high temperature strength properties.

Computed from a model of turbine design point efficiencies. Efficiency predictions include the effects of turbine nozzle angle and tip leakage.

TABLE XVI (Cont.)

ASSUMPTIONS

Turbine Hub/Tip Ratio 0.8 Maximum

Turbine Rotor Material Waspaloy

18. Turbine Efficiency Computed

TABLE XV (cont.)

VIII. VALVES

JUSTIFICATION

ASSUMPTIONS

Poppet

Positive shutoff sealing. Less opening stroke required. Applicable for line sizes to 2 inches. Above 2 inches consideration would be coaxial poppet, ball, or butterfly.

Maintain close tolerances at cryogenic temperatures. Machinability and surface good finish control.

Application (temperature, life cycle, pressure, leakage criteria, and seal function) will determine material selection.

Fast response is not required. Difficult to obtain positive sealing, at cryogenic temperature, with gas actuation. Electric motor adaptable to modulating valve application.

Response varies as a function of valve concept, actuation configuration, line pressure, available power to actuator, and valve size.

2. Material

Body

Stainless Series

Seals  
(Dynamic and  
Shutoff)

Plastic or Metal to Metal

3. Actuation

Electric

4. Response

Fast and slow response considered.

6. Engine Cycle Evaluation for 8K to 50K Thrust

This section presents the results of the parametric evaluation study of the six engine cycles without consideration of engine design constraints. The purpose of these data is to provide information beyond current engineering design limits and to evaluate payoffs in payload capability through extension of these design limits.

This section is introduced by the result of the JANNAF thrust chamber performance analysis results and forms the basis of the engine performance presentation.

a. Nozzle Contour and Thrust Chamber Performance

The minimum Rao Nozzle contour data used for the parametric performance and weight calculation and the basic parametric thrust chamber performance is presented in Appendix A of this report.

b. Engine Cycle Characterization

The data presented is the result of a parametric study of the six engine cycles. The data is organized by engine cycles and includes:

Delivered vacuum specific impulse.

Engine weight for three different nozzle concepts.

Engine length and maximum engine diameter.

Suction line diameter.

The presented data are not restricted by envelope considerations or engine life requirements but is intended to give general relationships.

The suction line diameter is assumed to be independent of engine cycle and therefore is presented separately.

(1) General Parametric Data

(a) Suction Line Diameter

Suction line internal diameters are shown in Figure 12 in the thrust range from 8K to 50K lb as functions of NPSH at pump suction for engine mixture ratio = 6.

(b) Engine Length and Diameter

For simplicity, the engine length and maximum engine diameter are presented in one figure (Figure 13) which is valid for all engine cycles except the Expander Cycle with a constant length between the gimbal bearing and the throat plane. The data are presented as a function of the thrust to chamber pressure ratio, and area ratio at a mixture ratio = 6.

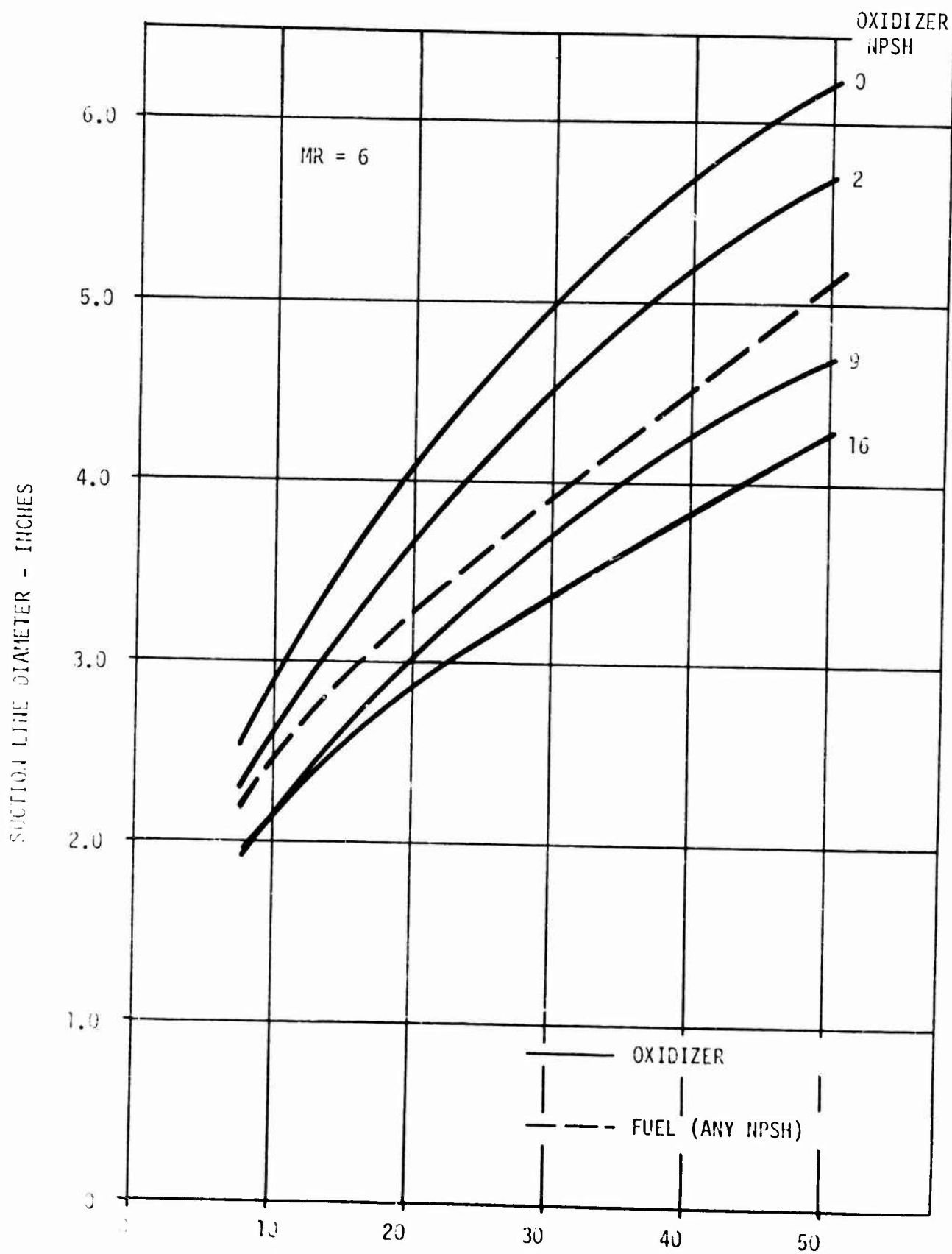


Figure 12. Suction Line Diameter

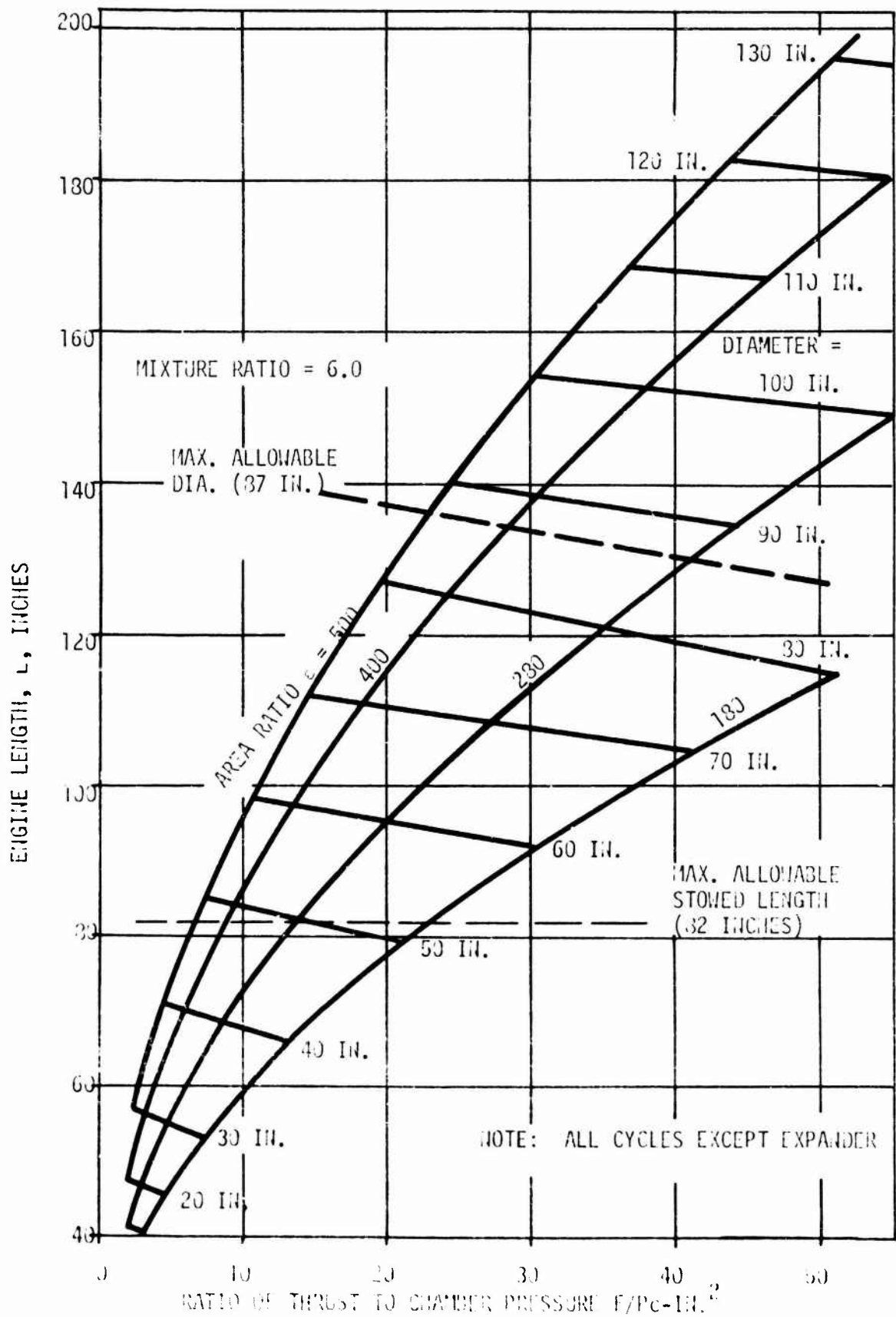
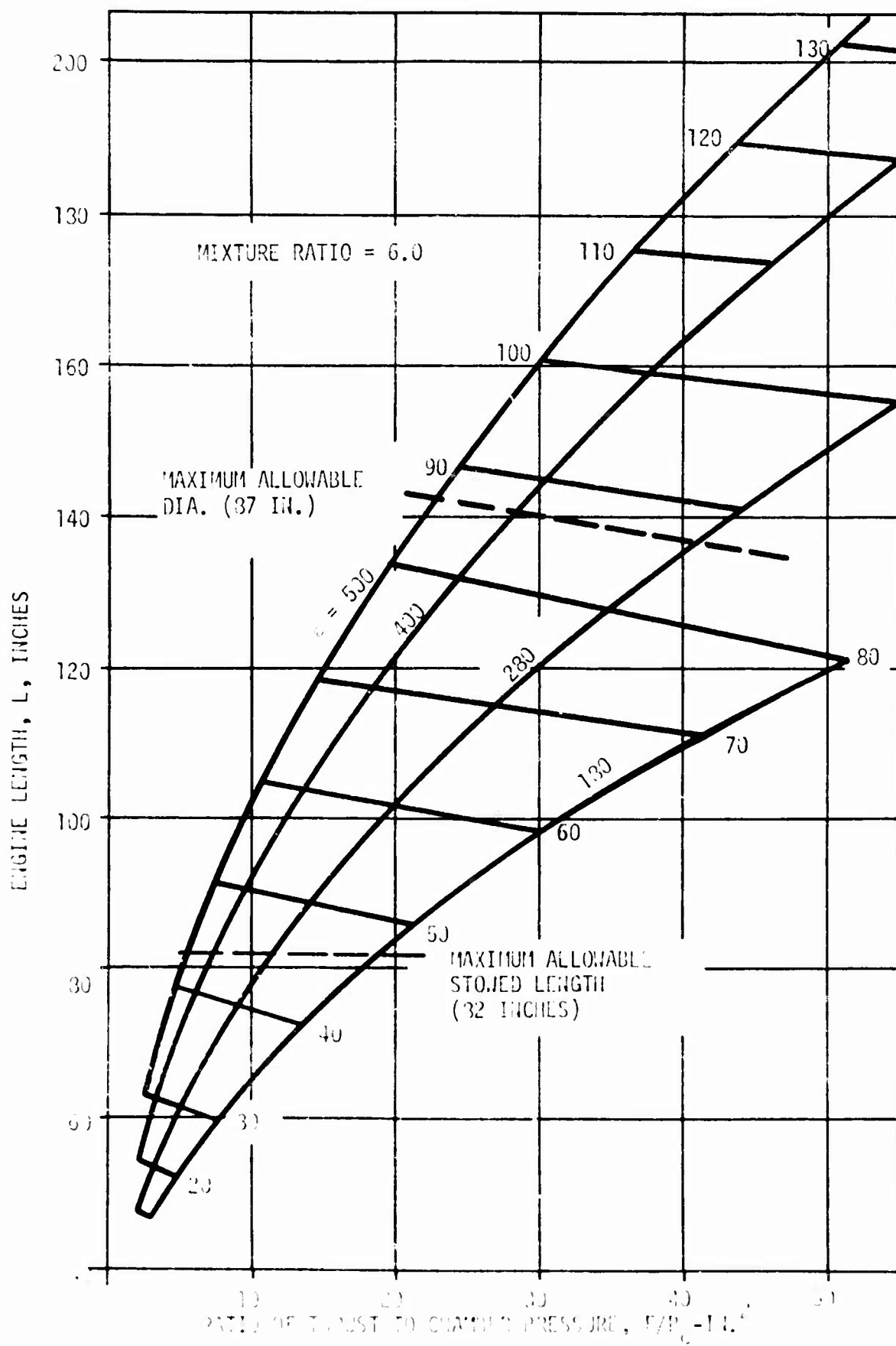


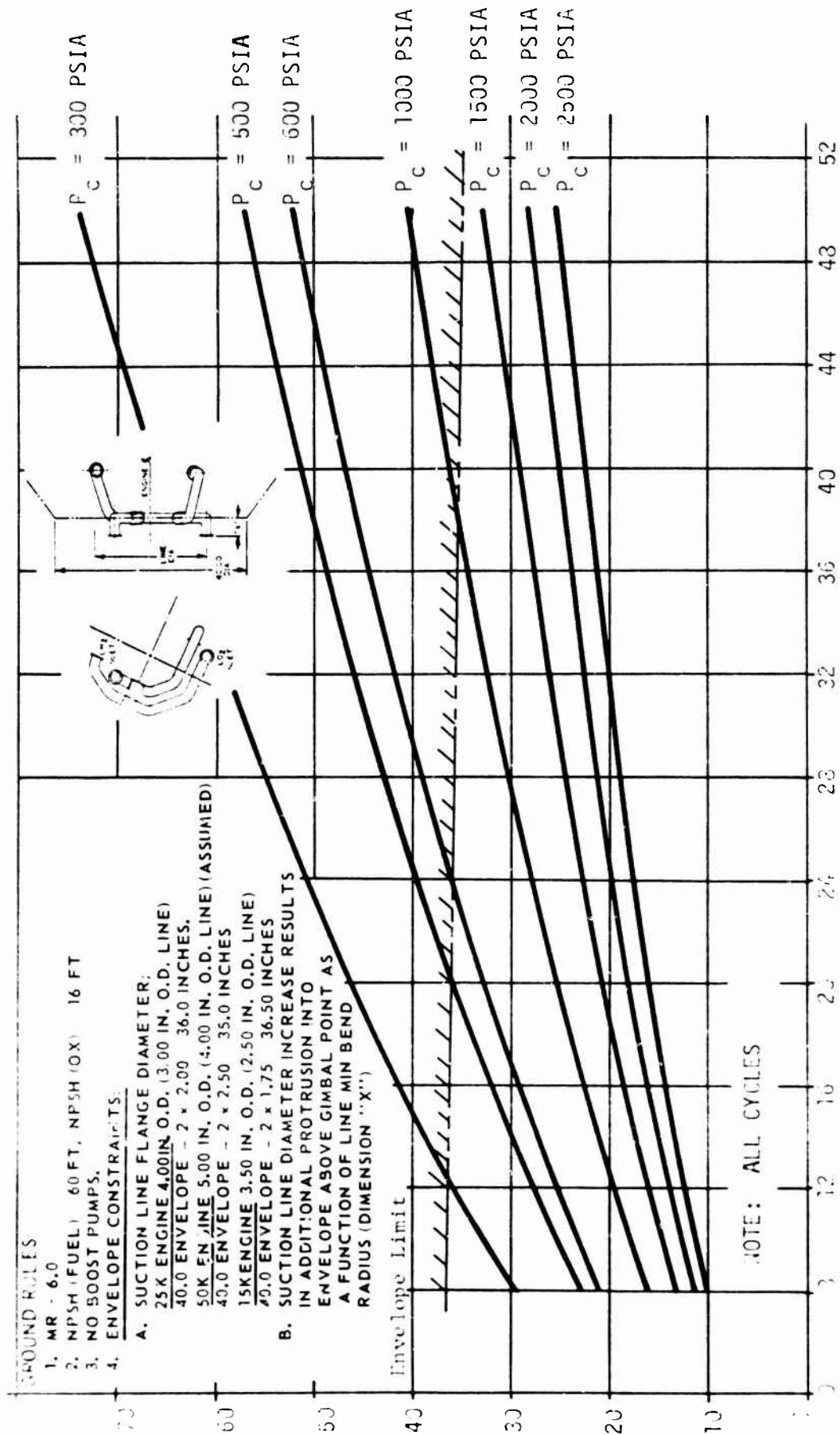
Figure 13. Engine Length, All Cycles Except Expander

### III. A. Engine Design Parametric Study (Task IV) (cont.)

The Expander Cycle chamber length is shown separately in Figure 14 for mixture ratio = 6.0. The difference in engine length compared to the other cycles is due to an additional chamber length of 8 in.

Data are also included in this section, for the suction line location relative to the thrust chamber axis as shown in Figure 15.





THRUST, 1000 POUNDS

Figure 15. Suction Line Interface Diameter

### III, A, Engine Design Parametric Study (Task IV) (cont.)

#### (2) Gas Generator and Combustion Gas Tap-Off Cycle Characteristics

A configuration drawing of the gas generator bleed cycle engine is shown in Figure 16 and a schematic design is shown in Figure 17.

The performance of the gas generator bleed cycle and combustion chamber tap-off cycle are identical and is shown in Figures 18 through 21. Separate weight charts are presented for each of the two cycles. Figures 22 through 24 show the weights for the gas generator bleed cycle and Figures 25 and 26 summarize the interaction of engine weight and performance for the gas generator bleed cycle.

Figure 27 is a configuration drawing of the chamber gas tap-off engine cycle and Figure 22 is a schematic diagram of that cycle. Figures 29 and 30 are weight data. All weights include low speed pumps.

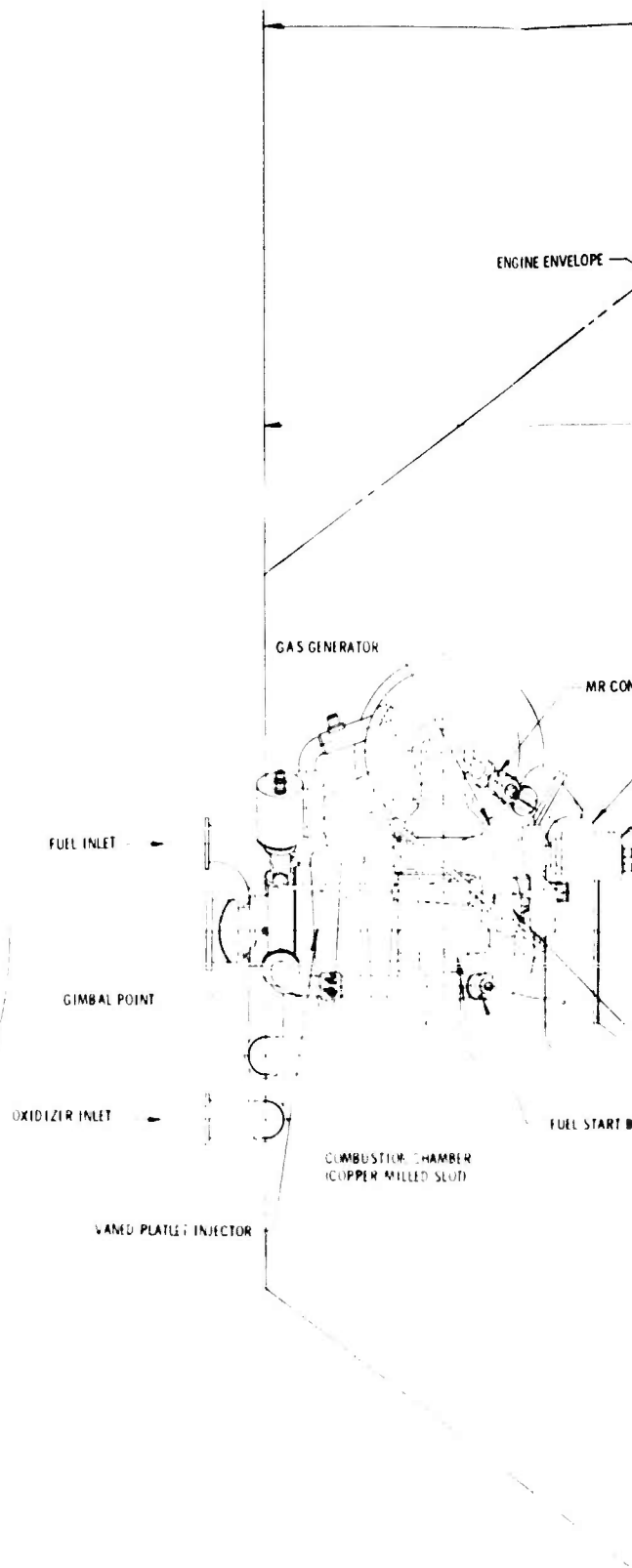
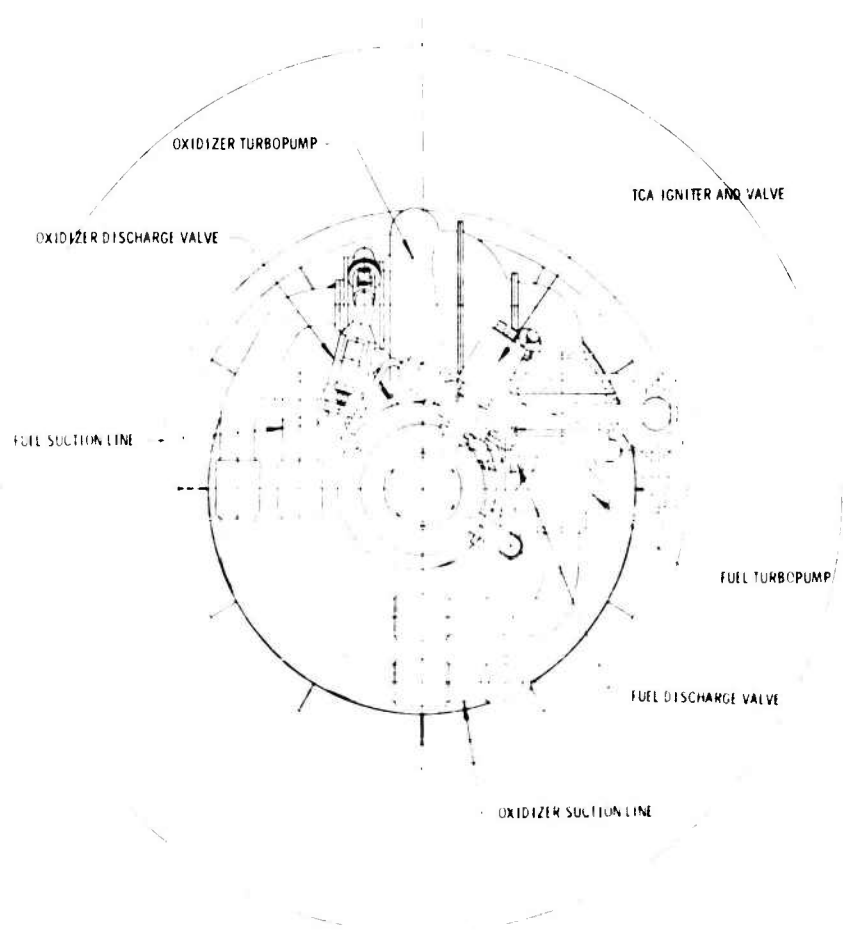
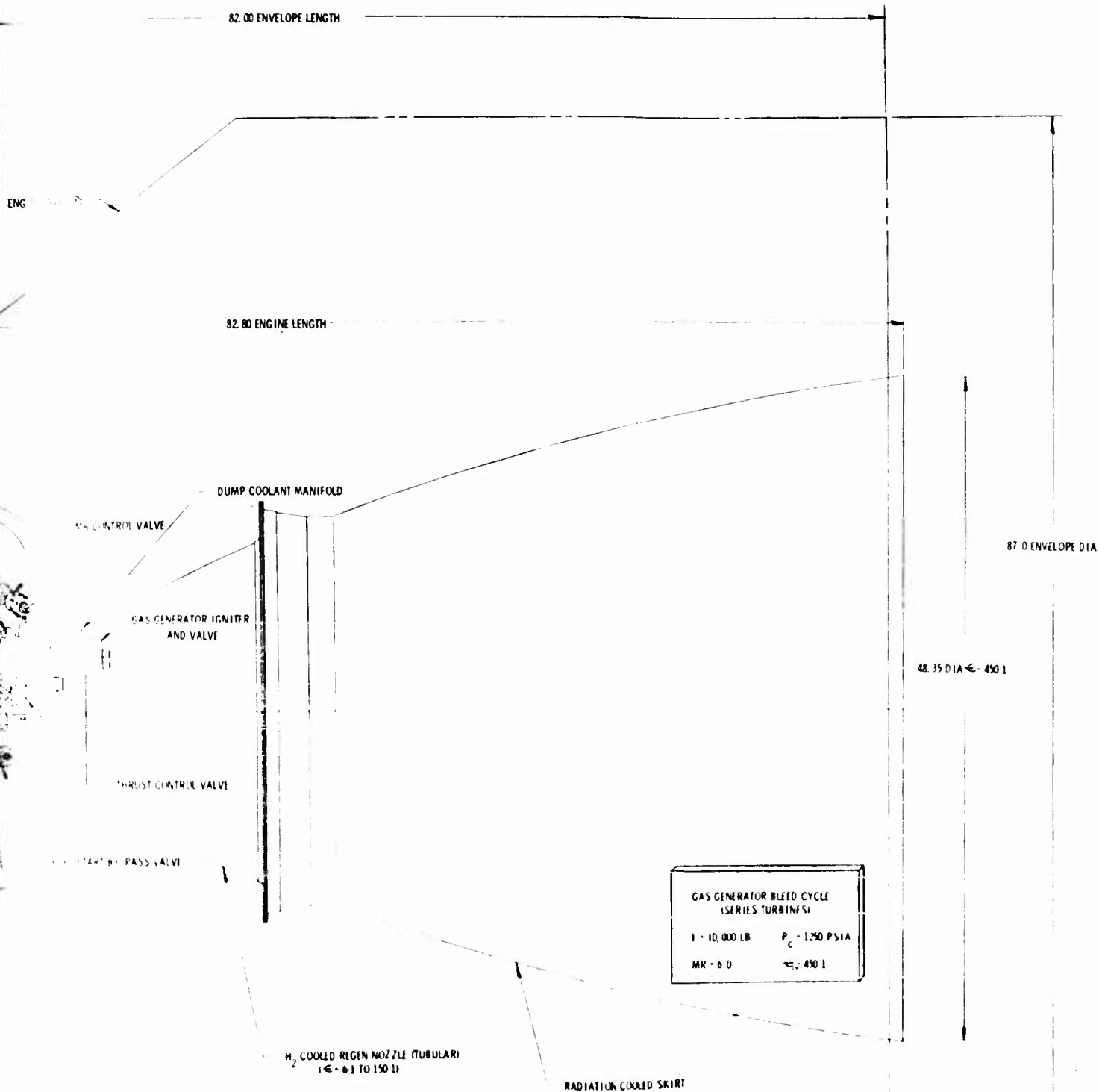


Figure 16. Configur



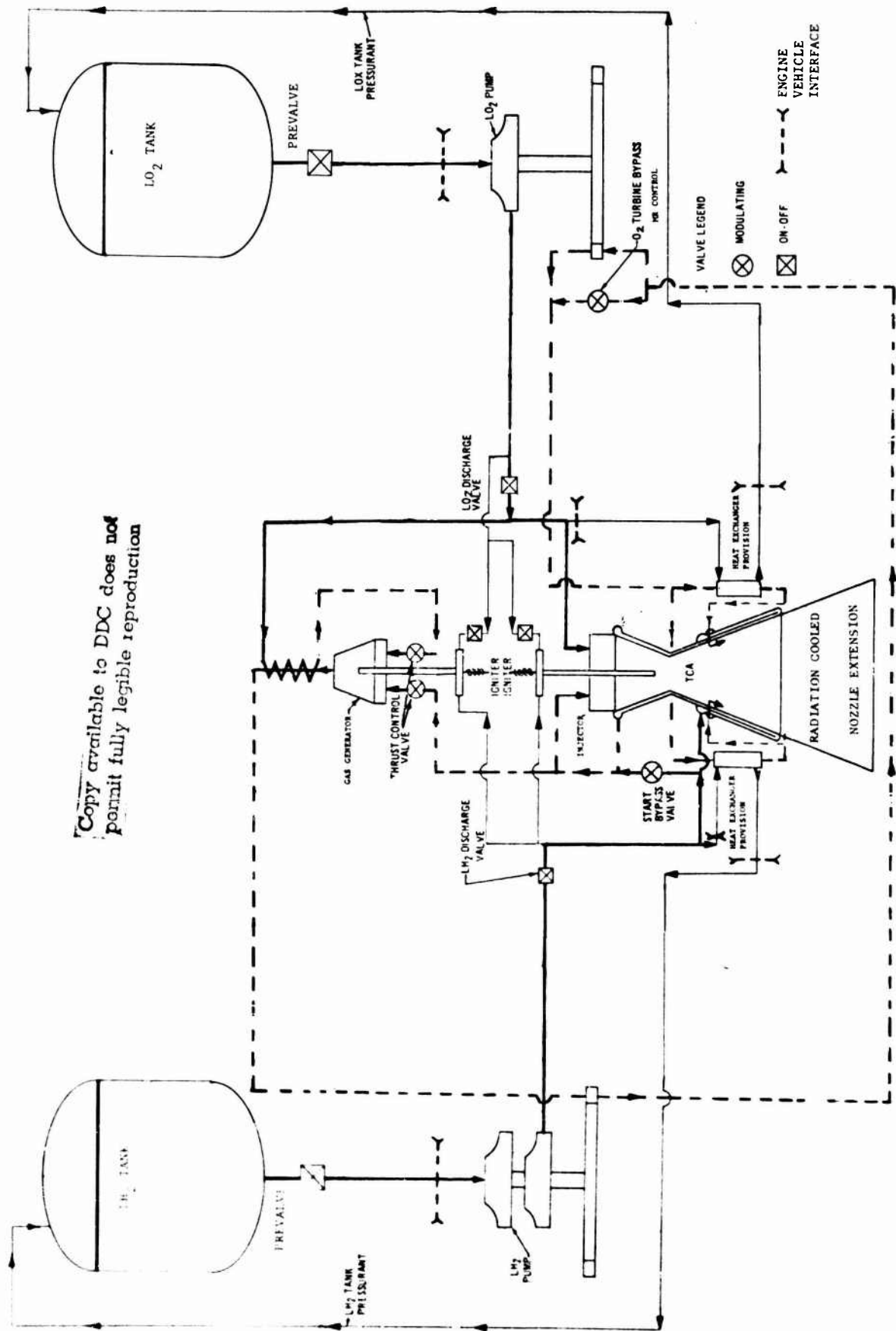


Figure 17. Engine Schematic, Gas Generator Bleed Cycle

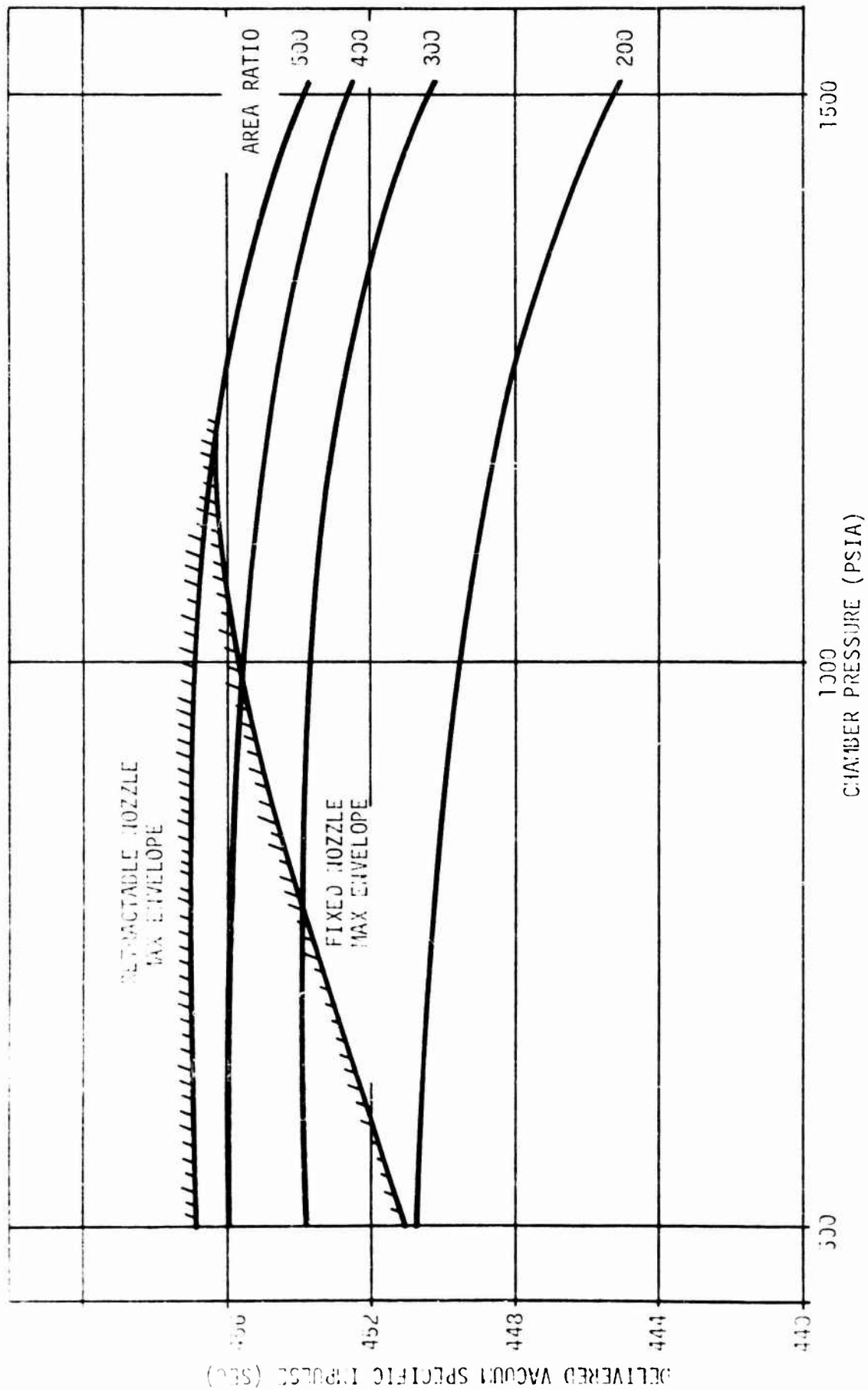


Figure 12.  $I_s$  vs  $P_c$ ,  $MR = 6$ , F-8K, Gas Generator Bleed Cycle

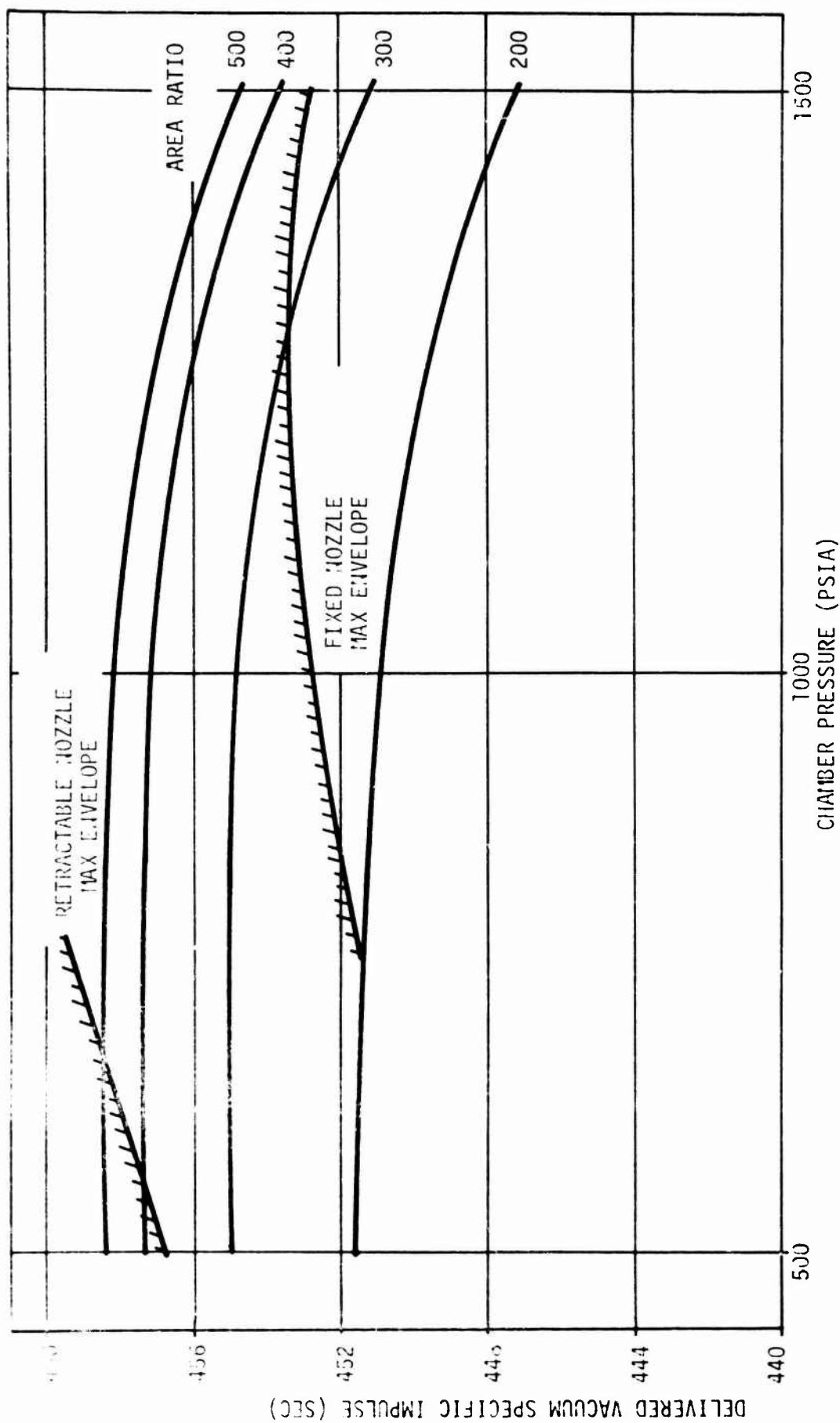


Figure 1D.  $I_s$  vs  $P_c$ ,  $MR = 6$ ,  $F = 15K$ , Gas Generator Bleed Cycle

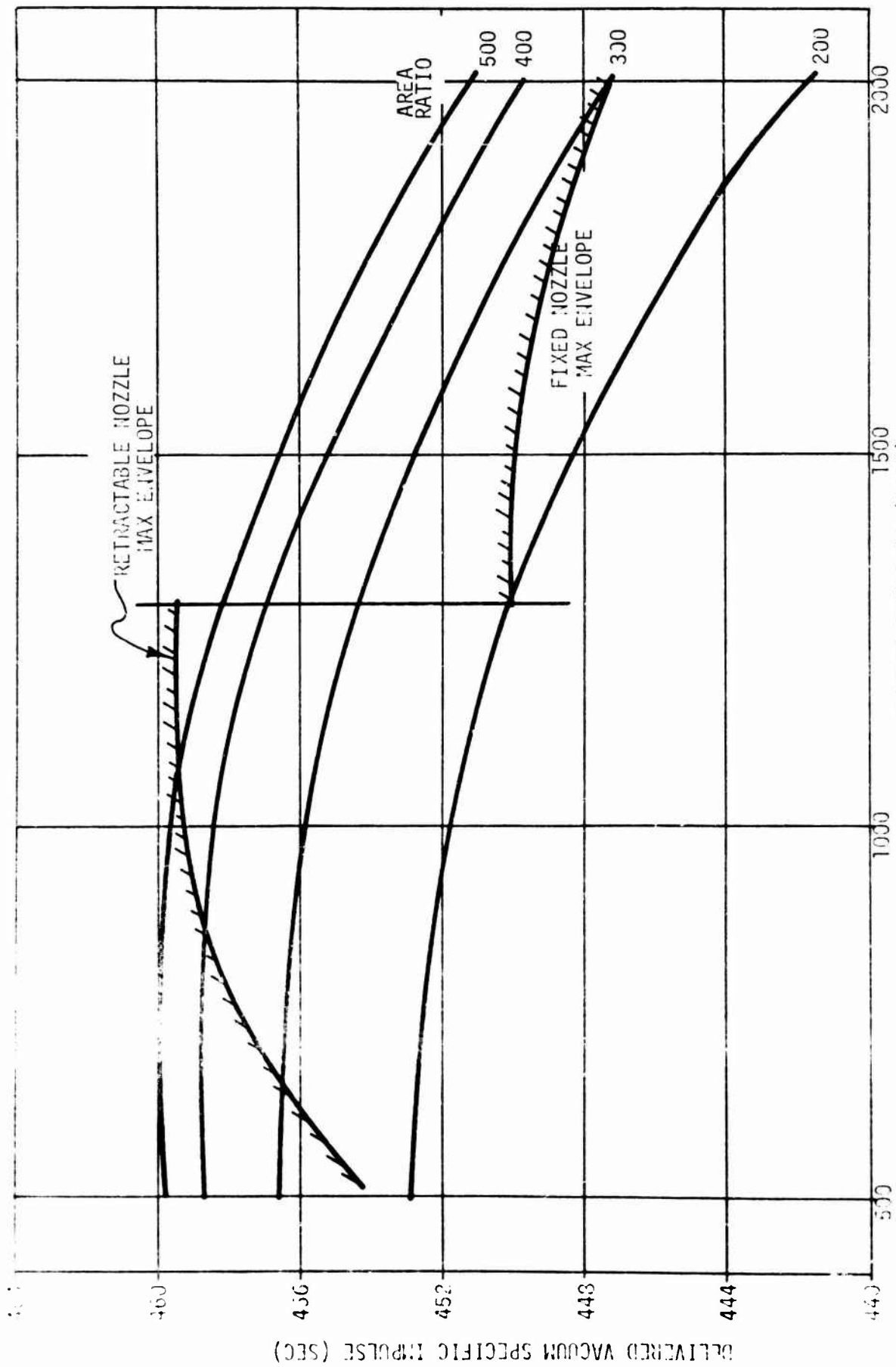


Figure 20.  $I_s$  vs  $P_c$ ,  $IR = 6$ ,  $F = 25K$ , Gas Generator Bleed Cycle

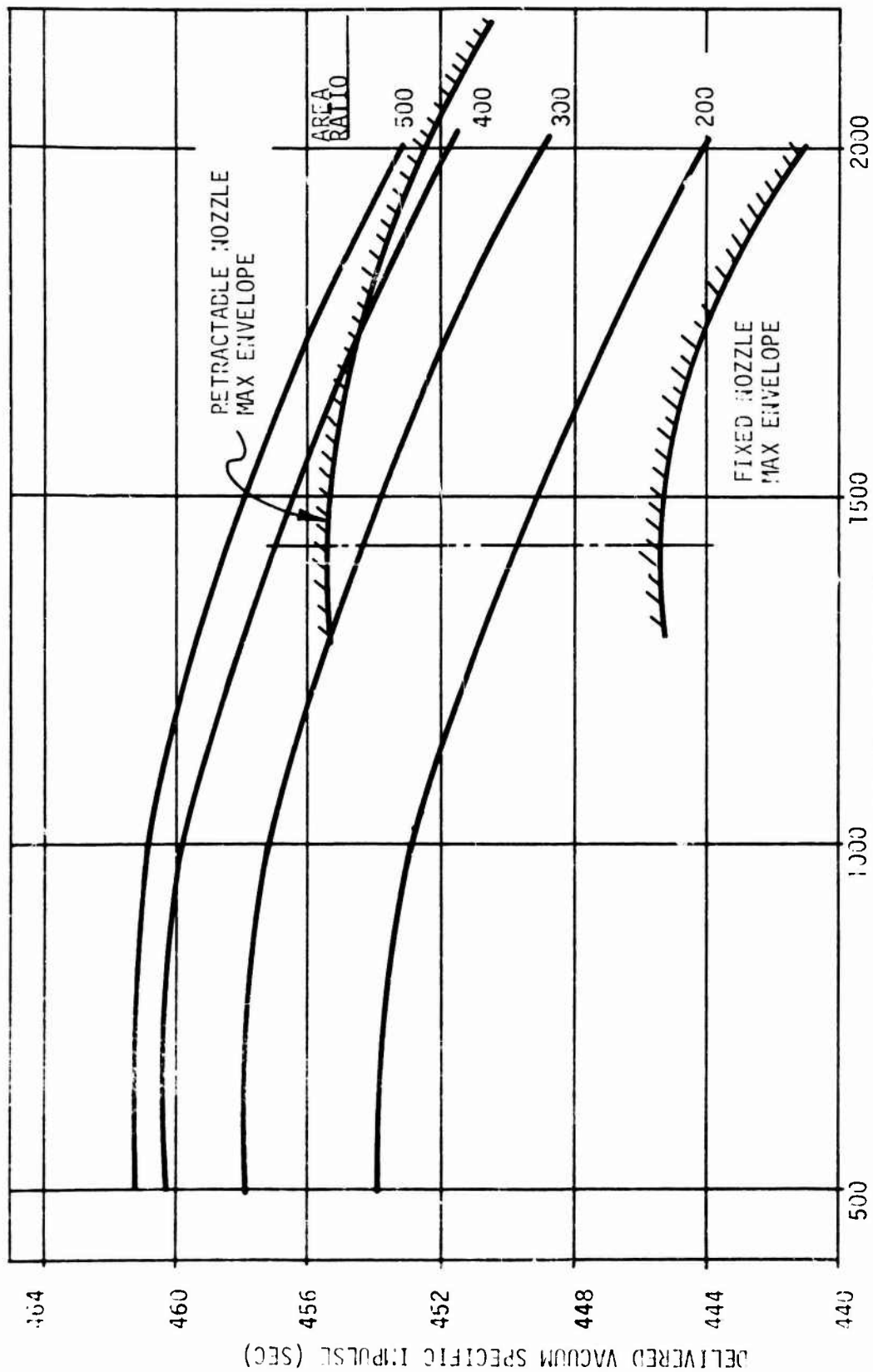


Figure 21.  $I_s$  vs  $P_c$ ,  $M = 6$ ,  $F = 50K$ , Gas Generator Bleed Cycle

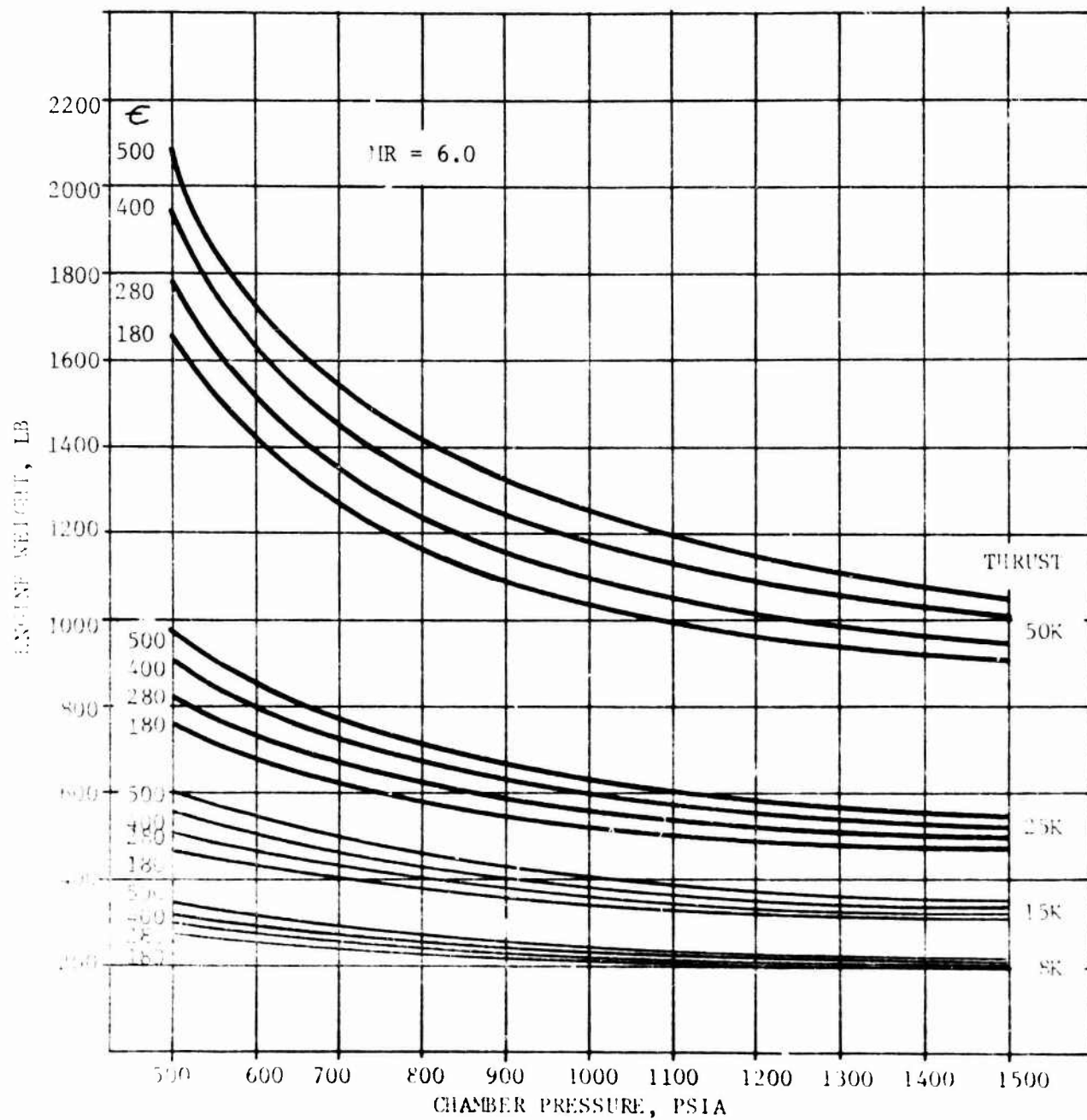


Figure 22. Engine Weight vs  $P_c$ , Fixed Nozzle, Gas Generator Bleed Cycle

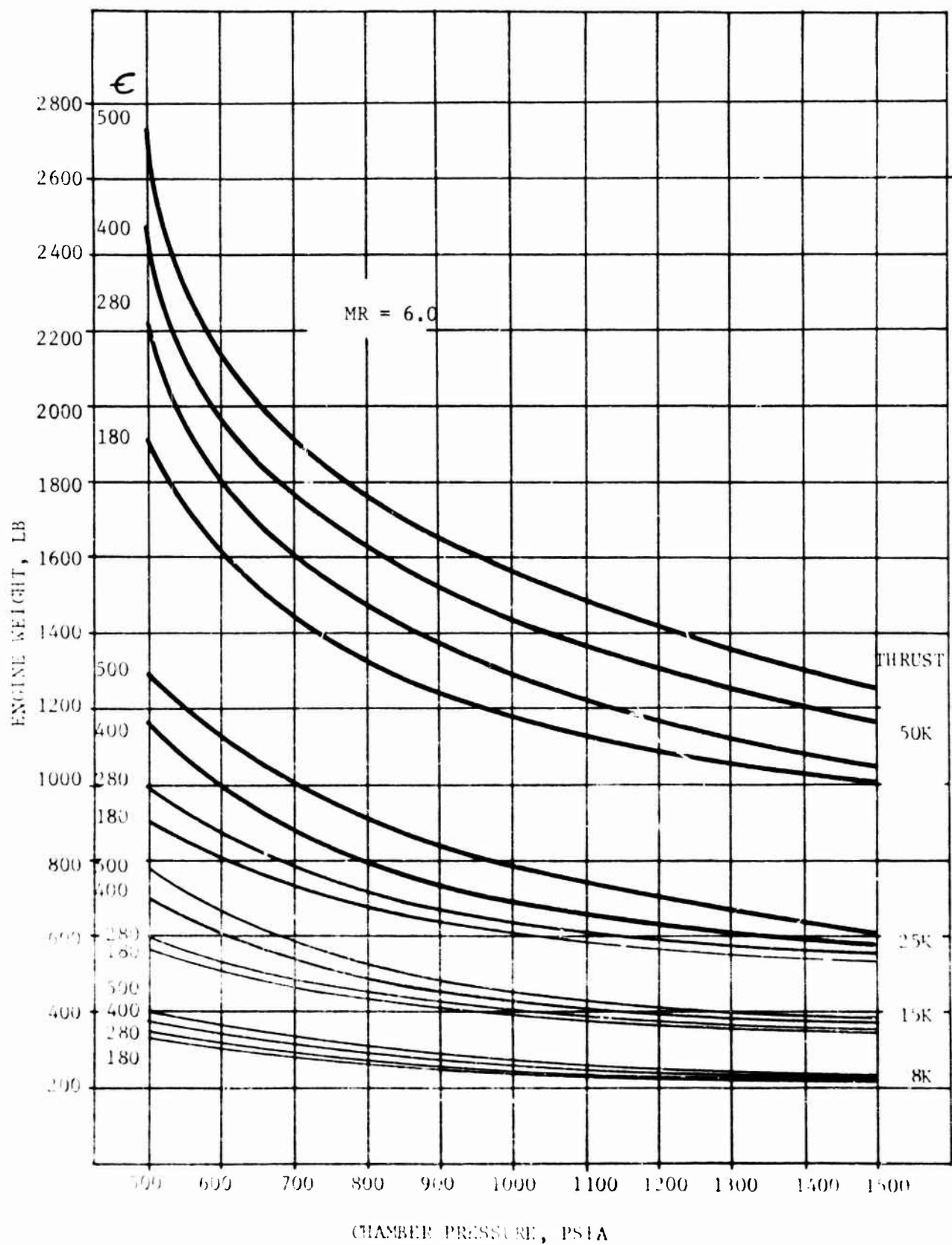


Figure 2-3. Engine Weight vs  $P_c$ , Minimum Weight Retractable Nozzle, Gas Generator Closed Cycle

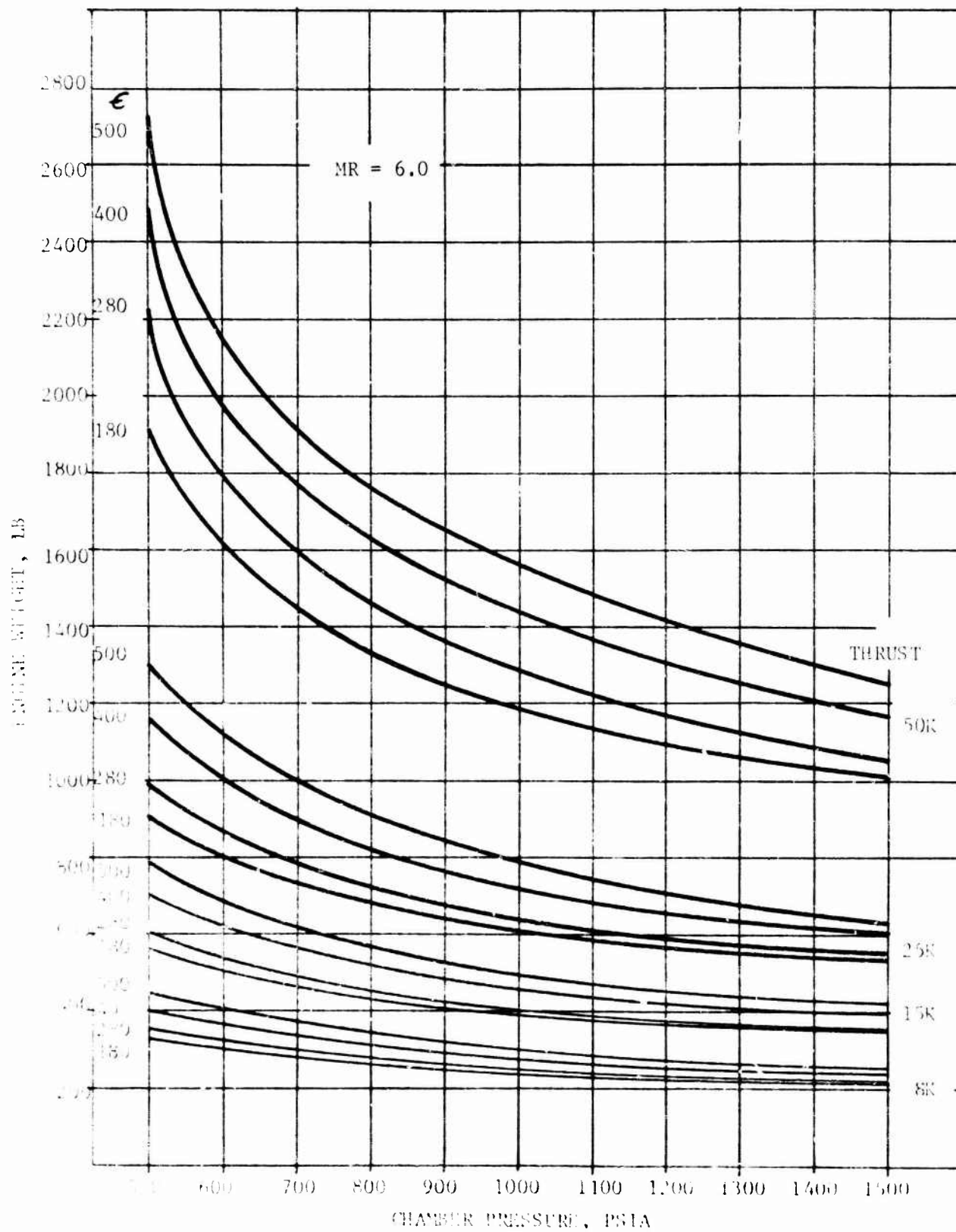


Fig. 14. Engine Weight vs  $P_c$ , Minimum Length Retractable Nozzle, Gas Generator Bleed Cycle

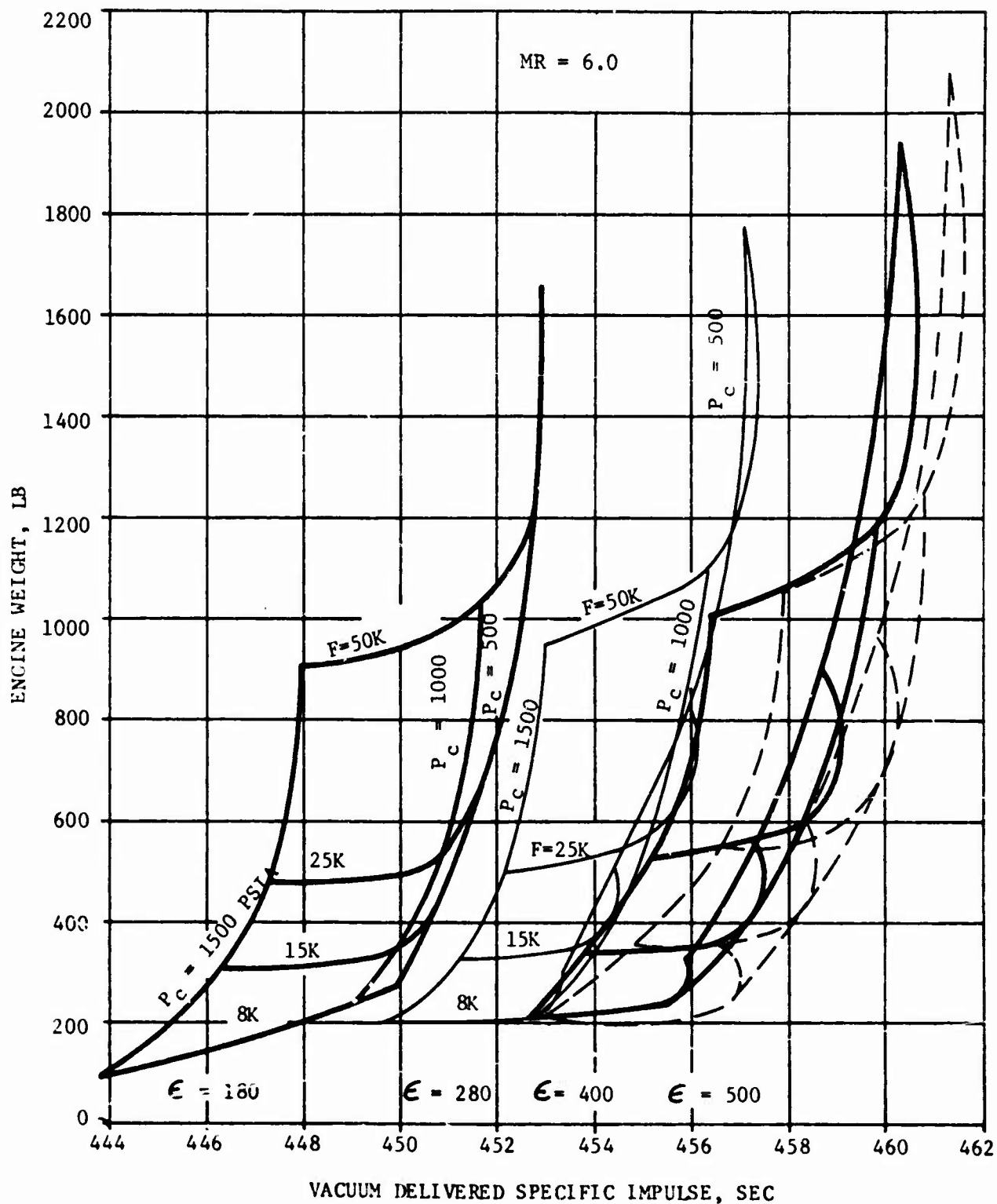


Figure 25. Engine Weight vs  $I_s$ , MR = 6 Fixed Nozzle, Gas Generator Bleed Cycle

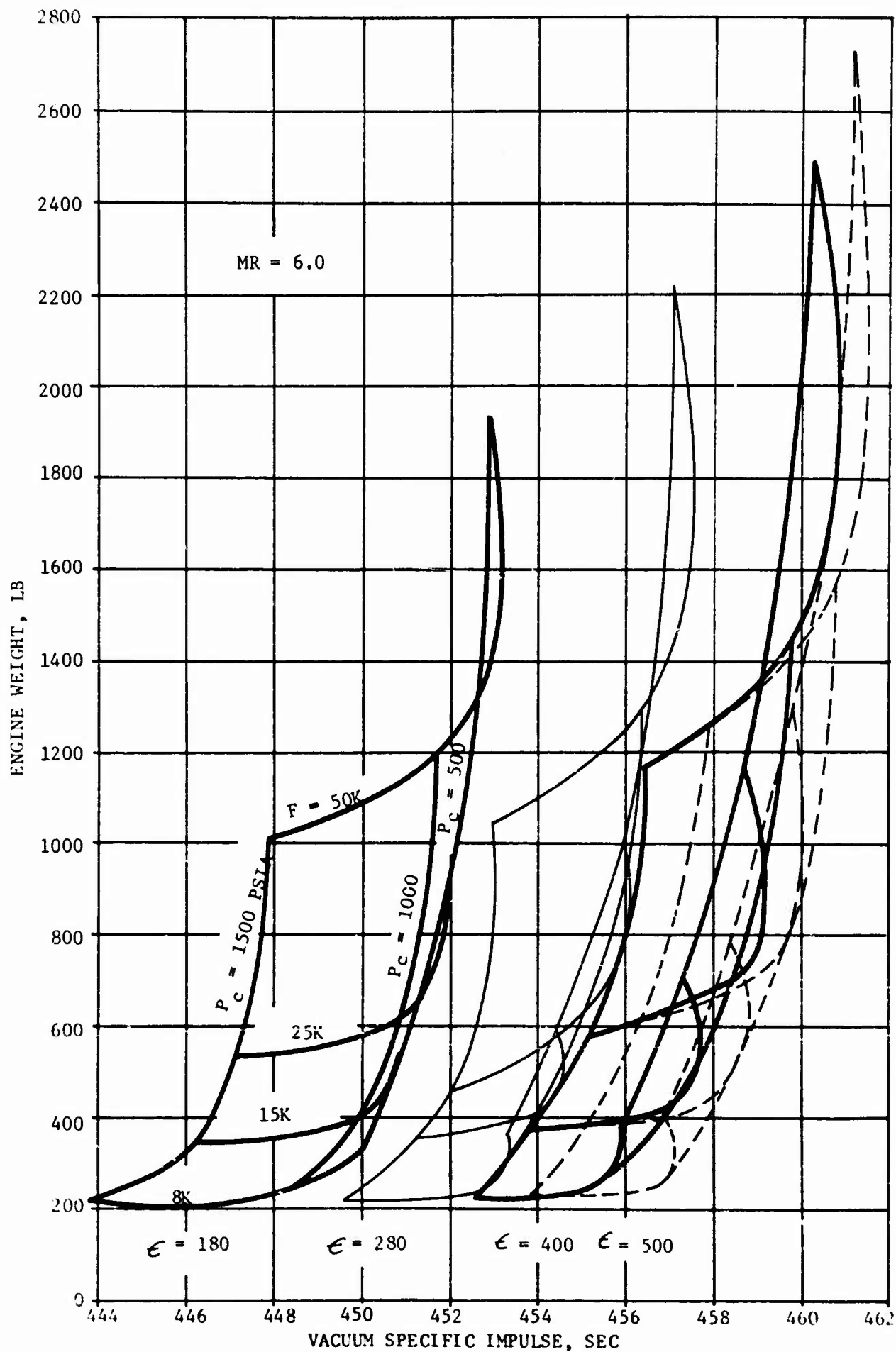


Figure 26. Engine Weight vs  $I_s$ , MR = 6, Minimum Weight Retractable Nozzle, Gas Generator Bleed Cycle

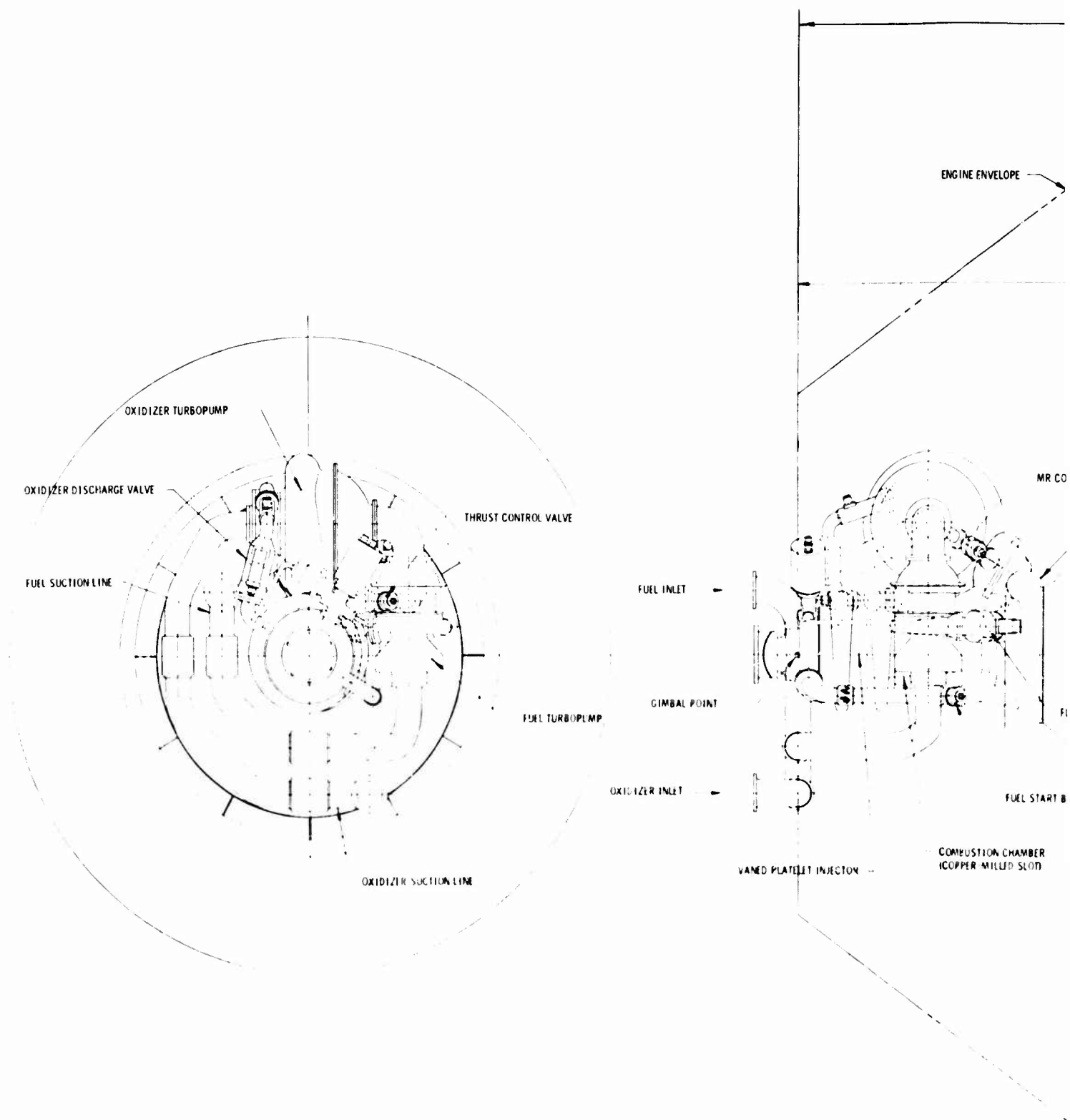
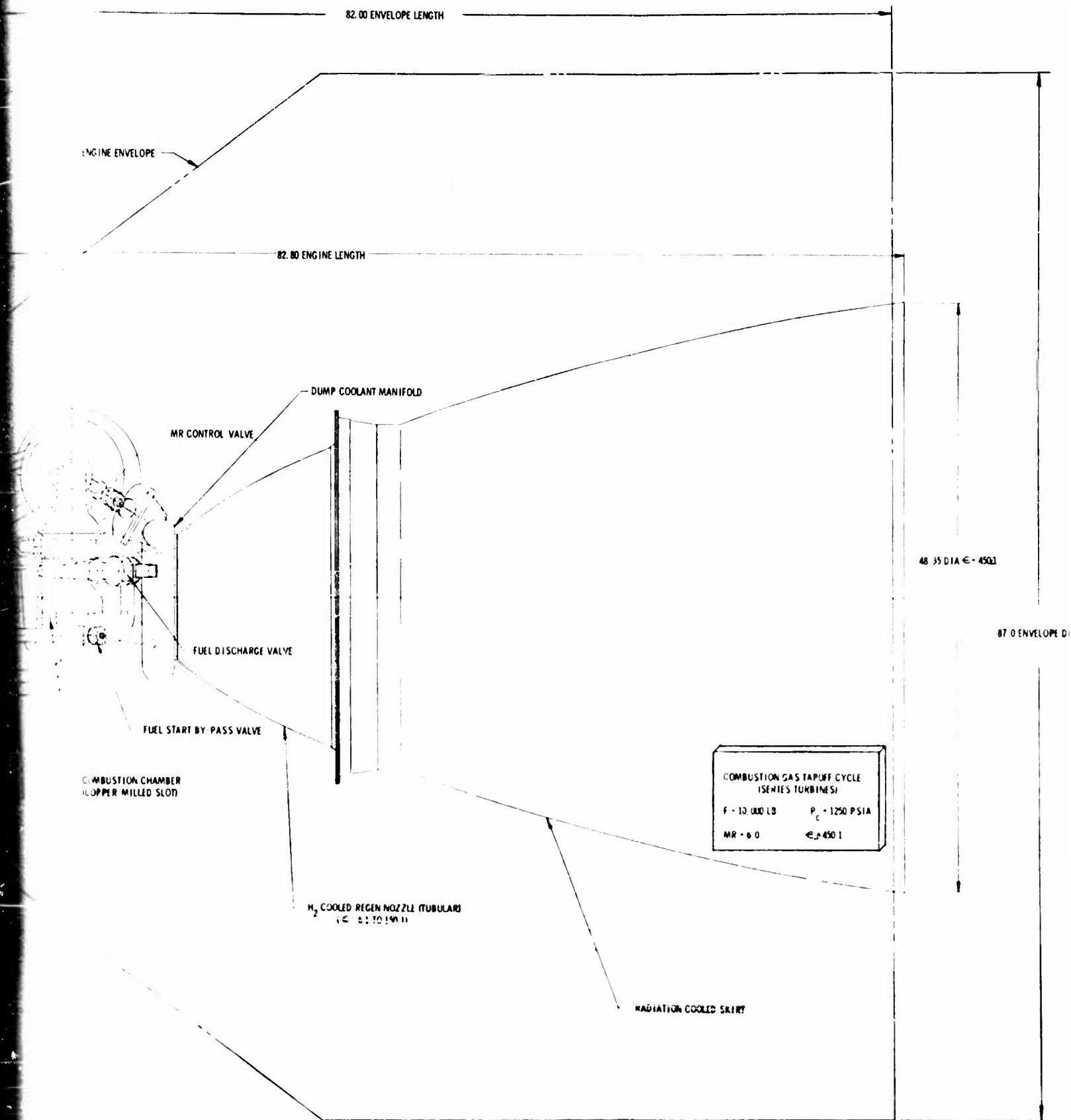


Figure 27. Configuration Drawing



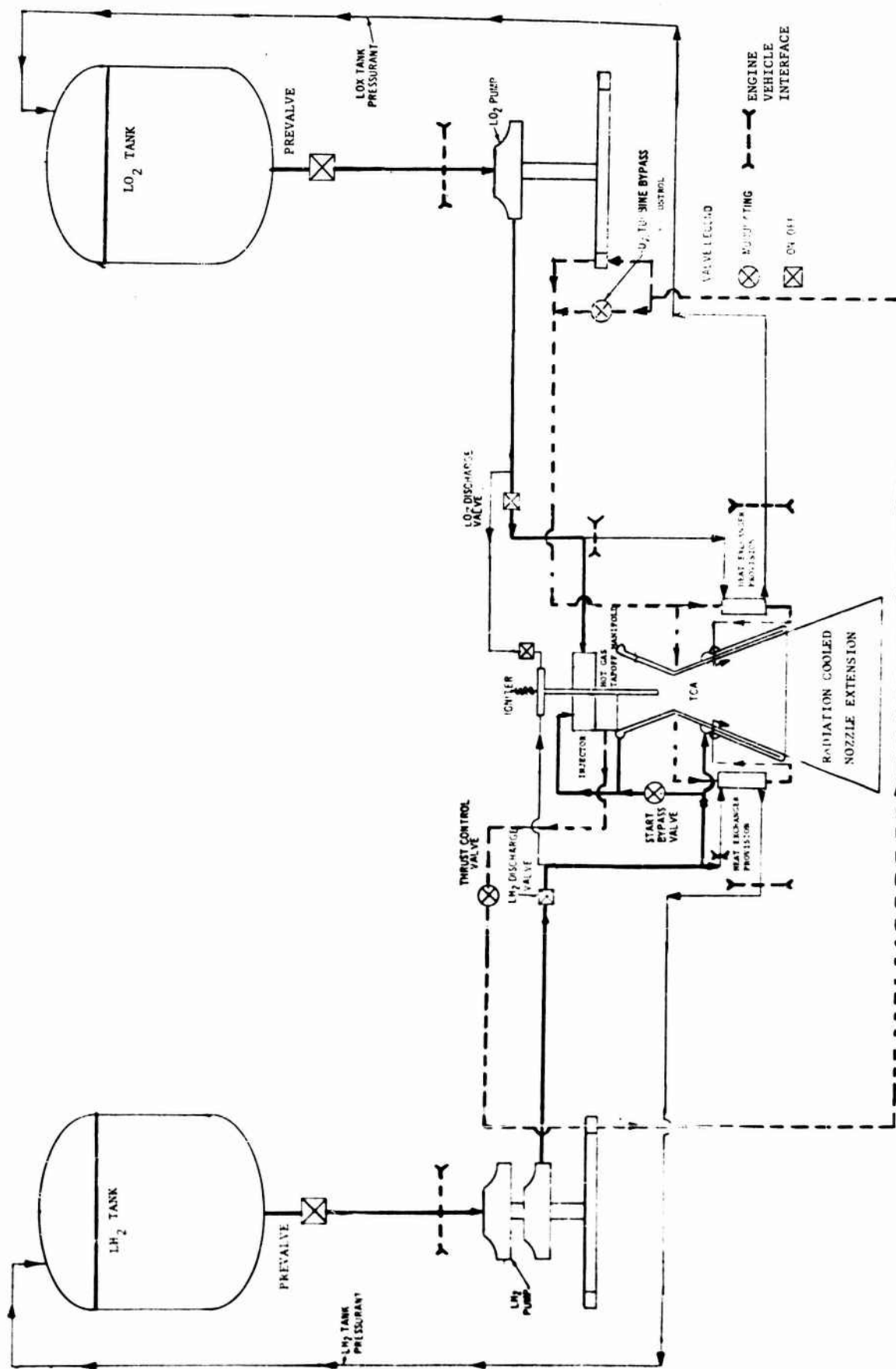


Figure 28. Engine Schematic, Combustion Gas Tapoff Cycle

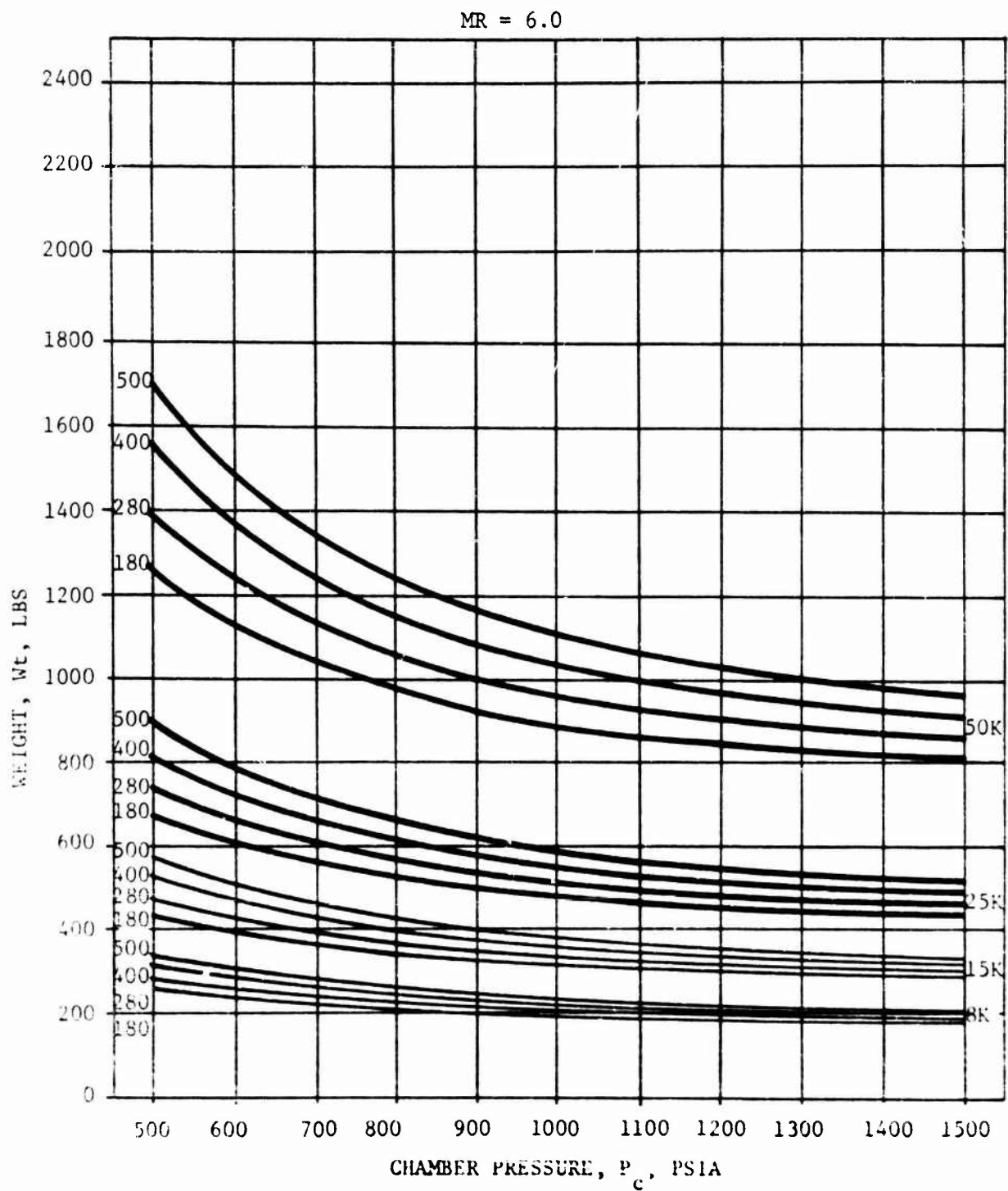


Figure 29. Engine Weight vs  $P_c$ , Fixed Nozzle, Chamber Tapoff Cycle

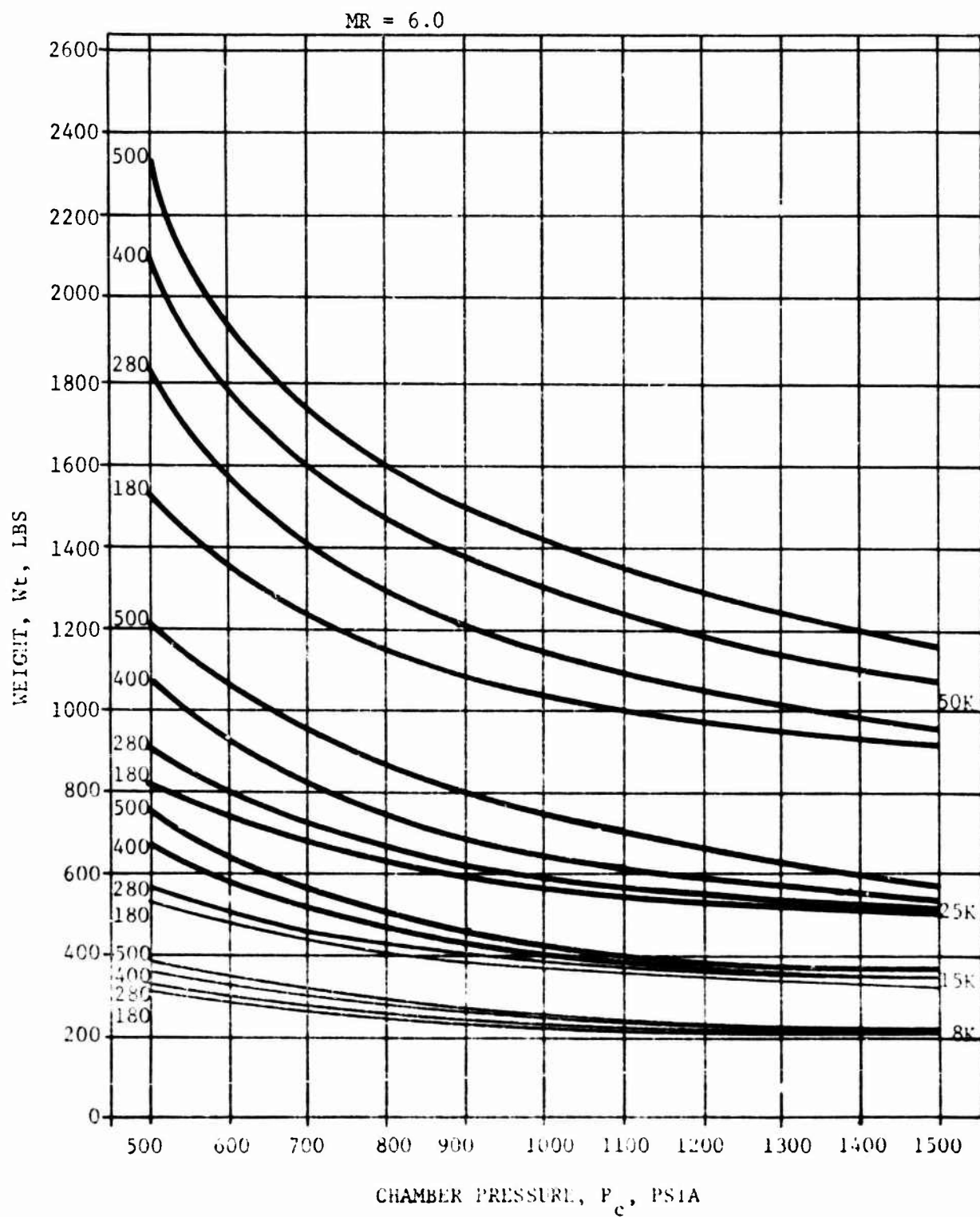


Figure 30. Engine Weight vs  $P_c$ , Minimum Weight Retractable Nozzle, Chamber Tapoff Cycle

### III. A, Engine Design Parametric Study (Task IV) (cont.)

#### (3) Coolant Bleed Cycle

This section includes the engine delivered vacuum performances and calculated engine weight as functions of thrust chamber pressure and expansion area ratio including the interaction of weight and engine performance. All weights include low speed pumps.

Figure 31 is a configuration drawing of the coolant bleed cycle engine and Figure 32 is a schematic diagram of the cycle. Figures 33 through 36 show the engine performance. Figures 37 through 39 are weight data for the three nozzle configurations. Figures 40 and 41 depict the interaction of engine weight and performance.

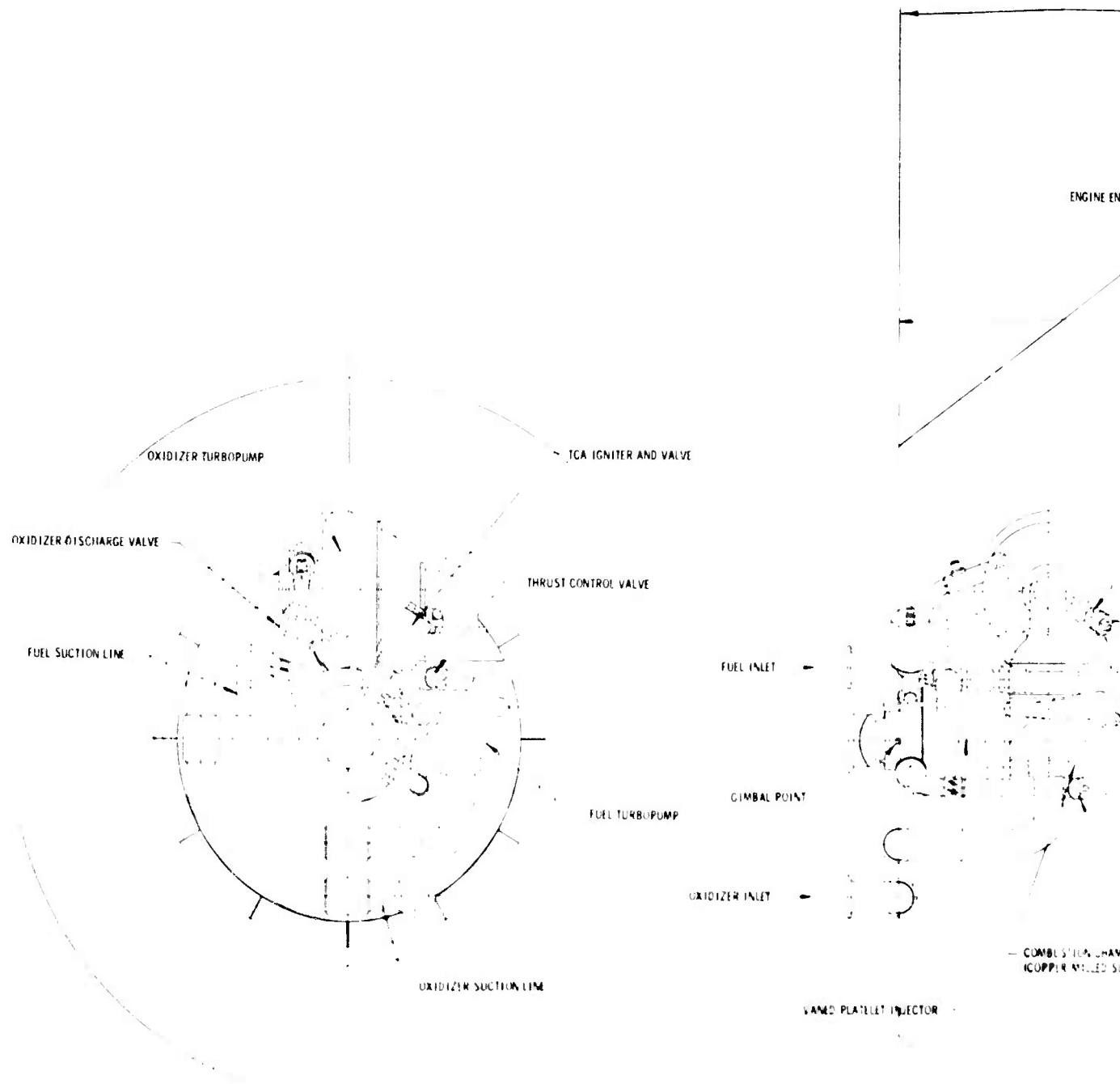


Figure 31. Configuration Dr.

82.00 ENVELOPE LENGTH

ENGINE ENVELOPE

82.80 ENGINE LENGTH

DUMP COOLANT MANIFOLD

MR CONTROL VALVE

FUEL DISCHARGE VALVE

FUEL START BY PASS VALVE

COMBUSTION CHAMBER  
HC PPEP-MILLED SLOT

H<sub>2</sub> COOLED REGEN NOZZLE (TUBULAR)  
HC - 6.1 TO 150.1

| COOLANT TAPOFF CYCLE<br>(SERIES TURBINES) |                        |
|-------------------------------------------|------------------------|
| F - 10,000 LB                             | P <sub>c</sub> - 1,250 |
| MR - 0.0                                  | C <sub>p</sub> 450.1   |

87.0 ENVELOPE DIA

48.35 DIA @ 450.1

RADIATING COOLED SKIRT

2

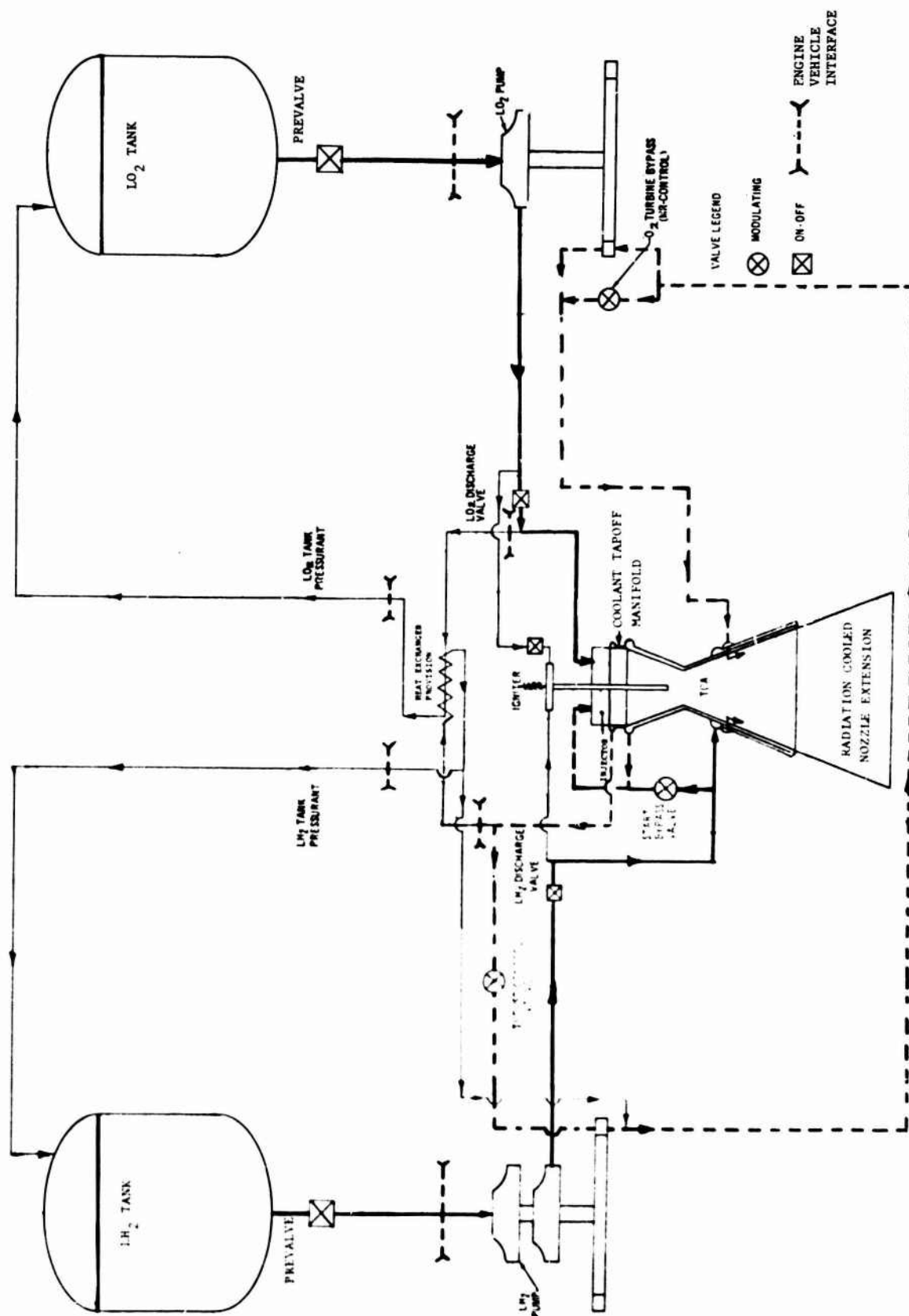


Figure 32. Engine Schematic, Coolant Bleed Cycle

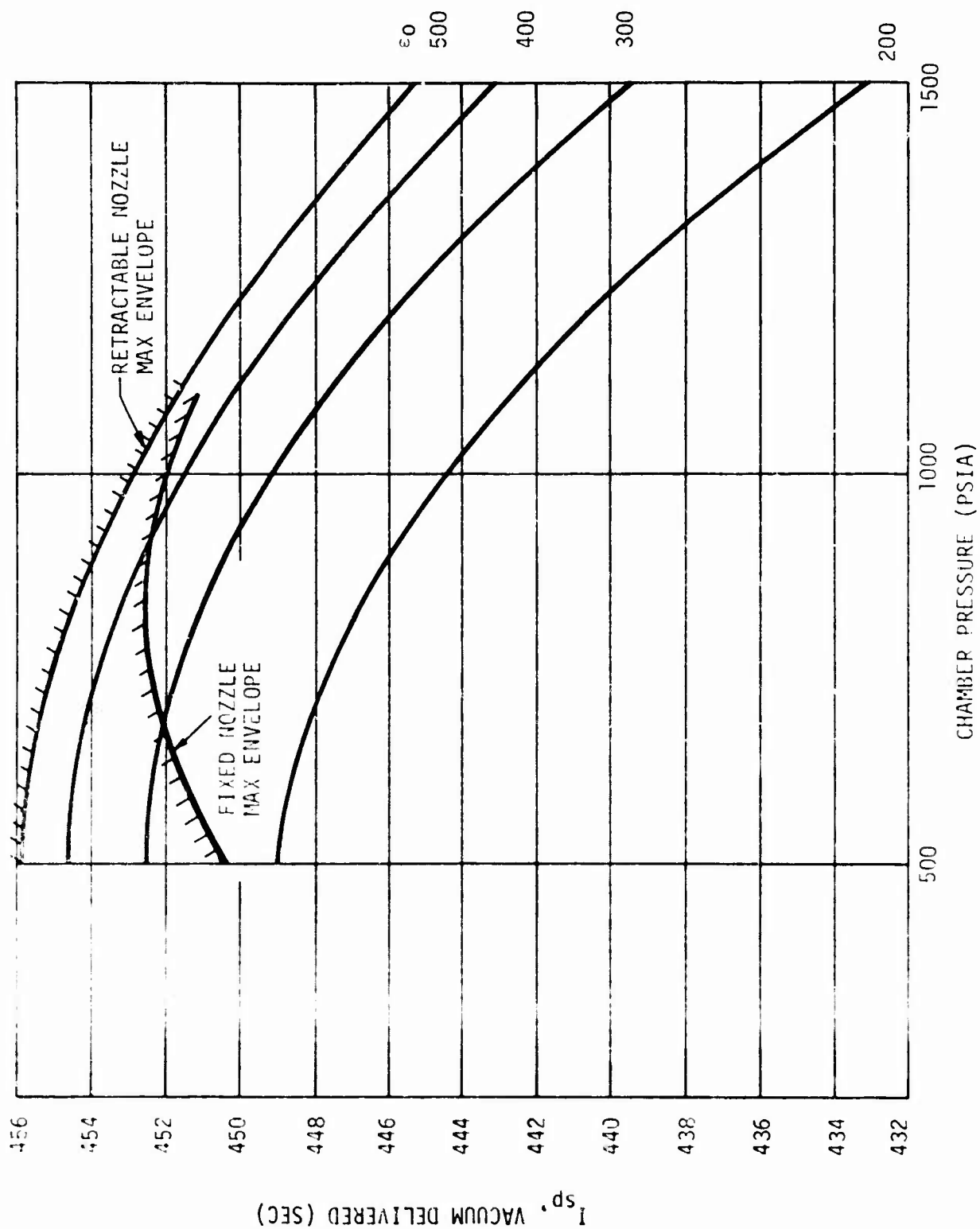


Figure 33.  $I_s$  vs  $P_c$ ,  $MR = 6$ ,  $F = 8K$ , Coolant Bleed Cycle

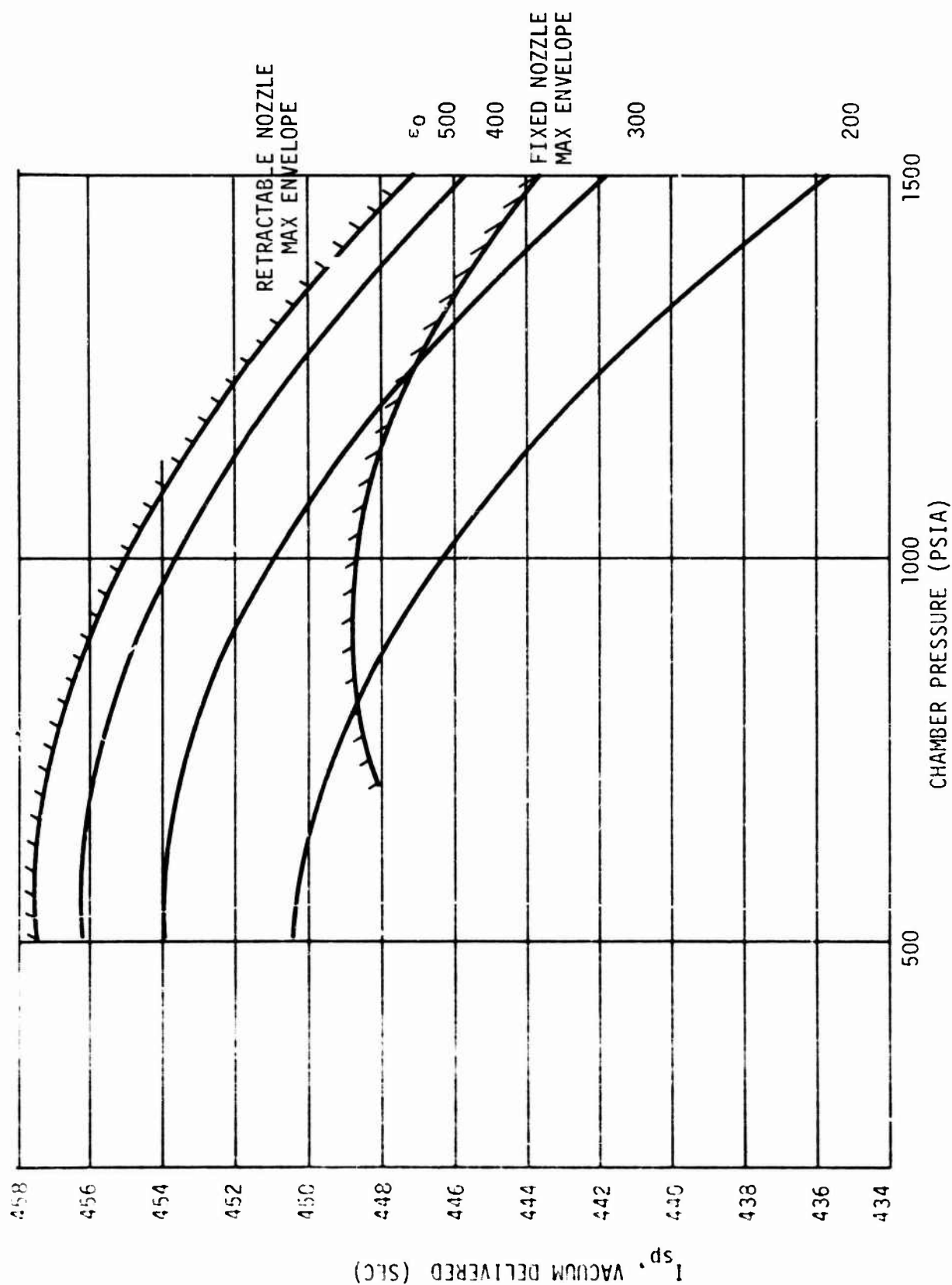


Figure 34.  $I_s$  vs  $P_c$ ,  $MR = 6$ ,  $F = 15K$ , Coolant Bleed Cycle

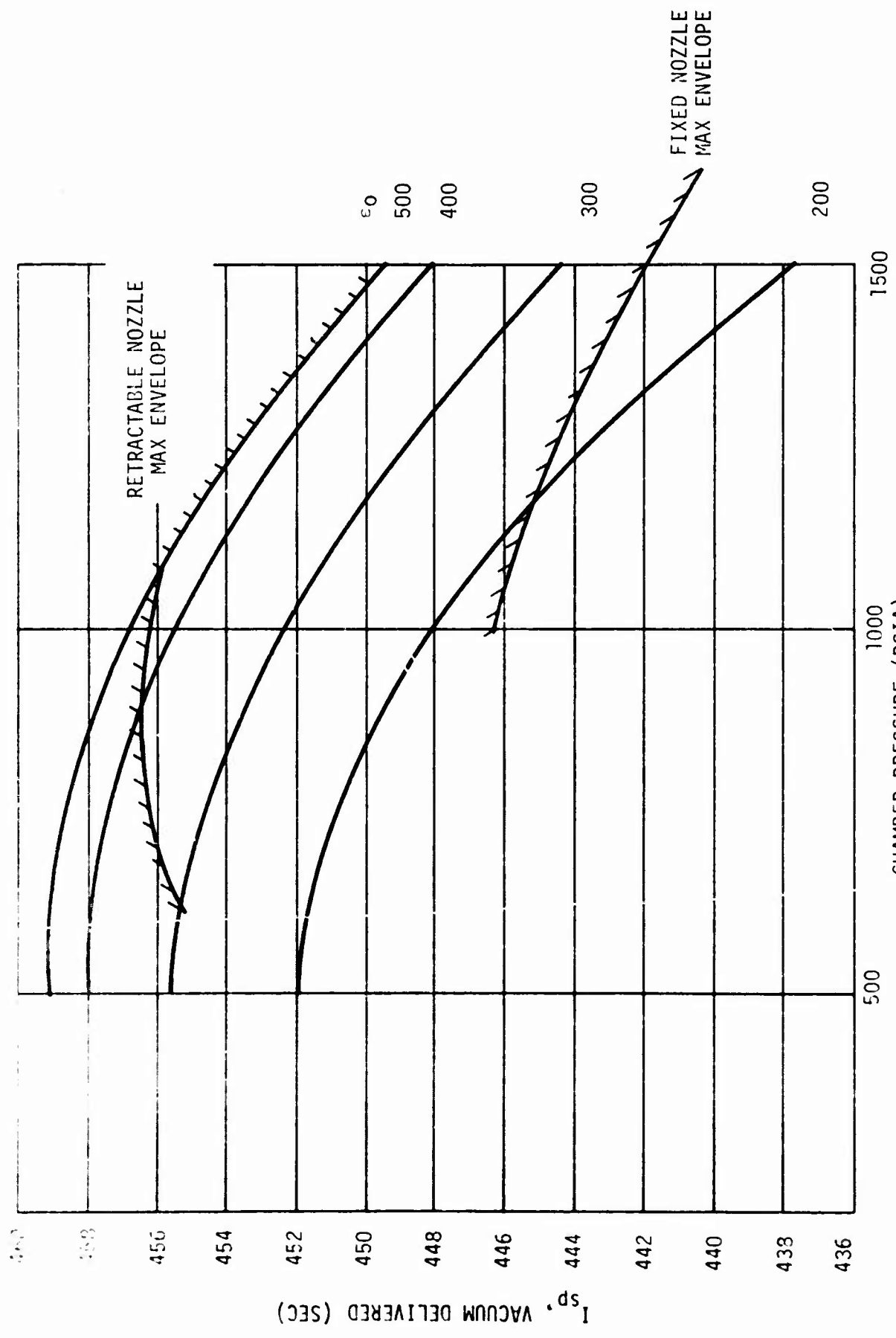


Figure 35.  $I_s$  vs  $P_c$ ,  $MR = 6$ ,  $F = 25K$ , Coolant Bleed Cycle

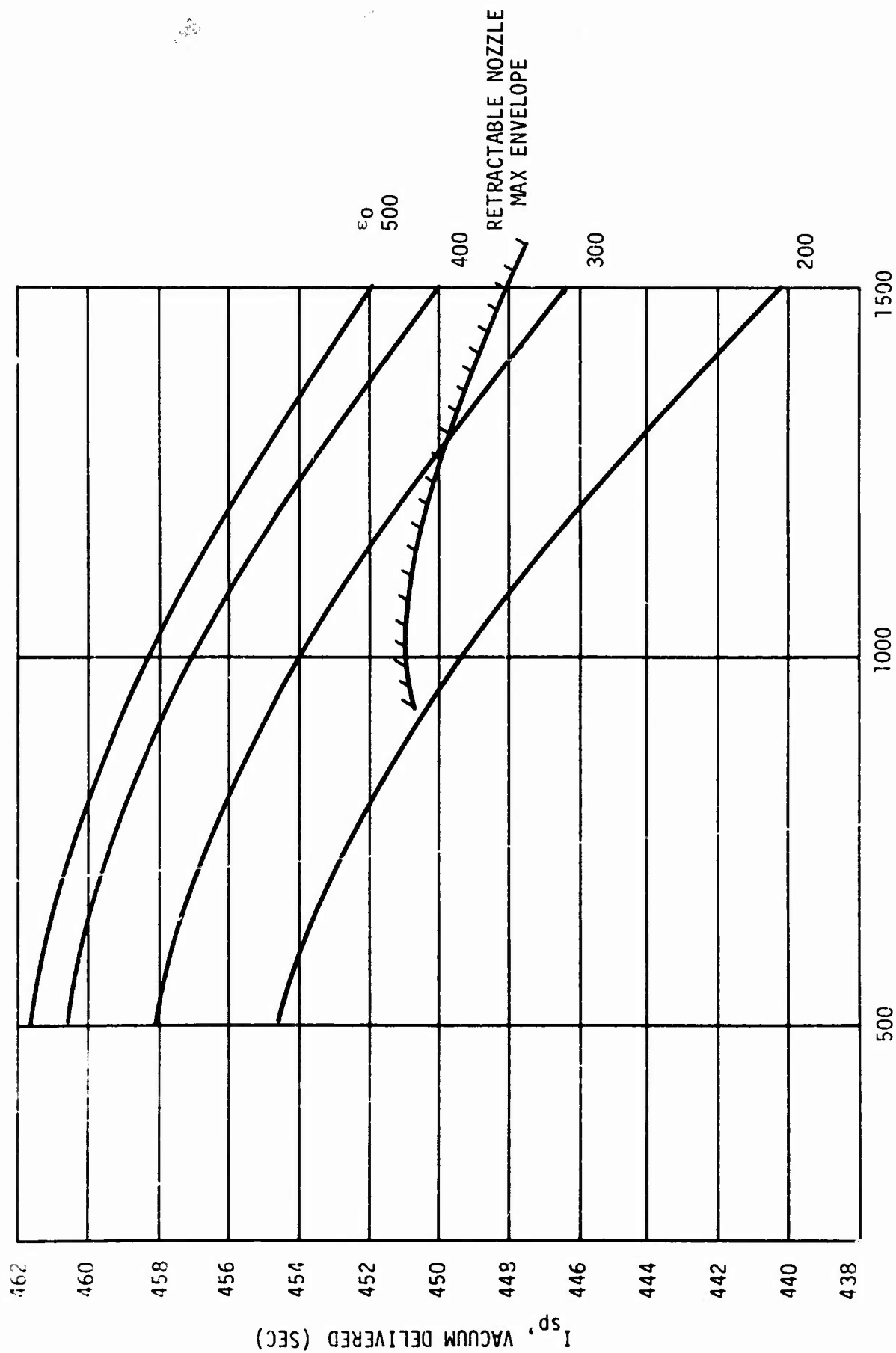


Figure 36.  $I_s$  vs  $P_c$ ,  $MR = 6$ ,  $F = 50K$ , Coolant Bleed Cycle

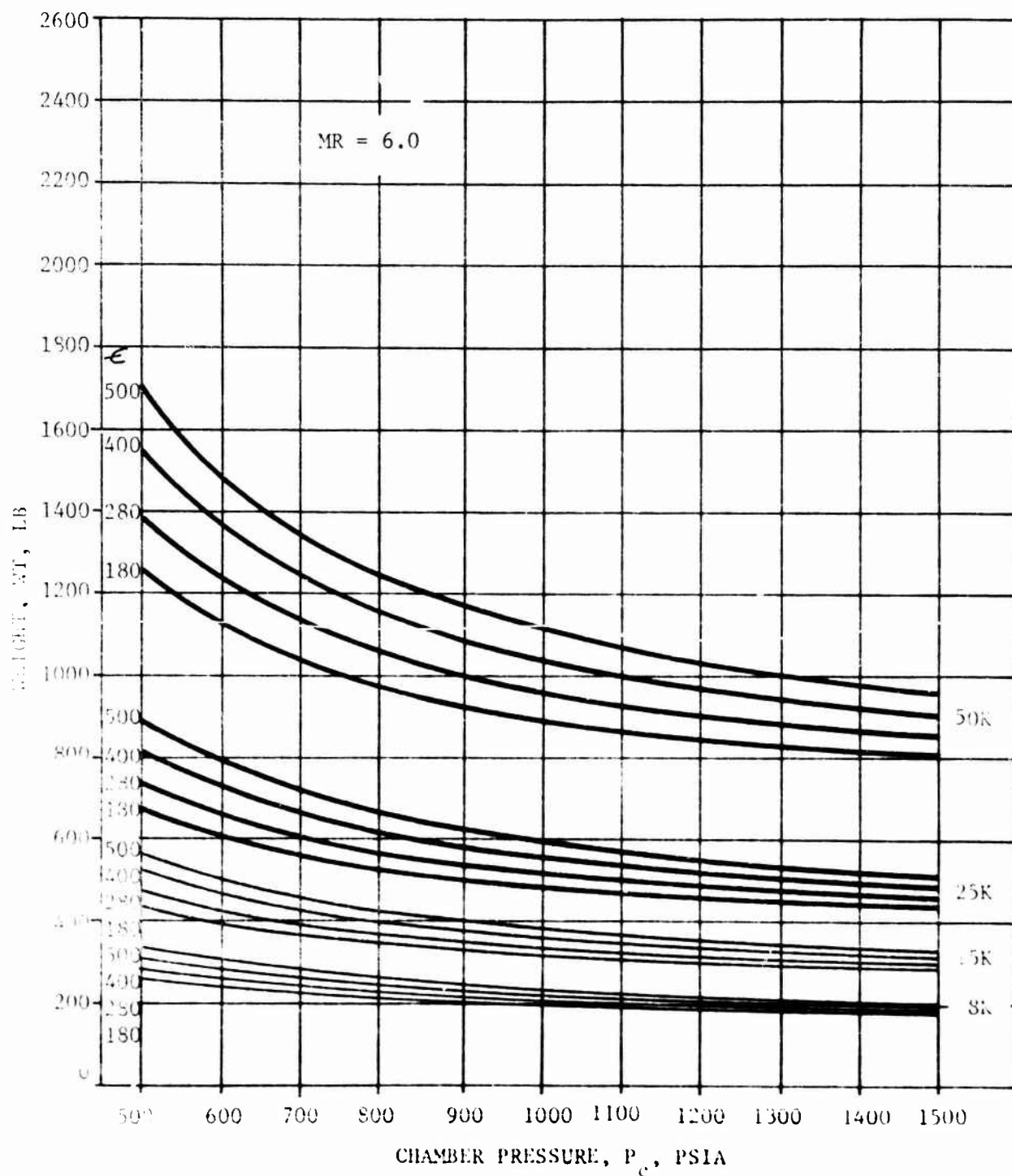


Figure 37. Engine Weight vs  $P_c$ , Fixed Nozzle, Coolant Bleed Cycle

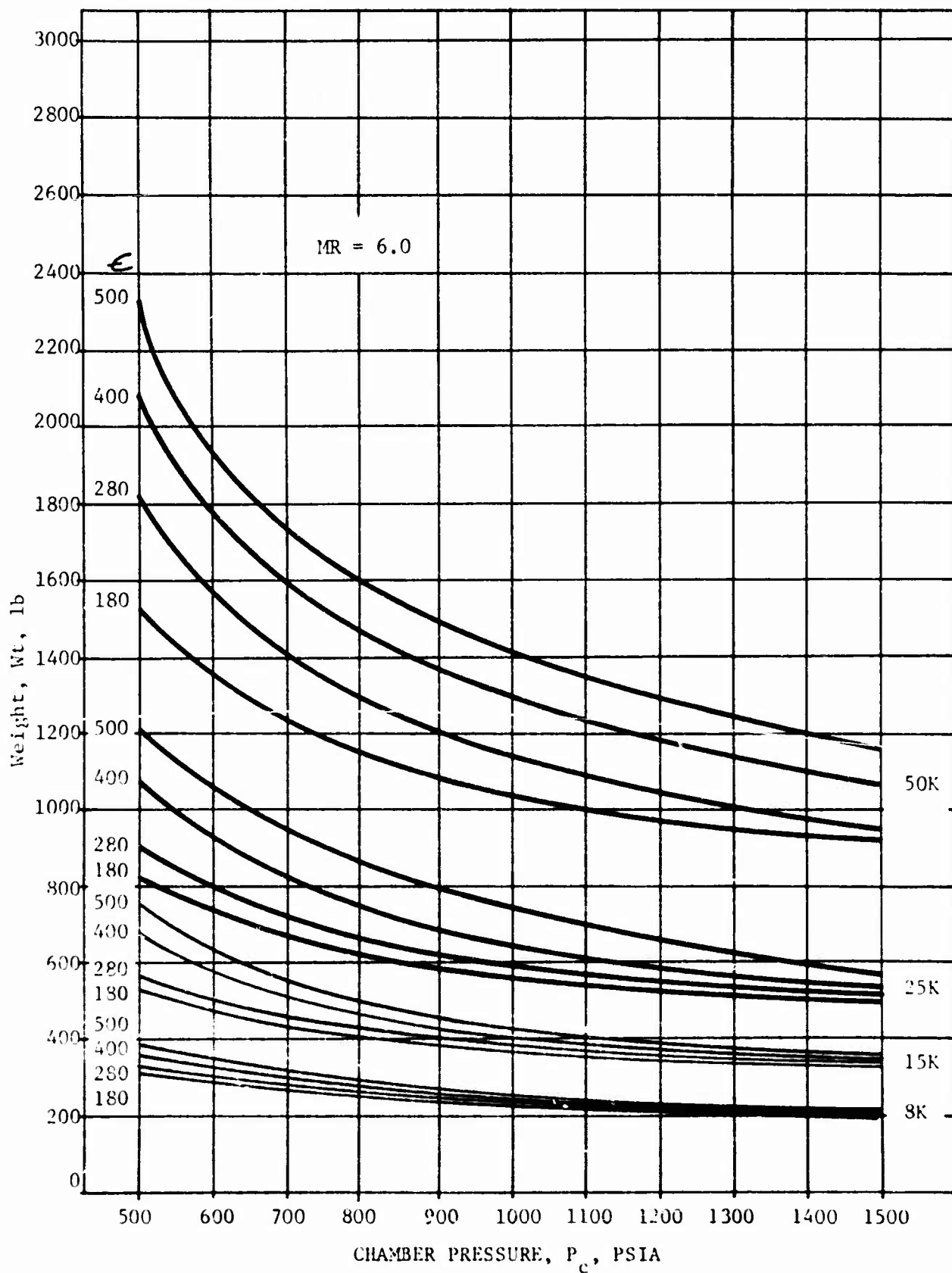


Figure 38. Engine Weight vs  $P_c$ , Minimum Weight Retractable Nozzle, Coolant Bleed Cycle

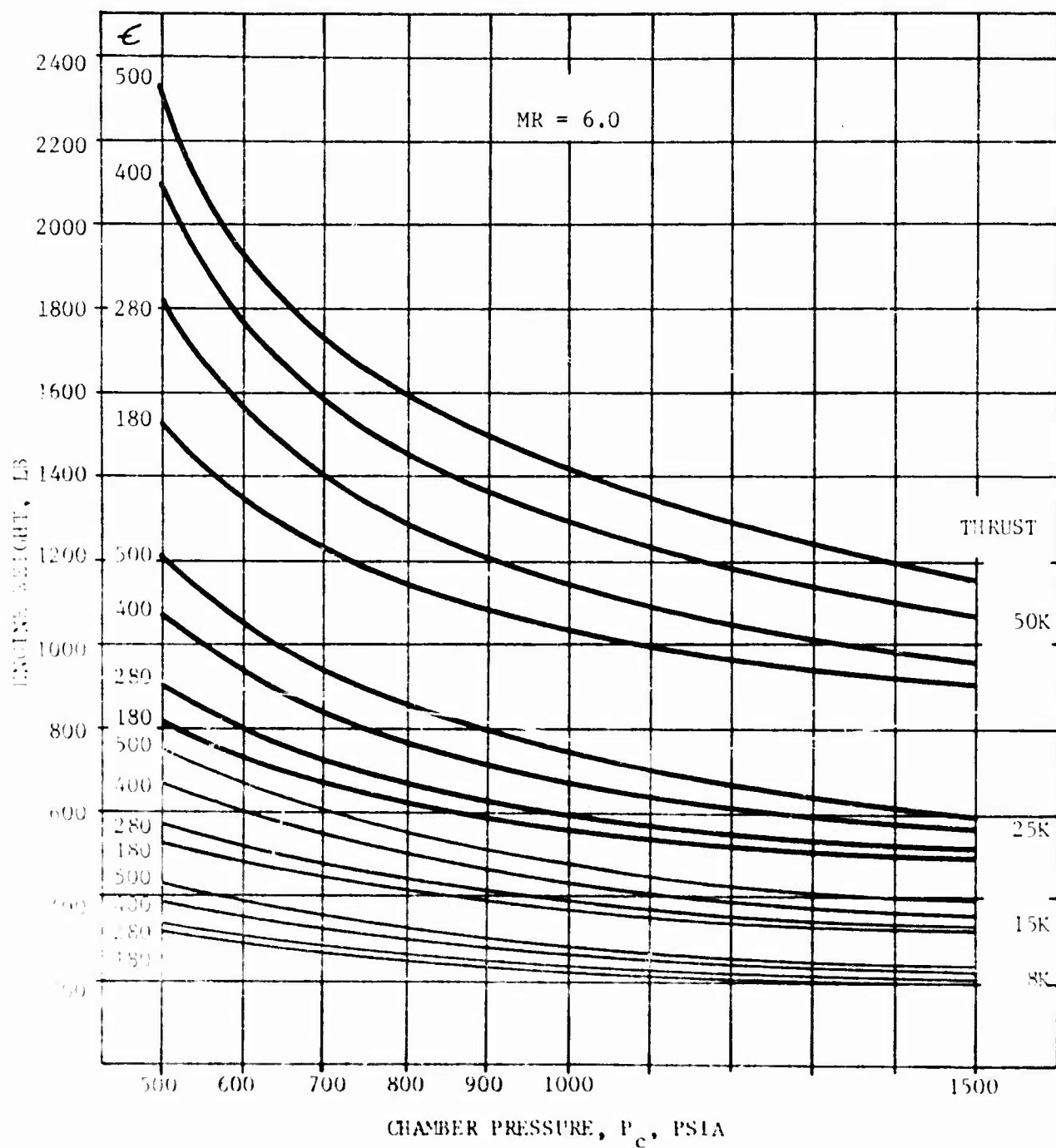


Figure 39. Engine Weight vs  $P_c$ , Minimum Length Retractable Nozzle, Coolant Bleed Cycle

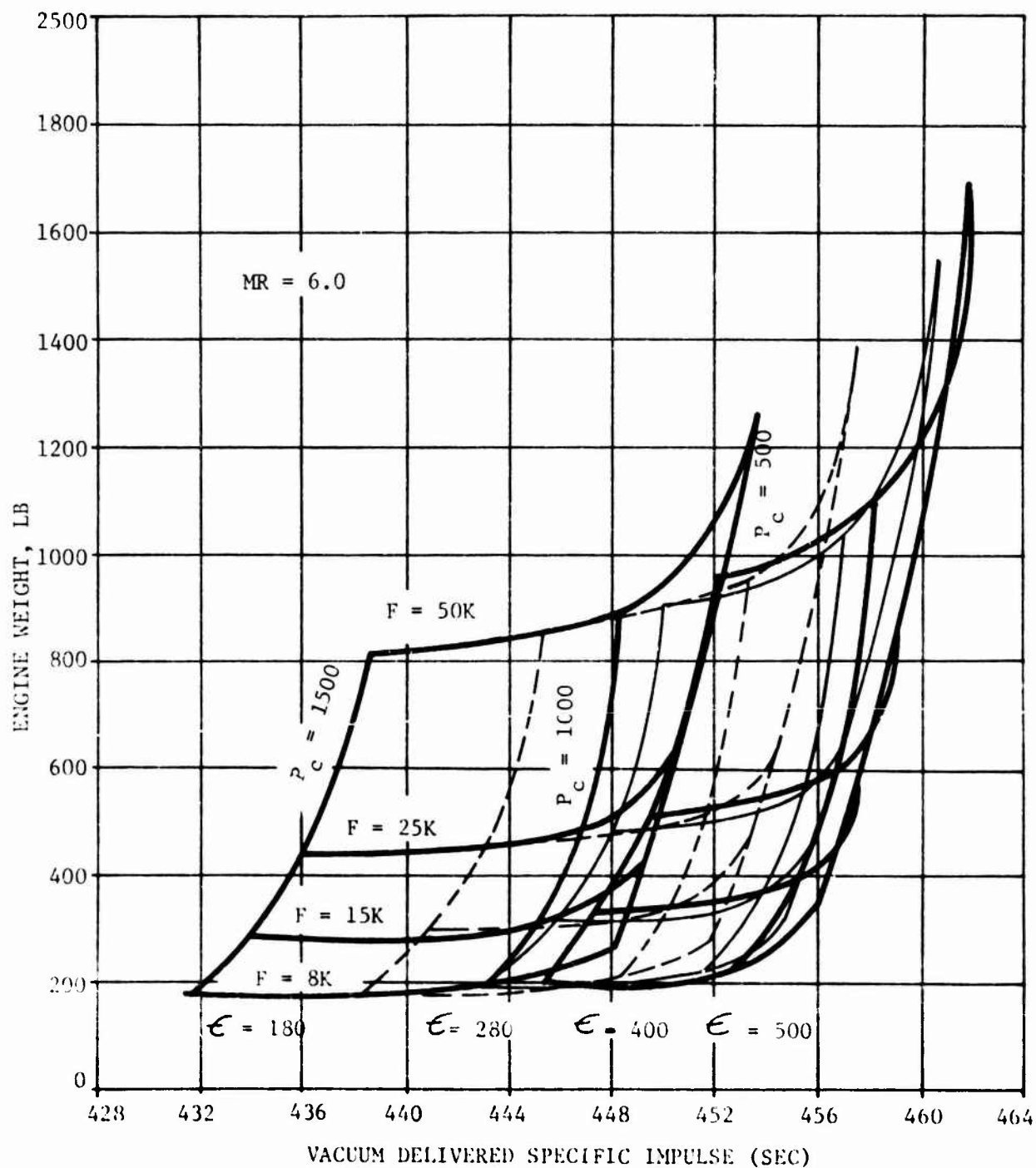


Figure 40. Engine Weight vs  $I_s$ , Fixed Nozzle, Coolant Bleed Cycle

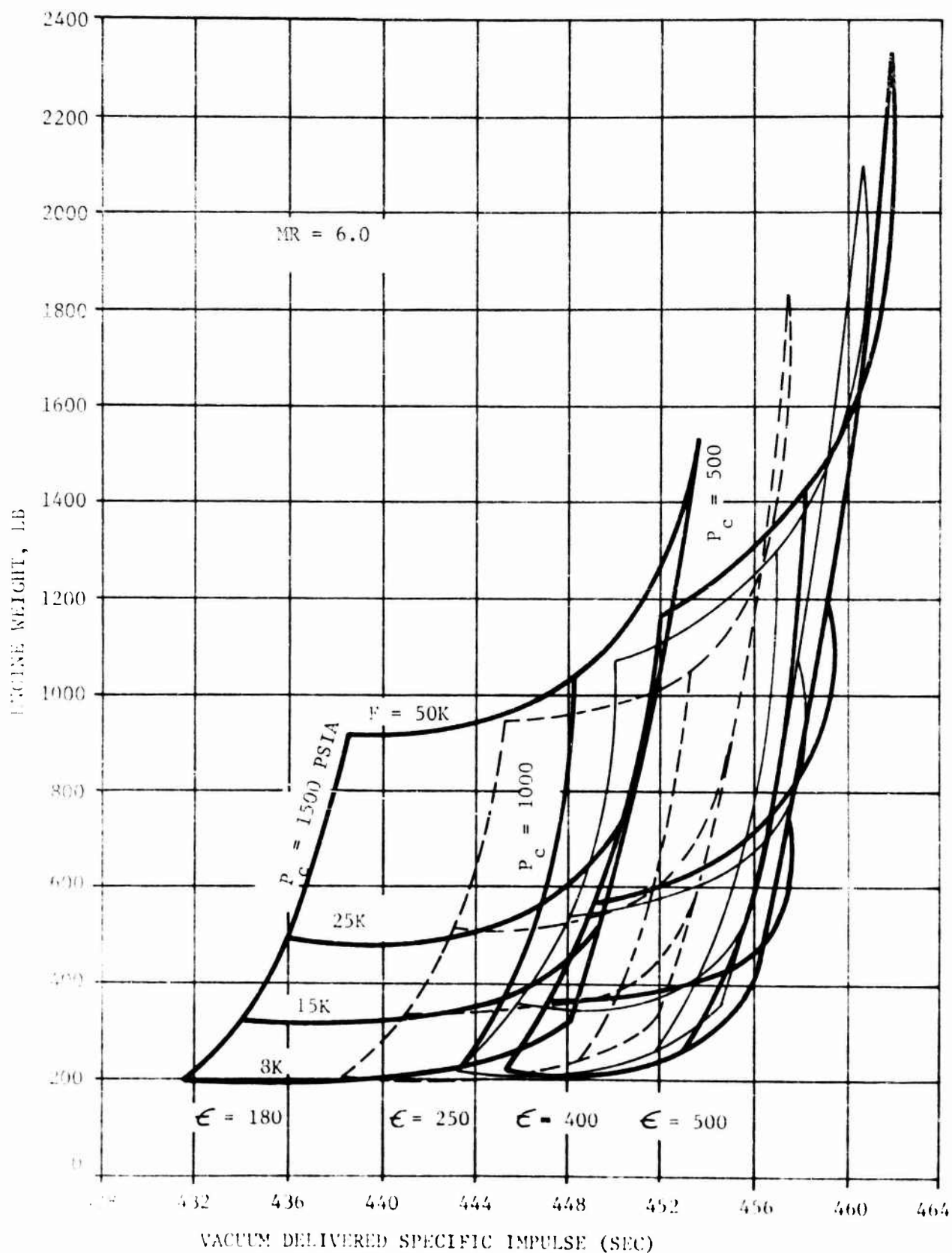


Figure 41. Engine Weight vs  $I_s$ , Minimum Weight Retractable Nozzle, Coolant Bleed Cycle

### III, A, Engine Design Parametric Study (Task IV) (cont.)

#### (4) Expander Cycle

This section includes the calculated weight of the expander cycle for mixture ratio = 6.0

The engine performance is equal to the thrust chamber performance. Since the staged combustion cycle performance is identical, the expander cycle performance is not shown separately.

All engine data shown are for a 14-in. thrust chamber length.

Figure 42 is the configuration drawing and Figure 43 the schematic. Figures 44, 45 and 46 are weight data.

The interaction of engine weight and performance are shown in Figures 47 and 48. All weights include low speed pumps.

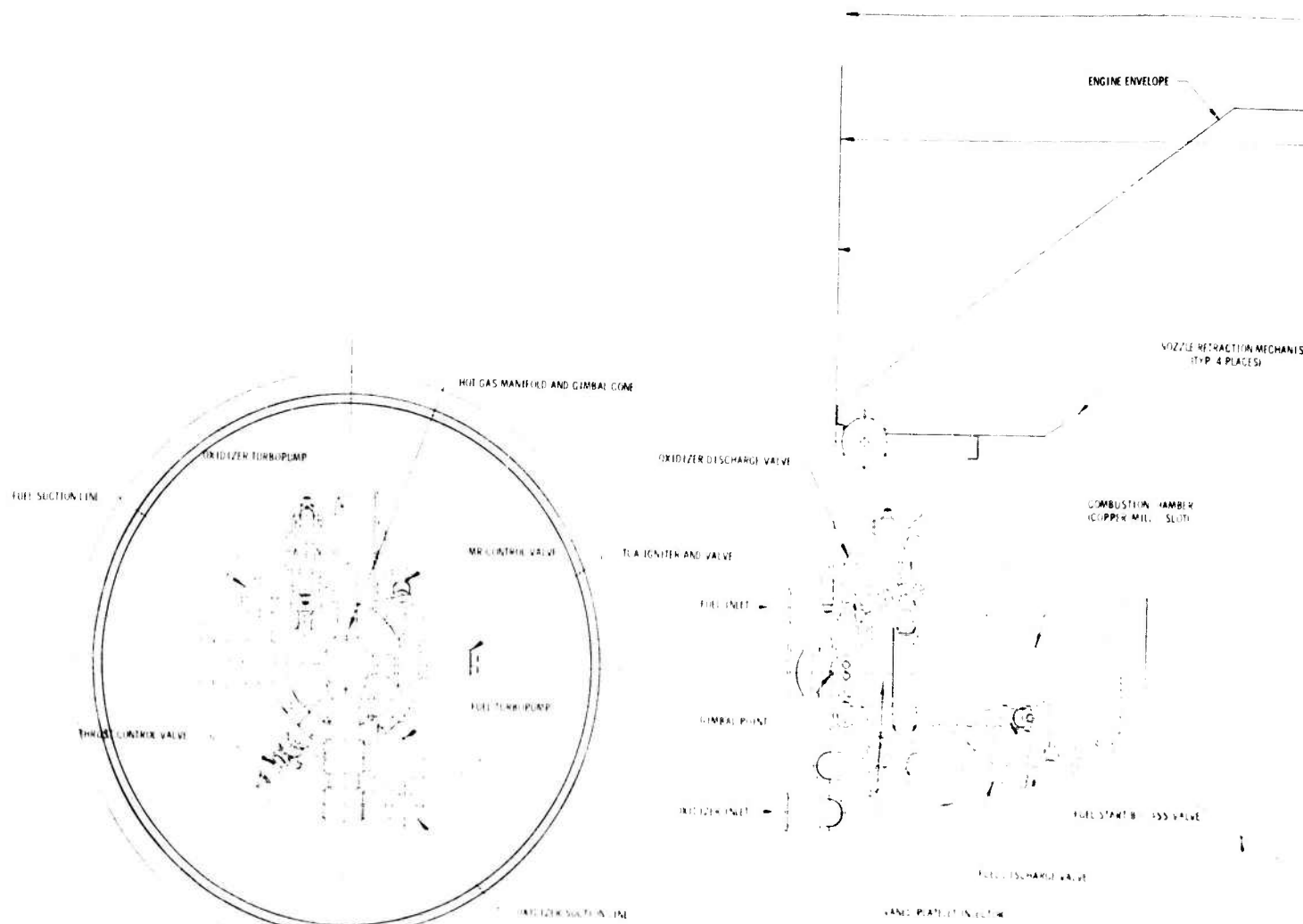


Figure 42. Configuration Drawing



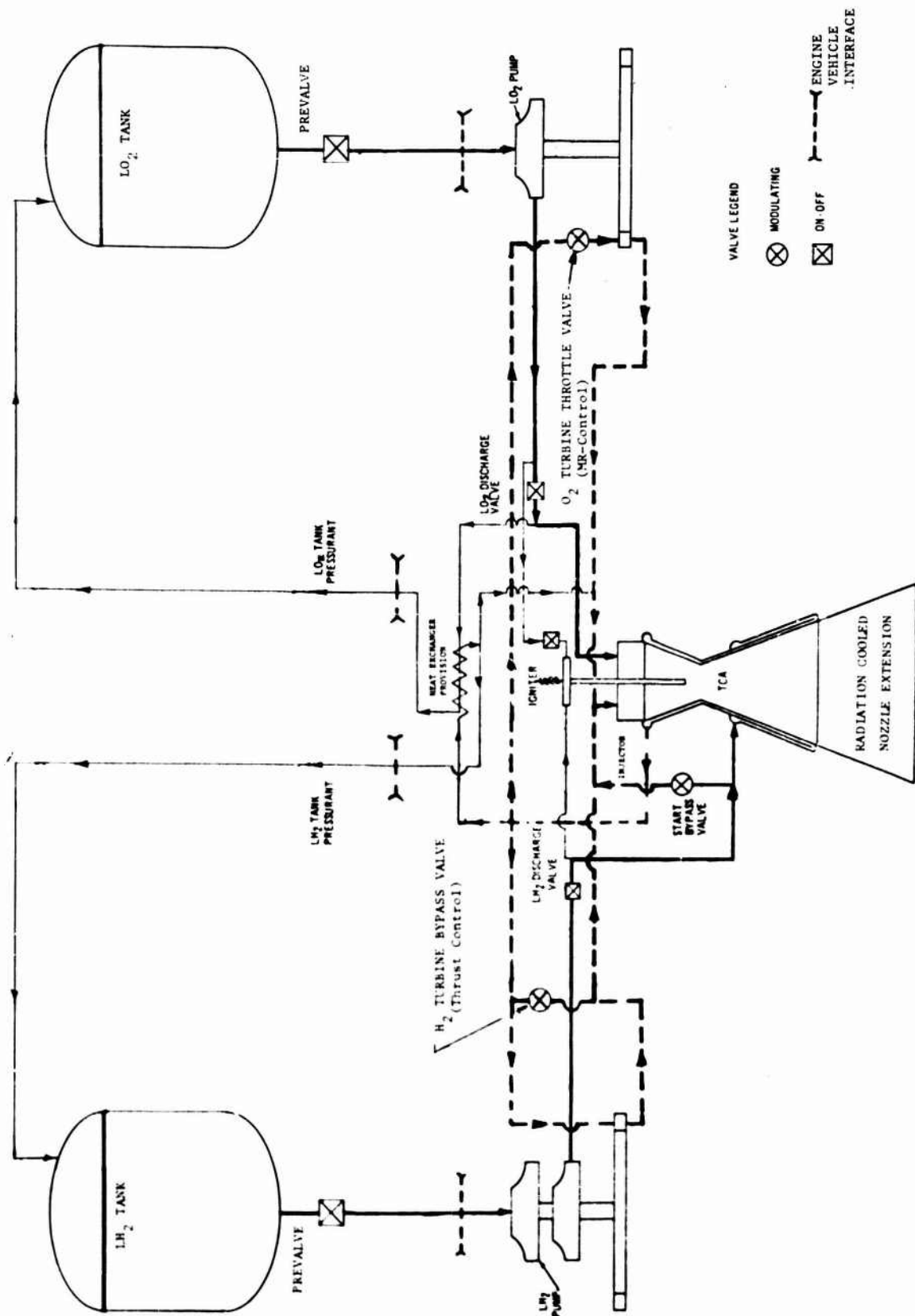


Figure 43. Engine Schematic, Expander Cycle

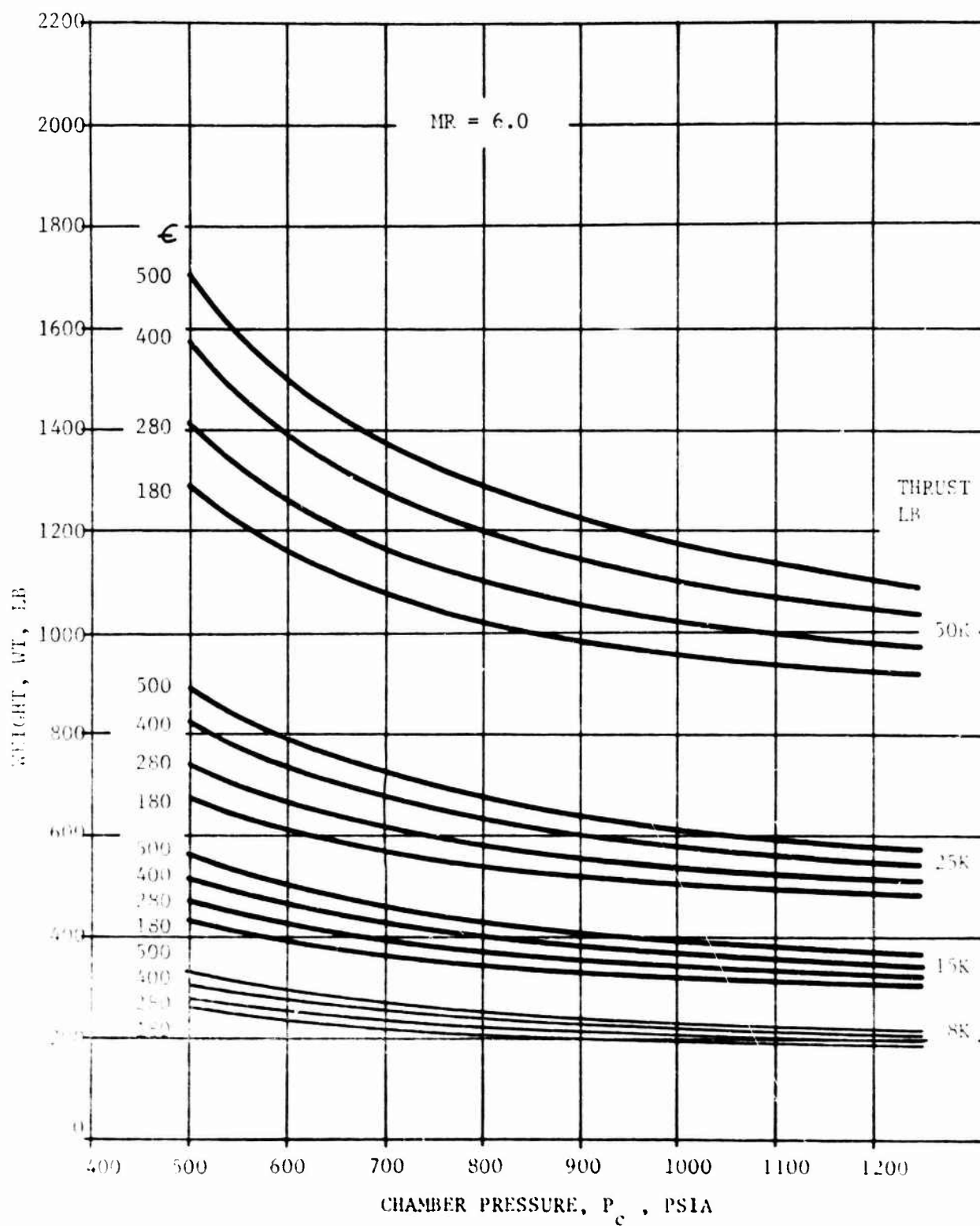


Figure 44. Engine Weight vs  $P_c$ , Fixed Nozzle, Expander Cycle

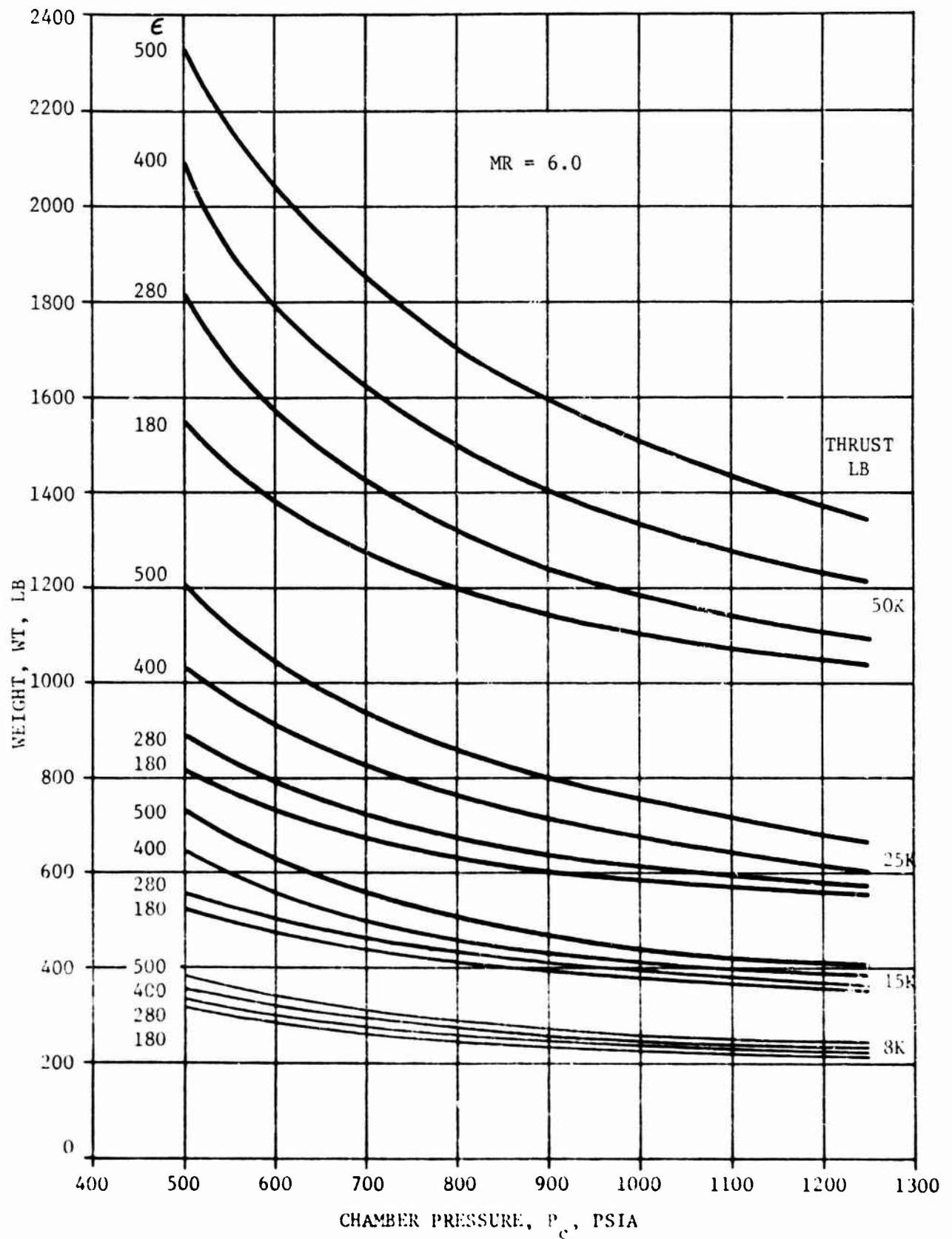


Figure 45. Engine Weight vs  $P_c$ , Minimum Weight Retractable Nozzle, Expander Cycle

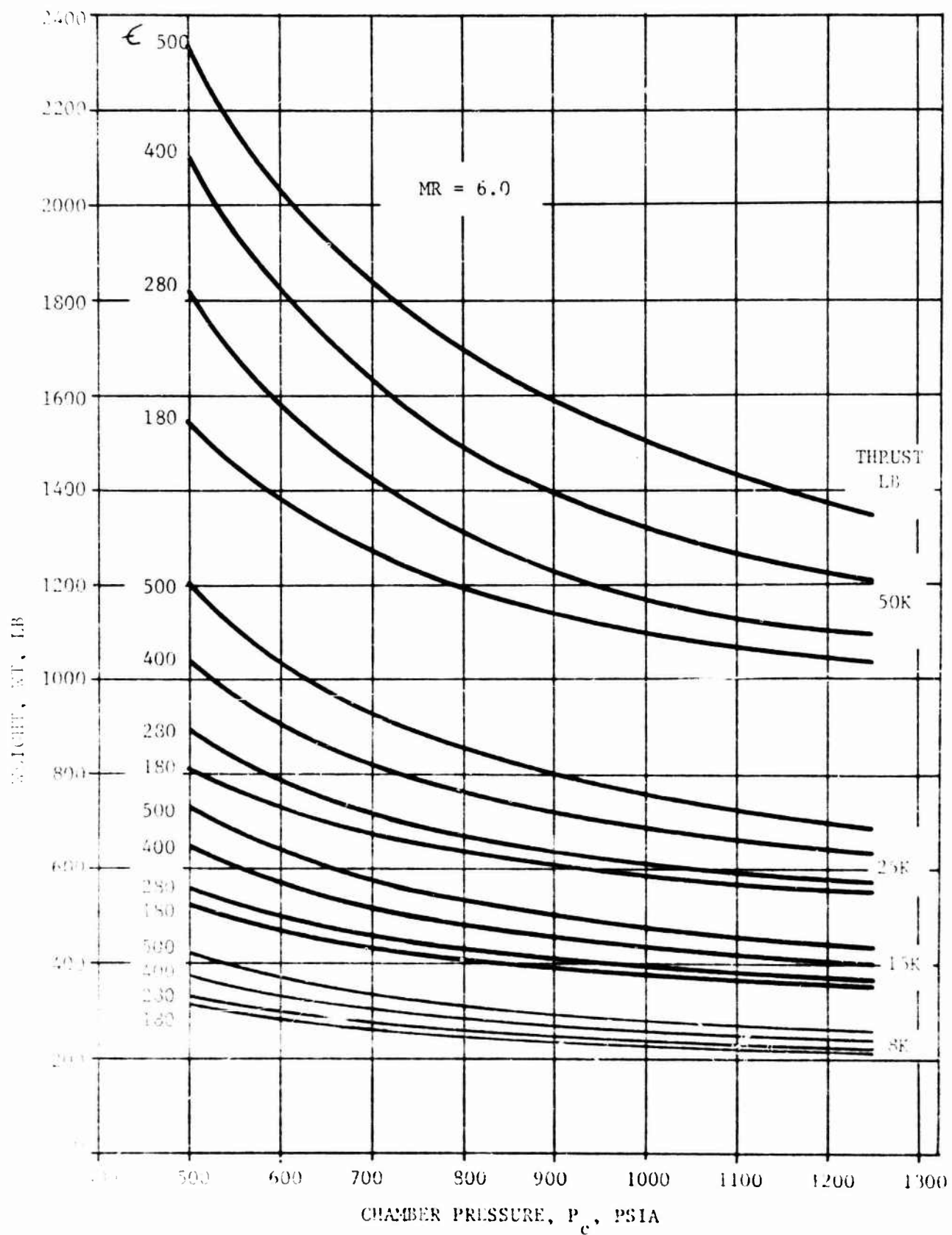


Figure 46. Engine Weight vs  $P_c$ , Minimum Length Retractable Nozzle, Expander Cycle

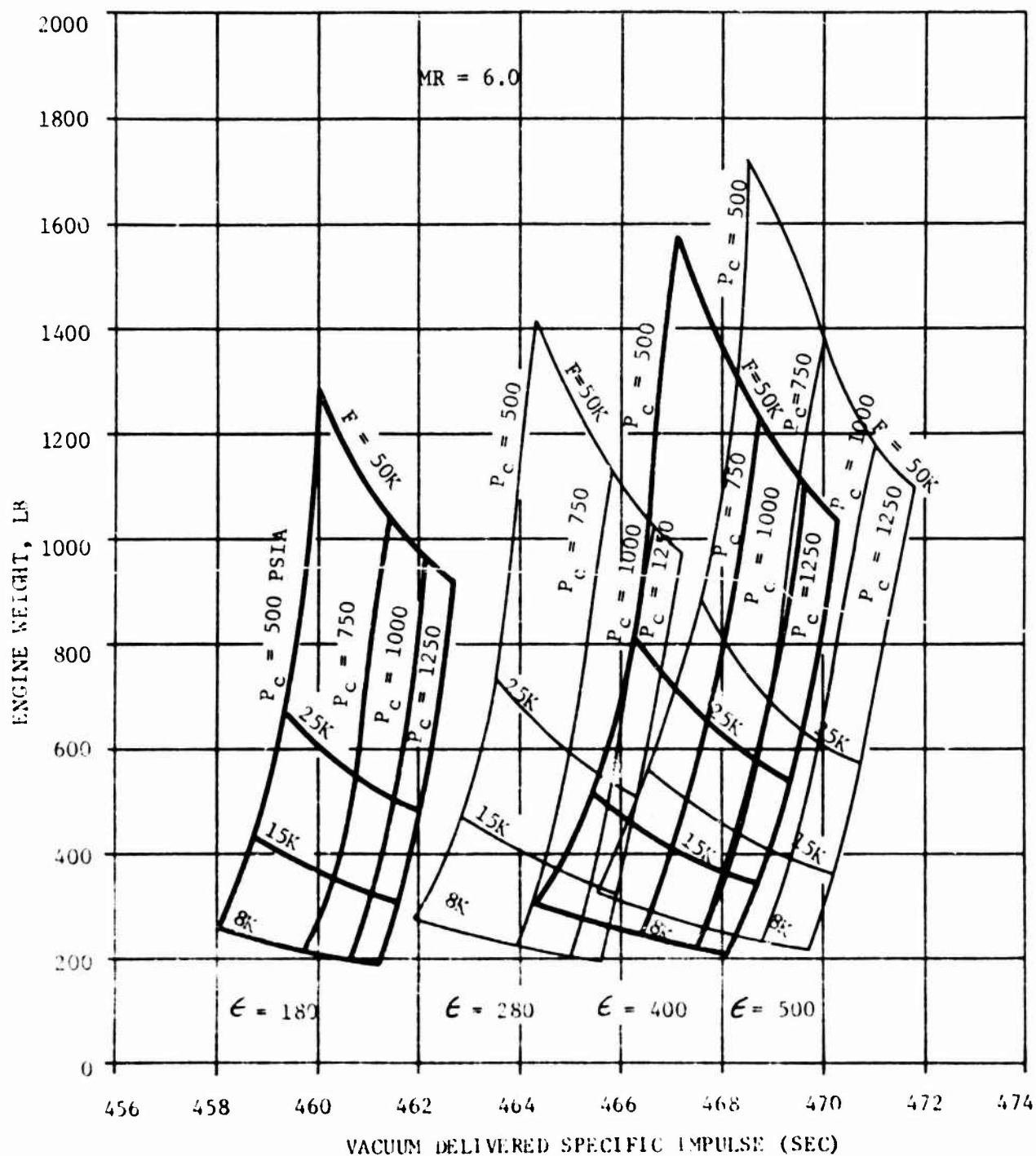
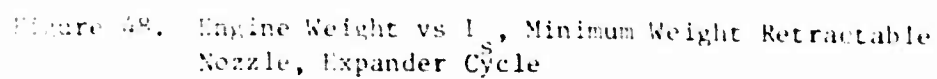


Figure 47. Engine Weight vs  $I_s$ , Fixed Nozzle, Expander Cycle



III, A, Engine Design Parametric Study (Task IV) (cont.)

(5) Staged Combustion Cycle

This engine cycle is the highest performing cycle over the whole thrust range of 8K to 50K lb.

Figures 49 and 50 are the configuration and schematic drawings and Figures 51 through 57 are the appropriate performance and weight data. Figures 58 and 59 are the interaction charts. All weights shown include low speed pumps.

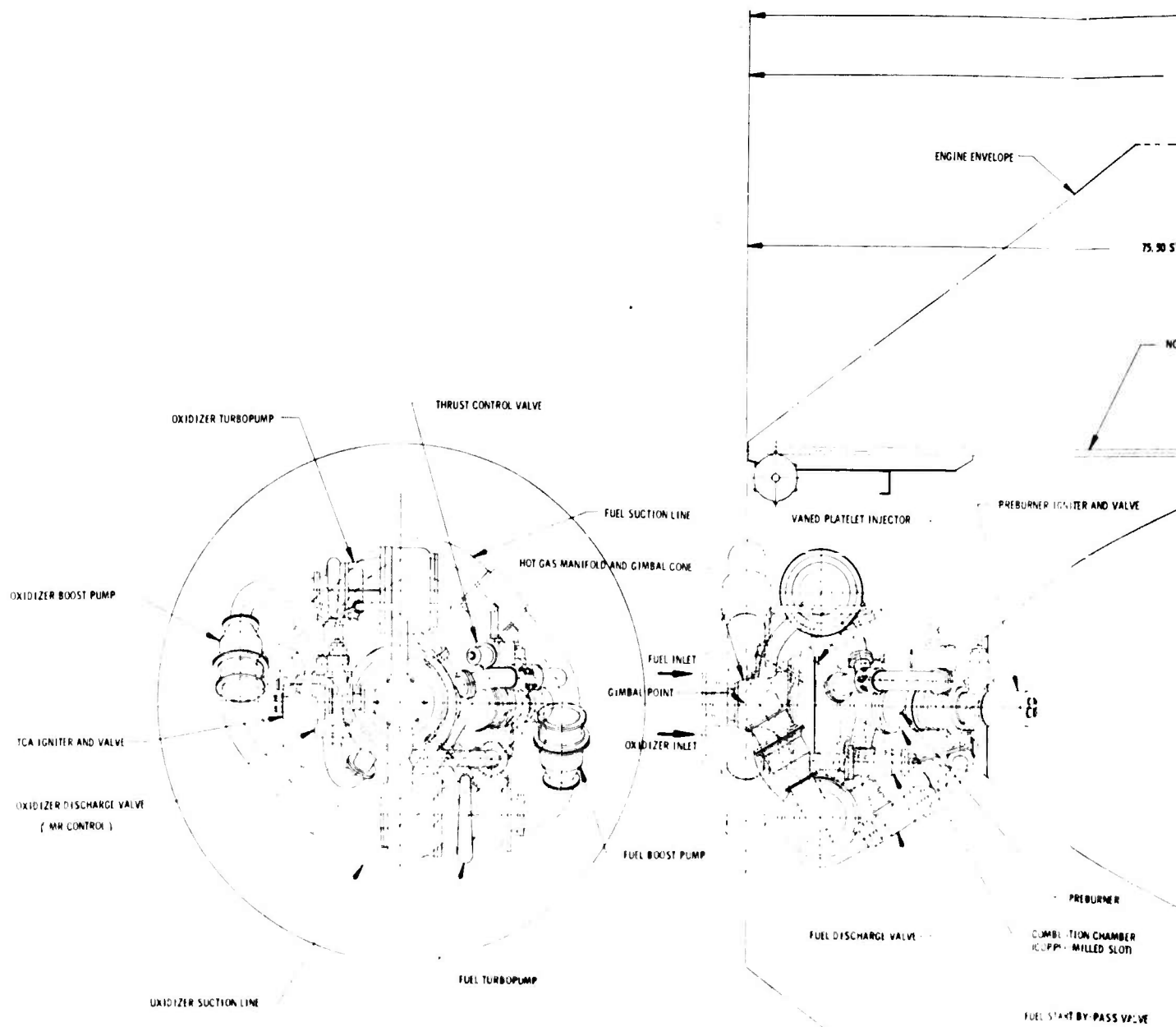
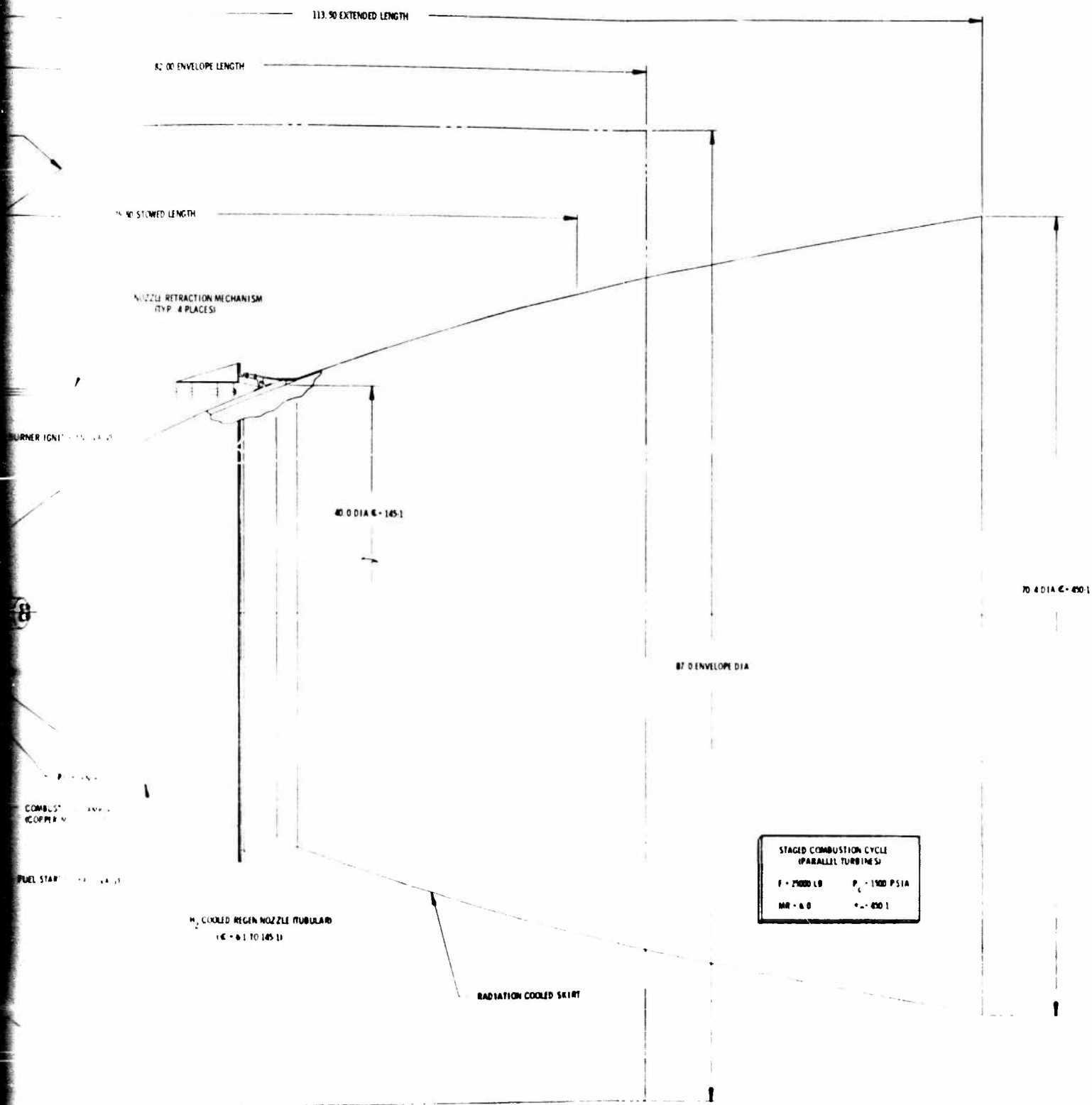


Figure 49. Configuration Drawing



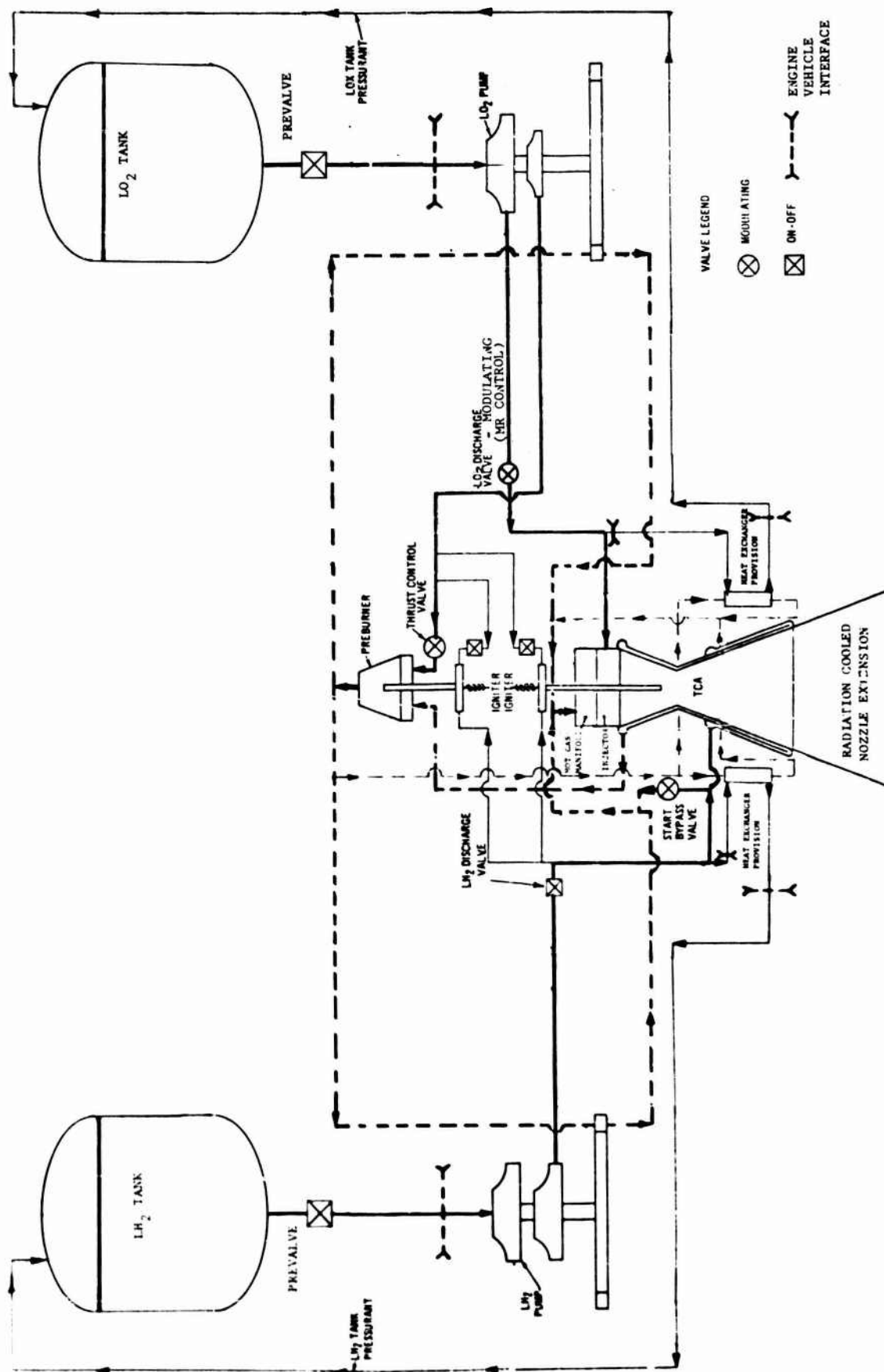


Figure 50. Engine Schematic, Staged Combustion Cycle

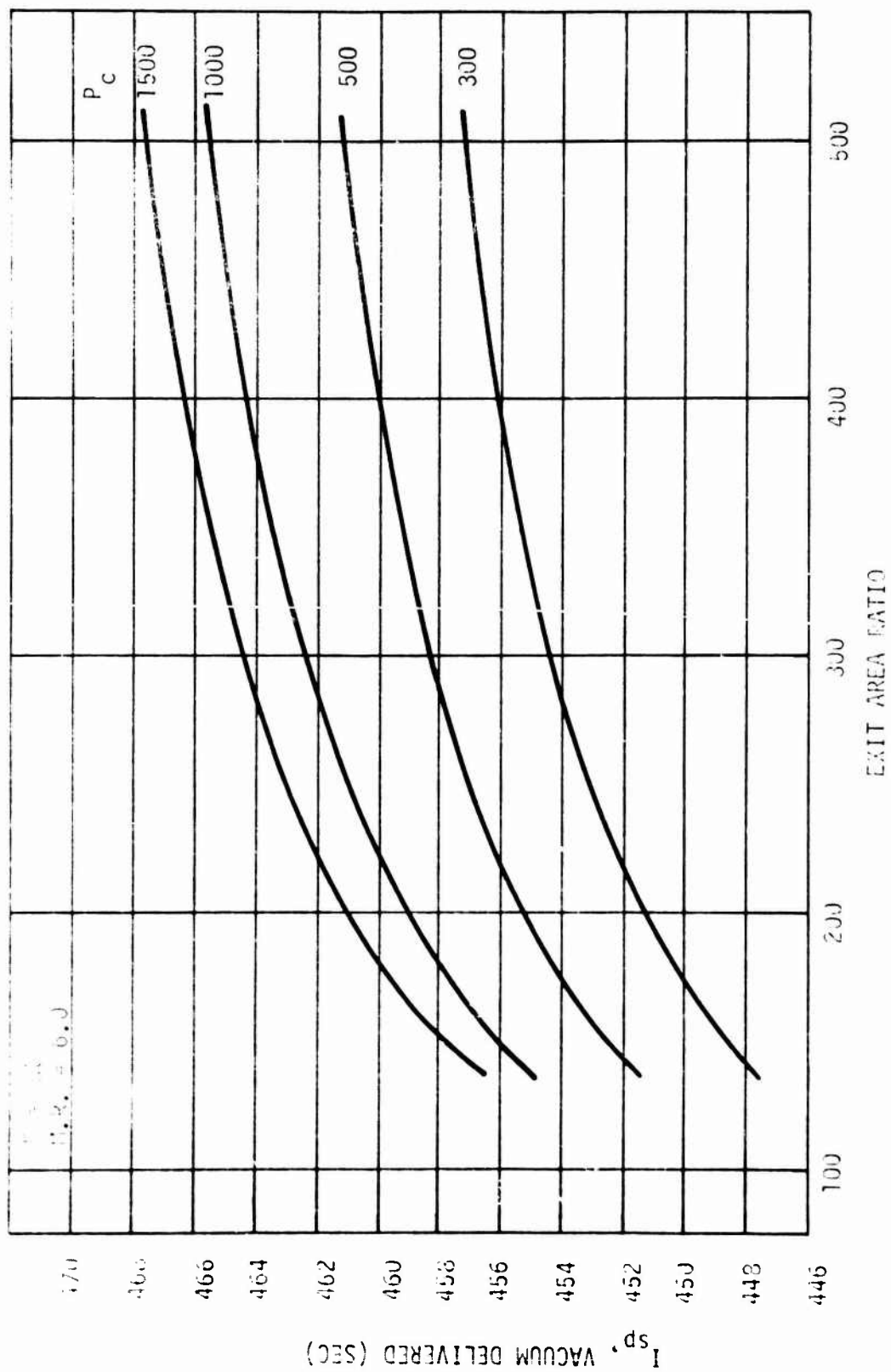


Figure 51.  $I_s$  vs Exit Area Ratio,  $MR = 0.5$ ,  $P = 8K$ , Staged Combustion Cycle

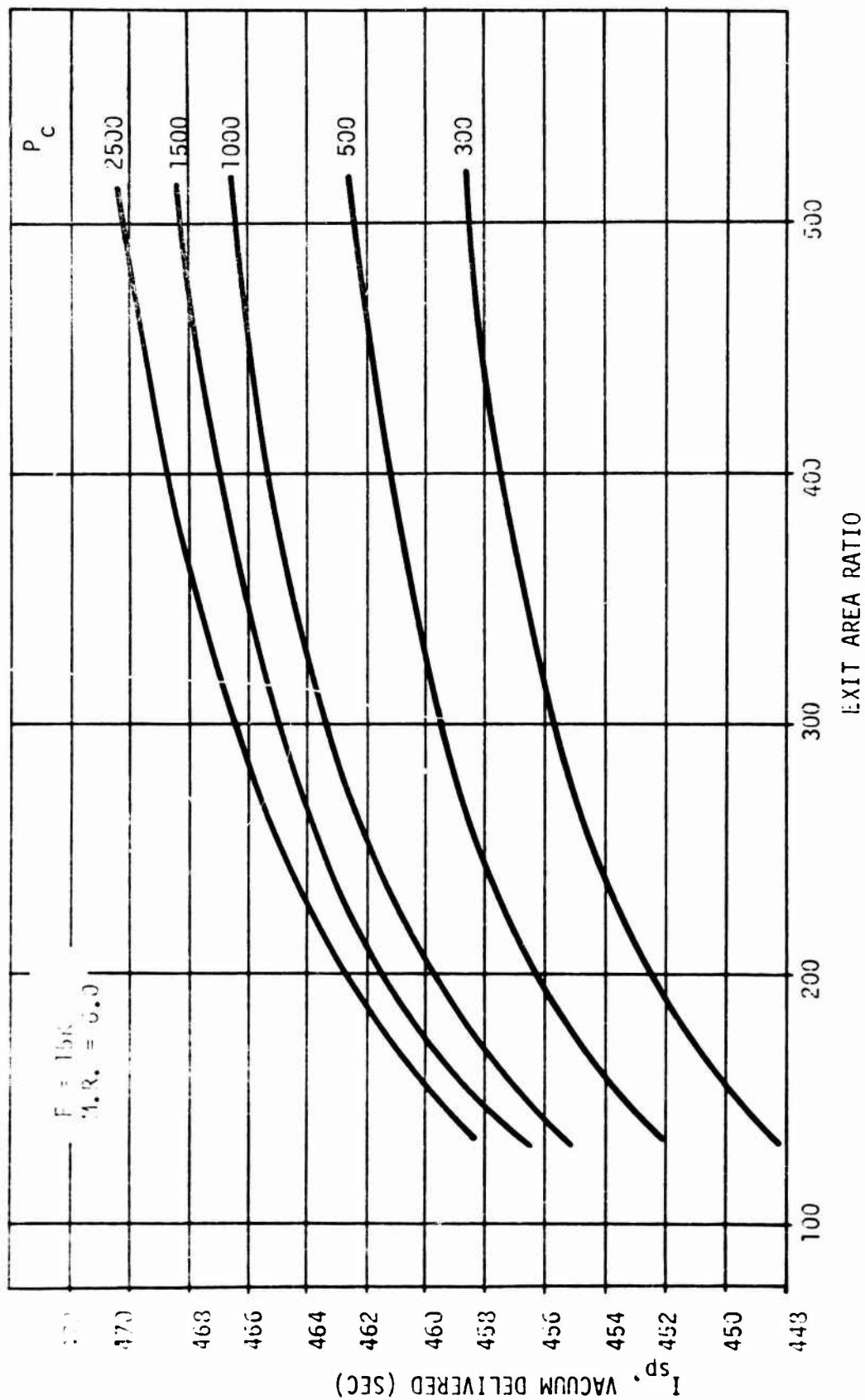


Figure 52.  $I_s$  vs Exit Area Ratio,  $MR = 6$ ,  $F = 15K$ , Staged Combustion Cycle

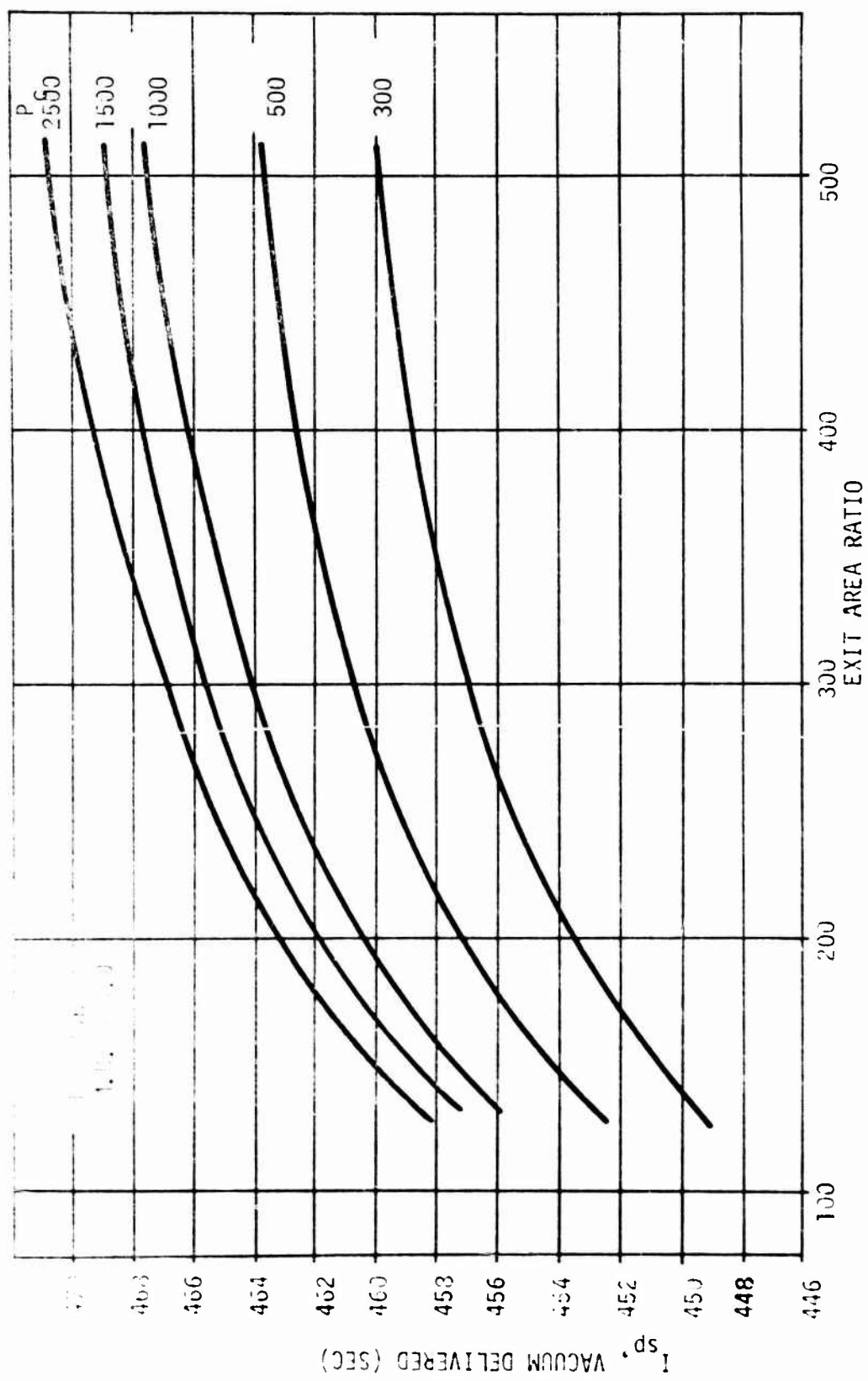


Figure 53.  $I_{sp}$  vs Exit Area Ratio,  $M = 6$ ,  $F = 25K$ , Staged Combustion Cycle

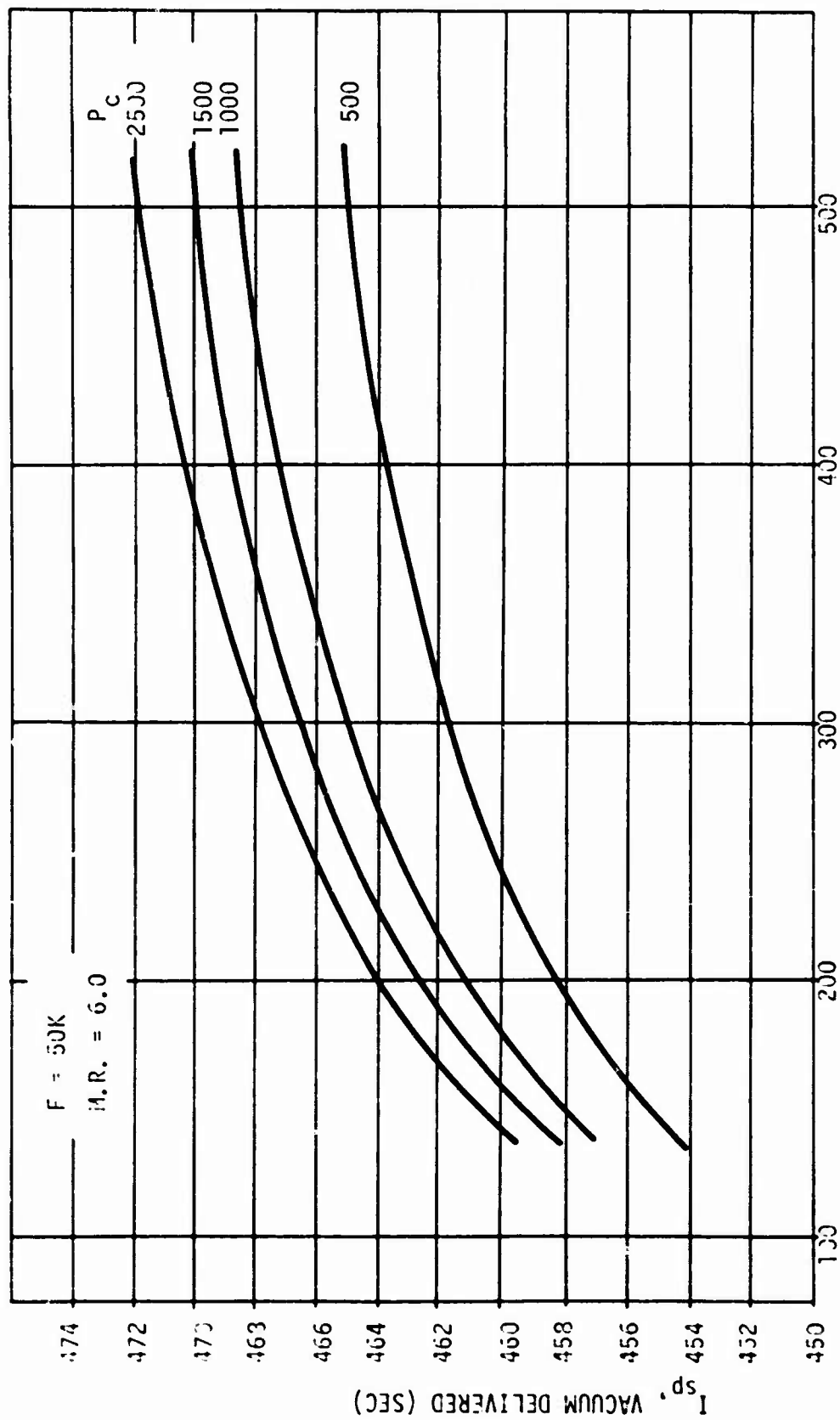


Figure 54.  $I_s$  vs Exit Area Ratio,  $M.R. = 6$ ,  $F = 50K$ , Staged Combustion Cycle

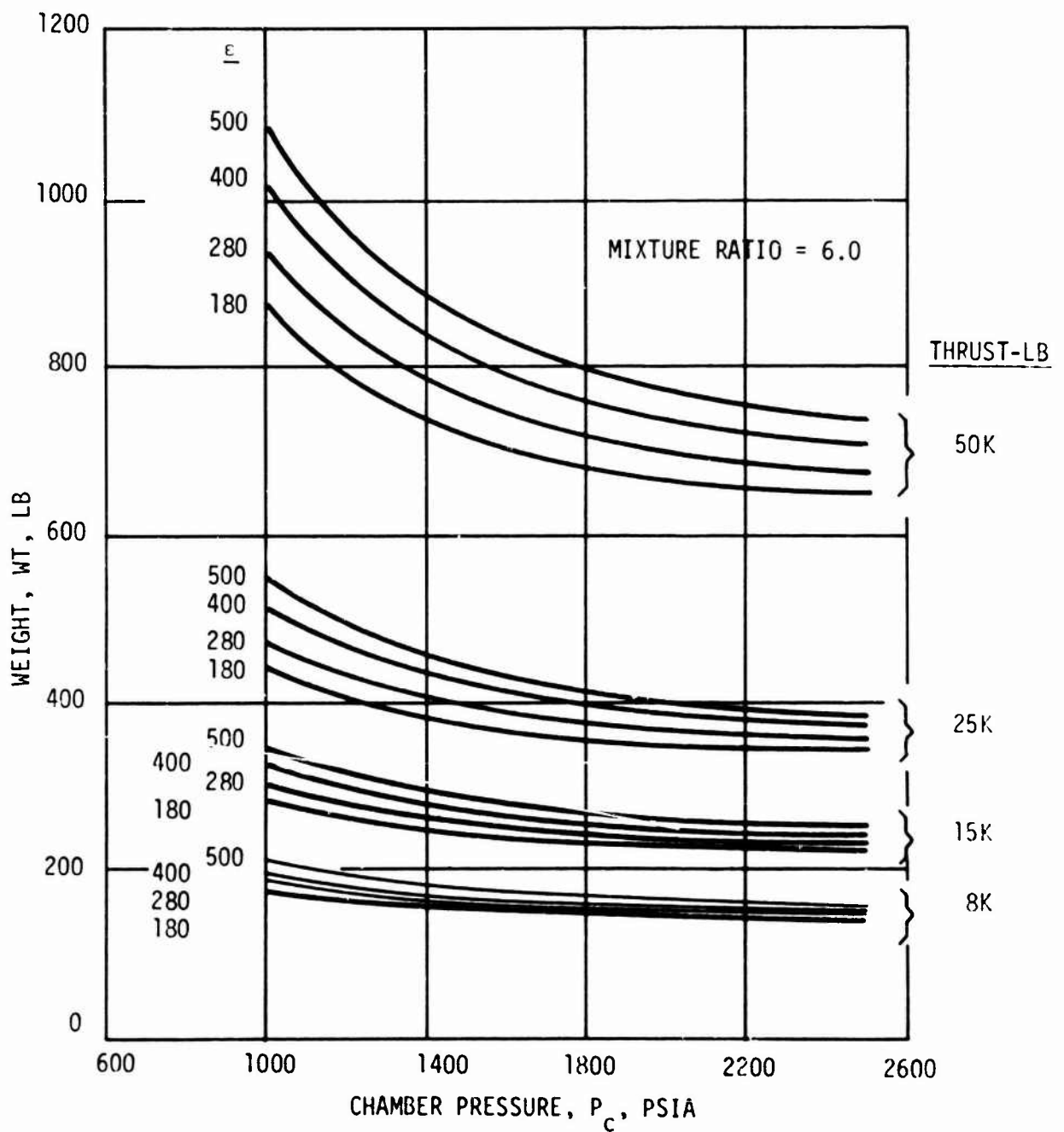


Figure 55. Engine Weight vs  $P_c$ , Fixed Nozzle, Staged Combustion Cycle

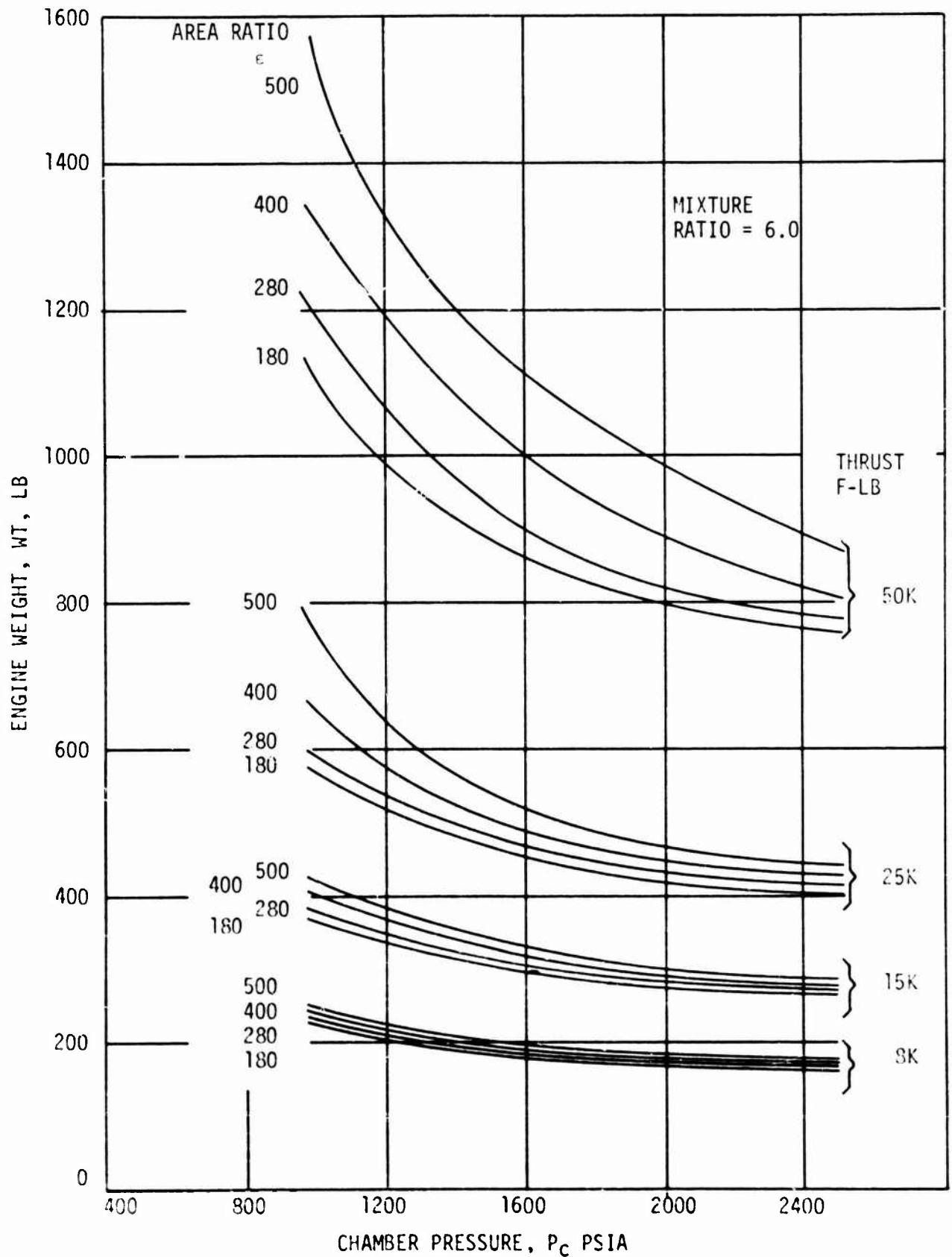


Figure 56. Engine Weight vs  $P_c$ , Minimum Weight Retractable Nozzle, Staged Combustion Cycle

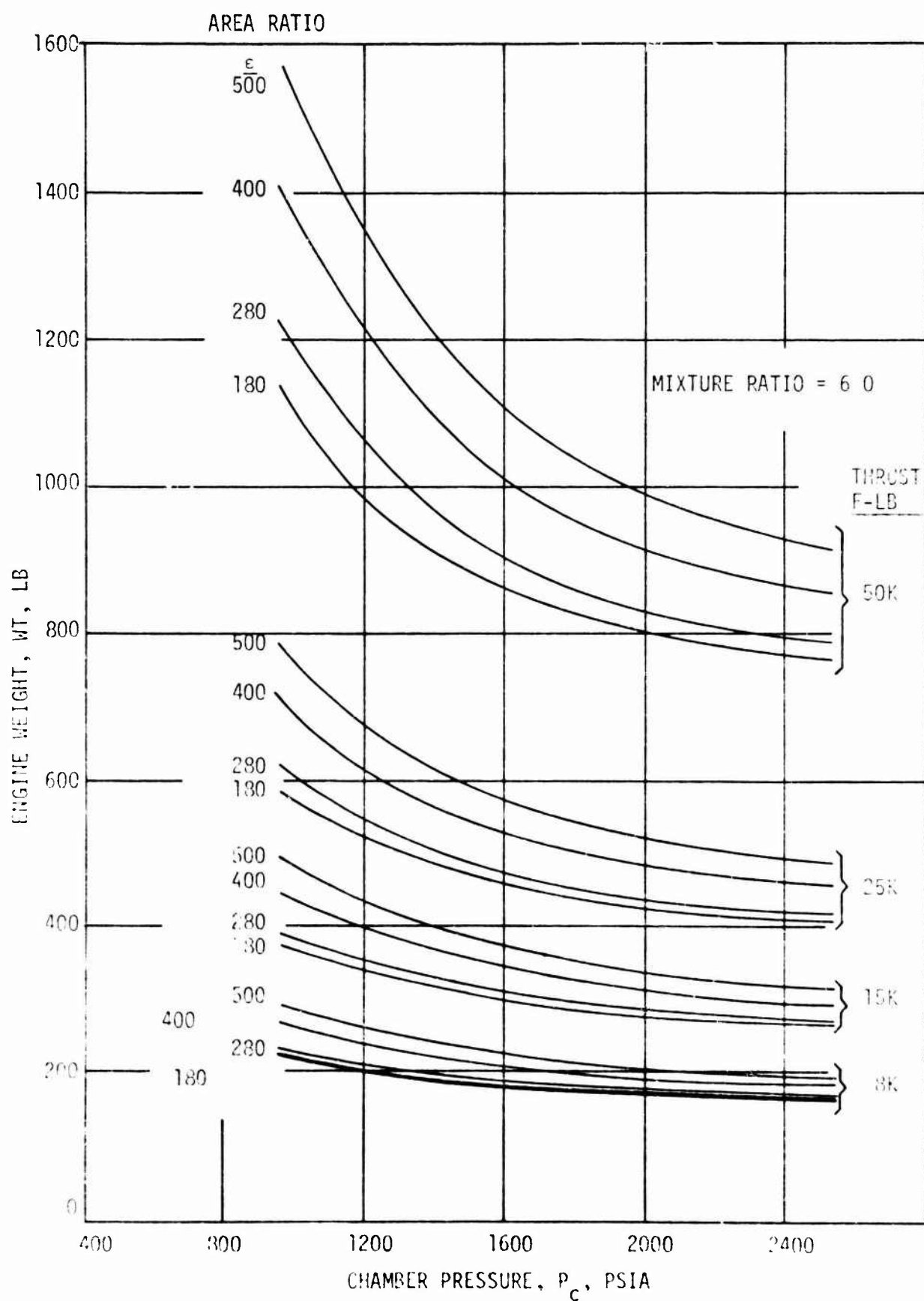


Figure 57. Engine Weight vs  $P_c$ , Minimum Length Retractable Nozzle, Staged Combustion Cycle

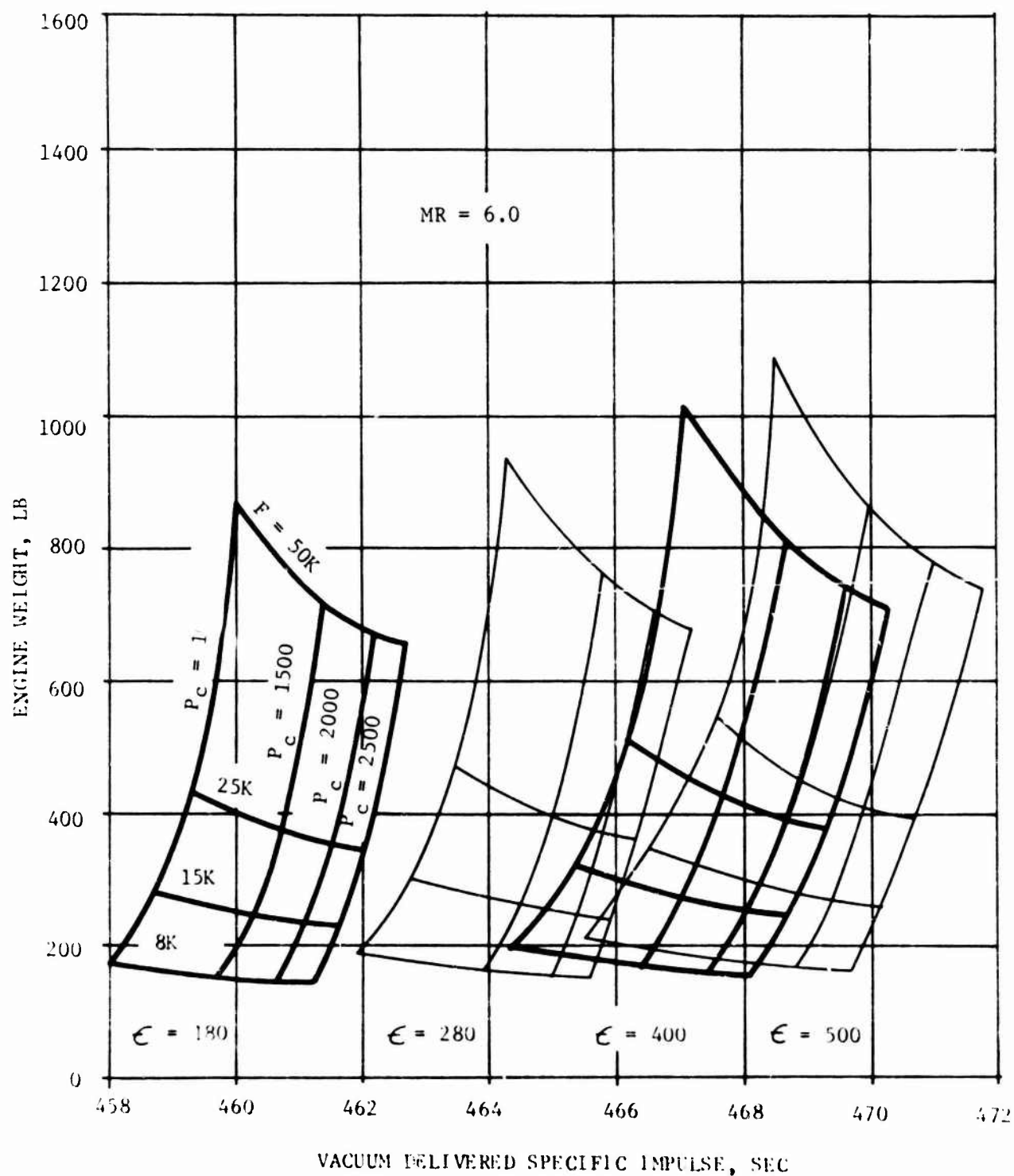


Figure 58. Engine Weight vs  $I_s$ , Fixed Nozzle, Staged Combustion Cycle

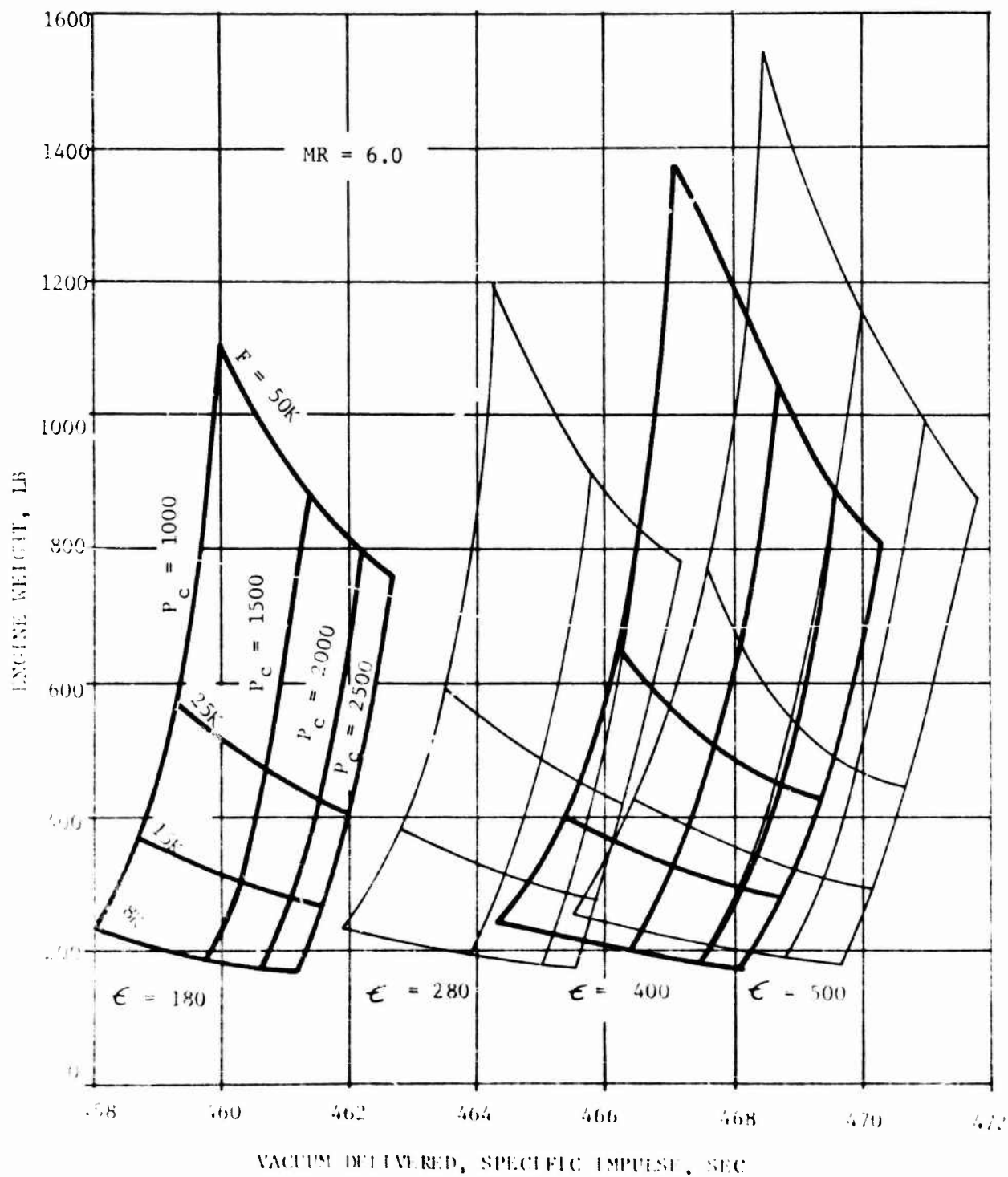


Figure 59. Engine Weight vs  $I_{sp}$ , Minimum Weight Retractable Nozzle, Staged Combustion Cycle

(6) Stage Combustion Bleed Cycle

The configuration of the staged combustion bleed cycle is shown in Figure 60 and the schematic diagram in Figure 61. Engine performance, weight and interaction data is presented in Figures 62 through 70 and include low speed pump weights.

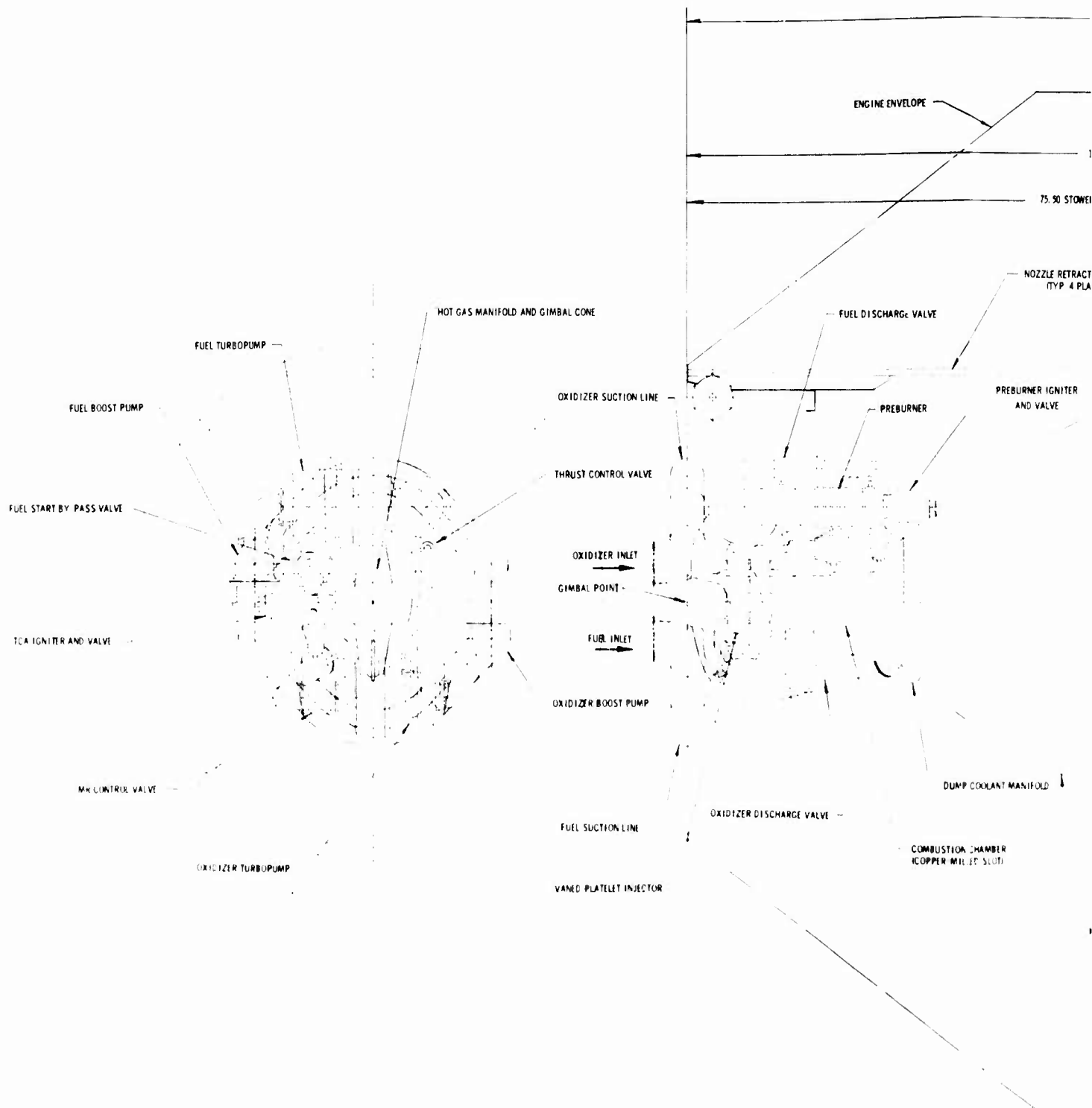
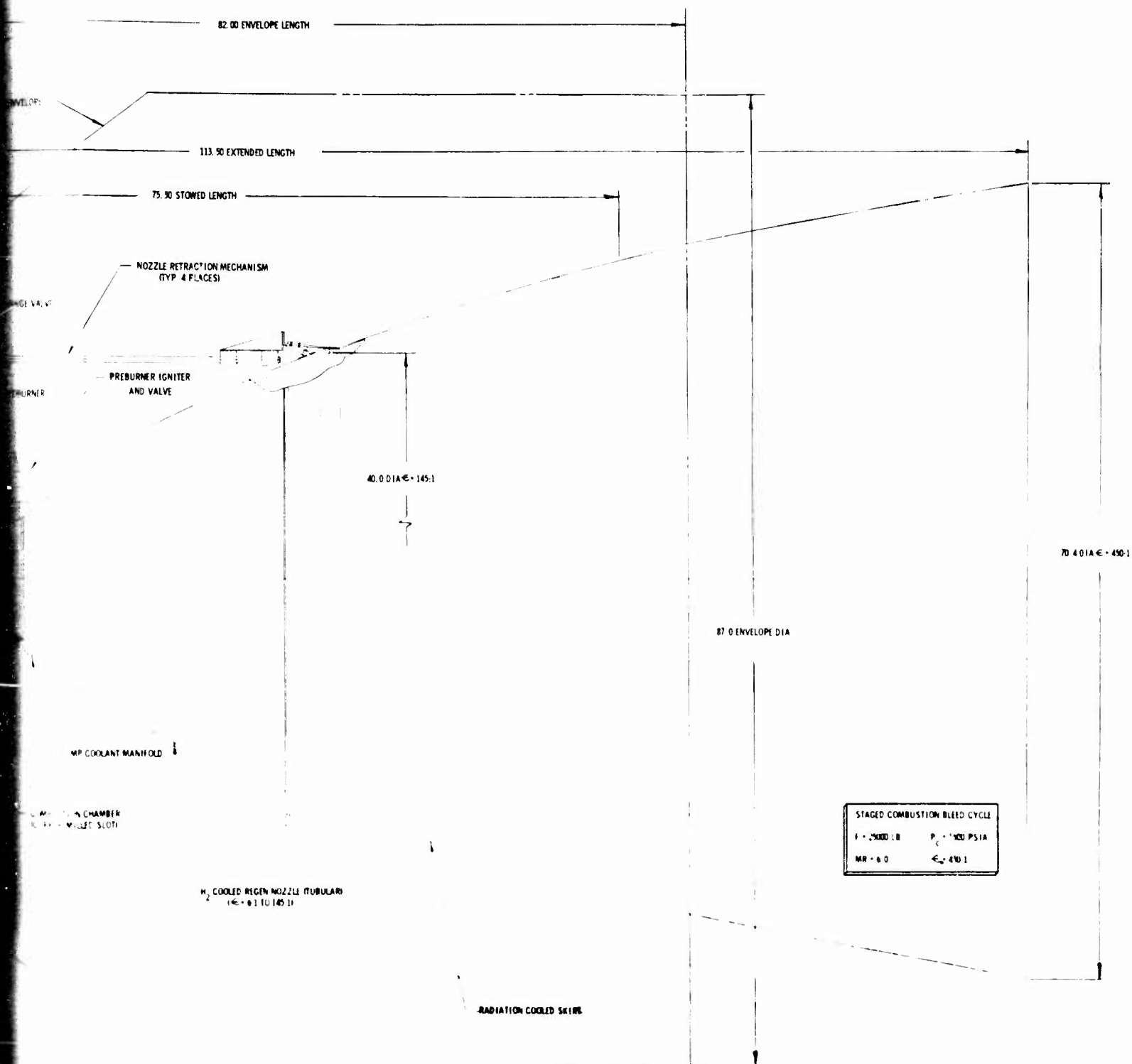


Figure 60. Configuration Drawing.



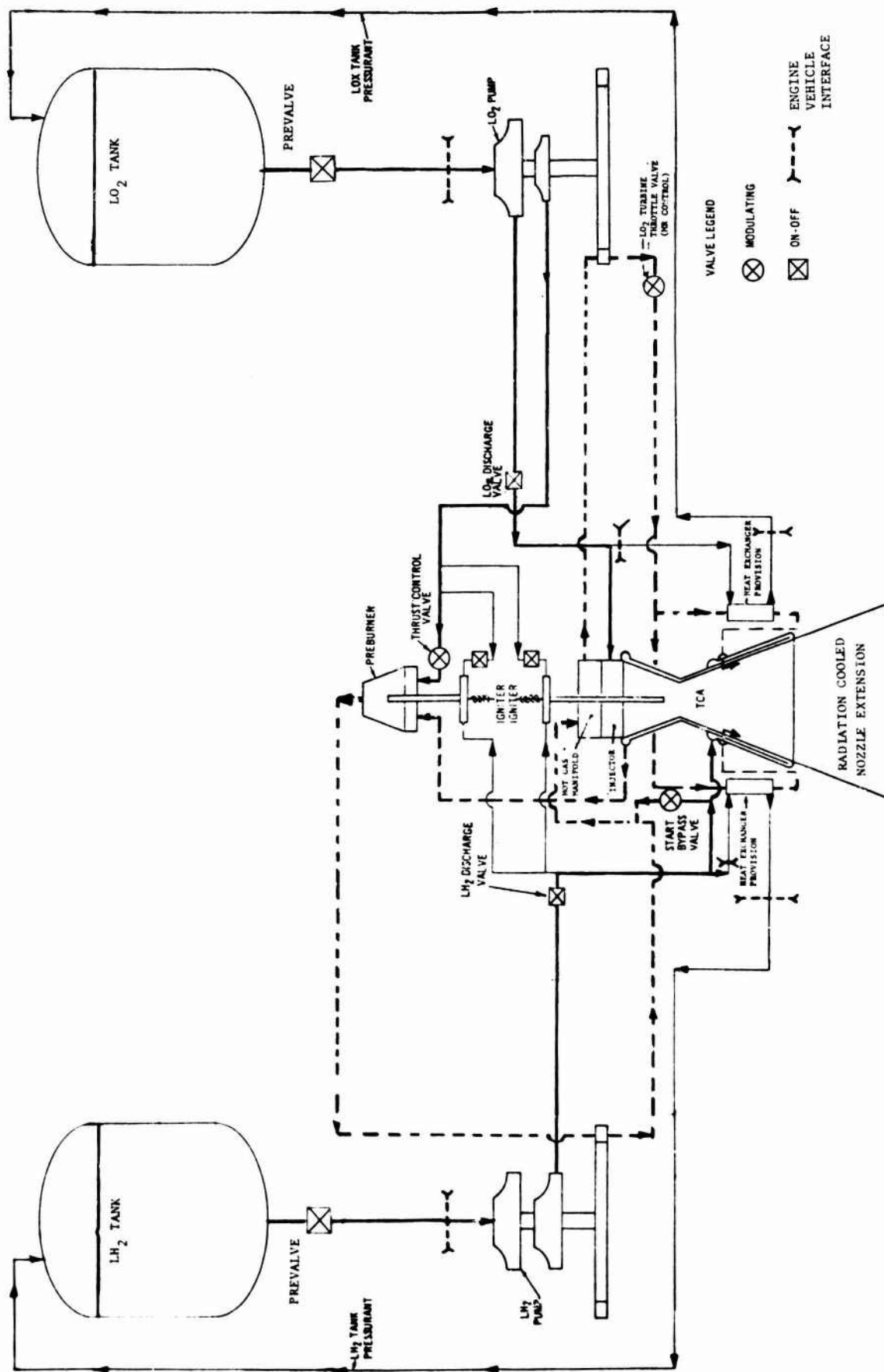


Figure 61. Engine Schematic, Staged Combustion Bleed Cycle

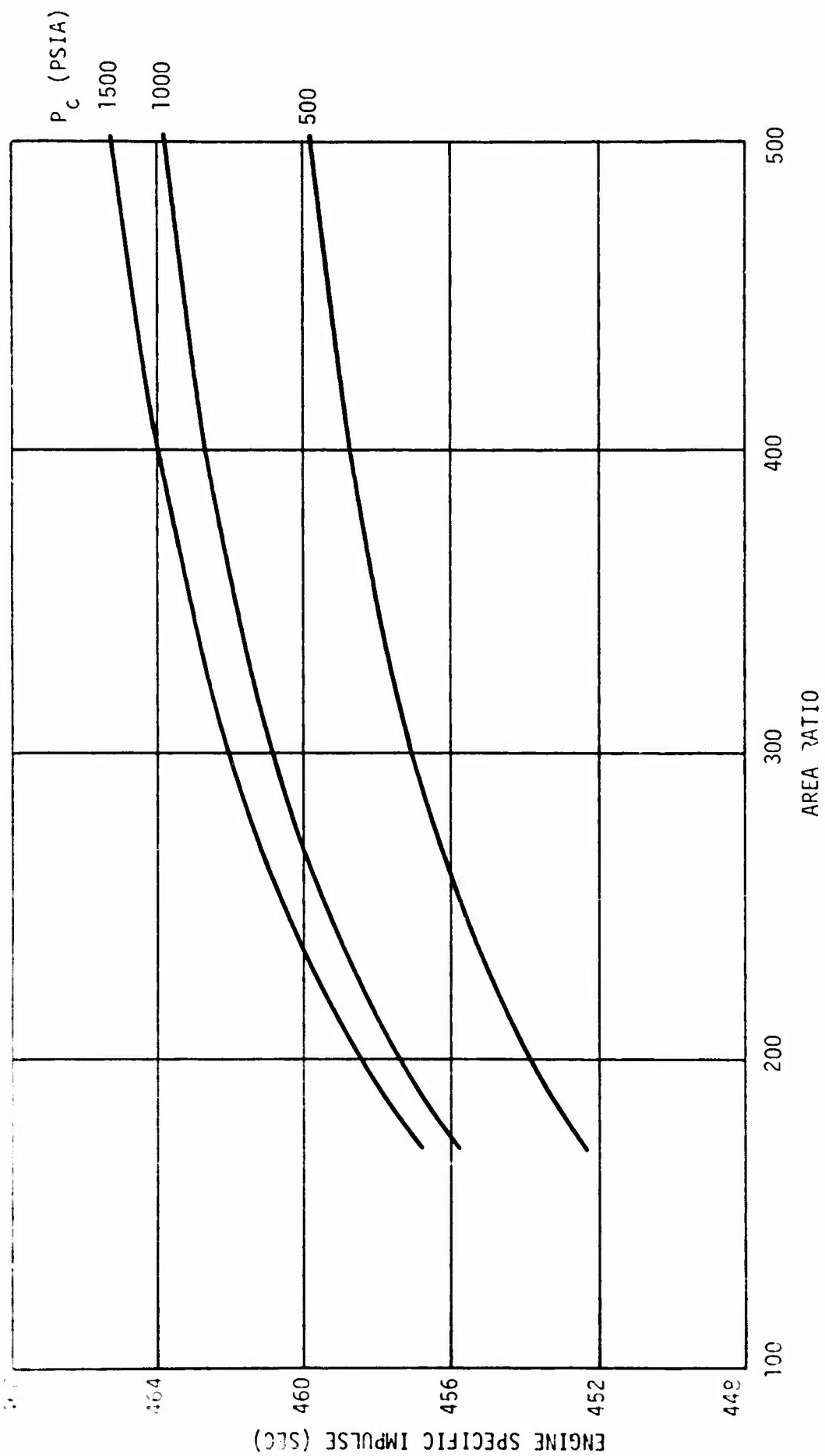


Figure 62.  $I_s$  vs  $P_c$  and Exit Area Ratio,  $M_R = 6$ ,  $F = 8K$ , Staged Combustion Bleed Cycle

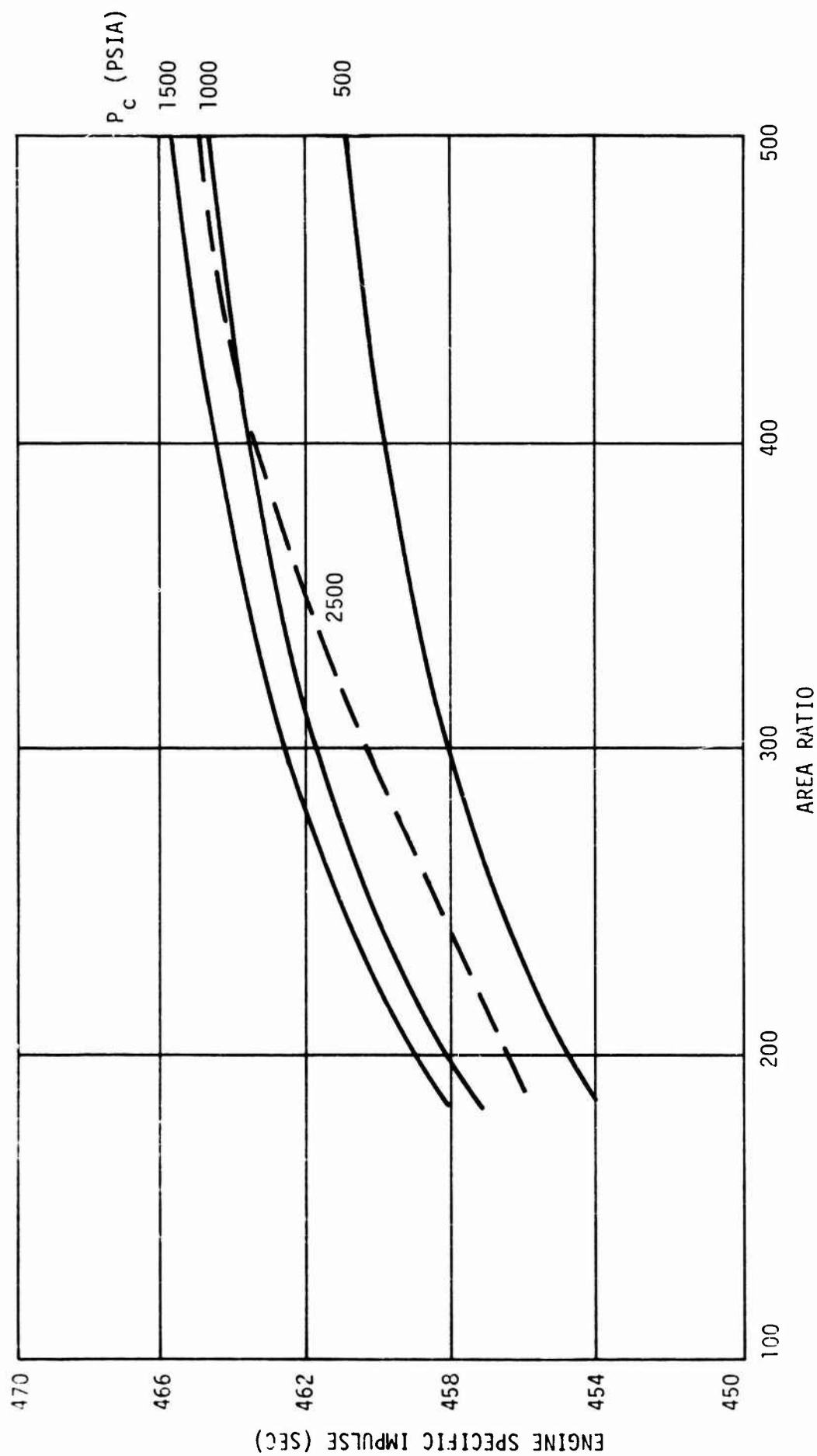


Figure 63.  $I_s$  vs  $P_c$  and Exit Area Ratio,  $MR = 6$ ,  $F = 15K$ , Staged Combustion Bleed Cycle

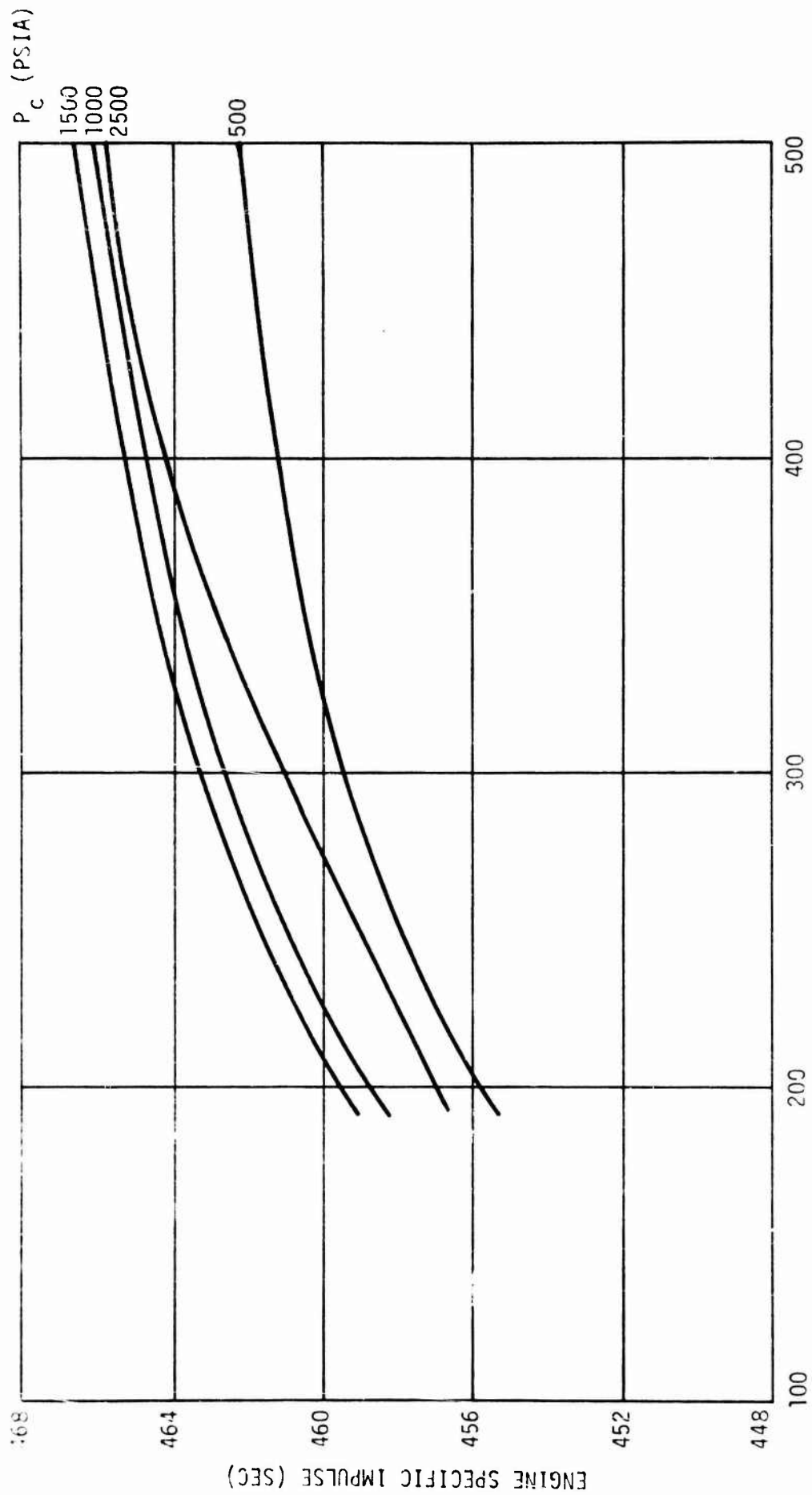


Figure 64.  $I_s$  vs  $P_c$  and Exit Area Ratio,  $MR = 6$ ,  $F = 25K$ , Staged Combustion Bleed Cycle

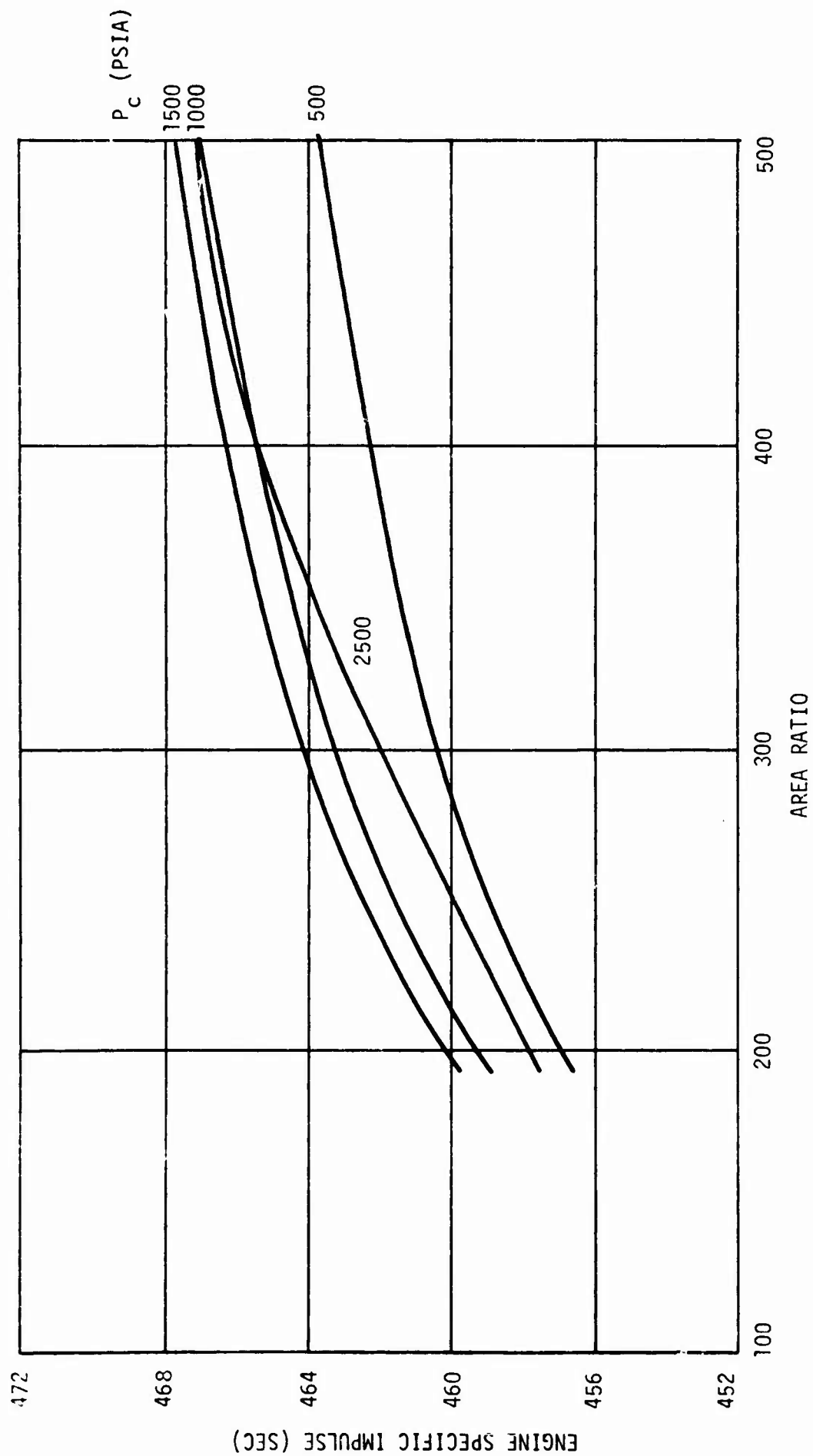


Figure 65.  $I_s$  vs  $P_c$  and Exit Area Ratio,  $MR = 6$ ,  $F = 50K$ , Staged Combustion Bleed Cycle

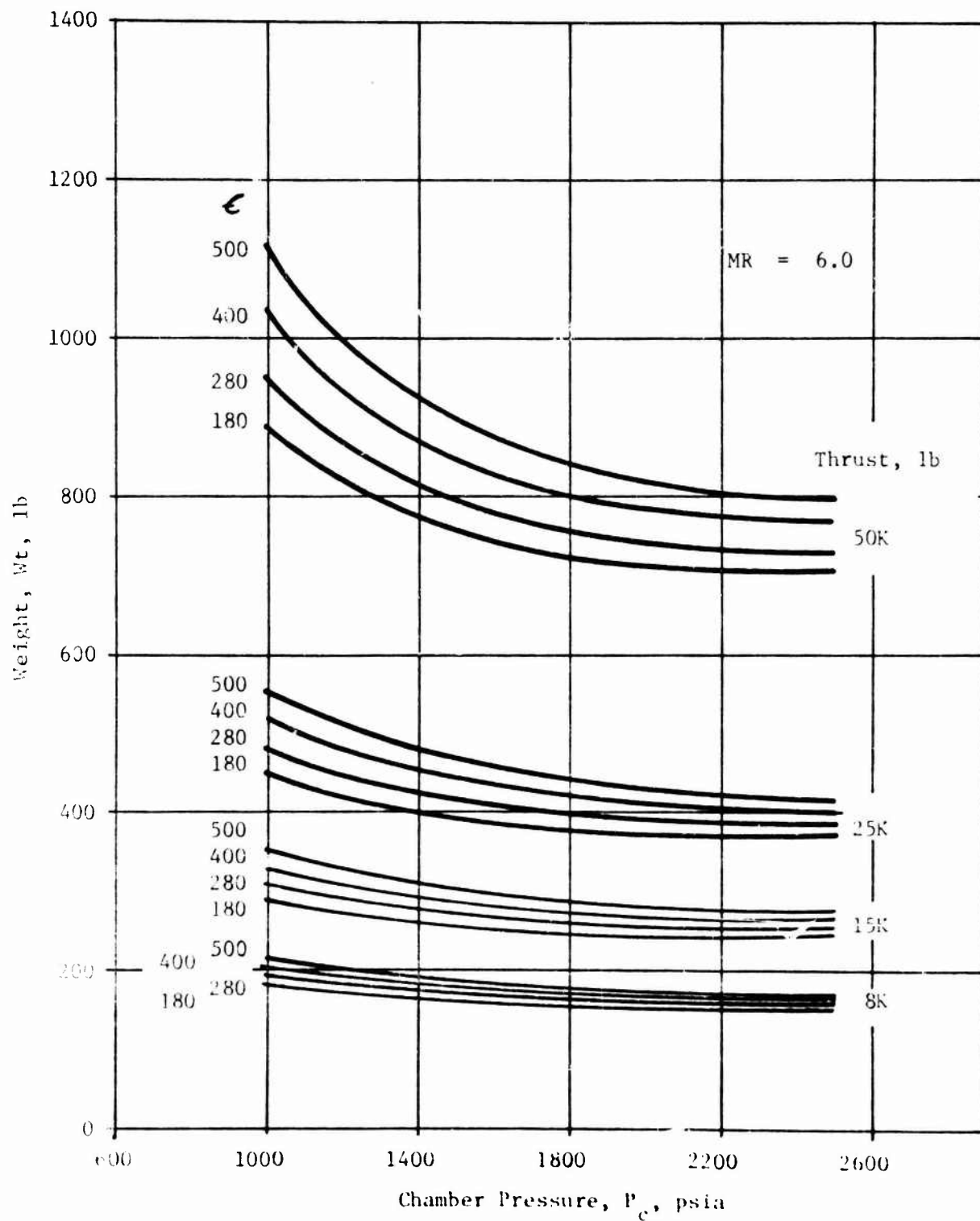


Figure 10. Engine Weight vs  $P_c$ , Fixed Nozzle, Staged Combustion Bleed Cycle

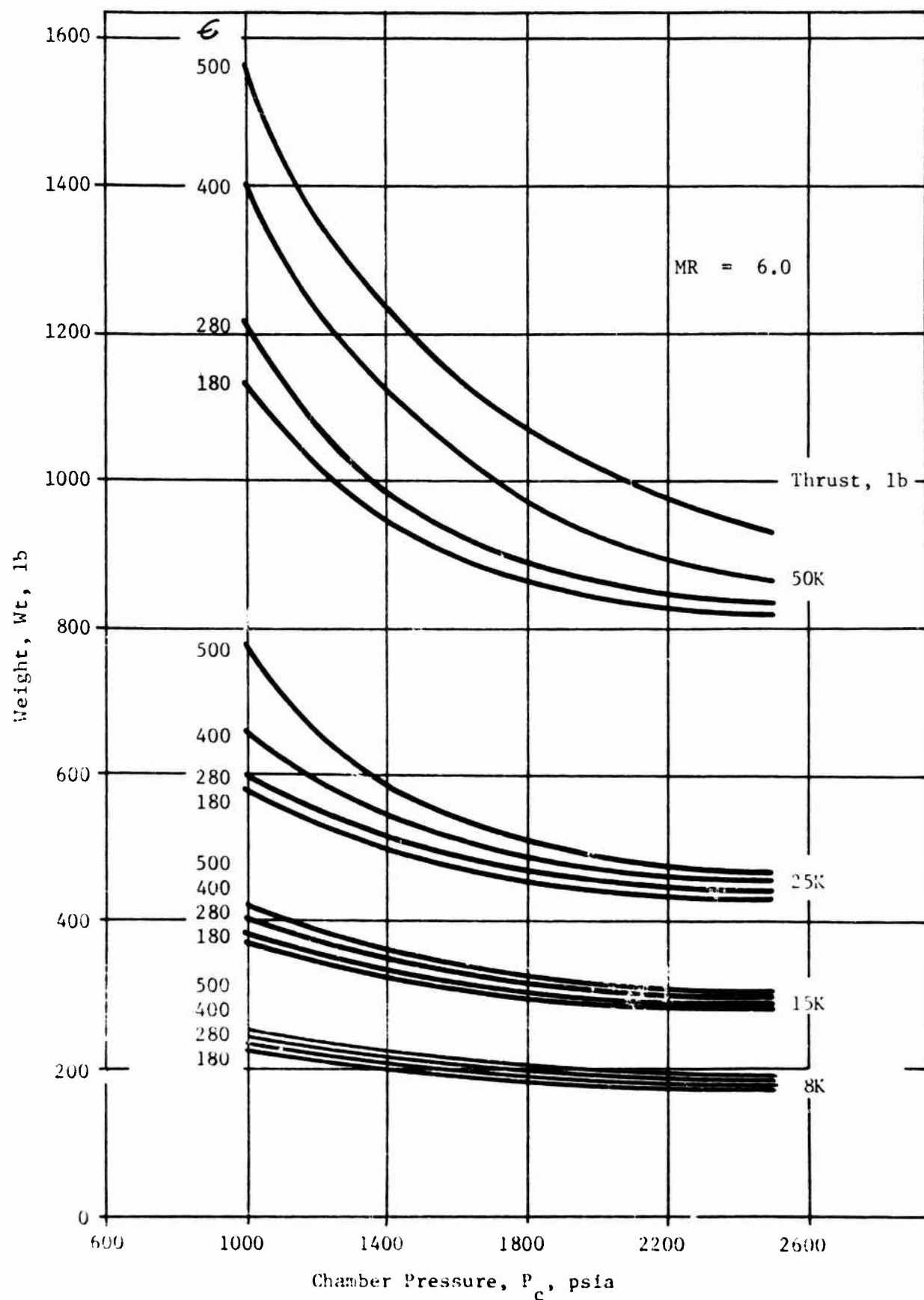


Figure 67. Engine Weight vs  $P_c$ , Minimum Weight Retractable Nozzle, Staged Combustion Bleed Cycle

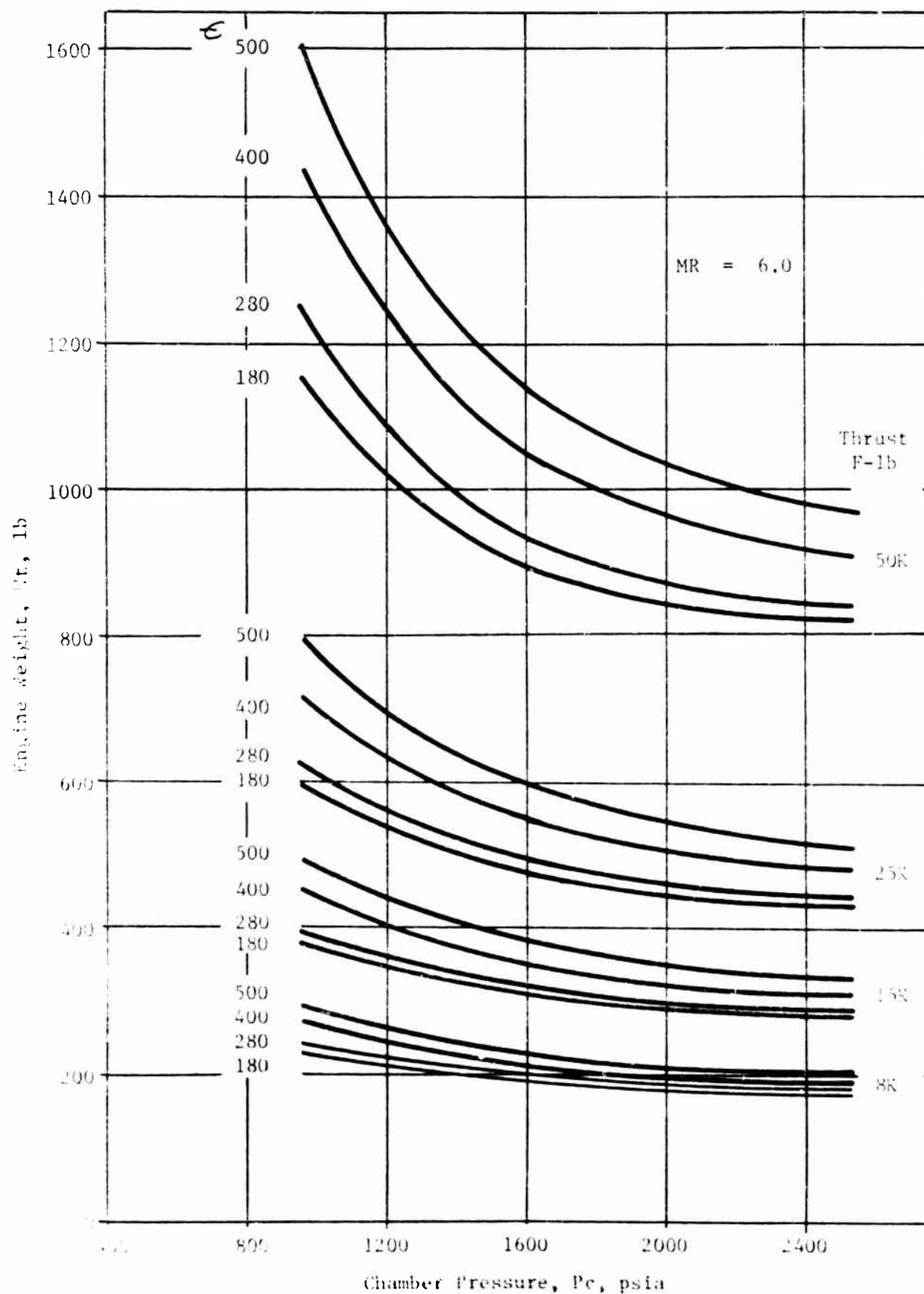


Figure 68. Engine Weight vs  $P_c$ , Minimum Length Retractable Nozzle, Staged Combustion Bleed Cycle

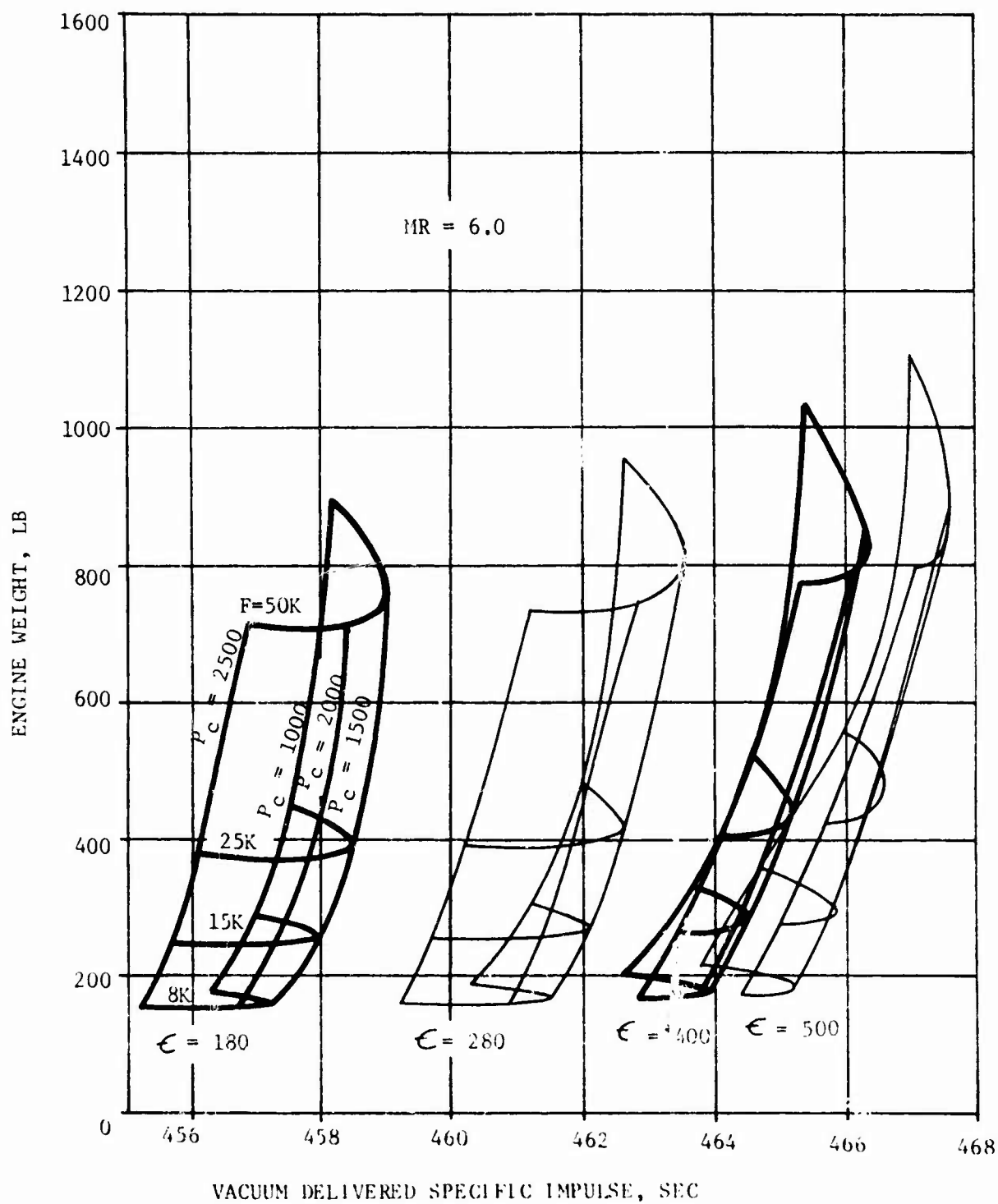


Figure 69. Engine Weight vs  $I_s$ , Fixed Nozzle, Staged Combustion Bleed Cycle

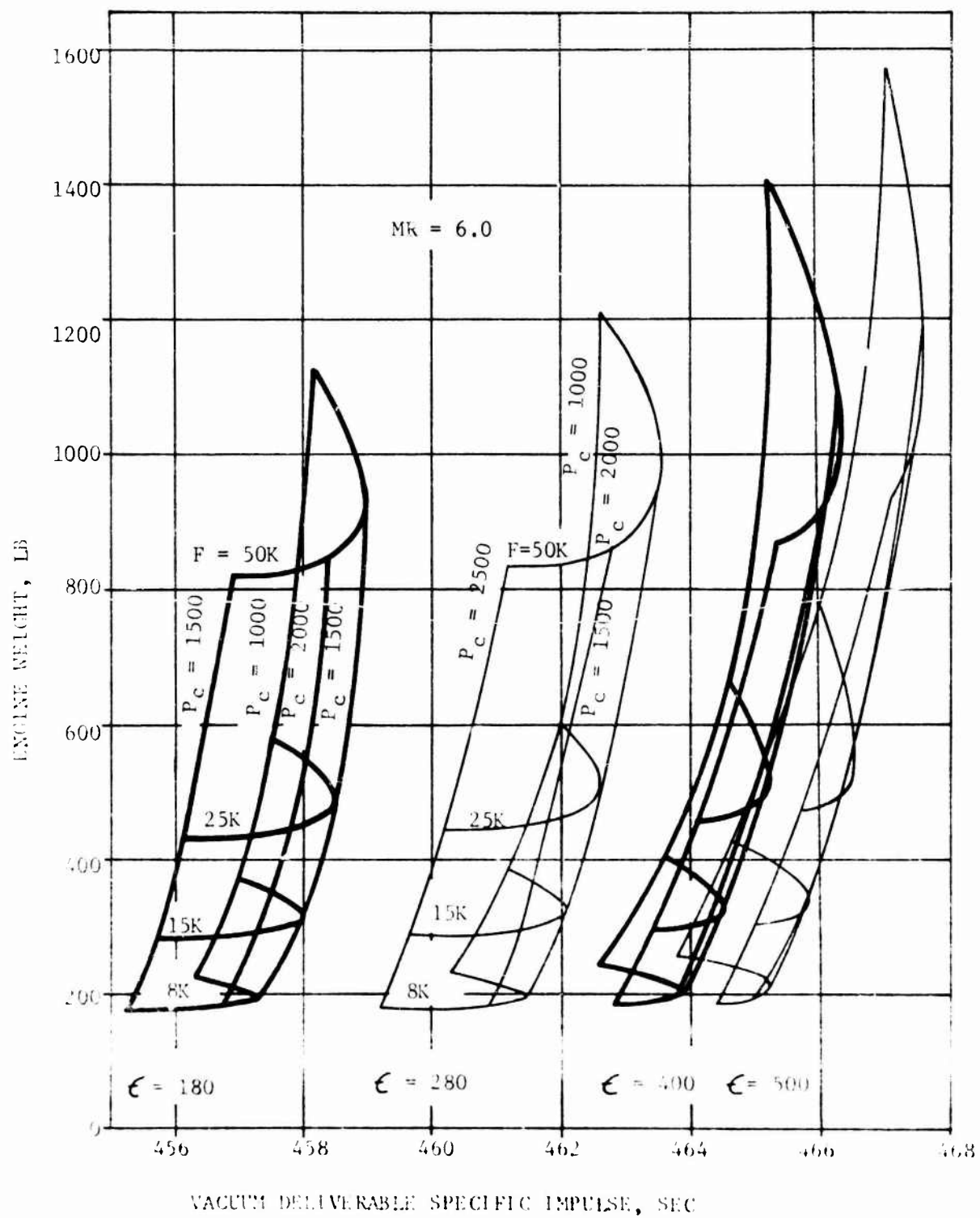


Figure 10. Engine Weight vs.  $I_g$ , Minimum Weight Retractable Nozzle, Staged Combustion Bleed Cycle

### III. A. Engine Design Parametric Study (Task IV) (cont.)

#### 7. Engine Design Constraints

This section characterizes the engine cycles with respect to the engine constraints described in the Table of Requirements.

The main constraints are the engine life, envelope, and mission payload sensitivity parameters. All engines are designed to meet the throttle range of 5:1 and can operate over a mixture ratio of 5.5 to 6.5 at the required NPSH of 60 ft for the hydrogen pump and 16 ft for the oxygen pump.

##### a. Engine Throttling Range

Engine throttling is achieved by the control system selected for each cycle as presented in the appropriate flow schematic. Stability consideration consists of the selection of adequate injector stiffness for both the main and preburner or gas generator injectors.

##### b. Mixture Ratio Range

The mixture ratio range is achieved by the mixture ratio control valve and the selection of adequate coolant pressure drop to facilitate adequate cooling over the whole operating range. Injector stiffness is sufficient to achieve stable operation over the required mixture ratio range at any thrust level within the required throttling range.

##### c. Engine Life Requirements

In the parametric analysis, engine life is constrained by the life of the thrust chamber since it strongly influences the maximum operating chamber pressure at each thrust level. To obtain the maximum payload capability of each cycle within the envelope limitation, the chamber pressure must be selected as high as possible. High pressure permits high expansion nozzle area ratios with minimum engine weight. The absolute potential level of chamber pressure within the life limit is strongly influenced by the chamber material selected.

Zirconium-Copper (ZrCu) was selected for all engine cycles. This selection is based on sample tests conducted on an Aerojet material investigation program. The low cycle fatigue capability of ZrCu is summarized in Figure 9, indicating the low thermal fatigue life cycle as a function of the gradient across the thrust chamber wall in the throat plane.

Based on these data, it was assumed that the temperature gradient at the wall must be restricted to  $\Delta T_w = 935^\circ\text{F}$ . This assumption results in a safety factor  $SF = 4.0$  at the upper data limit and a  $SF = 2.0$  at the lower data limit. The flame side wall temperature  $T_w$  is limited to  $T_w = 1000^\circ\text{F}$ .

### III. A. Engine Design Parametric Study (Task IV) (cont.)

Since the low cycle fatigue life shown in Figure 9 is probably the most important assumption within this parametric analysis, a conservative approach has been taken. Unfortunately, the supporting data is limited and should be confirmed under actual operating conditions. Consequently, it is recommended for future technology investigation.

The chamber life is obtained by designing the thrust chamber for  $\Delta T_w = 935^\circ\text{F}$  and  $T_{w_{\max}} = 1000^\circ\text{F}$ . This is achieved by selection of the proper coolant mach number at the throat location which in turn sets the chamber coolant pressure drop requirements.

The analysis of the coolant pressure drop requirements was the subject of a very involved heat transfer analysis which is presented in Appendix B, and summarized in Figures 71 and 72 as functions of thrust level, chamber pressure, and coolant outlet pressure.

#### d. Engine Envelope

The engine envelope defines the stowed engine envelope. This requirement restricts the fixed engine length to an overall length of 82 inches. The achievable nozzle expansion area ratios are dependent upon the nozzle contour and thrust chamber length. For the retractable nozzles, the achievable expansion area ratios are also dependent on the retraction (i.e., minimum weight or minimum length).

The achievable expansion area ratios were computed for all three nozzle types as function of thrust/chamber pressure ratio, and various chamber lengths and are presented in Figures 73 through 80 for  $MR = 6.0$ .

In addition, for the retractable nozzles, the area ratios at which the division between the fixed and retractable section is located are shown in Figure 75 through Figure 77 for the minimum length nozzle and Figures 78 through 80 for the minimum weight retractable nozzle.

#### e. Power Balance for Topping Cycles

A power balance analysis for the topping cycles, including the expander and staged combustion cycles, was conducted using the coolant pressure drops required to meet the low cycle fatigue life of the thrust chamber. The results of this analysis are shown in Figures 81 and 82, yielding fuel pump discharge requirements as function of thrust level and chamber pressures. This analysis was used to assign the proper chamber pressures to achieve adequate power balance capability. 80% of the maximum achievable chamber pressure was selected for the staged combustion cycle and 90% for the expander cycle.

Figure 71. Coolant Pressure Drop vs  $P_c$

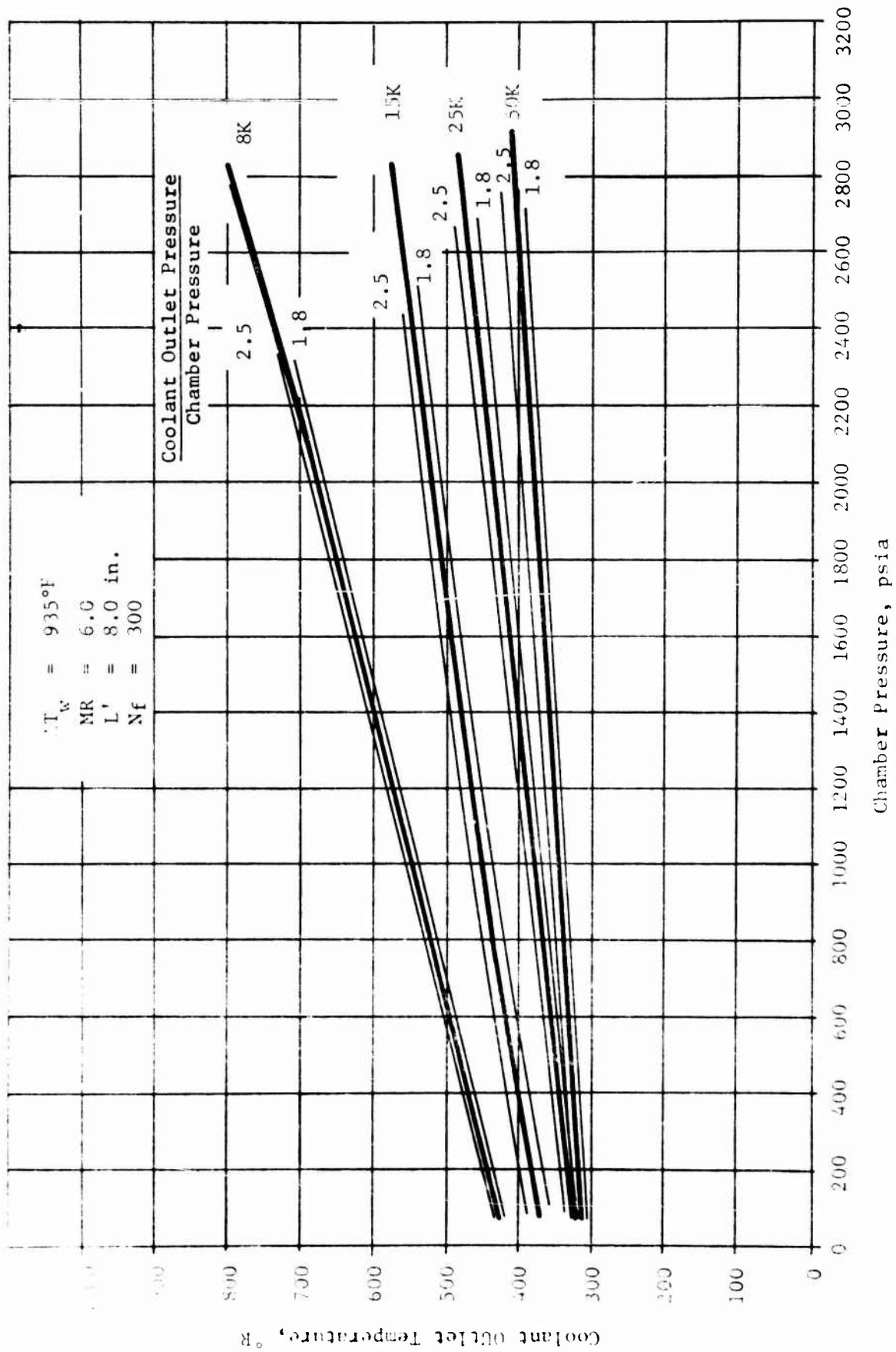


Figure 72. Coolant Temperature Rise vs  $P_c$

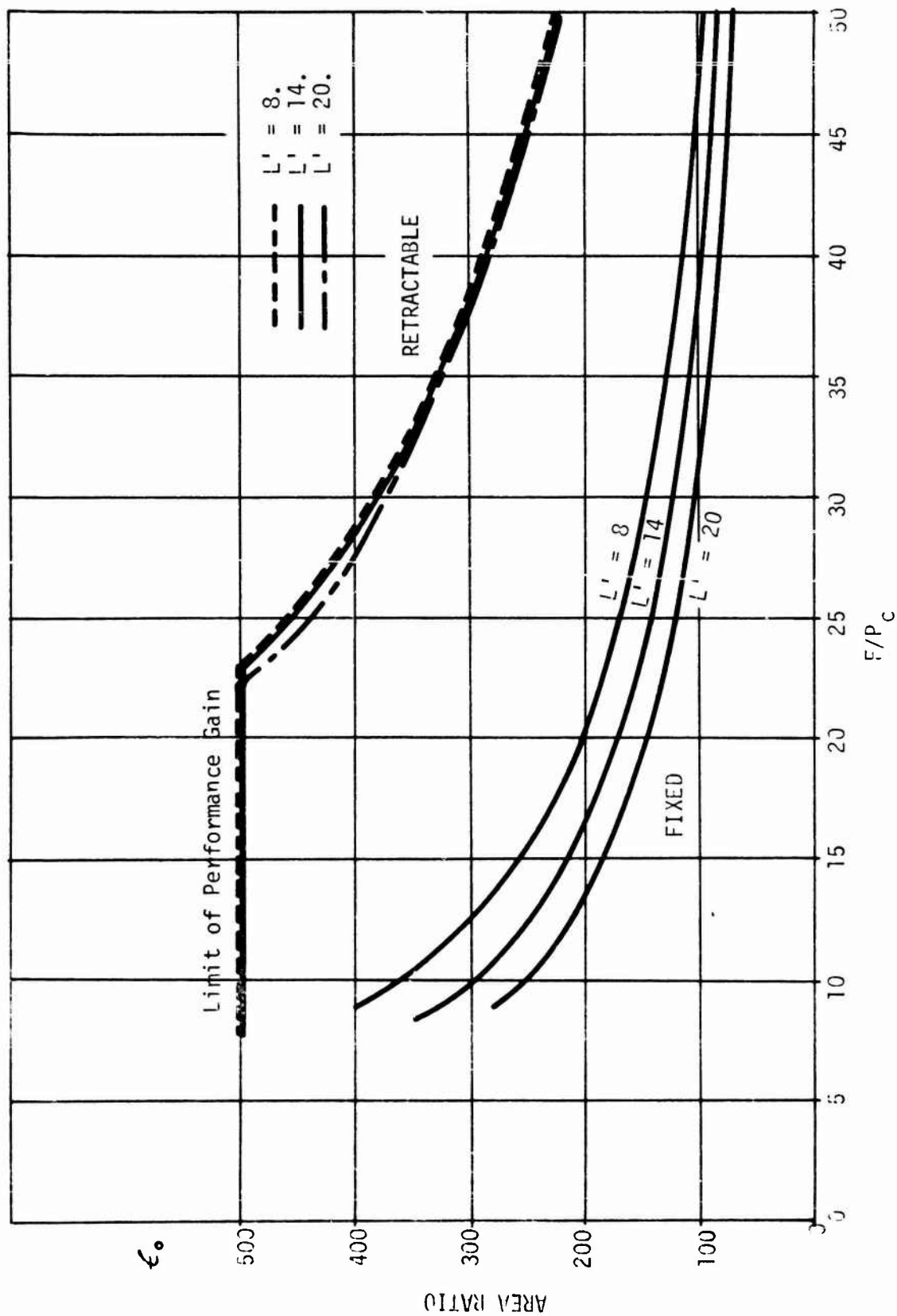


Figure 73. Maximum Area Ratio for Fixed Nozzles and Minimum Stowed Length Retractable Nozzles

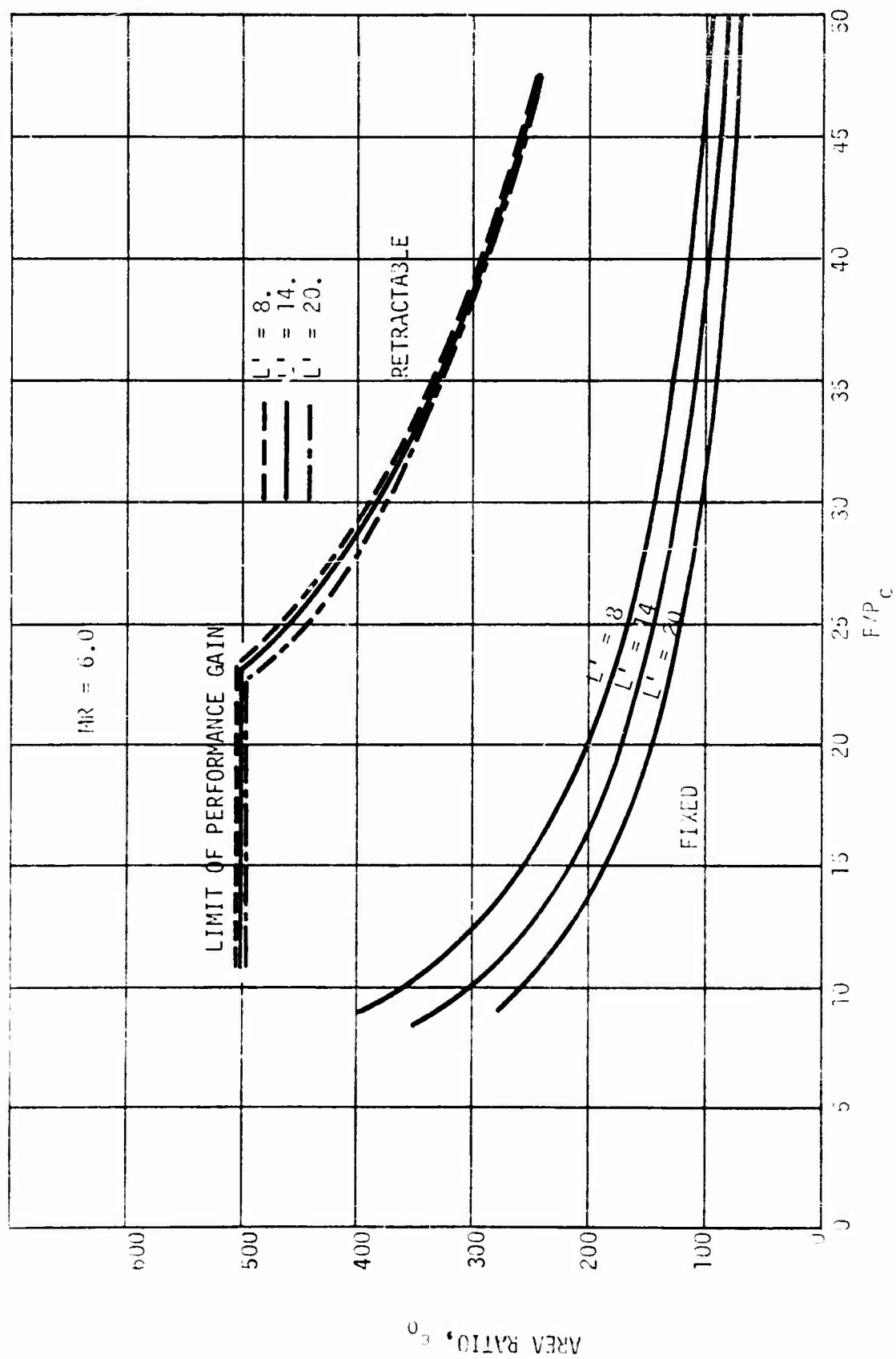


Figure 74. Maximum Area Ratio for Fixed Nozzles and Minimum Weight Retractable Nozzles

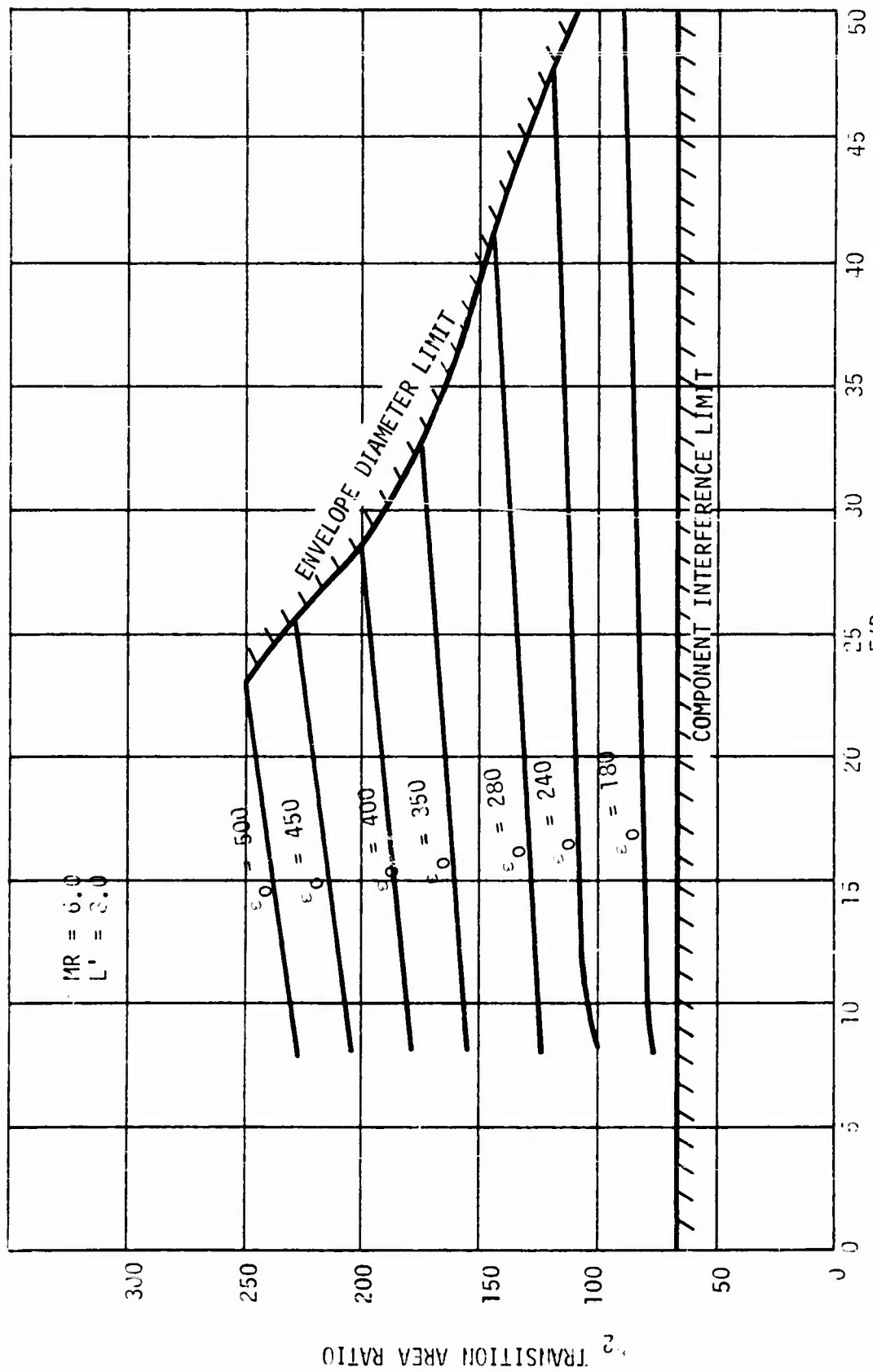


Figure 75. Transition Area Ratios for Minimum Stowed Length Retractable Nozzle,  $L' = 8$ -in.

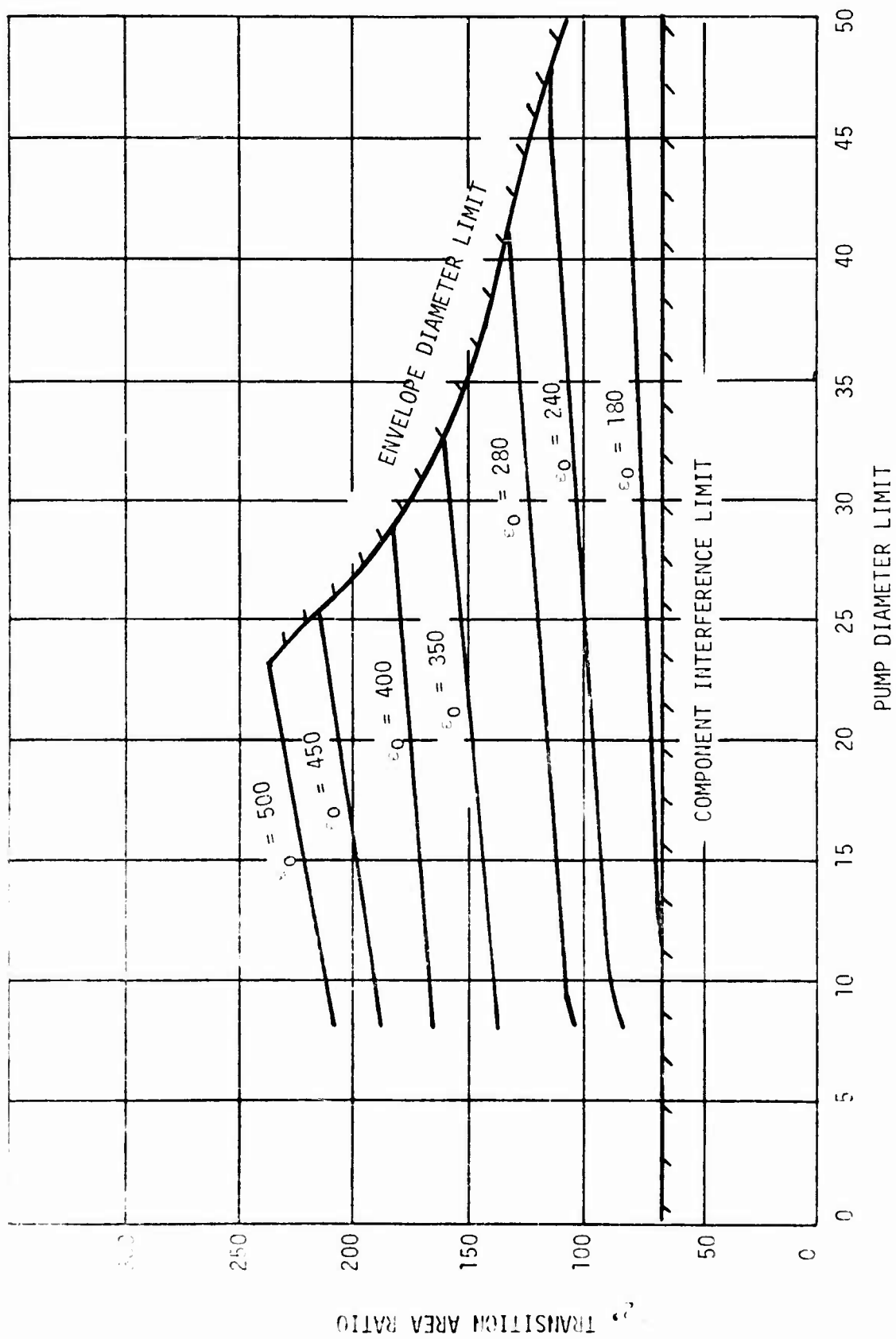


Figure 76. Transition Area Ratios for Minimum Stowed Length Nozzle,  $L' = 14$ -in.

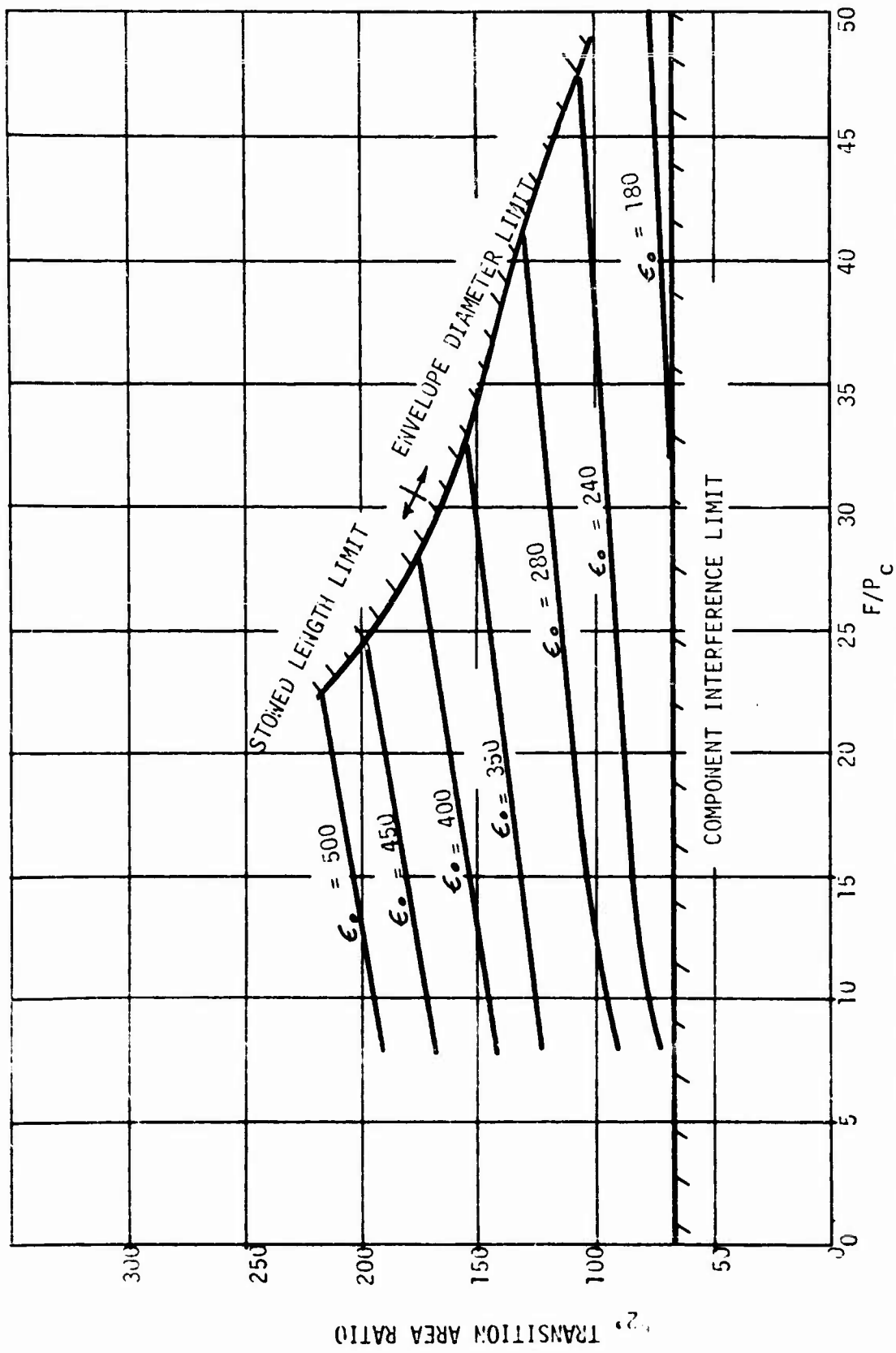


Figure 77. Transition Area Ratios for Minimum Stowed Length,  $L' = 20$ -in.

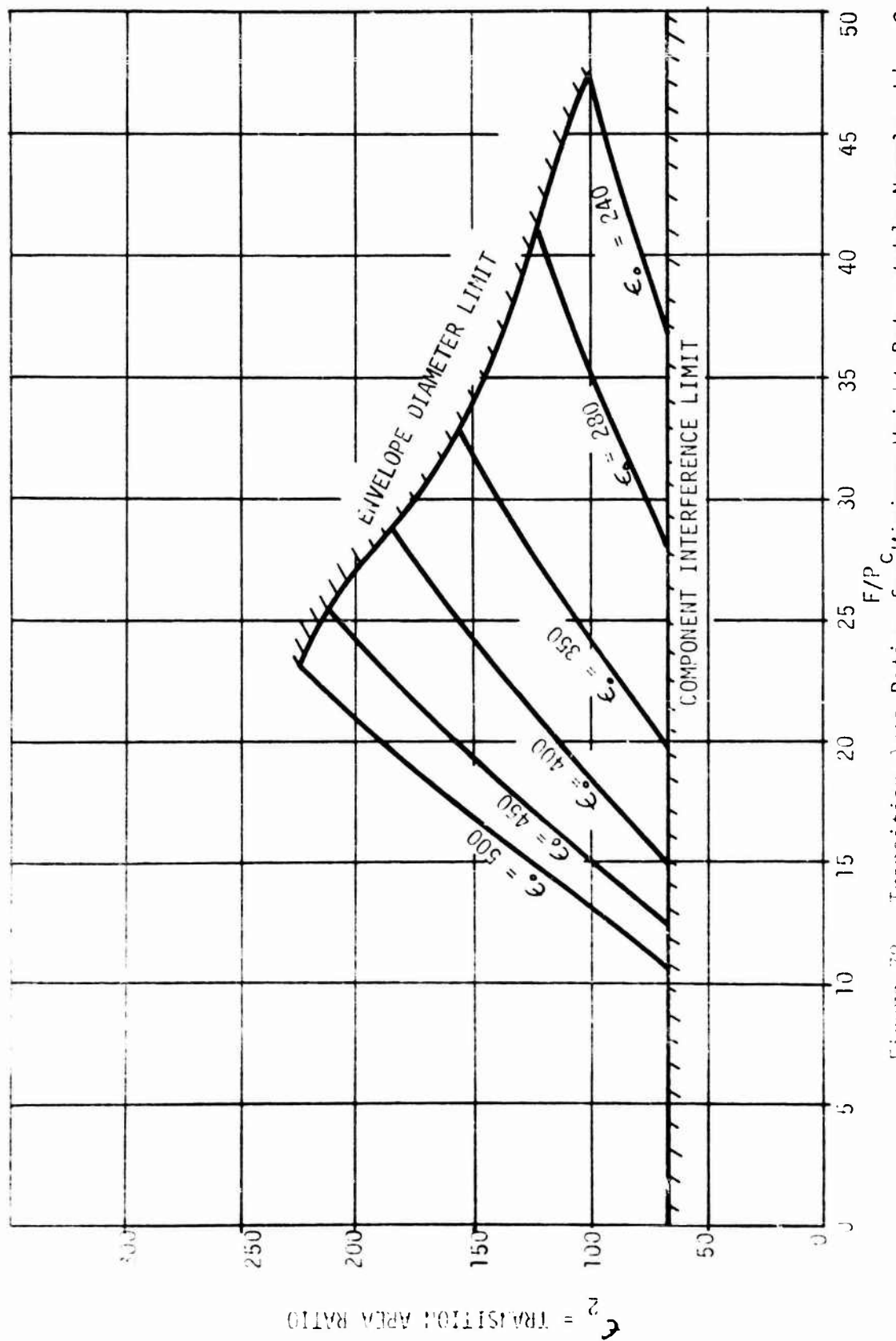


Figure 78. Transition Area Ratios for Minimum Weight Retractable Nozzle,  $L' = 8$ -in.

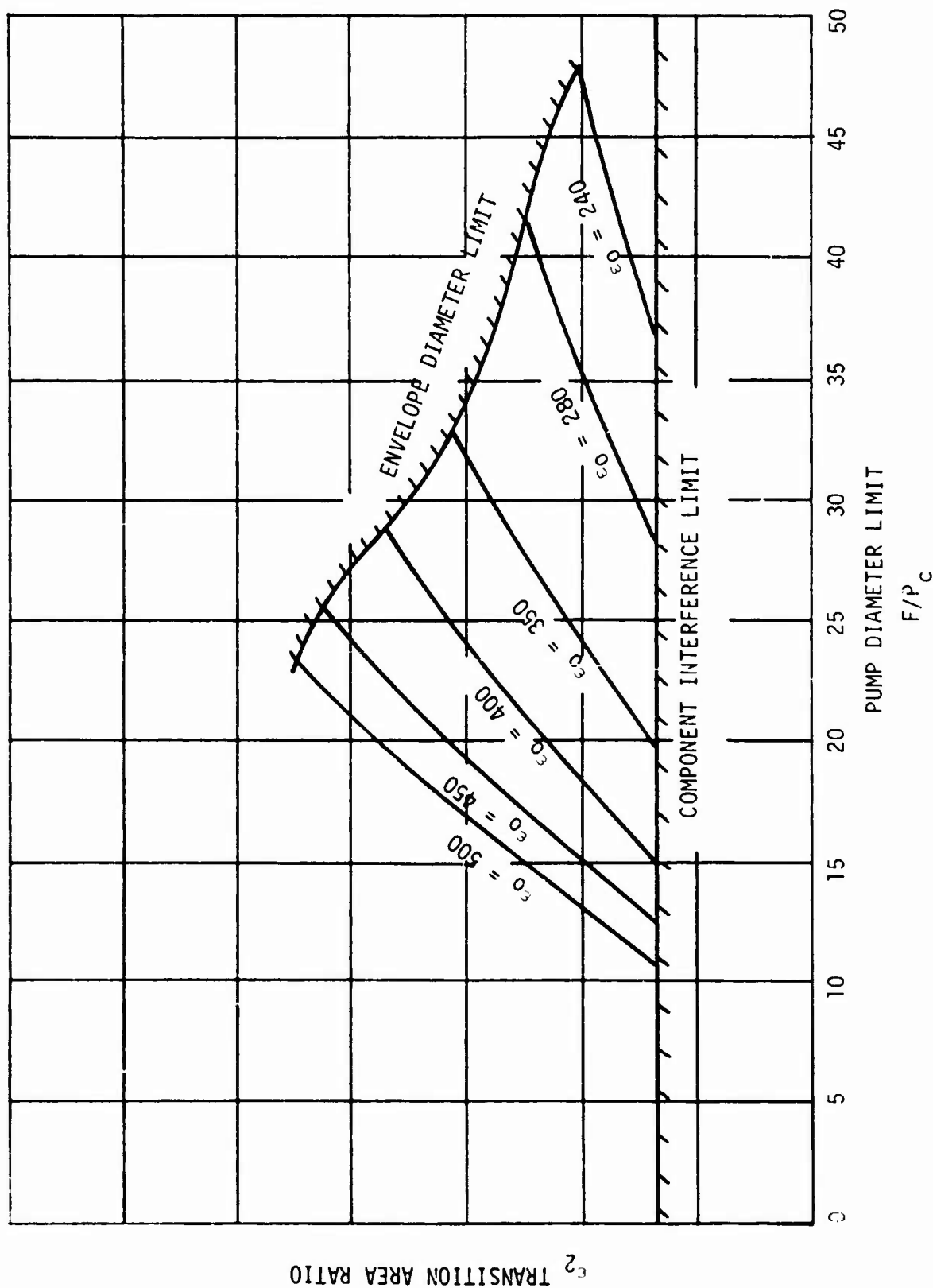


Figure 79. Transition Area Ratios for Minimum Weight Retractable Nozzle,  $L' = 14$ -in.

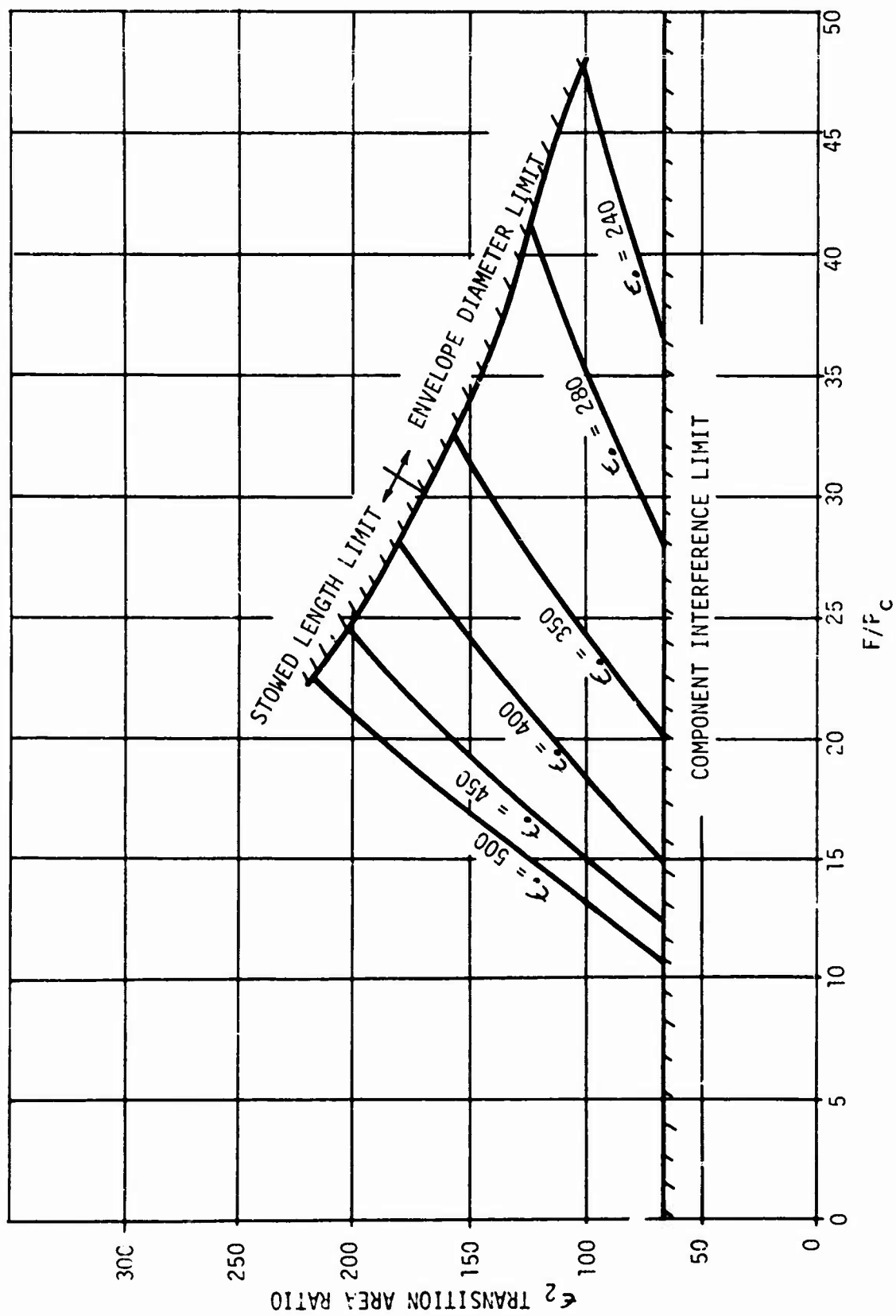


Figure 80. Transition Area Ratios for Minimum Weight Retractable Nozzle,  $L' = 20$ -in.

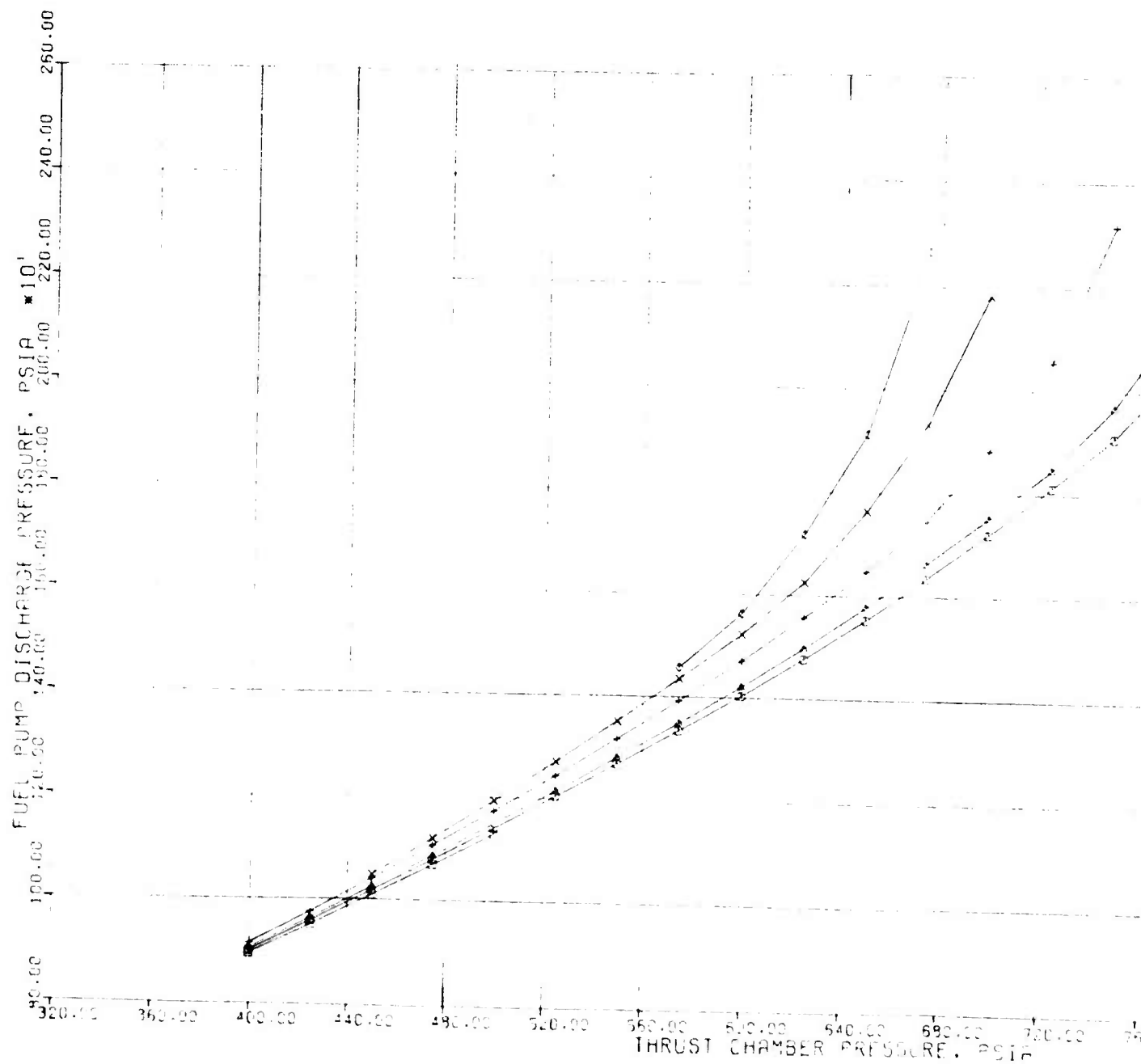


Figure 81. Power Balance for Expander C

# EXPANDER

PARALLEL TURBINES

MR=6. TTIF - Computed

## THRUST

□ 5,000 LB

○ 8,500

△ 10,000

+ 15,000

x 20,000

◇ 25,000

LH<sub>2</sub> PUMP STAGES - 2

TURB. ' - 2

LO<sub>2</sub> PUMP ' - 1

TURB. ' - 1

940.00 990.00 920.00 950.00

Expander Cycle, MR = 6

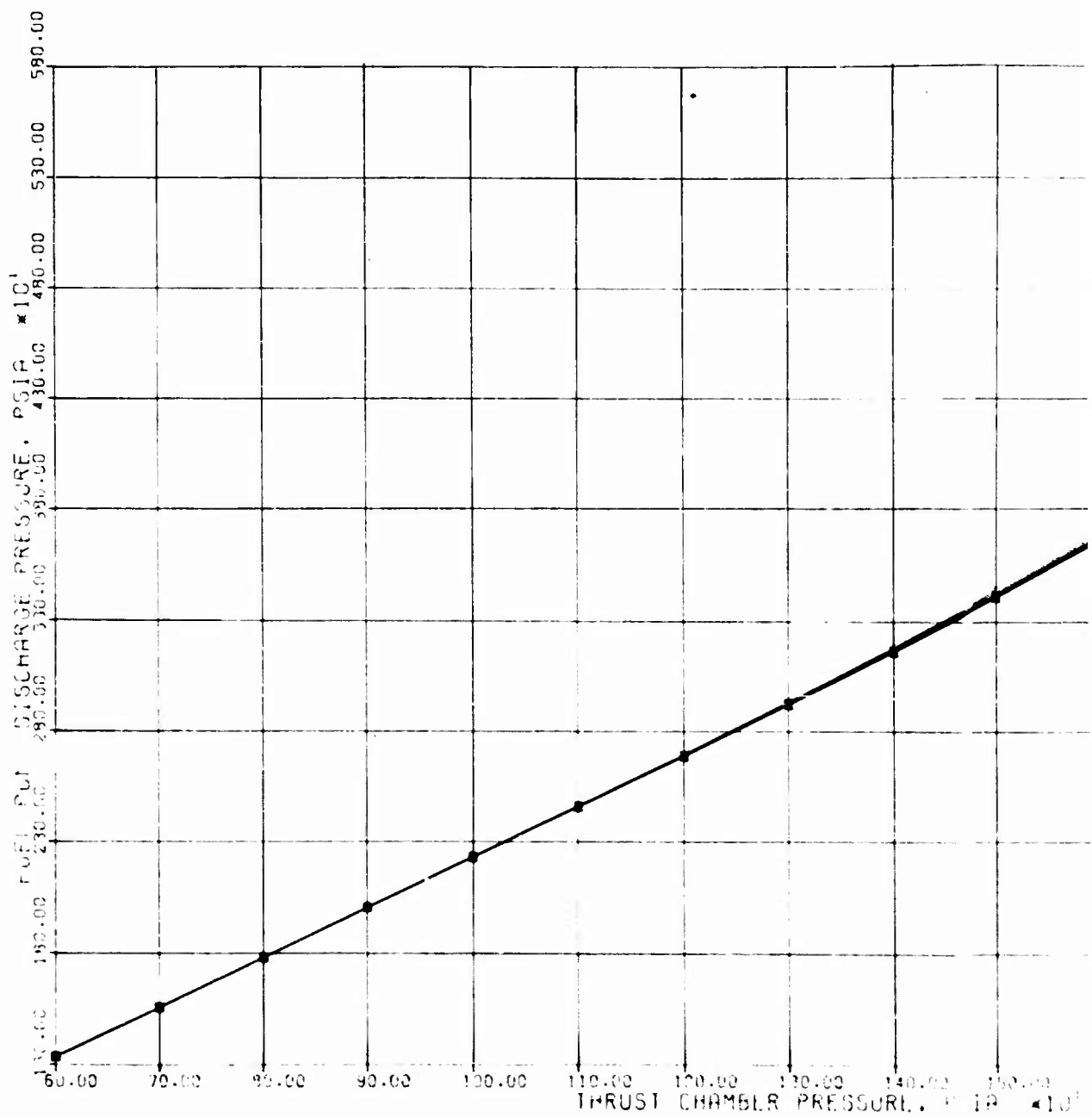


Figure 82. Power Balance 10

# STAGE COMBUSTION

CHAMBER MR = 6,

TTIF = 1860 °R

LH<sub>2</sub> PUMP STAGES - 2

TURB " - 2

LO<sub>2</sub> PUMP " - 1

TURB " - 1

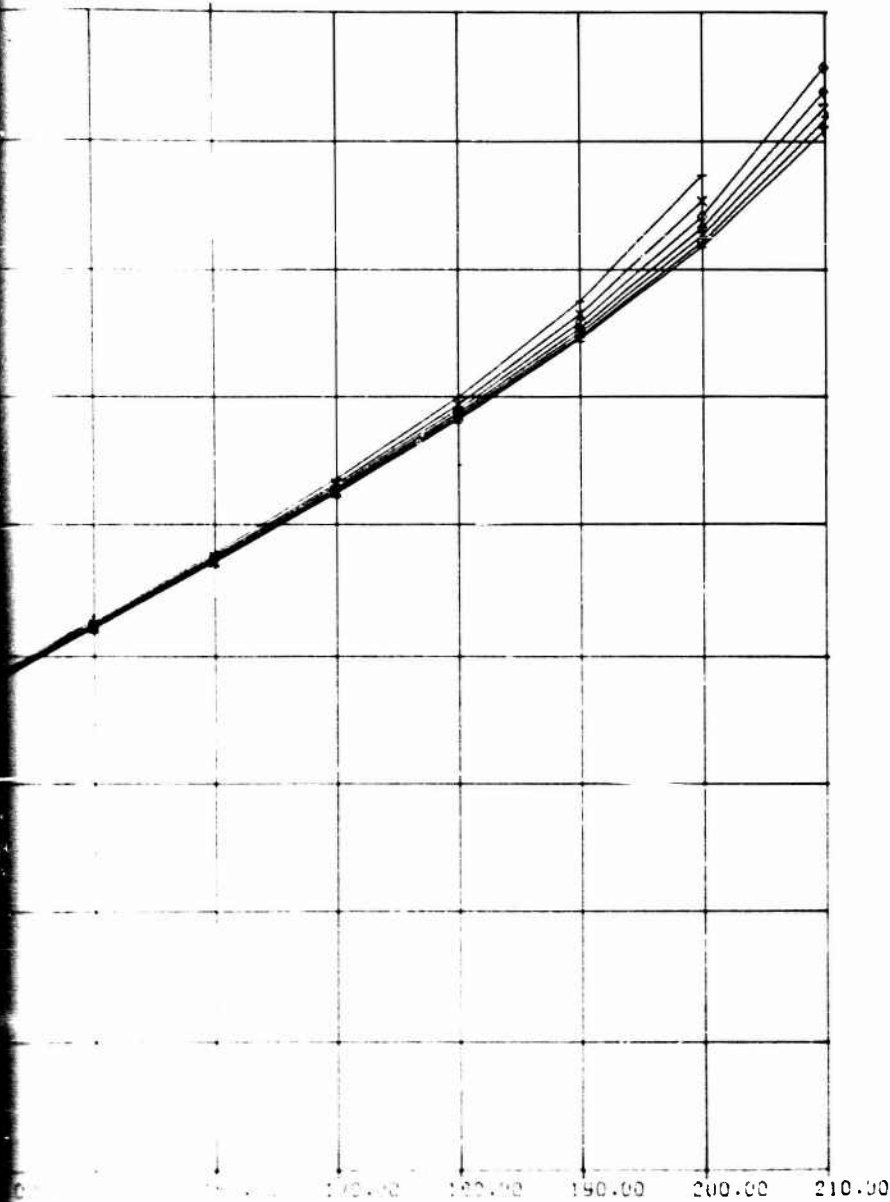
CHAMBER

THRUST

CHAMBER

PRESS. RANGE

|            |                |
|------------|----------------|
| □ 8,000 LB | 600 - 800 PSIA |
| ○ 10,000   | 600 - 1000     |
| △ 15,000   | 600 - 1500     |
| + 20,000   | 600 - 2000     |
| X 25,000   | 600 - 2000     |
| ◇ 30,000   | 700 - 2100     |
| ⊕ 35,000   | 800 - 2100     |
| ⊗ 40,000   | 900 - 2100     |
| Z 45,000   | 1000 - 2100    |
| Y 50,000   | 1200 - 2100    |



er balance for Staged Combustion Cycle, MR = 6

f. Performance Optimization of Bleed Cycles

A chamber pressure optimization survey was conducted for the bleed cycles to obtain the optimum performance within the given envelope for both the fixed and minimum weight retractable nozzles. The relationship is indicated in the generalized performance curves shown in Figure 83.

g. Maximum Chamber Pressure Determination

In Figure 83, the maximum recommended chamber pressures are summarized for each cycle over a thrust range of 8K to 50K lb. The results indicate that the staged combustion type cycle has the highest chamber pressure capability over the whole thrust range followed by the gas generator bleed cycle. This relationship was used to determine the engine performance and payload capability of the various cycles as a function of thrust level.

8. Comparison of Engine Cycles over 8K to 50K Thrust Range

Engine cycles compared for specific impulse and payload capability at the design requirements.

Staged Combustion Cycle

Staged Combustion - Bleed Cycle

Expander Cycle

Gas Generator and Chamber Tap-off Cycle

Coolant Bleed Cycle

The gas generator cycle and chamber tap-off cycle are identical in weight and performance and therefore no differentiation is made between them. Both fixed and the minimum weight retractable nozzles are compared. The comparisons are valid for a mixture ratio of 6.0 for fixed and stowed nozzle envelopes over all thrust levels. The comparison of specific impulse is shown in Figure 84. The results indicate that the staged combustion cycle has the highest performance over the whole thrust range from 8K to 50K thrust for both the fixed and retractable nozzles. It also indicates an increase in performance with an increase in thrust for the retractable nozzle and a decrease in performance with increasing thrust for the fixed nozzle concept.

The staged combustion bleed cycle shows similar trends with slightly reduced performance as compared to the staged combustion cycle. The slightly reduced performance is due to the bleed losses.

The expander cycle shows optimum performance for the retractable nozzle at the 15K thrust level. The performance gain of the retractable nozzle over the fixed nozzle is considerable.

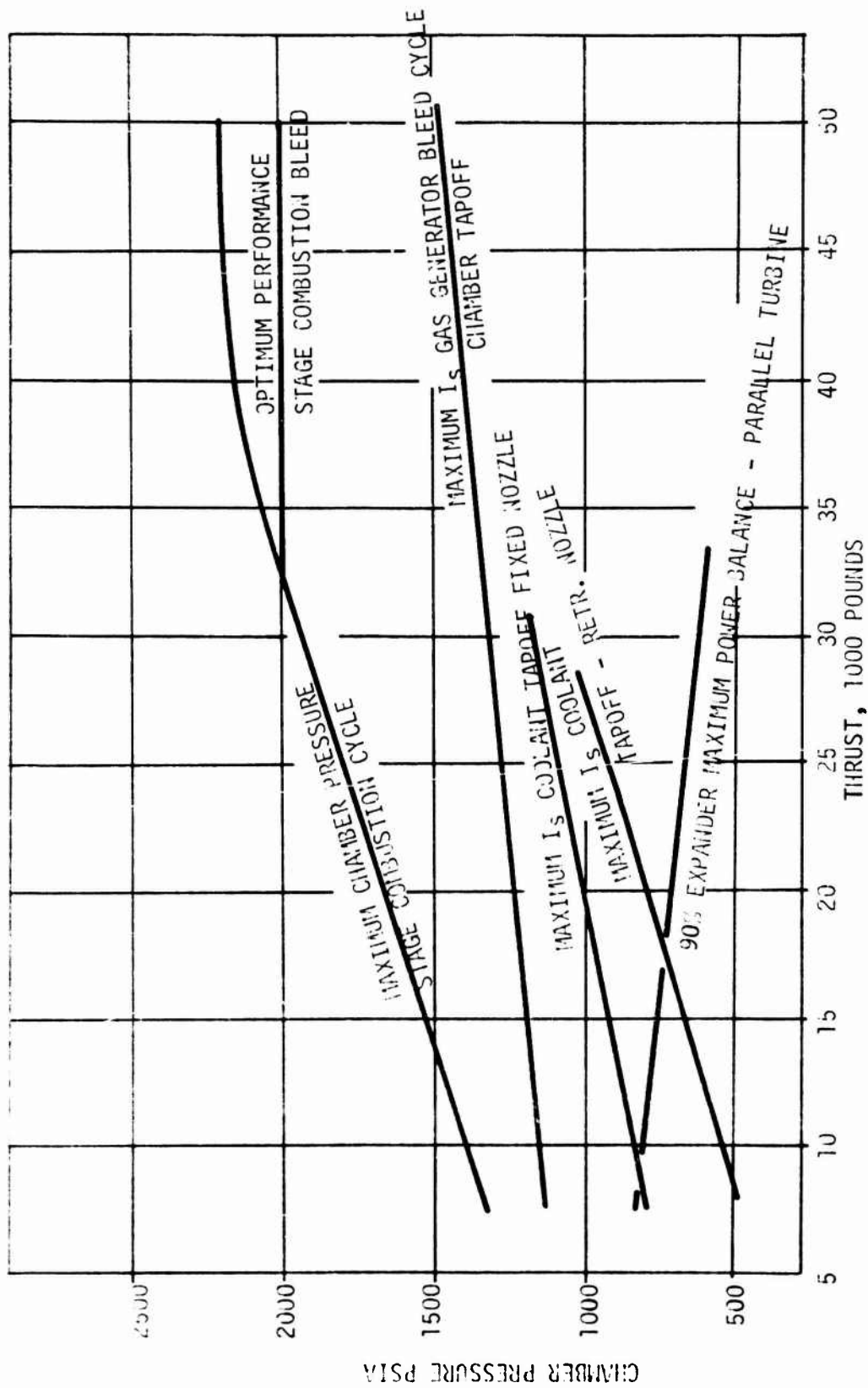


Figure 83. Optimum Chamber Pressure for Various Engine Cycles

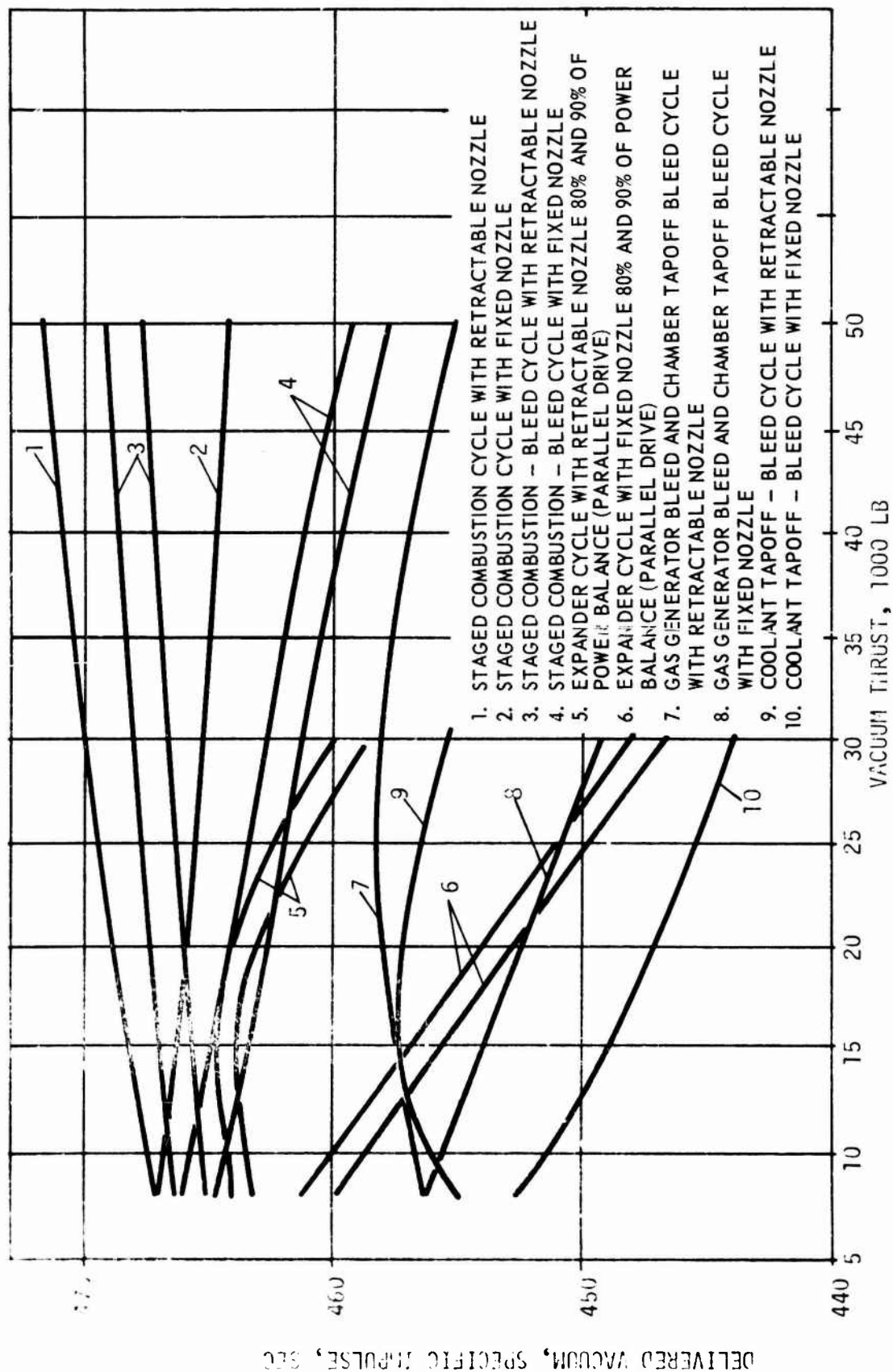


Figure 84.  $I_s$  vs Thrust for Various Engine Cycles

### III. A. Engine Design Parametric Study (Task IV) (cont.)

The gas generator bleed cycle and chamber tap-off cycle for the retractable nozzle optimizes at the 25K thrust level. It will be noted the bleed cycles can only obtain performance levels below 460 sec of specific impulse because of the relatively large bleed losses at  $MR = 6.0$ .

The coolant tap-off cycle for retractable nozzle compares favorably with the gas generator bleed cycle but shows lower performance for the fixed nozzle.

All cycles show a very small gain due to the retractable nozzle at the 8K thrust level and is due to the fact that the given envelope permits the small, fixed nozzle engines to operate at high nozzle expansion area ratio.

A further comparison was made on the basis of payload capability for the orbit-to-orbit mission and the result is presented in Figure 85. In this comparison, the relative payload gains are presented relative to the stage combustion cycle at the 25K thrust level for fixed nozzle concept. The various engine weights used for this analysis are identical to the generalized parametric engine weights for the related chamber pressures and nozzle expansion areas. All weight and performance values used are documented in Table XVI.

The payload comparison which include engine weight effects shows the same order of cycle preference as the specific impulse comparison. The staged combustion cycle gives the highest payload capability over the whole thrust range from 8K to 50K thrust. The significance of this comparison is that the smaller thrust level shows increased payload capability over the larger thrust engines but this is only true when comparing single engine applications.

At the 8K thrust level, the retractable nozzle shows no payload gain as compared to the fixed nozzle due to the fact that fixed nozzles can obtain near optimum nozzle area ratios within the given envelope.

Low pressure engines gain considerable payload at the larger thrust level compared to the high pressure cycles, such as the staged combustion cycles. Very little payload is gained with the retractable nozzle concept at any thrust level for the high pressure cycles.

#### 9. Staged Combustion Cycle Engine Description for Discrete Thrust Levels of 8K, 15K, 25K, and 50K

This section characterizes the staged combustion cycle for discrete thrust levels. Figure 86 presents the fixed nozzle engine weight and delivered vacuum performance at mixture ratio = 6.0 in generalized form as a function of thrust chamber pressure and nozzle expansion area ratio. Figure 87 shows identical data for the minimum weight retractable nozzle.

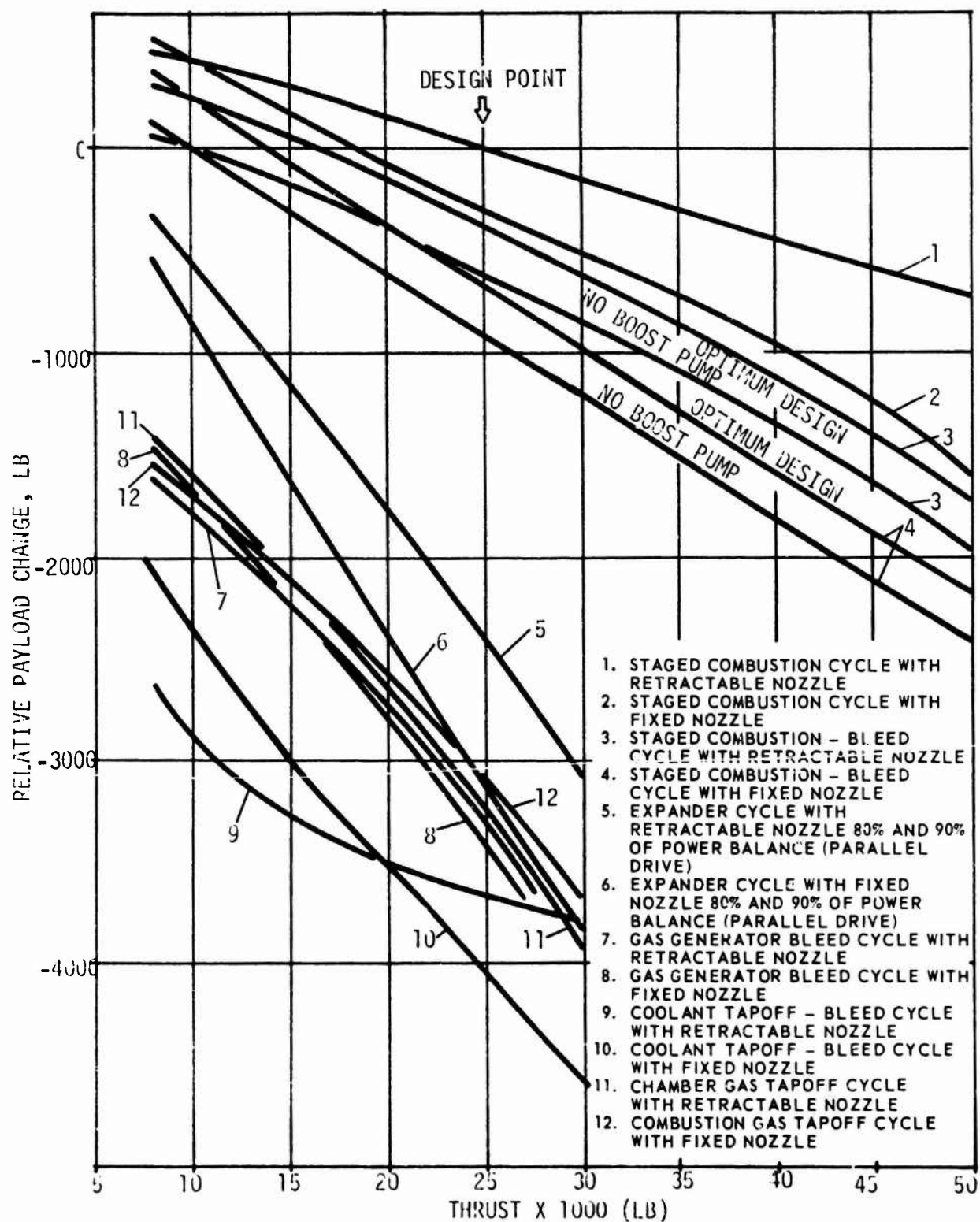


Figure 35. Relative Payload vs Thrust for Various Engine Cycles

TABLE XVI

## PARAMETRIC STUDY, PAYLOAD OPTIMIZATION

Page 1 of 10

ENGINE CYCLEStaged Combustion - Parallel Turbine Drive

MR = 6.0

Nom. NPSH(F) = 60 ft.

NPSH(O) = 16 ft.

FIXED NOZZLE CONFIGURATION

|                                   | 8,000 | 15,000 | 25,000 | 40,000 | 50,000 |
|-----------------------------------|-------|--------|--------|--------|--------|
| $P_c$                             | 500   | 360    | 270    | 205    | 180    |
| $P_c$                             | 1,200 | 1450   | 1800   | 2140   | 2200   |
| $I_s$                             | 466.5 | 465.8  | 465.3  | 463.5  | 461.6  |
| $W_{B.O}$<br>(Lbs)                | 200.0 | 270.0  | 380.0  | 580    | 660.0  |
| 157 $I_s$                         | 73306 | 150    | 73052  | 72800  | 550    |
| -3.68 $W_{B.O}$                   | 736   | 993    | 1398   | 2134   | 2430   |
| Relative<br>PAYLOAD (PL)<br>(Lbs) | 72564 | 72157  | 71654  | 70676  | 69920  |

MINIMUM WEIGHT RETRACTABLE NOZZLE CONFIGURATION

|                                   | 8,000 | 15,000 | 25,000 | 40,000 | 50,000 |
|-----------------------------------|-------|--------|--------|--------|--------|
| $P_c$                             | 500   | 500    | 500    | 500    | 500    |
| $P_c$                             | 1200  | 1450   | 1800   | 2140   | 2200   |
| $I_s$                             | 466.6 | 468.3  | 469.1  | 471.0  | 471.4  |
| $W_{B.O}$<br>(Lbs)                | 230.0 | 330.0  | 490.0  | 730.0  | 940    |
| 157 $I_s$                         | 73319 | 73523  | 73650  | 73947  | 74073  |
| -3.68 $W_{B.O}$                   | 847   | 1214   | 1803   | 8684   | 3460   |
| Relative<br>PAYLOAD (PL)<br>(Lbs) | 72472 | 72309  | 71847  | 71863  | 70613  |

TABLE XVI (cont.)

Page 2 of 10

ENGINE CYCLE

Staged Combustion - Bleed

Series Turbine DriveFIXED NOZZLE CONFIGURATION

MR = 6.0

Nom NPSH(F) = 60 ft.

NPSH(O) = 16 ft.

| F                     | 8,000 | 15,000 | 25,000 | 40,000 | 50,000 |
|-----------------------|-------|--------|--------|--------|--------|
| $\epsilon_o$          | 500   | 360    | 270    | 200    | 170    |
| $P_c$                 | 1200  | 1500   | 1800   | 2000   | 2000   |
| $I_s$ Optimum         | 466.1 | 465.0  | 462.5  | 461.0  | 459.2  |
| $I_s$ Delivered       | 464.6 | 463.5  | 462.0  | 459.5  | 457.7  |
| $W_{B.O}$<br>(lbs)    | 200.0 | 280.0  | 400.0  | 620.0  | 700.0  |
| 157 $I_s$ Opt.        | 73178 | 73005  | 72770  | 72377  | 72094  |
| 157 $I_s$             |       |        |        |        |        |
| -3.68 $W_{B.O}$       | 736   | 1030   | 1472   | 2282   | 2580   |
| PAVLOAD Opt.          | 72465 | 72015  | 71423  | 70511  | 69923  |
| PAVLOAD (PL)<br>(lbs) | 72442 | 71975  | 71298  | 70095  | 69514  |

MINIMUM WEIGHT RETRACTABLE NOZZLE CONFIGURATION

| F                     | 8,000 | 15,000 | 25,000 | 40,000 | 50,000 |
|-----------------------|-------|--------|--------|--------|--------|
| $\epsilon_o$          | 500   | 500    | 500    | 500    | 460    |
| $P_c$                 | 1200  | 1500   | 1800   | 2000   | 2000   |
| $I_s$ Optimum         | 466.1 | 467.0  | 467.7  | 468.5  | 468.5  |
| $I_s$ Delivered       | 464.6 | 465.5  | 466.2  | 467.0  | 467.0  |
| $W_{B.O}$<br>(lbs)    | 235.0 | 350.0  | 510.0  | 740.0  | 930.0  |
| 157 $I_s$ Opt.        | 73178 | 73319  | 73429  | 73555  | 73555  |
| 157 $I_s$             |       |        |        |        |        |
| -3.68 $W_{B.O}$       | 864   | 1250   | 1877   | 2720   | 3420   |
| PAVLOAD Opt.          | 72392 | 72149  | 71708  | 70986  | 70373  |
| PAVLOAD (PL)<br>(lbs) | 72314 | 72069  | 71552  | 70735  | 70135  |

ENGINE CYCLE

Expander - Parallel Turbine Drive

MR = 6.0

Nom. NPSH(F) = 60 ft

NPSH(O) = 16 ft.

FIXED NOZZLE CONFIGURATION

| F                                 | 8,000 | 15,000 | 25,000 | 30,000          | 50,000 |
|-----------------------------------|-------|--------|--------|-----------------|--------|
| $E_c$                             | 300   | 180    | 100    | N/A             | N/A    |
| $r_c$                             | 820   | 760    | 680    | 660             | -      |
| $I_s$                             | 461.2 | 456.8  | 451.2  | Weight Increase |        |
|                                   |       |        |        | Excessive       |        |
| $W_{B.O}$<br>(lbs)                | 227.9 | 343.5  | 507.2  | —               | —      |
| 157 $I_s$                         | 72408 | 71718  | 70838  | —               | —      |
| -3.68 $W_{B.O}$                   | 839   | 1265   | 1866   | —               | —      |
| Relative<br>PAYLOAD (PL)<br>(lbs) | 71569 | 70453  | 68972  | —               | —      |

MINIMUM WEIGHT RETRACTABLE NOZZLE CONFIGURATION

| F                                 | 8,000 | 15,000 | 20,000 | 25,000 | 30,000 |
|-----------------------------------|-------|--------|--------|--------|--------|
| $E_c$                             | 500   | 500    | 400    | 320    | 250    |
| $r_c$                             | 820   | 760    | 710    | 680    | 660    |
| $I_s$                             | 464.0 | 464.6  | 464.0  | 462.4  | 460.2  |
| $W_{B.O}$<br>(lbs)                | 293.5 | 545.4  | 678.8  | 789.8  | 878.4  |
| 157 $I_s$                         | 72848 | 72942  | 72848  | 72597  | 72251  |
| -3.68 $W_{B.O}$                   | 1080  | 2007   | 2498   | 2906   | 3233   |
| Relative<br>PAYLOAD (PL)<br>(lbs) | 71768 | 70935  | 70350  | 69691  | 69018  |

TABLE XVI (cont.)ENGINE CYCLEGas Generator Bleed - Series Turbine Drive

MR = 6.0

Nominal NPSH(F) = 60 Ft.

NPSH(O) = 16 Ft.

FIXED NOZZLE CONFIGURATION

| F                                 | 8,000 | 15,000 | 20,000 | 25,000 |
|-----------------------------------|-------|--------|--------|--------|
| $\epsilon_o$                      | 500   | 295    | 235    | 205    |
| $P_c$                             | 1130  | 1190   | 1225   | 1270   |
| $I_s$                             | 455.6 | 454.0  | 453.0  | 451.6  |
| $W_{B.O}$<br>(lbs)                | 230.0 | 340.0  | 420.0  | 500.0  |
| 157 $I_s$                         | 71550 | 71278  | 71100  | 70900  |
| -3.68 $W_{B.O}$                   | 846   | 1250   | 1545   | 1840   |
| Relative<br>PAYLOAD (PL)<br>(lbs) | 70764 | 70028  | 69555  | 69.060 |

MINIMUM WEIGHT RETRACTABLE NOZZLE CONFIGURATION

| F                                 | 8,000 | 15,000 | 20,000 | <del>25,000</del> |
|-----------------------------------|-------|--------|--------|-------------------|
| $\epsilon_o$                      | 500   | 500    | 500    | 500               |
| $P_c$                             | 1130  | 1190   | 1225   | 1270              |
| $I_s$                             | 455.6 | 457.6  | 458.7  | 459.5             |
| $W_{B.O}$<br>(lbs)                | 260.0 | 410.0  | 550.0  | 680.0             |
| 157 $I_s$                         | 71400 | 71812  | 72000  | 72080             |
| -3.68 $W_{B.O}$                   | 957   | 1508   | 2025   | 2503              |
| Relative<br>PAYLOAD (PL)<br>(lbs) | 70443 | 70304  | 69975  | 69577             |

TABLE XVI (cont.)ENGINE CYCLECoolant Tapoff - Series Turbine Drive

MR = 6.0

Nom. NPSH(F) = 60 ft

NPSH(O) = 16 ft.

FIXED NOZZLE CONFIGURATION

| F                                 | 8,000 | 15,000 | 20,000 | 25,000 | 30,000                             |
|-----------------------------------|-------|--------|--------|--------|------------------------------------|
| $\epsilon_0$                      | 360   | 240    | 200    | 180    | 165                                |
| $P_c$                             | 800   | 930    | 1000   | 1090   | 1170                               |
| $I_s$                             | 453.4 | 450.2  | 448.5  | 446.8  | 445.4                              |
| $W_{B.O}$<br>(lbs)                | 230.0 | 330.0  | 400.0  | 47.0   | Area Ratio<br>$\epsilon_0$ Limited |
| 157 $I_s$                         | 71200 | 70700  | 70400  | 70100  |                                    |
| -3.68 $W_{B.O}$                   | 846   | 1215   | 1473   | 1730   | —                                  |
| Relative<br>PAYLOAD (PL)<br>(lbs) | 70354 | 69485  | 68927  | 68370  | —                                  |

MINIMUM WEIGHT RETRACTABLE NOZZLE CONFIGURATION

| F                                 | 8,000 | 15,000 | 20,000 | 25,000 | 30,000              |
|-----------------------------------|-------|--------|--------|--------|---------------------|
| $\epsilon_0$                      | 500   | 500    | 460    | 430    | 405                 |
| $P_c$                             | 500   | 680    | 800    | 930    | 1060                |
| $I_s$                             | 454.5 | 458.5  | 458.4  | 457.7  | 456.7               |
| $W_{B.O}$<br>(lbs)                | 390.0 | 570.0  | 630.0  | 700.0  | Weight<br>Excessive |
| 157 $I_s$                         | 71400 | 72000  | 72000  | 71820  |                     |
| -3.68 $W_{B.O}$                   | 1435  | 2100   | 2320   | 2580   | —                   |
| Relative<br>PAYLOAD (PL)<br>(lbs) | 69965 | 69900  | 69680  | 69240  | —                   |

TABLE XVI (cont.)

ENGINE CYCLE

Staged Combustion - Bleed

Series Turbine DriveFIXED NOZZLE CONFIGURATION

MR = 6.0

Nom NPSH(F) = 60 ft.

NPSH(O) = 16 ft.

| F                     | 8,000 | 15,000 | 25,000 | 40,000 | 50,000 |
|-----------------------|-------|--------|--------|--------|--------|
| $\epsilon_o$          | 500   | 360    | 270    | 200    | 170    |
| $P_c$                 | 1300  | 1500   | 1800   | 2000   | 2000   |
| $I_s$ Optimum         | 466.1 | 465.0  | 463.5  | 461.0  | 459.2  |
| $I_s$ Delivered       | 464.6 | 463.5  | 462.0  | 459.5  | 457.7  |
| $W_{B.O}$<br>(lbs)    | 193.7 | 269.0  | 366.1  | 507.0  | 590.0  |
| 157 $I_s$ Opt.        | 73178 | 73005  | 72770  | 72377  | 72094  |
| 157 $I_s$             | 72942 | 72770  | 72534  | 72142  | 71859  |
| -3.68 $W_{B.O}$       | 713.  | 990.   | 1347.  | 1866.  | 2171.  |
| Relative PAYLOAD Opt. | 72465 | 72015  | 71423  | 70511  | 69923  |
| PAYLOAD (PL)<br>(lbs) | 72229 | 71780  | 71187  | 70276  | 69688  |

MINIMUM WEIGHT RETRACTABLE NOZZLE CONFIGURATION

| F                     | 8,000 | 15,000 | 25,000 | 40,000 | 50,000 |
|-----------------------|-------|--------|--------|--------|--------|
| $\epsilon_o$          | 500   | 500    | 500    | 500    | 460    |
| $P_c$                 | 1300  | 1500   | 1800   | 2000*  | 2000   |
| $I_s$ Optimum         | 466.1 | 467.0  | 467.7  | 468.5  | 468.5  |
| $I_s$ Delivered       | 464.6 | 465.5  | 466.2  | 467.0  | 467.0  |
| $W_{B.O}$<br>(lbs)    | 213.6 | 318.0  | 467.6  | 698.0  | 864.6  |
| 157 $I_s$ Opt.        | 73178 | 73319  | 73429  | 73555  | 73555  |
| 157 $I_s$             | 72942 | 73084  | 73193  | 73319  | 73319  |
| -3.68 $W_{B.O}$       | 786   | 1170   | 1721   | 2569   | 3182   |
| PAYLOAD (Opt.)        | 72392 | 72149  | 71708  | 70986  | 70373  |
| PAYLOAD (PL)<br>(lbs) | 72156 | 71914  | 71472  | 70750  | 70137  |

TABLE XVI (cont.)

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ENGINE CYCLE

Expander - Parallel Turbine Drive

MR = 6.0

Nom. NPSH(F) = 60 ft.

NPSH(O) = 16 ft.

FIXED NOZZLE CONFIGURATION

| F                                 | 8,000 | 15,000 | 25,000 | 30,000          | 50,000 |
|-----------------------------------|-------|--------|--------|-----------------|--------|
| $r_o$                             | 300   | 180    | 100    | N/A             | N/A    |
| $r_c$                             | 820   | 760    | 680    | 660             | -      |
| $I_s$                             | 461.2 | 456.8  | 451.2  | Weight Increase |        |
|                                   |       |        |        | Excessive       |        |
| $W_{B.O}$<br>(lbs)                | 227.9 | 343.5  | 507.2  | —               | —      |
| 157 $I_s$                         | 72408 | 71718  | 70838  | —               | —      |
| -3.68 $W_{B.O}$                   | 839   | 1265   | 1866   | —               | —      |
| Relative<br>PAYLOAD (PL)<br>(lbs) | 71569 | 70453  | 68972  | —               | —      |

MINIMUM WEIGHT RETRACTABLE NOZZLE CONFIGURATION

| F                                 | 8,000 | 15,000 | 20,000 | 25,000 | 30,000 |
|-----------------------------------|-------|--------|--------|--------|--------|
| $r_o$                             | 500   | 500    | 400    | 320    | 250    |
| $r_c$                             | 820   | 760    | 710    | 680    | 660    |
| $I_s$                             | 464.0 | 464.6  | 464.0  | 462.4  | 460.2  |
| $W_{B.O}$<br>(lbs)                | 293.5 | 545.4  | 678.8  | 789.8  | 878.4  |
| 157 $I_s$                         | 72848 | 72942  | 72848  | 72597  | 72251  |
| -3.68 $W_{B.O}$                   | 1080  | 2007   | 2498   | 2906   | 3233   |
| Relative<br>PAYLOAD (PL)<br>(lbs) | 71768 | 70935  | 70350  | 69691  | 69018  |

TABLE XVI (cont.)ENGINE CYCLEGas Generator Bleed - Series Turbine Drive

MR = 6.0

Nominal NPSH(F) = 60 Ft.

NPSH(O) = 16 Ft.

FIXED NOZZLE CONFIGURATION

| F                                 | 8,000 | 15,000 | 20,000 | 25,000 |
|-----------------------------------|-------|--------|--------|--------|
| $c_o$                             | 500   | 295    | 235    | 205    |
| $P_c$                             | 1130  | 1190   | 1225   | 1270   |
| $I_s$                             | 456.3 | 454.0  | 452.4  | 450.4  |
| $W_{B.O}$<br>(Lbs)                | 270.9 | 390.6  | 470.6  | 549.4  |
| 157 $I_s$                         | 71639 | 71278  | 71027  | 70713  |
| -3.68 $W_{B.O}$                   | 997.  | 1437.  | 1732.  | 2022   |
| Relative<br>PAYLOAD (PL)<br>(Lbs) | 70642 | 69841  | 69295  | 68691  |

MINIMUM WEIGHT RETRACTABLE NOZZLE CONFIGURATION

| F                                 | 8,000 | 15,000 | 20,000 | 25,000 |
|-----------------------------------|-------|--------|--------|--------|
| $c_o$                             | 500   | 500    | 500    | 500    |
| $P_c$                             | 1130  | 1190   | 1225   | 1270   |
| $I_s$                             | 456.3 | 457.4  | 458.1  | 458.3  |
| $W_{B.O}$<br>(Lbs)                | 317.1 | 538.5  | 697.1  | 860.7  |
| 157 $I_s$                         | 71639 | 71812  | 71922  | 71953  |
| -3.68 $W_{B.O}$                   | 1167. | 1982.  | 2565.  | 3167.  |
| Relative<br>PAYLOAD (PL)<br>(Lbs) | 70472 | 69830  | 69357  | 68786  |

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TABLE XVI (cont.)

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ENGINE CYCLECombustion Gas Tapoff - Series Turbine Drive

MR = 6.0

Nom. NPSH(F) = 60 ft

NPSH(O) = 16 ft

FIXED NOZZLE CONFIGURATION

|                                   | 8,000 | 15,000 | 20,000 | 25,000 |
|-----------------------------------|-------|--------|--------|--------|
| $P_o$                             | 500   | 295    | 235    | 205    |
| $P_c$                             | 1130  | 1190   | 1225   | 1270   |
| $I_s$                             | 456.3 | 454.0  | 452.4  | 450.4  |
| $W_{B.O}$<br>(lbs)                | 249.5 | 356.2  | 426.5  | 500.0  |
| $157 I_s$                         | 71639 | 71278  | 71027  | 70713  |
| $-3.68 W_{B.O}$                   | 918   | 1311   | 1570   | 1840   |
| Relative<br>PAYLOAD (PL)<br>(lbs) | 70721 | 69967  | 69457  | 68873  |

MINIMUM WEIGHT RETRACTABLE NOZZLE CONFIGURATION

|                                   | 8,000 | 15,000 | 20,000 | 25,000 |
|-----------------------------------|-------|--------|--------|--------|
| $P_o$                             | 500   | 500    | 500    | 500    |
| $P_c$                             | 1130  | 1190   | 1225   | 1270   |
| $I_s$                             | 456.3 | 457.4  | 458.1  | 458.3  |
| $W_{B.O}$                         | 295.6 | 503.9  | 655.0  | 807.4  |
| $157 I_s$                         | 71639 | 71812  | 71922  | 71953  |
| $1088$                            | 1088  | 1854   | 2410   | 2971   |
| Relative<br>PAYLOAD (PL)<br>(lbs) | 70551 | 69958  | 69512  | 68982  |

ENGINE CYCLECoolant Tapoff - Series Turbine Drive

MR = 6.0

Nom. NPSH(F) = 60 f

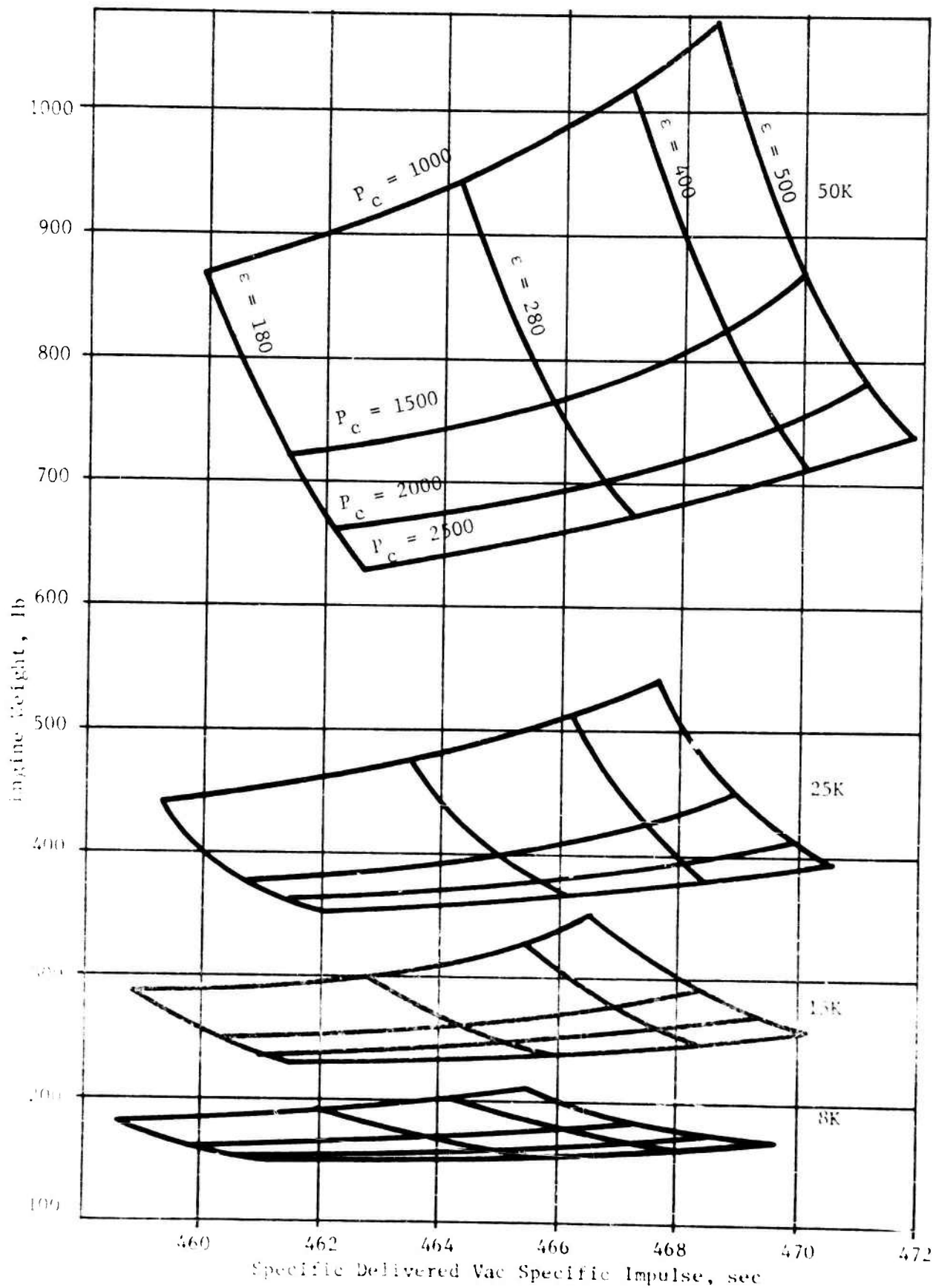
NPSH(O) = 16 f

FIXED NOZZLE CONFIGURATION

| F                                 | 8,000 | 15,000 | 20,000 | 25,000 | 30,000                             |
|-----------------------------------|-------|--------|--------|--------|------------------------------------|
| $\epsilon_o$                      | 360   | 240    | 200    | 180    | 165                                |
| $P_c$                             | 800   | 930    | 1000   | 1090   | 1170                               |
| $I_s$                             | 452.6 | 449.1  | 447.3  | 445.5  | 444.0                              |
| $W_{B.O}$<br>(lbs)                | 283.1 | 387.6  | 448.4  | 518.5  | Area Ratio<br>$\epsilon_o$ Limited |
| 157 $I_s$                         | 71058 | 70509  | 70226  | 69944  | 69708                              |
| -3.68 $W_{B.O}$                   | 1042  | 1426   | 1650   | 1908   | —                                  |
| Relative<br>PAYLOAD (PL)<br>(lbs) | 70016 | 69083  | 68576  | 68036  | —                                  |

MINIMUM WEIGHT RETRACTABLE NOZZLE CONFIGURATION

| F                                 | 8,000 | 15,000 | 20,000 | 25,000 | 30,000              |
|-----------------------------------|-------|--------|--------|--------|---------------------|
| $\epsilon_o$                      | 500   | 500    | 460    | 430    | 405                 |
| $P_c$                             | 500   | 680    | 800    | 930    | 1060                |
| $I_s$                             | 454.7 | 457.4  | 457.2  | 456.4  | 455.3               |
| $W_{B.O}$<br>(lbs)                | 523.7 | 816.3  | 912.0  | 945.0  | Weight<br>Excessive |
| 157 $I_s$                         | 71388 | 71812  | 71780  | 71655  | 71482               |
| -3.68 $W_{B.O}$                   | 1927  | 3004   | 3356   | 3478   | —                   |
| Relative<br>PAYLOAD (PL)<br>(lbs) | 69461 | 68808  | 68424  | 68177  | —                   |



Optimized Combustion Cycle Engine Weight and  $I_{sp}$ , MR = 6, Fixed Nozzle

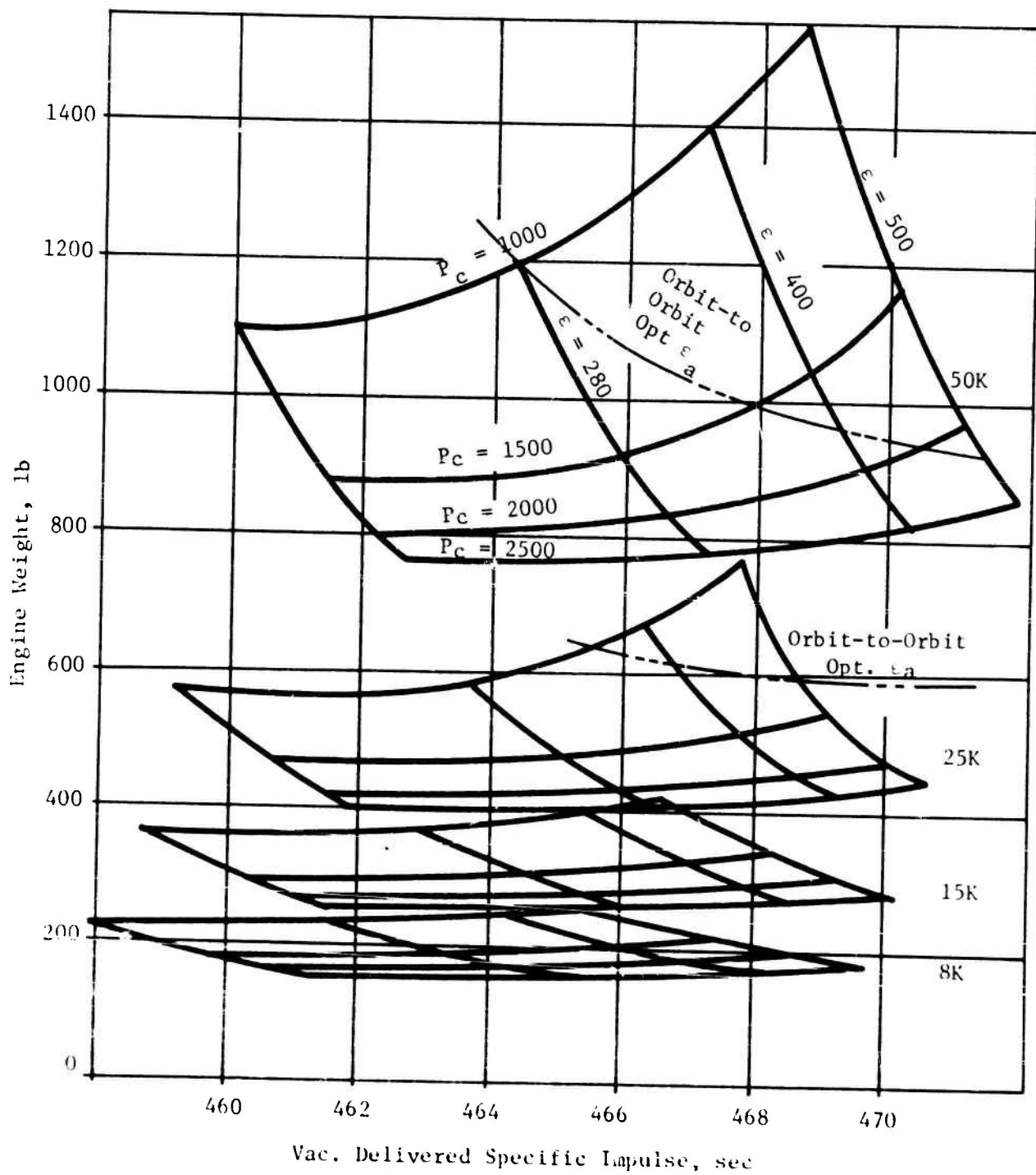


Figure 87. Staged Combustion Cycle Engine Weight and  $I_s$ , MR = 6, Minimum Weight Retractable Nozzle

### III. A. Engine Design Parametric Study (Task IV) (cont.)

The engine configuration is identical to that used in determining the parametric data with minimum length Rao nozzle and a thrust chamber length of 8 inches. The injector energy release efficiency is assumed to be 99% and the performance is calculated with the JANNAF performance prediction methods. Suction NPSH is 16 ft for the  $LO_2$  pump and NPSH = 60 ft for the hydrogen pump.

In Table XVII, the engines are characterized for the optimum chamber pressures meeting the thermal cycle requirements of  $N_t = 300$  cycles and conforms to the stowed engine length of 82 inches.

The turbine drive cycles are presented for the four discrete thrust levels in Figures 88 through 91 containing the flow pressure and temperature schedule for nominal conditions.

The following table describes the feed system selected for each thrust level.

TURBOPUMP - FUEL CIRCUIT  
Engine MR = 6    NPSH = 60 feet

|                            | Thrust |       |       |       |
|----------------------------|--------|-------|-------|-------|
|                            | 8K     | 15K   | 25K   | 50K*  |
| Boost Pump                 |        |       |       |       |
| Shaft Speed, rpm           | 31428  | 25714 | 22857 | 20000 |
| Suction Specific Speed     | 9816   | 10996 | 12622 | 15675 |
| Main Pump                  |        |       |       |       |
| Number of Stages           | 2      | 2     | 3     | 3     |
| Shaft Speed, rpm           | 11000  | 90000 | 80000 | 70000 |
| Impeller Tip Speed, ft/sec | 1755   | 1682  | 1502  | 1621  |
| Specific Speed             | 504    | 514   | 724   | 841   |
| Efficiency, %              | 51.7   | 54.7  | 61.6  | 66.0  |
| Discharge Pressure, psia   | 3279   | 3721  | 4260  | 4682  |
| Volume Flow, gpm           | 254    | 476   | 794   | 1598  |
| Turbine                    |        |       |       |       |
| Inlet Temperature, °R      | 1860   | 1860  | 1860  | 1860  |
| Mean Blade Speed, ft/sec   | 1300   | 1300  | 1300  | 1300  |
| Number Stages              | 2      | 2     | 2     | 2     |
| Nozzle Admission, %        | 100    | 100   | 100   | 100   |
| Efficiency, %              | 66.9   | 66.1  | 65.7  | 66.9  |
| Shaft Power, hp            | 979    | 1970  | 3343  | 7041  |

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TABLE XVII  
STAGED COMBUSTION CYCLE SUMMARY VS THRUST LEVEL

|                              | Fixed Nozzle |       |       |       | Min Height Retractable |       |       |        |
|------------------------------|--------------|-------|-------|-------|------------------------|-------|-------|--------|
|                              | 8            | 15    | 25    | 50    | 8                      | 15    | 25    | 50     |
| Thrust, lb                   |              |       |       |       |                        |       |       |        |
| Nozzle Area Ratio            | 500          | 360   | 270   | 180   | 500                    | 500   | 500   | 500    |
| Chamber Pressure, psia       | 1200         | 1450  | 1800  | 2200  | 1200                   | 1450  | 1800  | 2200   |
| Operating Engine Length, in. | 82           | 82    | 82    | 82    | -                      | 98    | 110   | 136    |
| Max Diameter, in.            | 47.5         | 49.5  | 50.5  | 53.0  | -                      | 60    | 68    | 87     |
| Engine Weight, in.           | 198          | 270   | 380   | 660   | -                      | 350   | 490   | 940    |
| Suction Line Dia Fuel, in.   | 2.2          | 2.9   | 3.60  | 4.90  | 2.2                    | 2.9   | 3.60  | 4.9    |
| Suction Line Dia LOX, in.    | 1.9          | 2.5   | 3.1   | 4.3   | 1.9                    | 2.5   | 3.1   | 4.3    |
| F/Pc                         | 6.60         | 10.33 | 13.88 | 22.70 | 6.6                    | 10.33 | 13.88 | 22.70  |
| Specific Impulse, sec        | 466.5        | 465.8 | 465.3 | 461.6 | -                      | 468.3 | 469.8 | 471.20 |
| NPSH Fuel, ft                | 60           | 60    | 60    | 60    | 60                     | 60    | 60    | 60     |
| NPSH LOX, ft                 | 16           | 16    | 16    | 16    | 16                     | 16    | 16    | 16     |



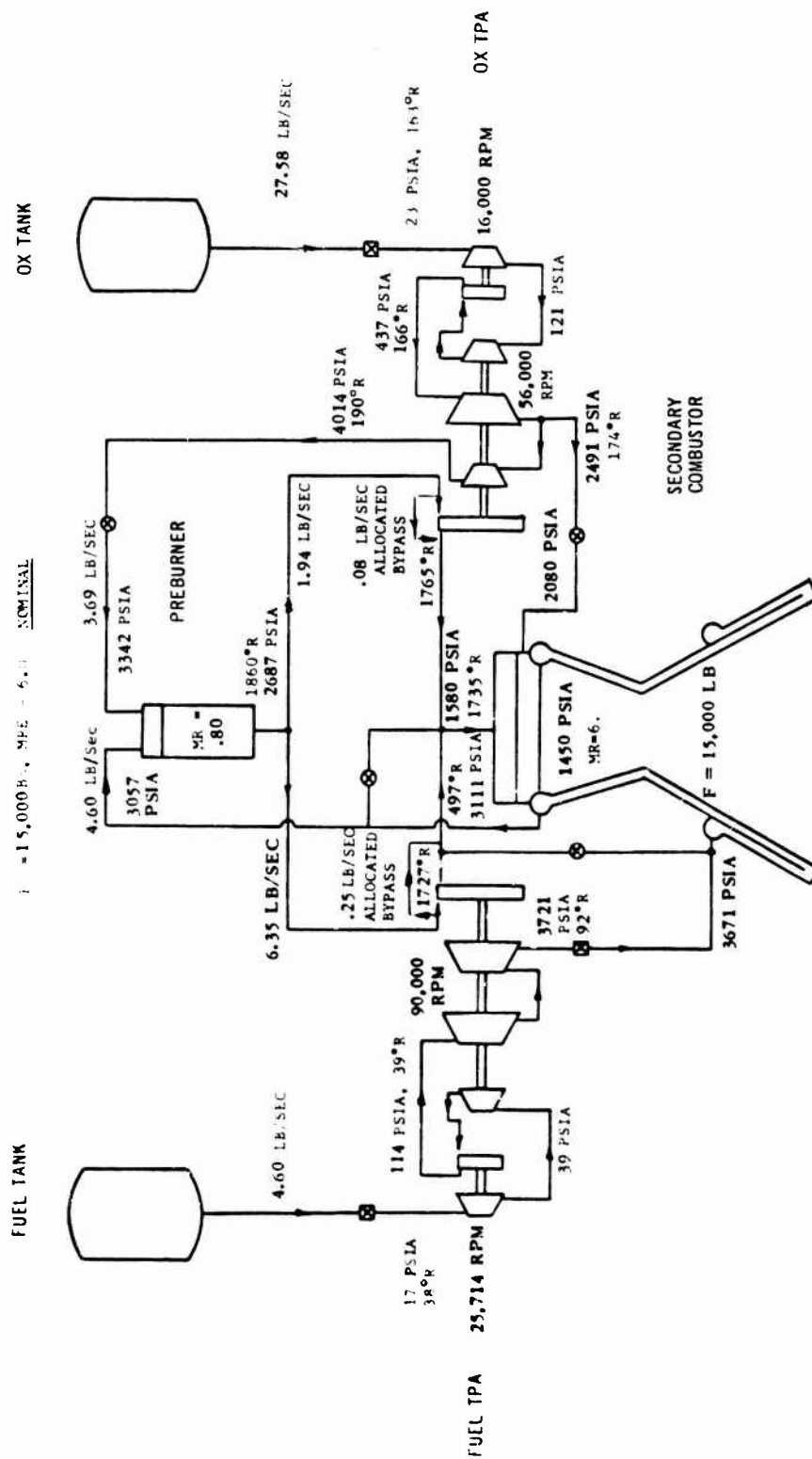


Figure 89. Parameters for Engine Operation at Full Thrust, F = 15%.



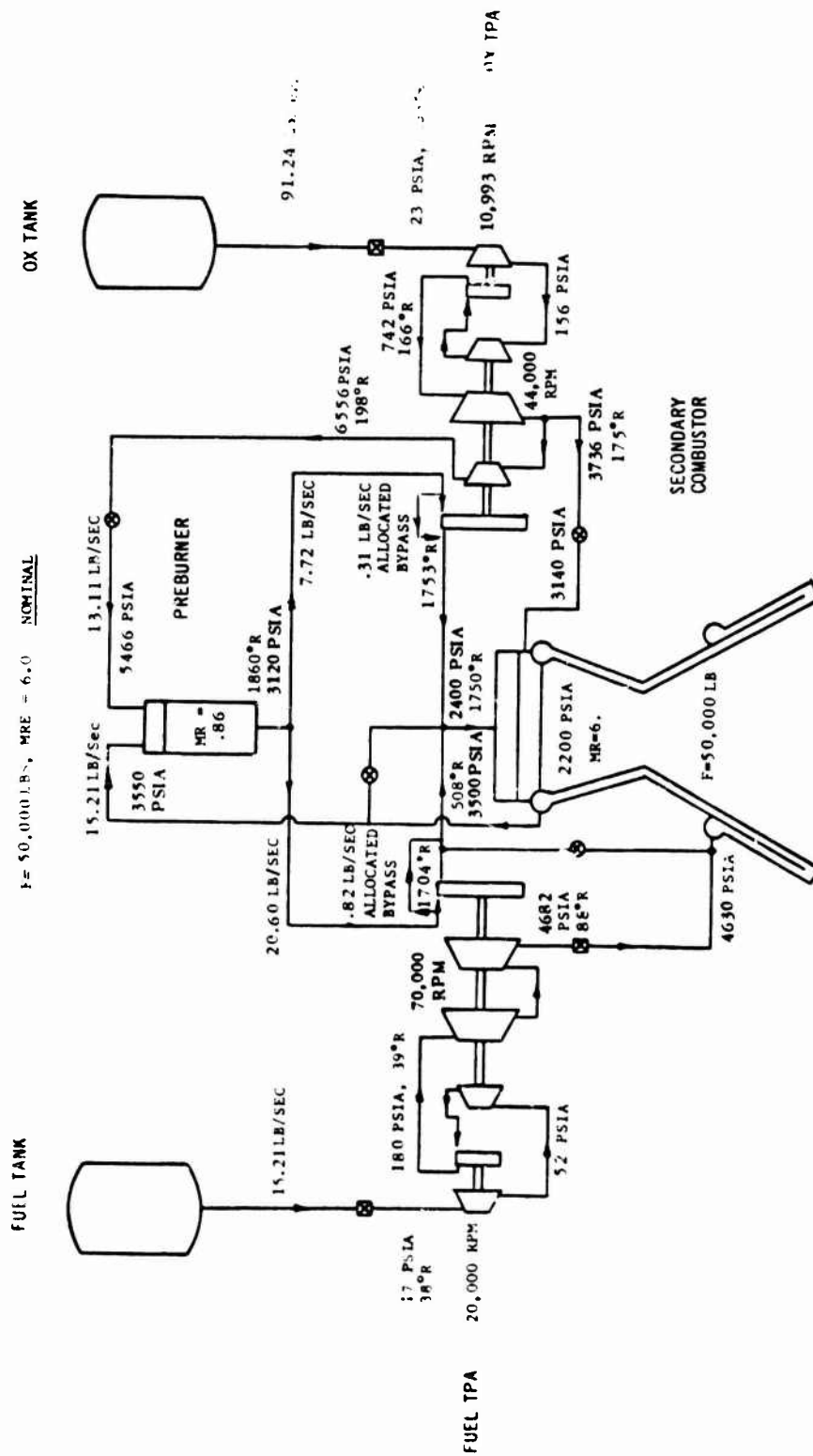


Figure 91. Parameters for Engine Operation at Full Thrust, F = 50K

### III. A, Engine Design Parametric Study (Task IV) (cont.)

#### TURBOPUMP - OXIDIZER CIRCUIT Engine MR = 6 NPSH = 16 Feet

|                            | Thrust |       |       |       |
|----------------------------|--------|-------|-------|-------|
|                            | 8K     | 15K   | 25K   | 50K** |
| Boost Pump                 |        |       |       |       |
| Shaft Speed, rpm           | 20000  | 16000 | 14286 | 10993 |
| Suction Specific Speed     | 20404  | 22350 | 25768 | 28140 |
| Main Pump                  |        |       |       |       |
| Number Stages              | 1-1/2  | 1-1/2 | 1-1/2 | 1-1/2 |
| Shaft Speed, rpm           | 70000  | 56000 | 50000 | 44000 |
| Impeller Tip Speed, ft/sec | 488    | 533   | 591   | 634   |
| Specific Speed             | 1522   | 1430  | 1399  | 1683  |
| Efficiency, %              | 57.6   | 61.1  | 63.8  | 68.6  |
| Discharge Pressure*, psia  | 2062   | 2491  | 3092  | 3736  |
| Volume Flow, gpm           | 93.1   | 175   | 291   | 586   |
| Turbine                    |        |       |       |       |
| Inlet Temperature, °R      | 1860   | 1860  | 1860  | 1860  |
| Mean Blade Speed, ft/sec   | 1100   | 1100  | 1100  | 1100  |
| Number Stages              | 1      | 1     | 1     | 1     |
| Nozzle Admission, %        | 28     | 27.5  | 32.3  | 44.3  |
| Efficiency, %              | 48.8   | 48.0  | 47.6  | 47.7  |
| Shaft Power, hp            | 228    | 487   | 972   | 1986  |

\*Main Stage

\*\*Ref Run: 23 Sept 71 22:02:22.593

24 Sept 71 16:10:03.076

#### 10. Mixture Ratio and NPSH Data for 8K, 15K and 25K Thrust

This section describes the effect of varying design mixture ratio and NPSH on the staged combustion cycle for three different thrust levels.

Design mixture ratio effect exerts a strong influence on engine performance and to a lesser extent on the engine weight and envelope. The effects are presented for the fixed and the minimum weight retractable nozzle.

Figures 92 and 93 present generalized data for engine weight and performance for MR = 5 and MR = 7.0 as a function of thrust, chamber pressure and nozzle expansion area ratio.

In addition, engine performances for MR = 5.0 and MR = 7.0 are shown separately for each thrust level in Figures 94 through 99.

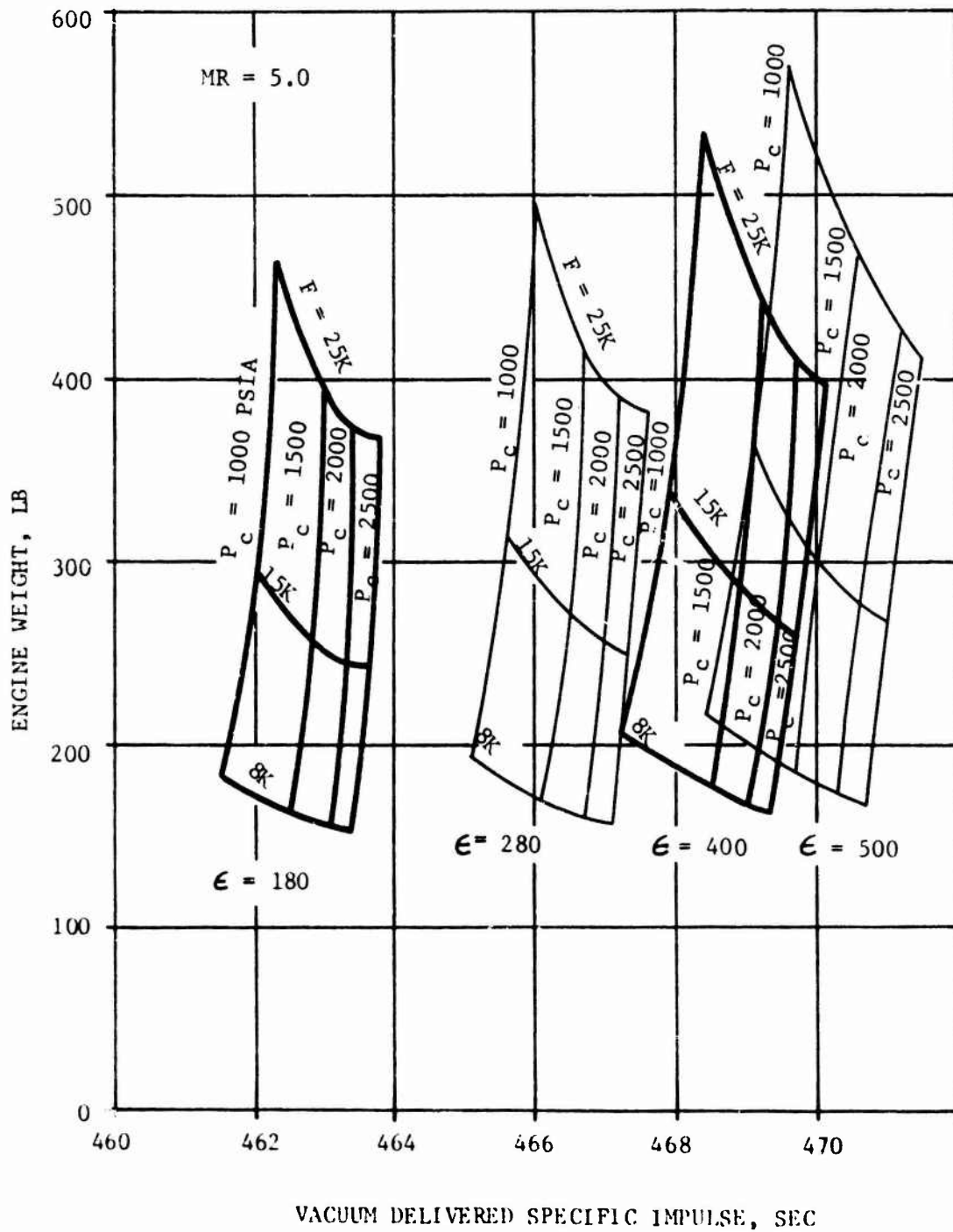


Figure 92. Generalized Weight and Performance Data, MR = 7, Staged Combustion Cycle

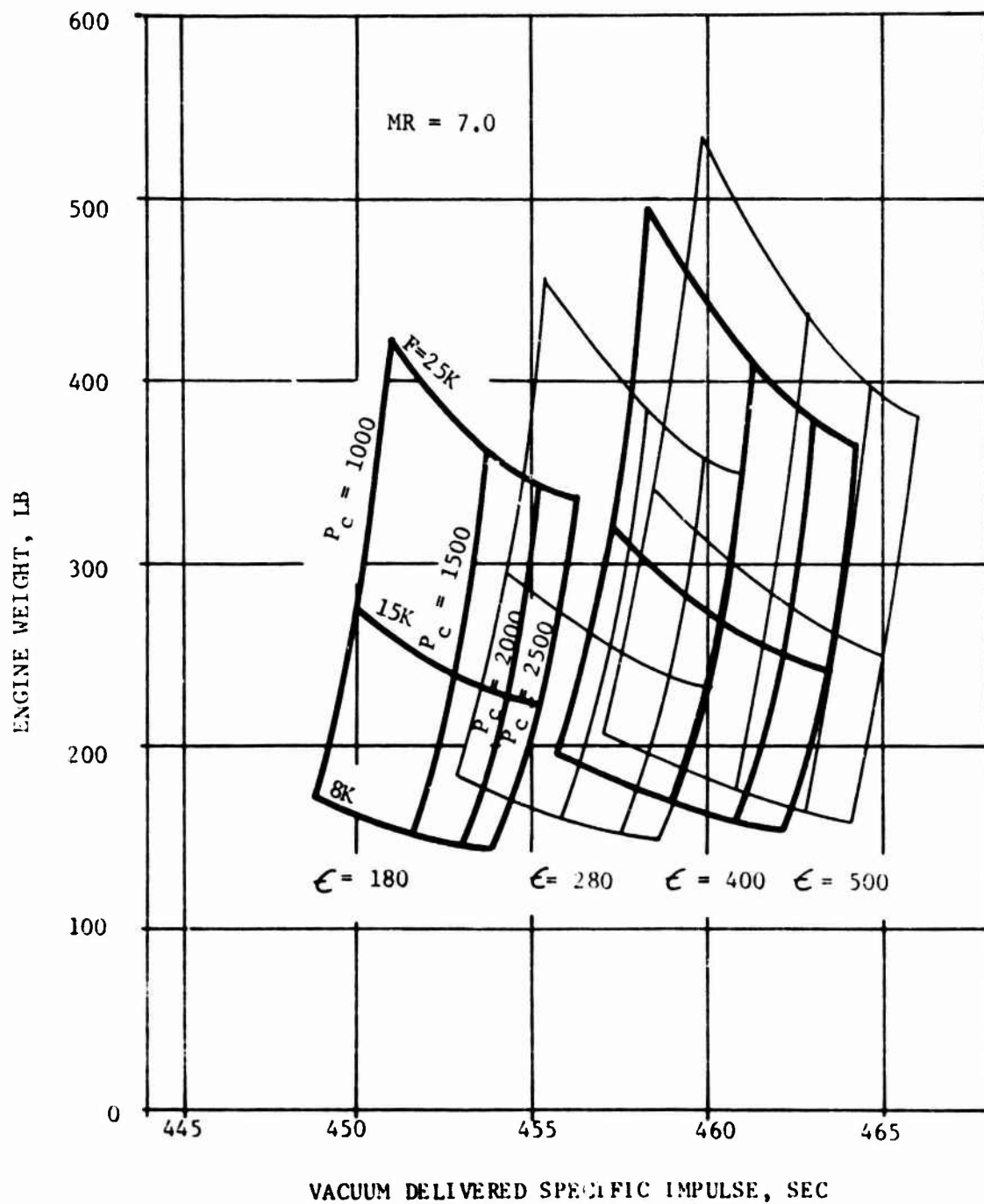


Figure 93. Generalized Weight and Performance Data,  $MR = 5$ , Staged Combustion Cycle

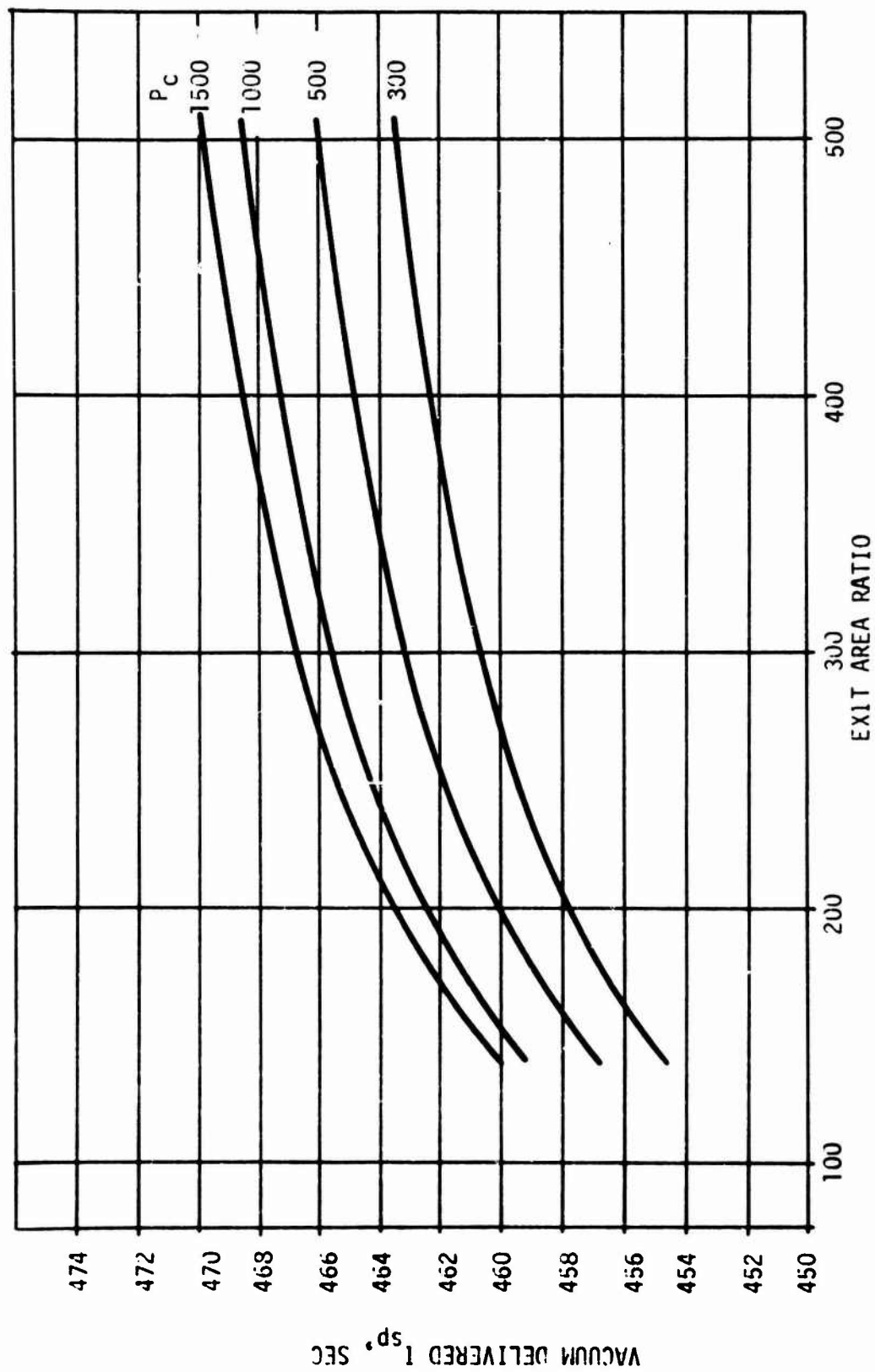


Figure 94.  $I_s$  vs Exit Area Ratio,  $F = 8K$ ,  $MR = 5$ , Staged Combustion Cycle

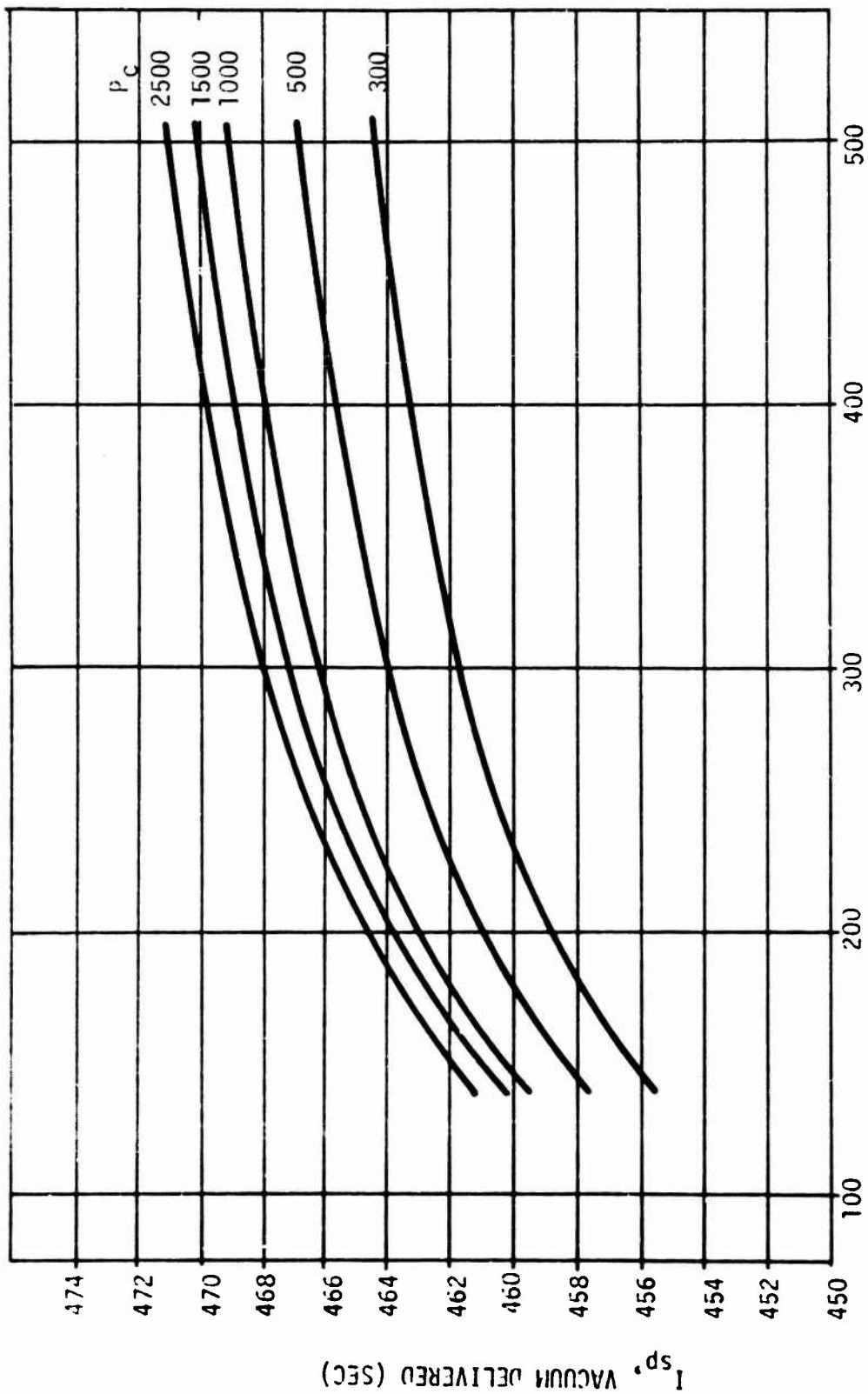


Figure 35.  $I_s$  vs Exit Area Ratio,  $F = 15K$ ,  $MR = 5$ , Staged Combustion Cycle

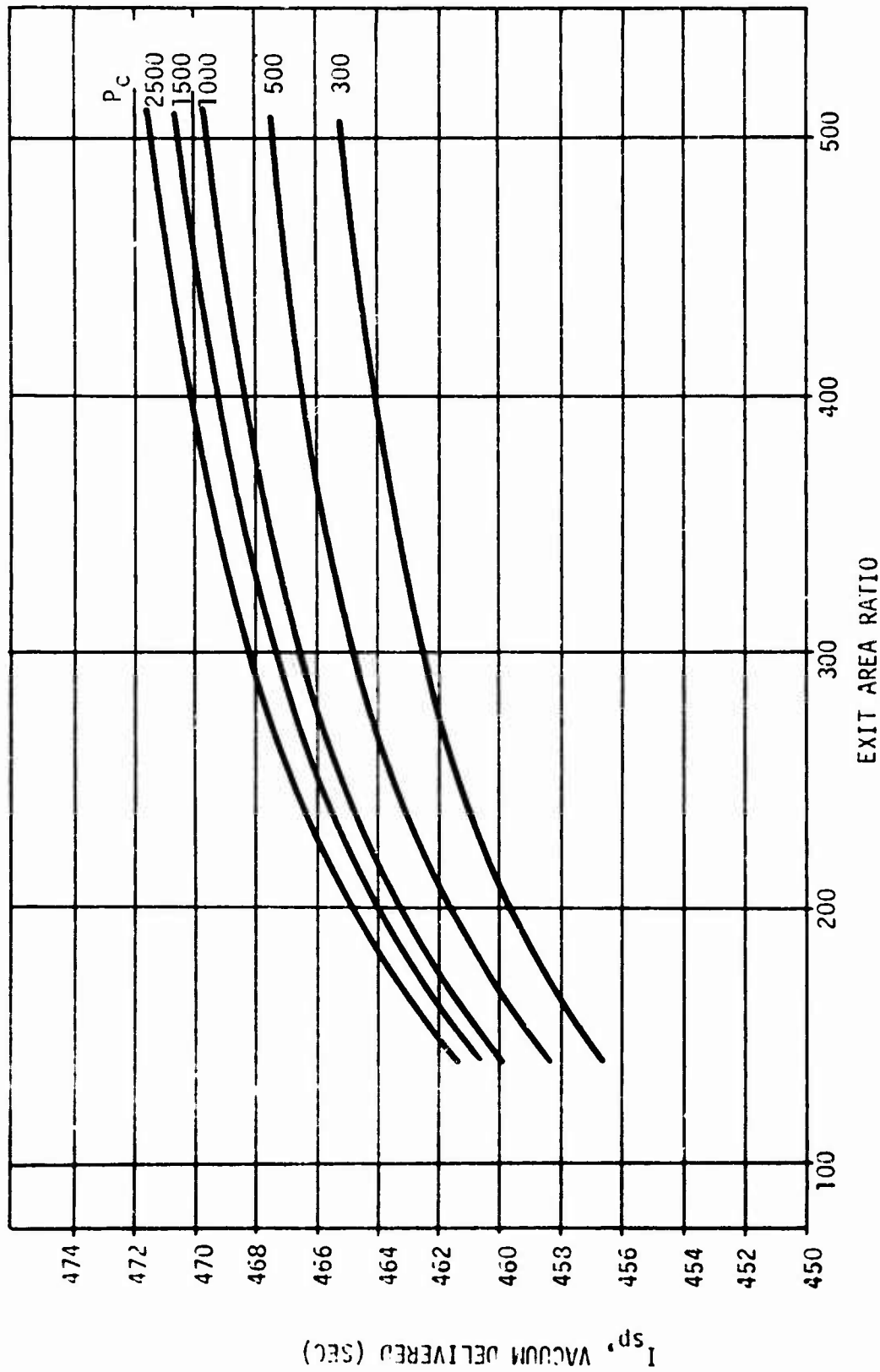


Figure 96.  $I_s$  vs Exit Area Ratio,  $F = 25K$ ,  $MR = 5$ , Staged Combustion Cycle

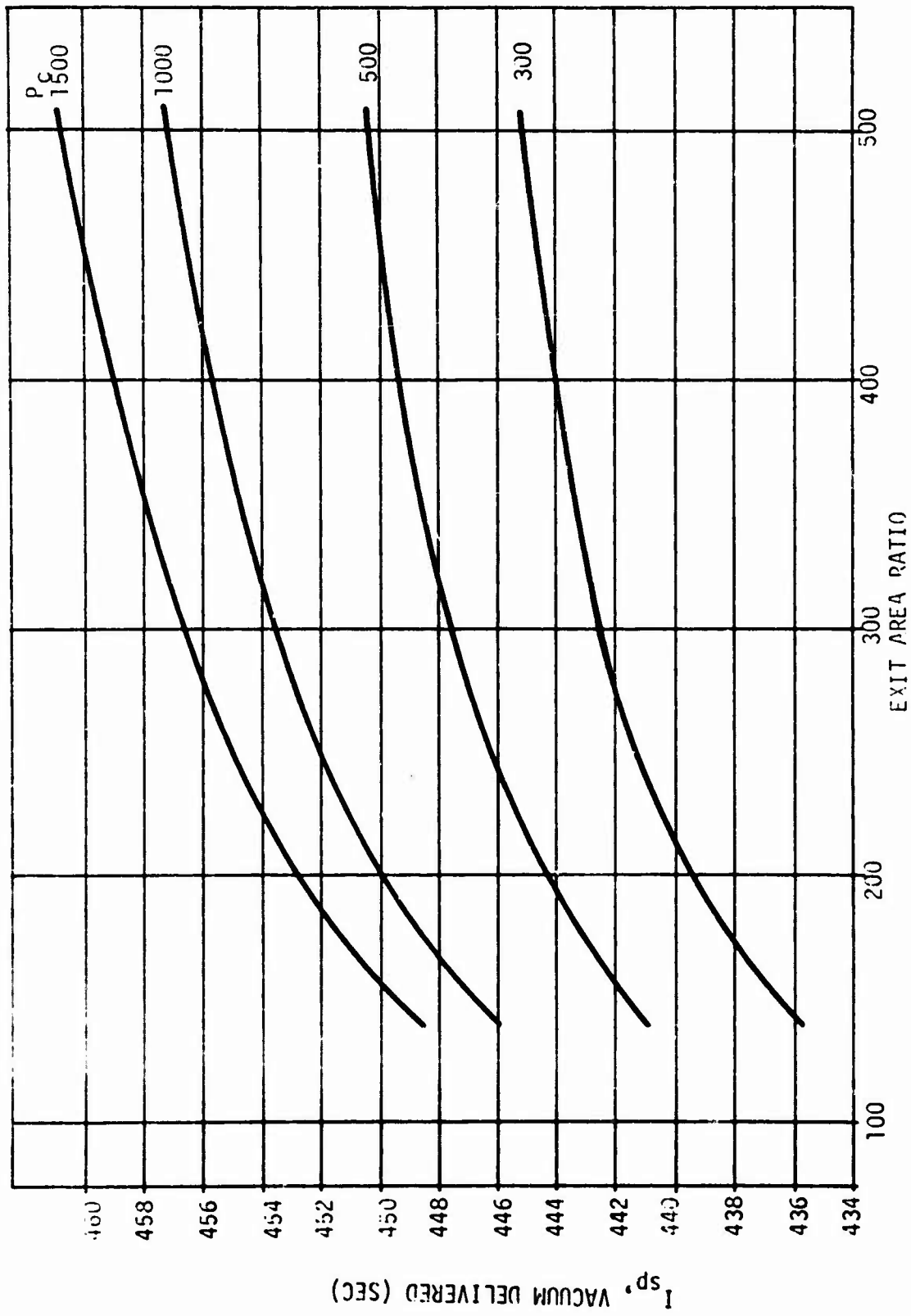


Figure 97.  $I_s$  vs Exit Area Ratio,  $F = 8K$ ,  $MR = 7$ , Staged Combustion Cycle

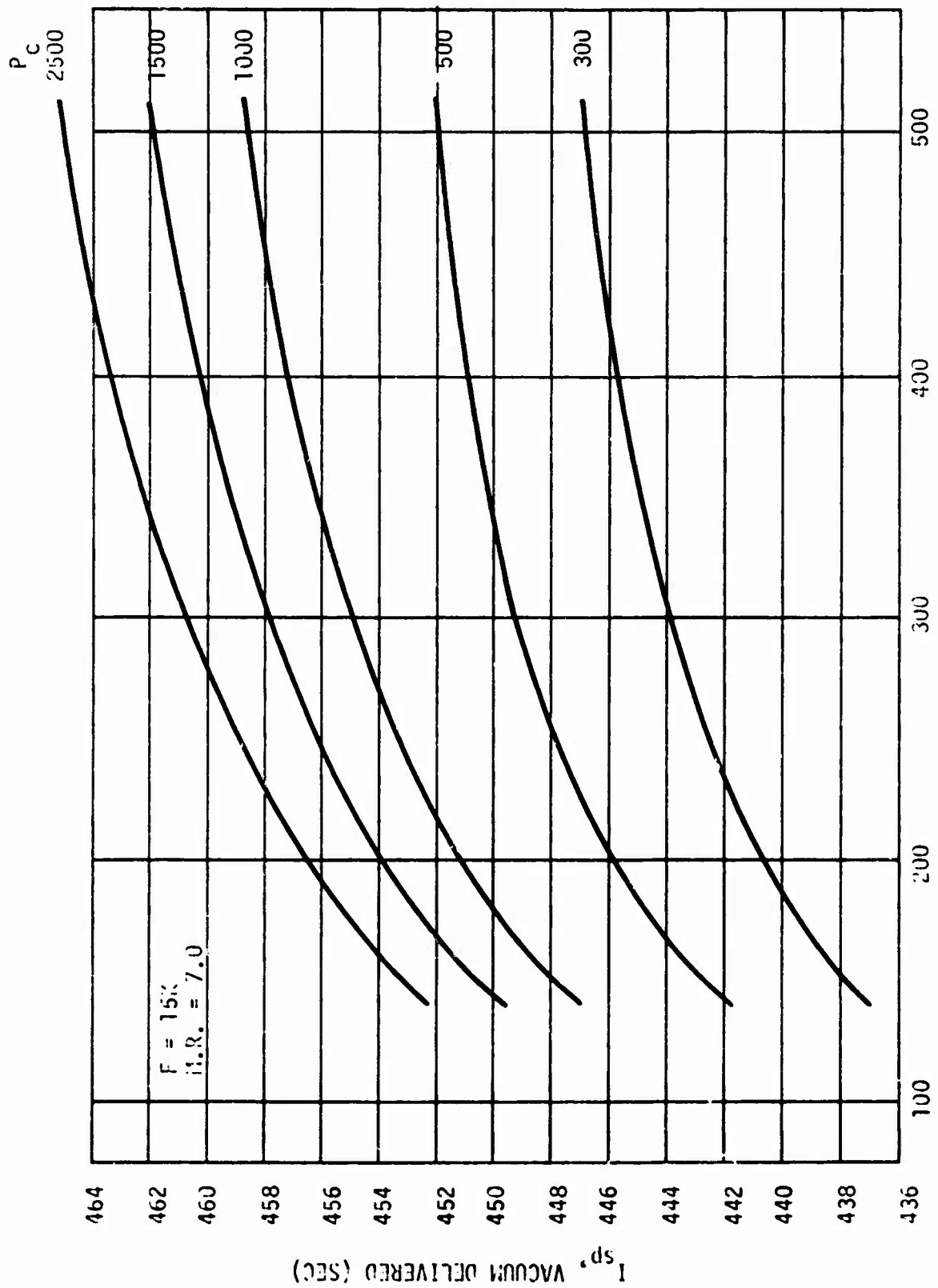


Figure 93.  $I_{sp}$  vs Exit Area Ratio,  $F = 15K$ ,  $MR = 7$ , Staged Combustion Cycle

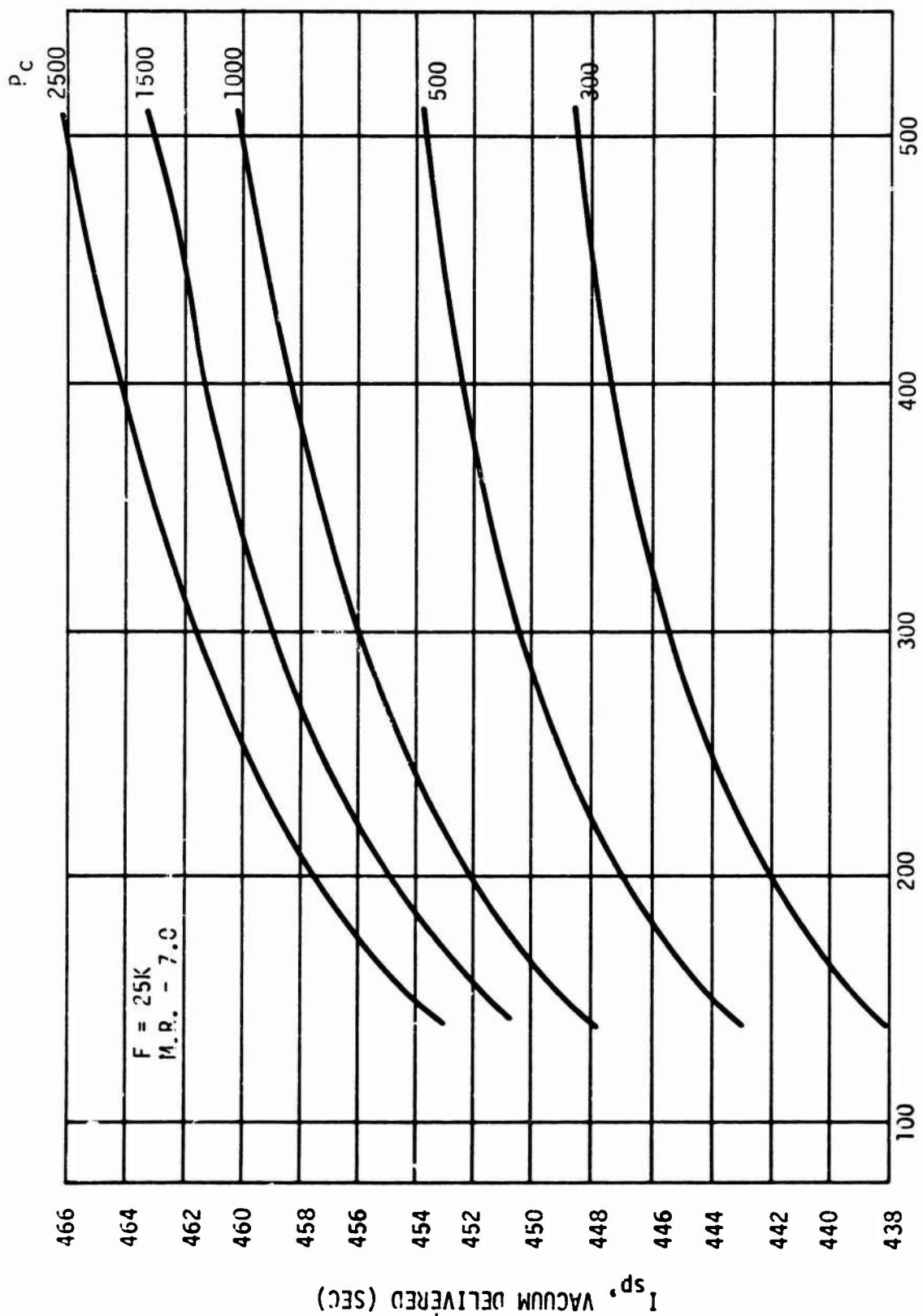


Figure 99.  $I_s$  vs Exit Area Ratio,  $F = 25K$ ,  $MR = 7$ , Staged Combustion Cycle

### III, A, Engine Design Parametric Study (Task IV) (cont.)

Figures 100 through 105 indicate the calculated engine weights for the three thrust levels also as a function of chamber pressure and nozzle expansion area ratio for the fixed, minimum weight retractable and minimum length retractable nozzles.

The engine envelope effects are shown in Figures 106 and 107 for  $MR = 5.0$  and in Figures 108 and 109 for  $MR = 7.0$  as a function of the thrust to chamber pressure ratio, and nozzle expansion area ratio. These figures indicate changes in engine envelope due to the changing nozzle contour required for different design mixture ratios. The engine lengths are operating engine lengths meeting the stowed engine length requirements.

Additional information is shown indicating effects of envelope constraints on achievable nozzle area ratios for both the fixed and retractable nozzle concept. Figure 106 indicates the feasible expansion area ratios for an engine mixture ratio 5.0 as function of thrust to chamber pressure ratio for both nozzle concepts. Figure 107 indicates that area ratio at which the retractable nozzle has to be split to stowed the nozzle in the available stowed envelope. Identical information is provided for  $MR = 7.0$  in Figures 108 and 109.

Figures 110 and 111 summarize the interactions at mixture ratios of 5 and 7, respectively. The effect on suction line diameters were calculated as a function of mixture ratio and discrete NPSH values. The fuel line diameter is very insensitive to the NPSH requirement. However, the oxidizer suction line is very dependent upon thrust and NPSH requirements. The results are indicated in Figure 112 and Figure 113 and are calculated with the procedures described in Section III,B,2,g.

NPSH effect on engine weight is very small since only the low speed pump weights are affected and only the oxygen low speed pump is significantly effected. The hydrogen low speed pump can take advantage of the TSH (thermal suppression head) and therefore is very insensitive. The results of the analysis are shown in Figure 114.

The staged combustion cycle characteristic is presented for the selected chamber pressures for three mixture ratios, and the NPSH values required. The characteristics are summarized in Table XVIII for both nozzle concepts where applicable.

For these selected chamber pressures, the engine flow schematic is shown for mixture ratios of 5.0 and 7.0. No influence of NPSH is shown in these schedules presented in Figures 115 and 116.

The effect of the turbomachinery design conditions are summarized in Table XIX for both the oxygen and fuel circuit.

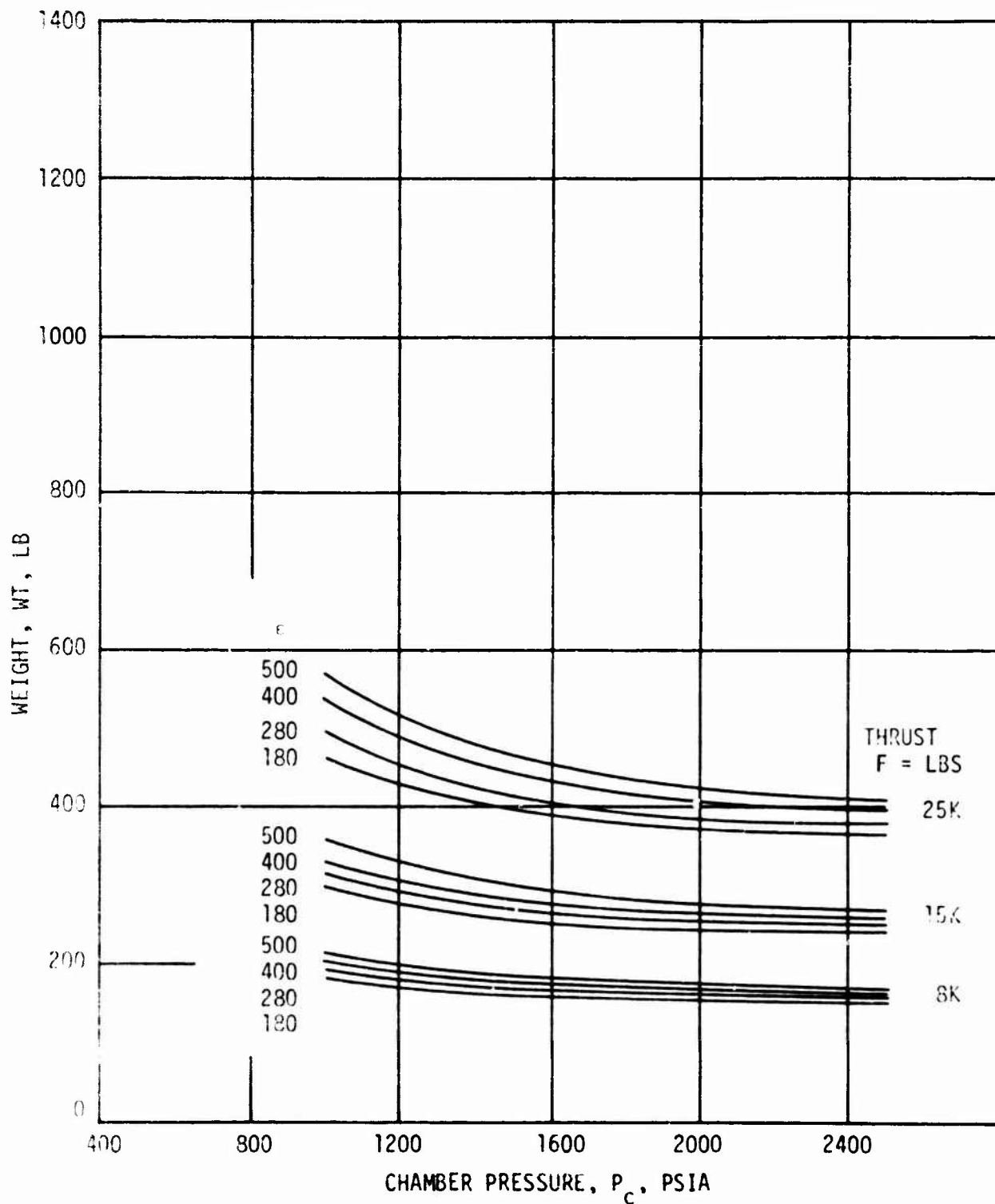


Figure 100. Weight vs  $P_c$ , Fixed Nozzle, MR = 5

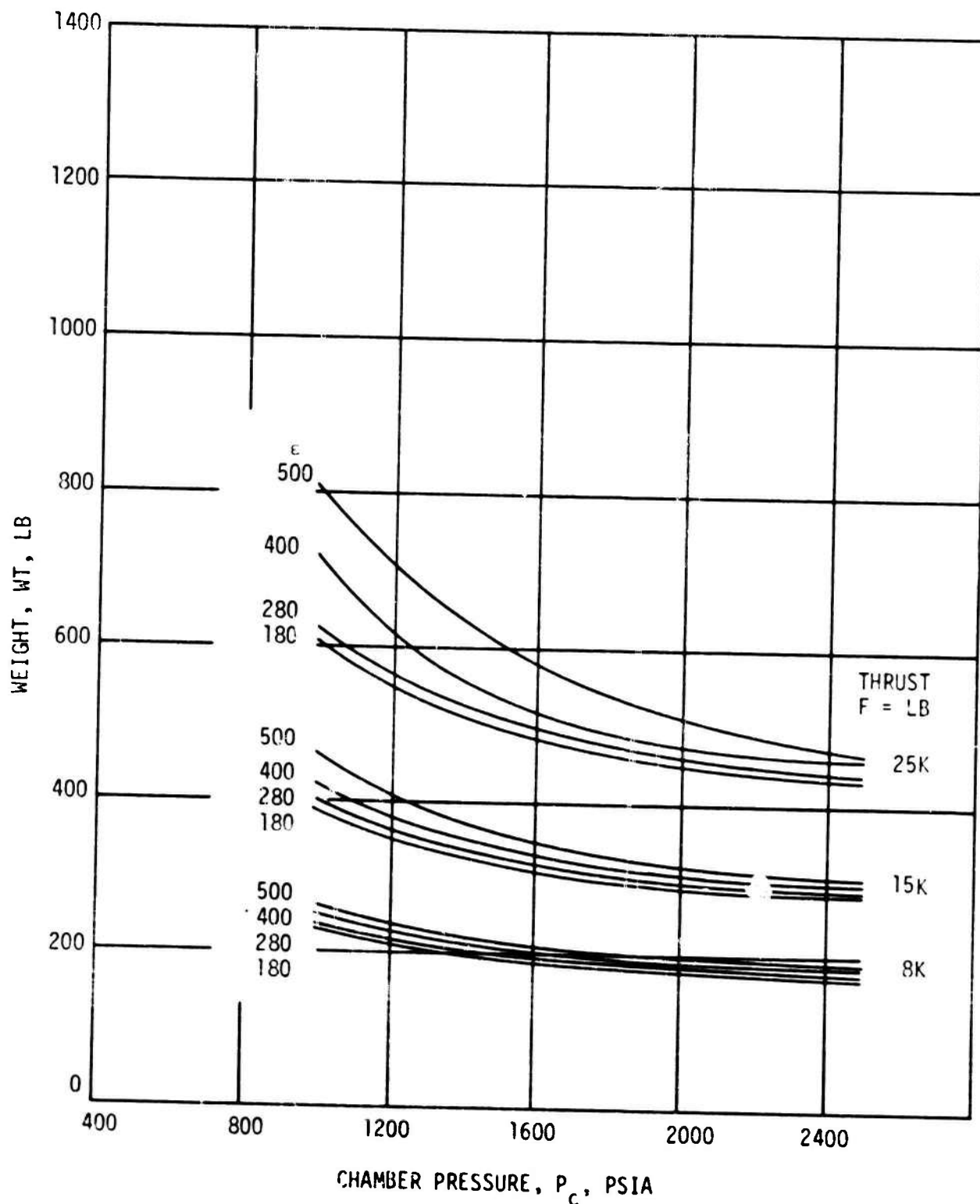


Figure 101. Weight vs  $P_c$ , Minimum Weight Retractable Nozzle, MR = 5

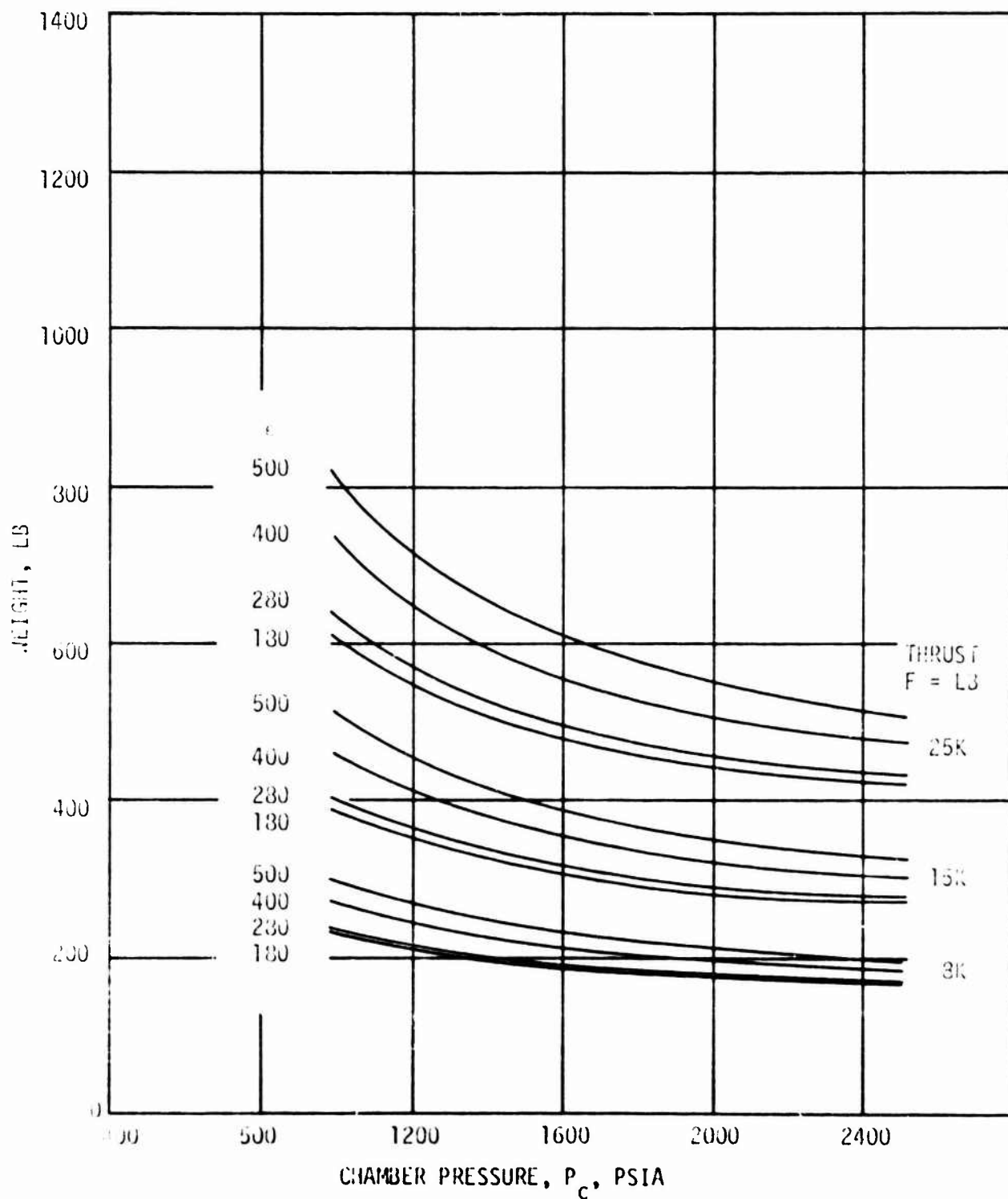


Figure 102. Weight vs  $P_c$ , Minimum Length Retractable Nozzle,  $MR = 5$

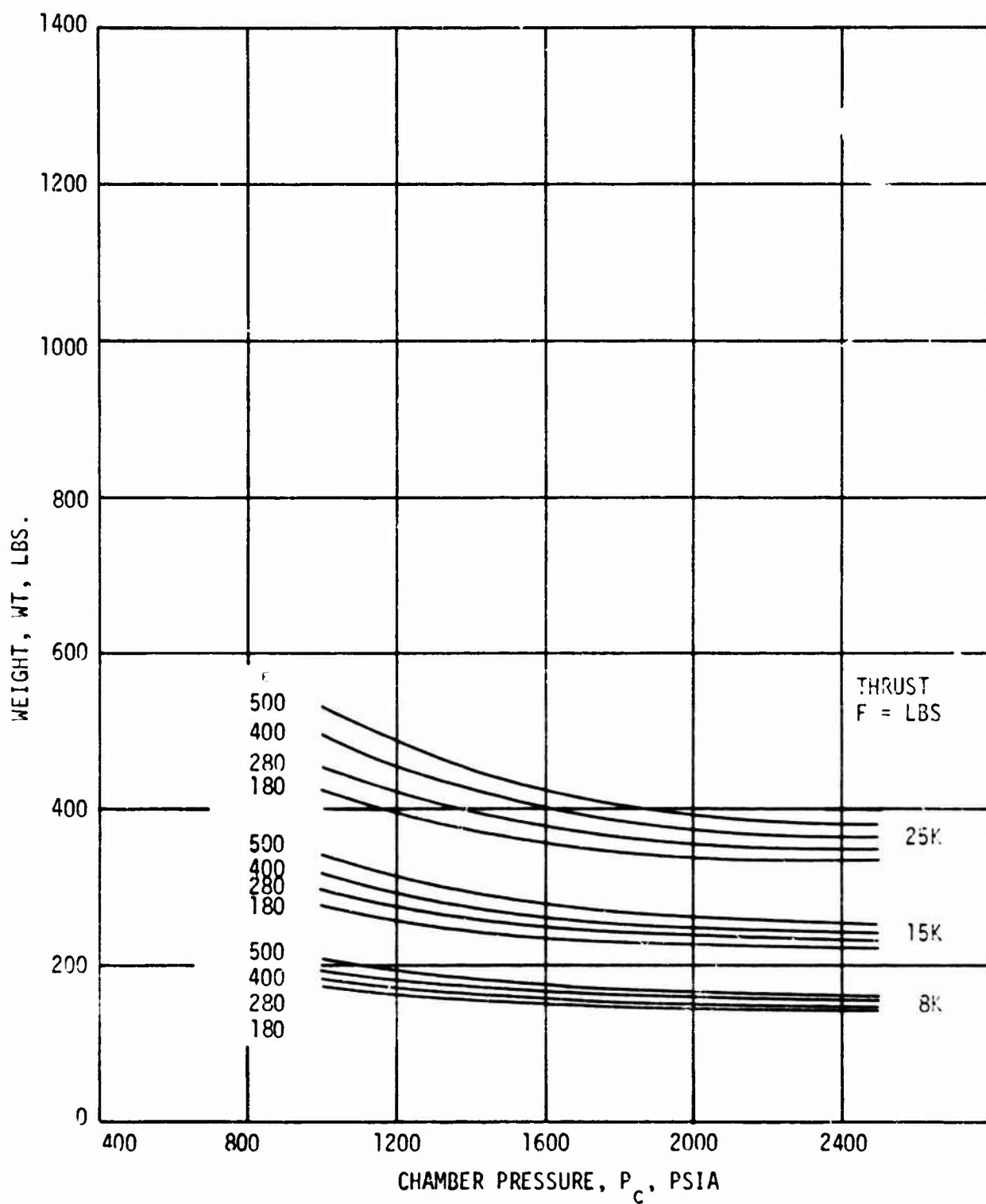


Figure 103. Weight vs  $P_c$ , Fixed Nozzle, MR = 7

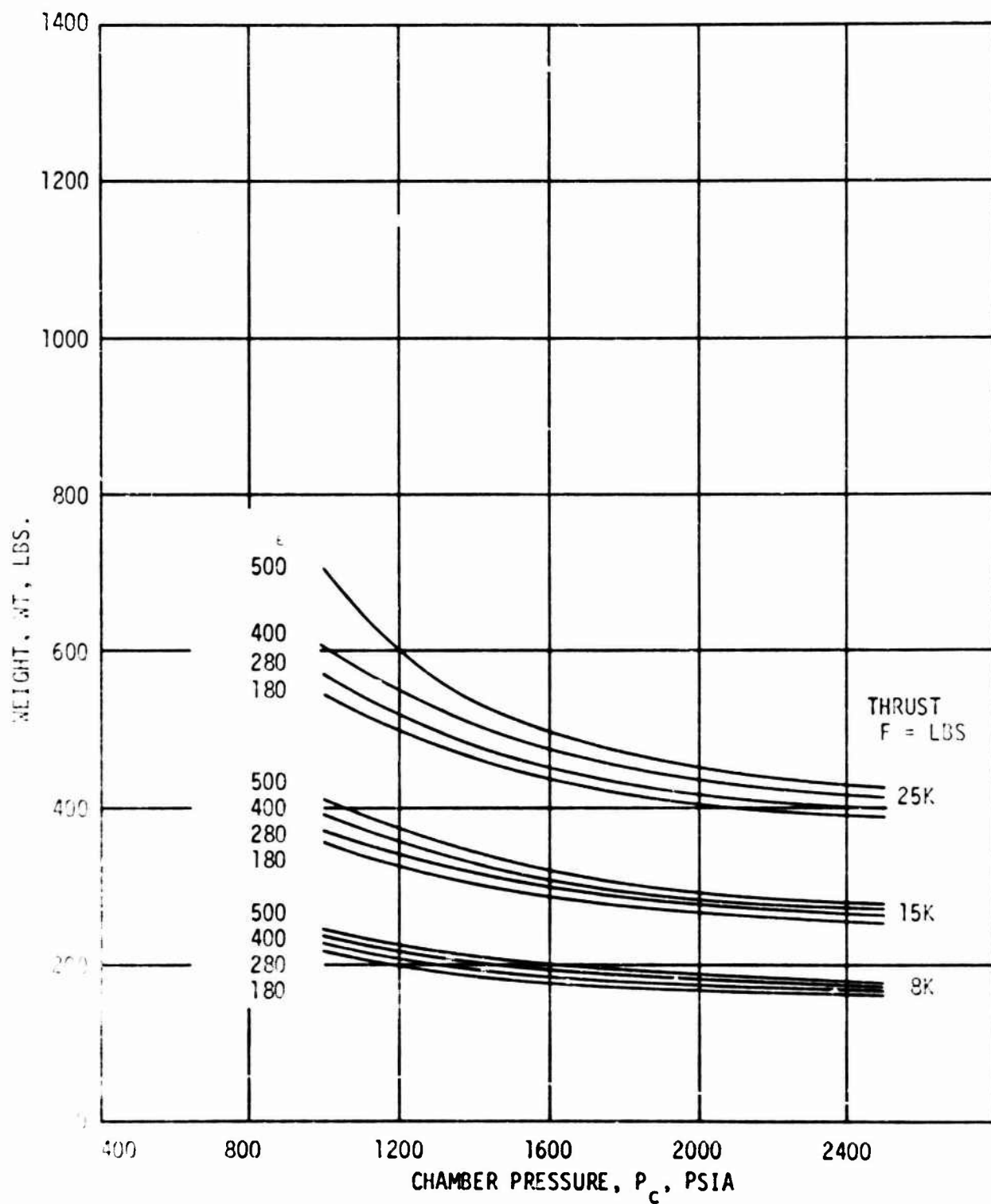


Figure 104. Weight vs  $P_c$ , Minimum Weight Retractable Nozzle, MR = 7

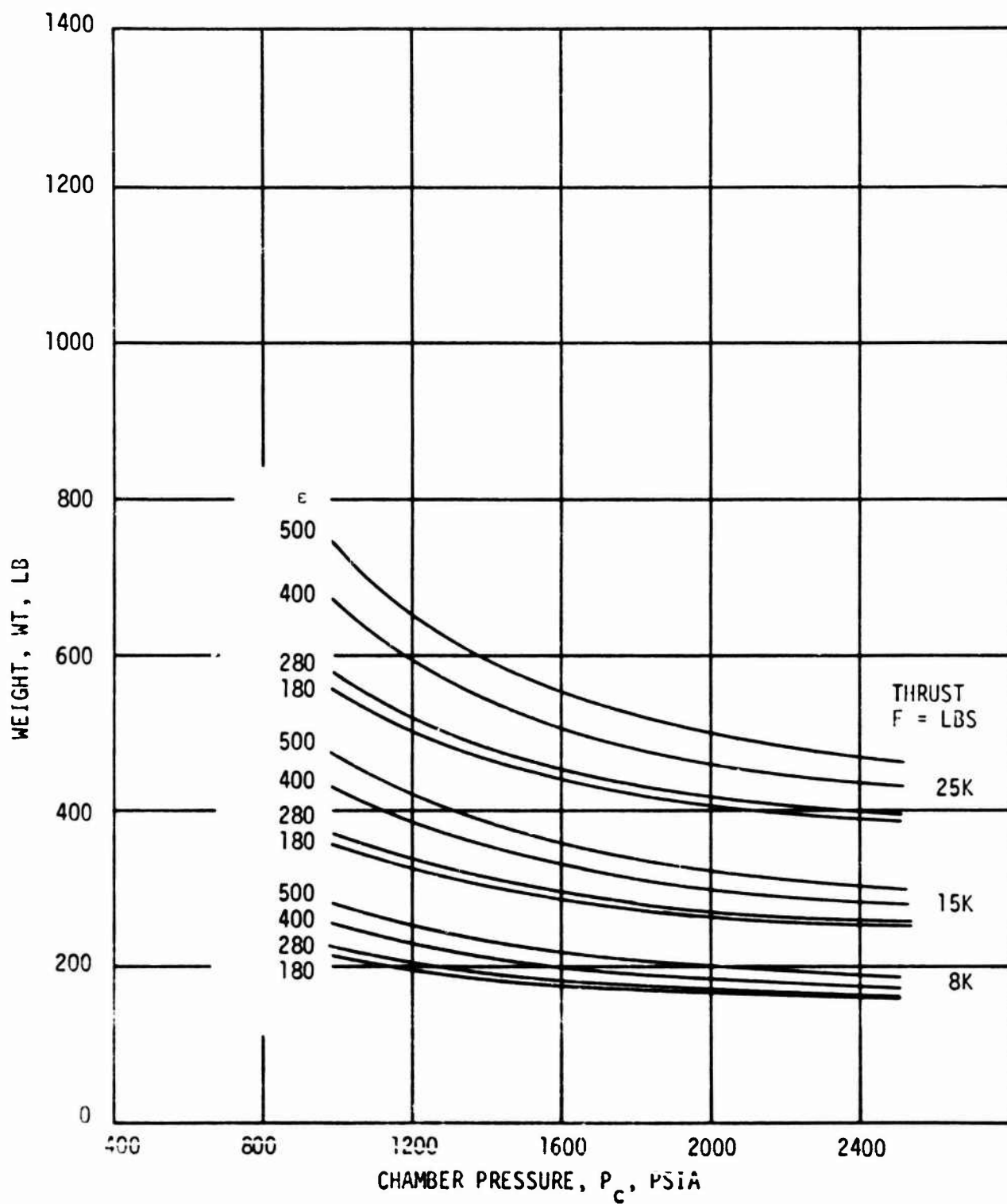


Figure 105. Weight vs  $P_c$ , Minimum Length Retractable Nozzle, MR = 7

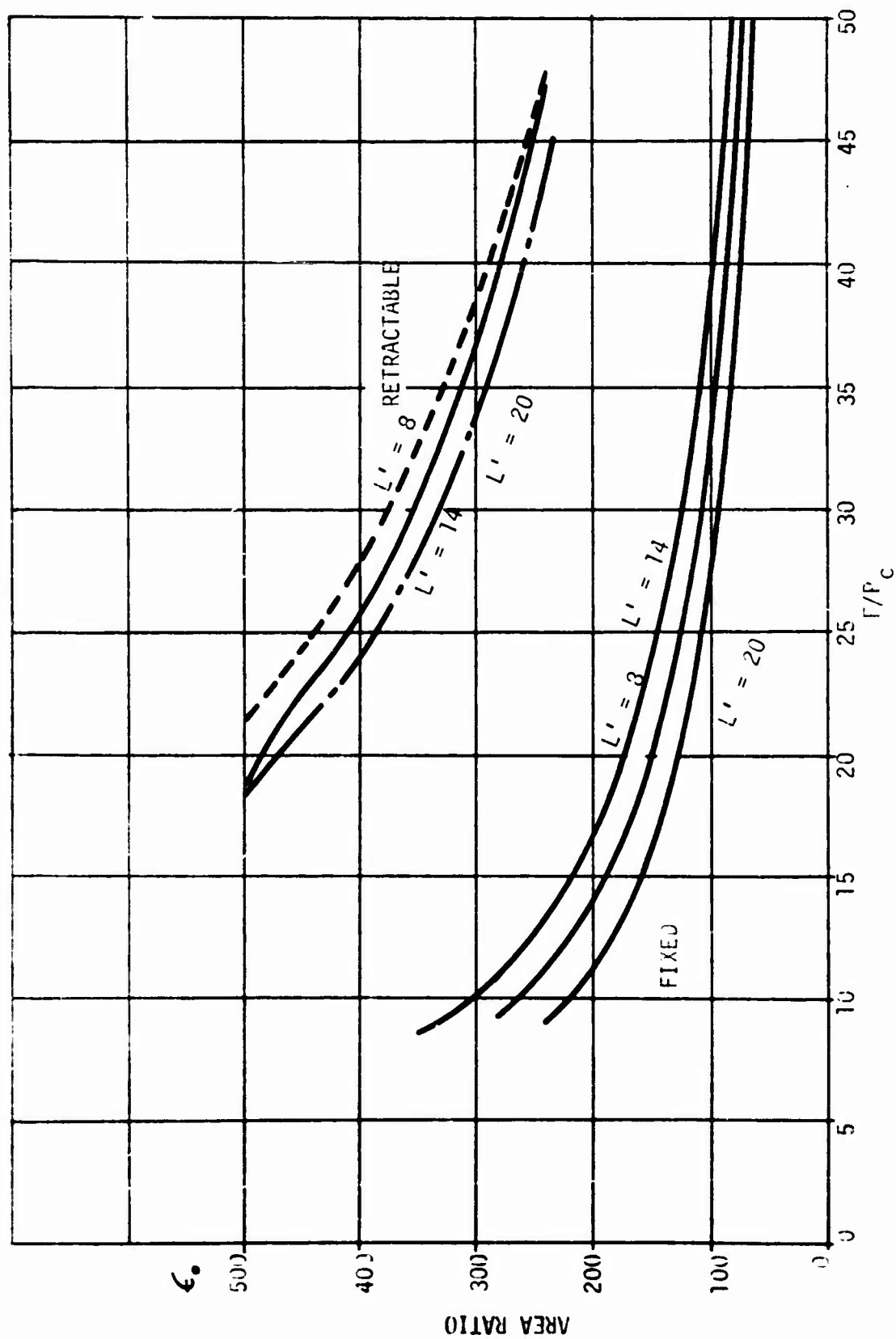


Figure 106. Maximum Area Ratio for Fixed Nozzles, Minimum Weight Retractable Nozzles

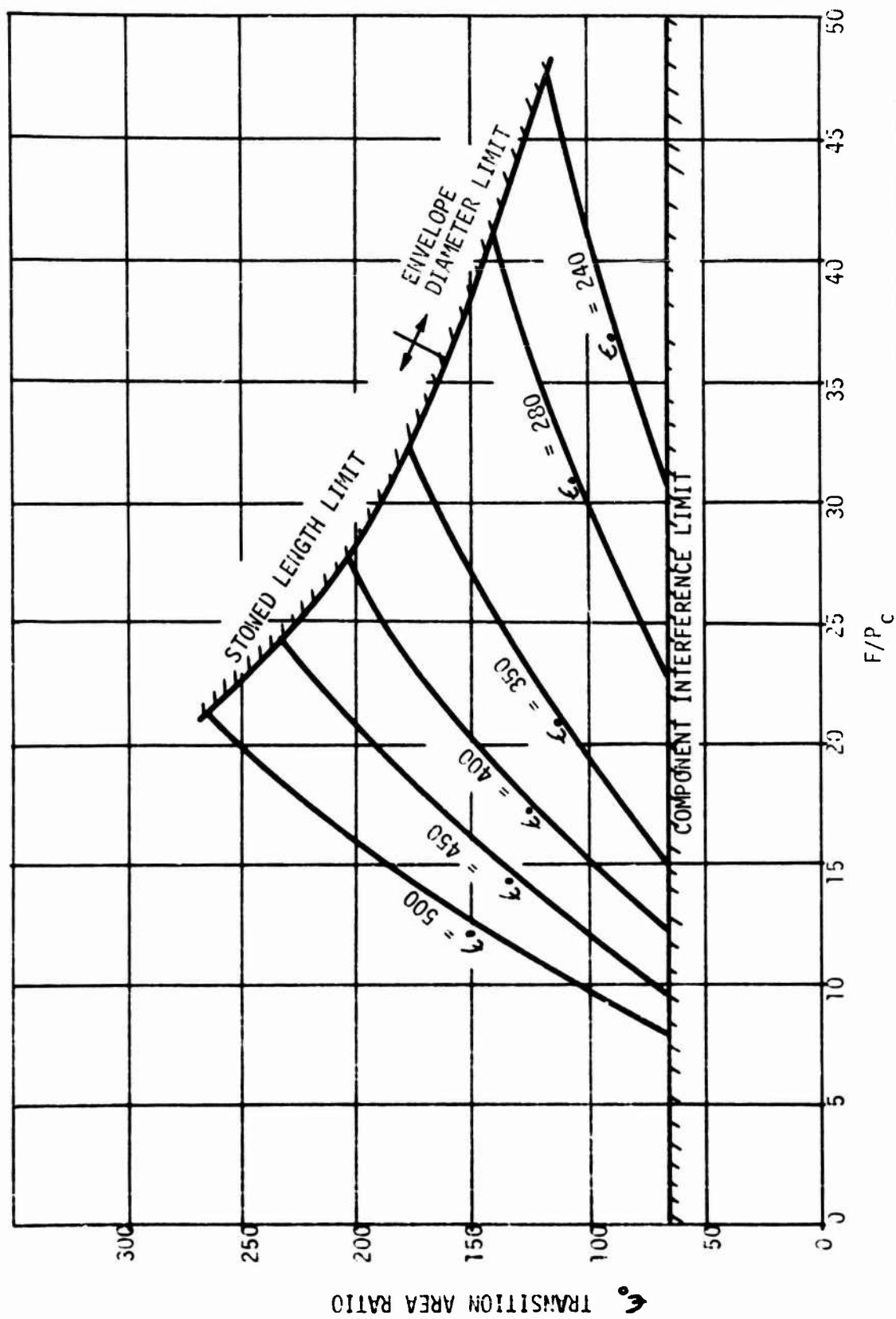


Figure 1J7. Transition Area Ratio for Minimum Weight Nozzle, MR = 5, L' = 8-in.

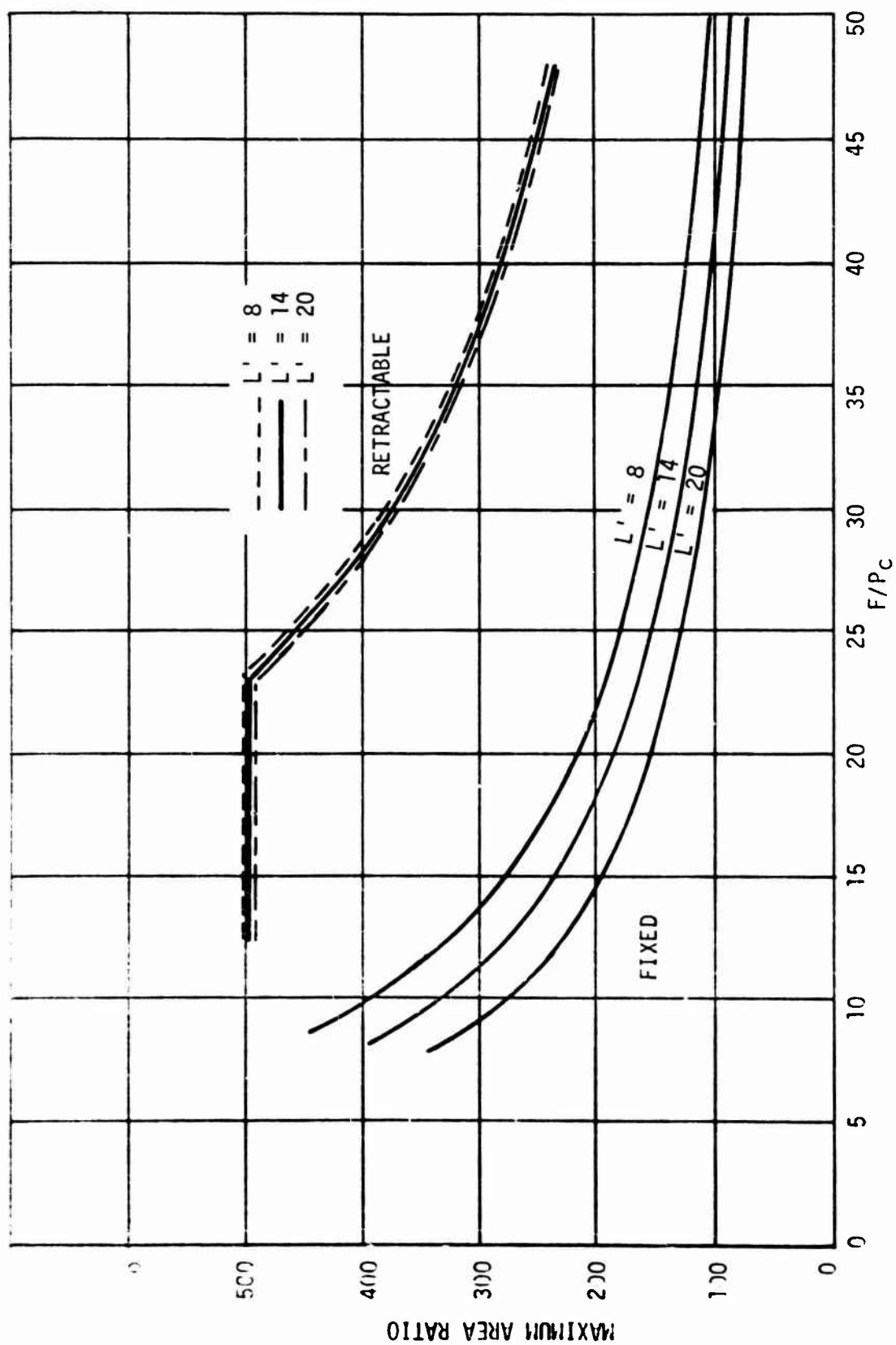


Figure 108. Maximum Area Ratio for Fixed Nozzles and Minimum Weight Retractable Nozzles,  $MR = 7$

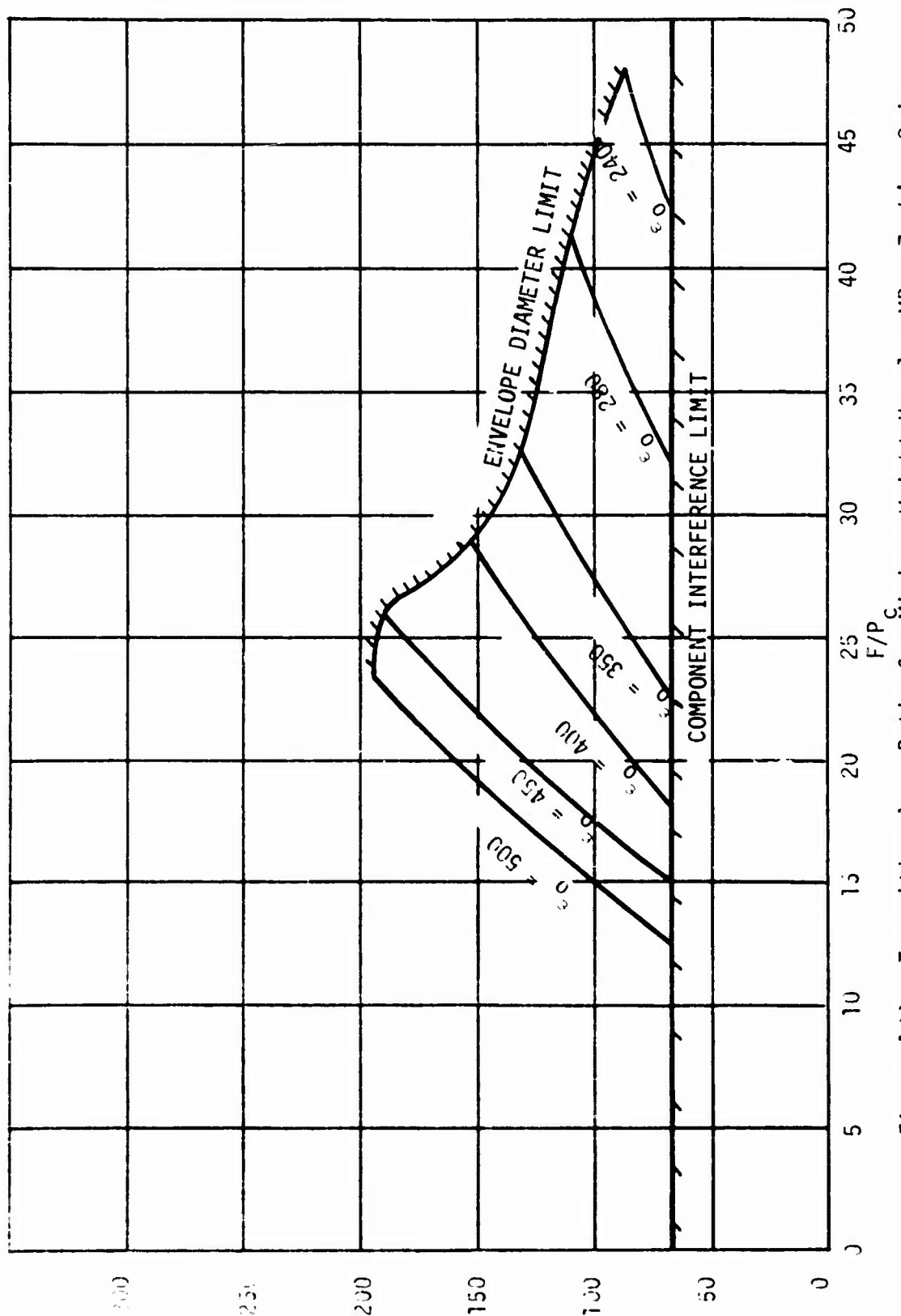


Figure 109. Transition Area Ratio for Minimum Weight Nozzle,  $MR = 7$ ,  $L' = 8$ -in.

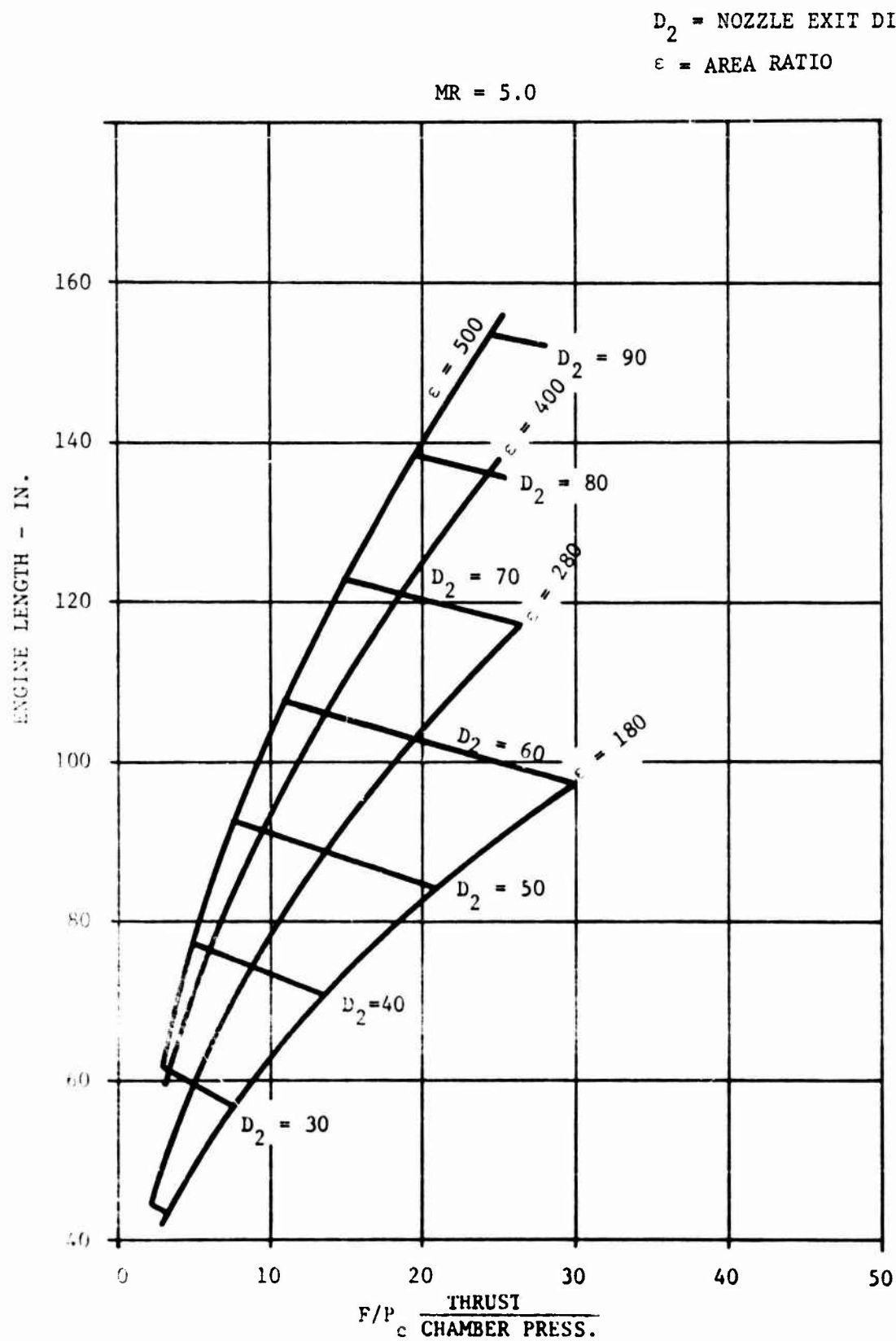


Figure 110. Engine Length vs  $F/P_c$ ,  $MR = 5$ , Staged Combustion Cycle

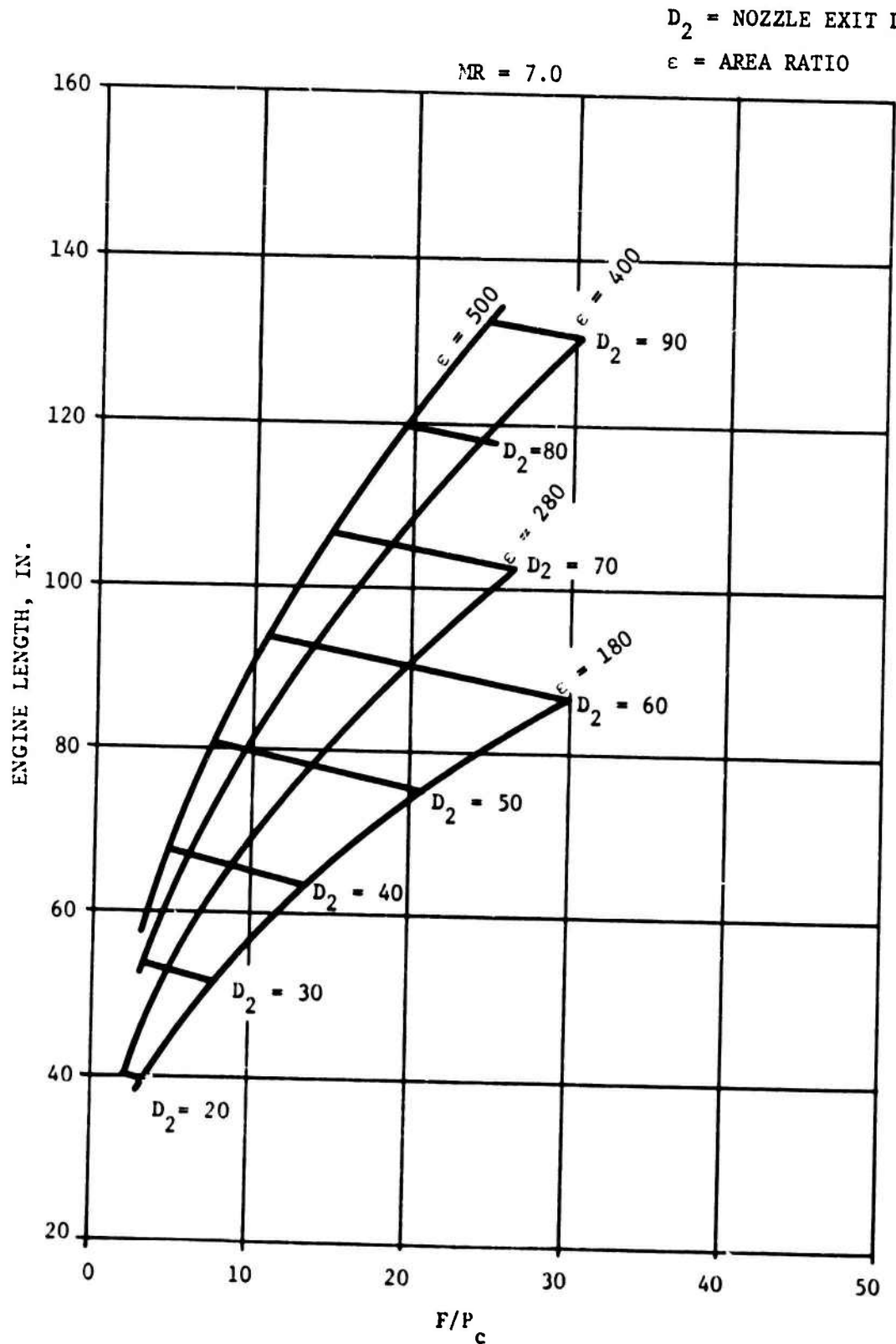


Figure 111. Engine Length vs  $F/P_c$ ,  $MR = 7$ , Staged Combustion Cycle

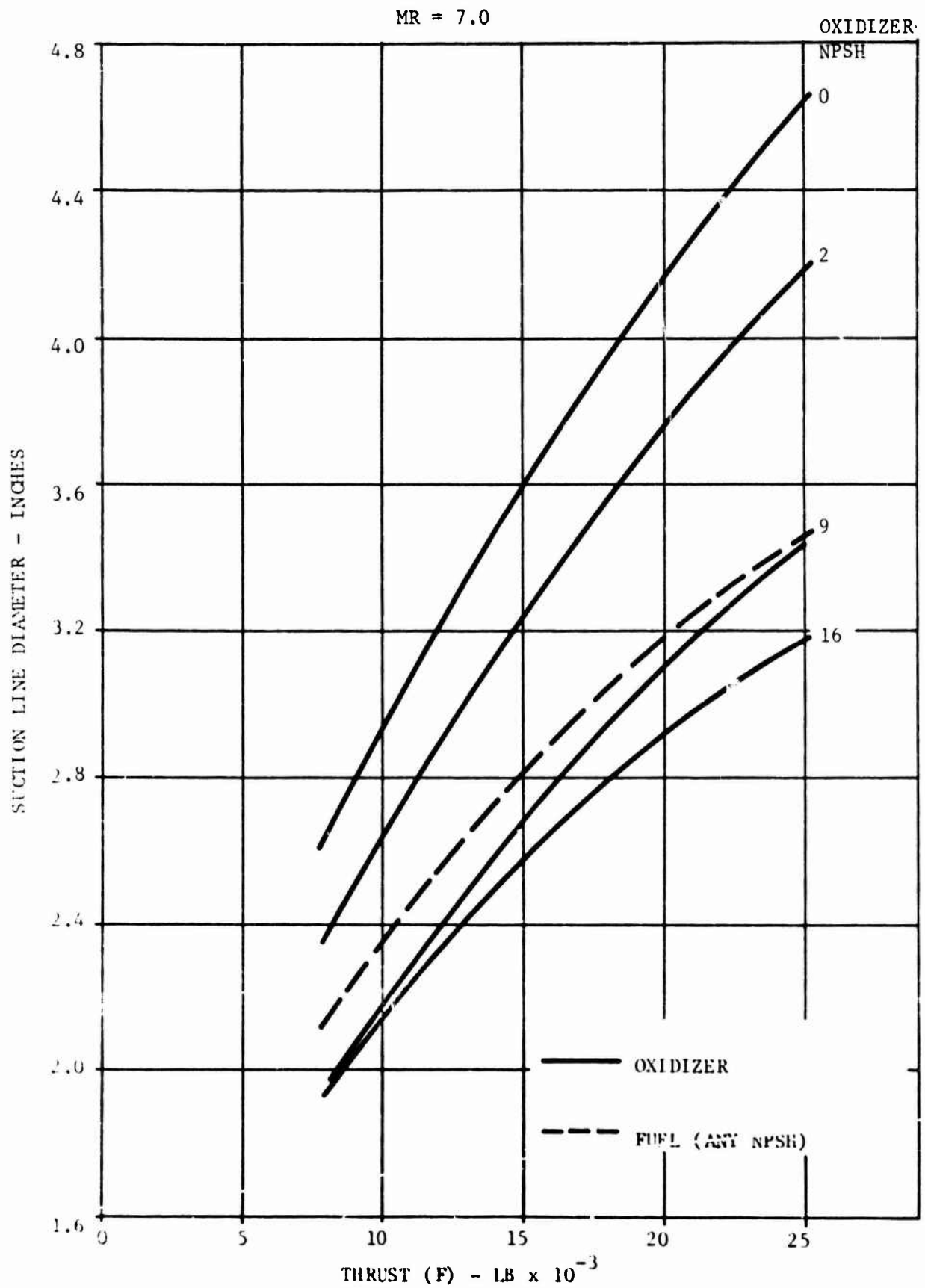


Figure 112. Suction Line Diameter vs Thrust, MR = 7

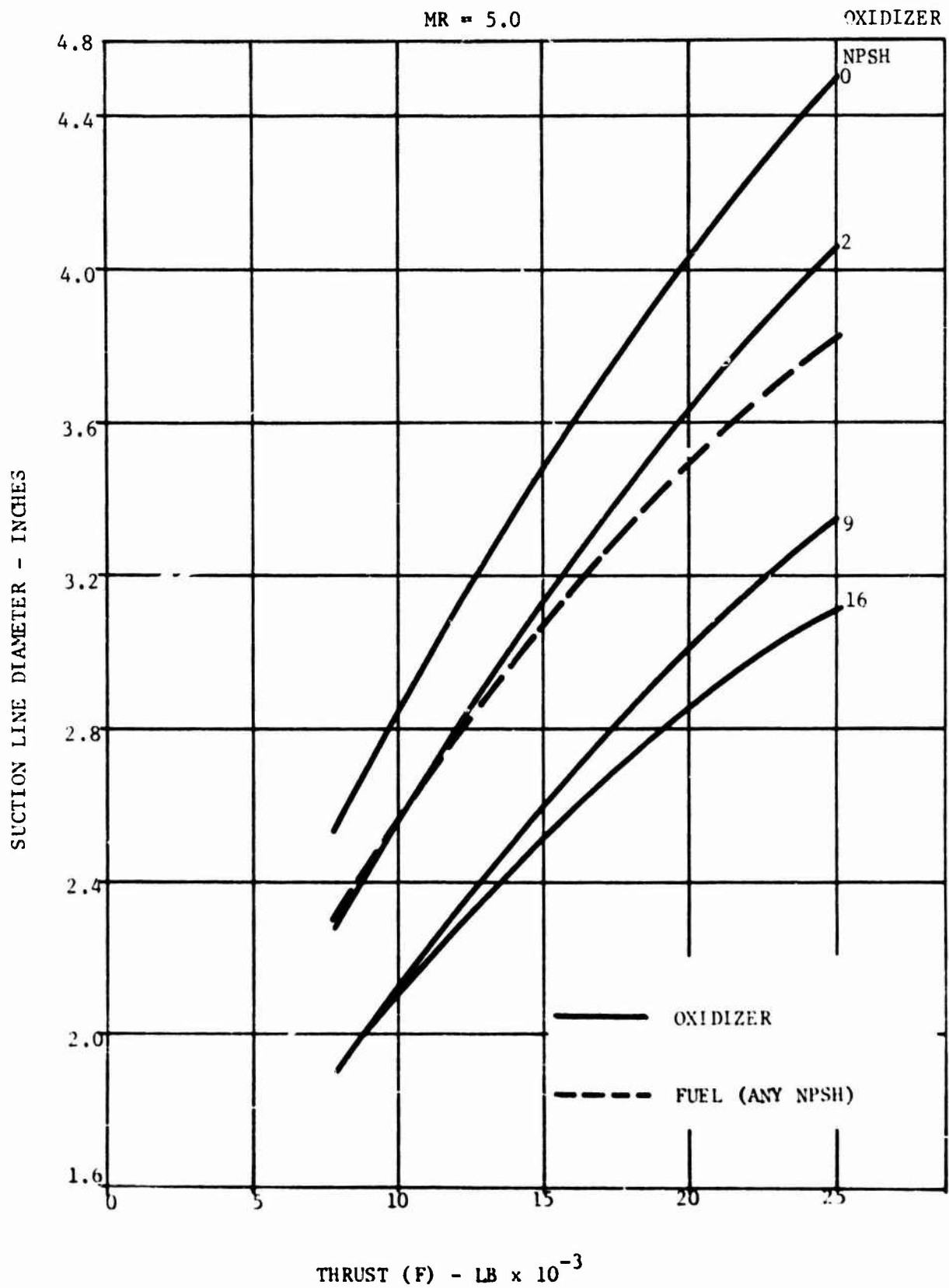


Figure 113. Suction Line Diameter vs Thrust, MR = 5

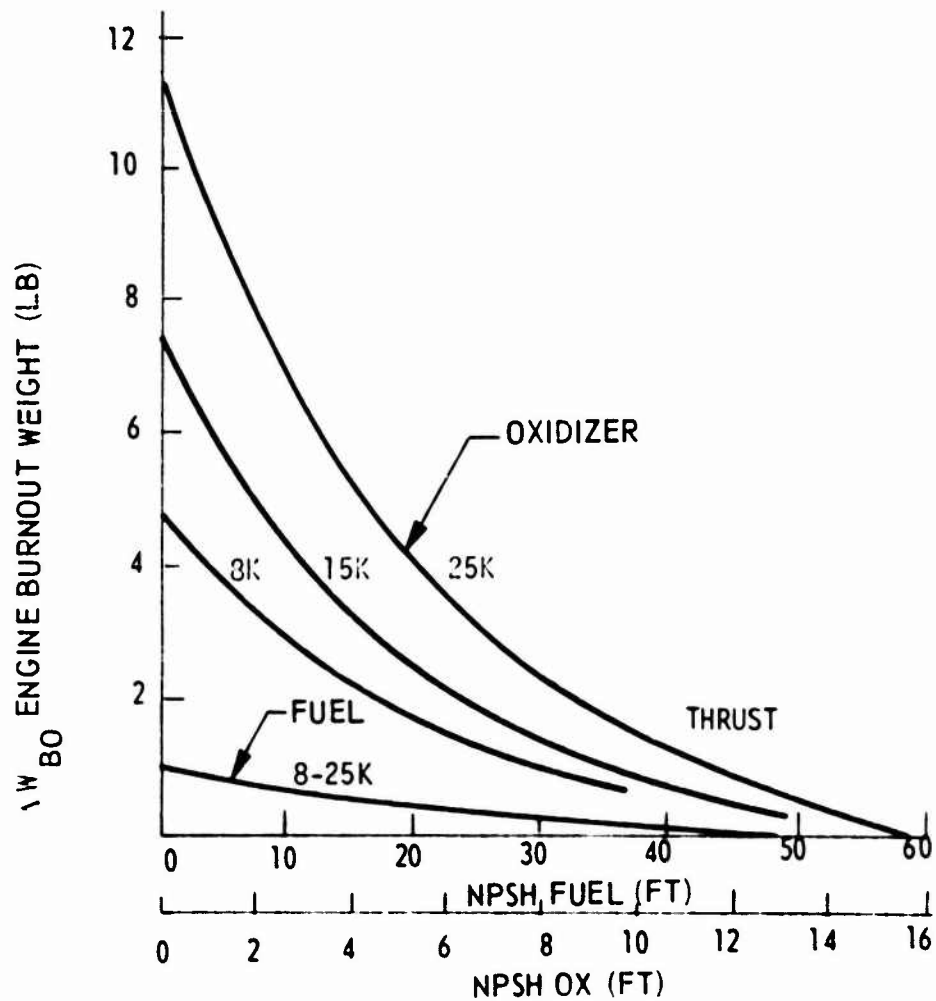


Figure 114. Staged Combustion Cycle Engine Weight vs NPSH,  
MR = 6

TABLE XVIII

STAGED COMBUSTION CYCLE CHARACTERISTICS FOR VARIOUS  $P_c$ , MR AND NPSH

| Nozzle Concept                                                       |         | Fixed                 |                       |                       |
|----------------------------------------------------------------------|---------|-----------------------|-----------------------|-----------------------|
| Thrust                                                               | 1000 lb | 8                     | 8                     | 8                     |
| Mixture Ratio                                                        |         | 5                     | 6                     | 7                     |
| Chamber Pressure                                                     | psia    | 1200                  | 1200                  | 1200                  |
| Area Ratio                                                           |         | 450                   | 500                   | 500                   |
| Specific Impulse                                                     | sec     | 469.4                 | 466.5                 | 458.5                 |
| Engine Length                                                        | in.     | 82                    | 82                    | 78.0                  |
| Maximum Diameter                                                     | in.     | 42.5                  | 47.5                  | 47.5                  |
| Suction Line Orientation                                             | in.     | 15                    | 15                    | 15                    |
| NPSH = 15/2 Engine Weight lb<br>F/O Suction Line dia in. Fuel<br>0x  |         | 200.5<br>2.33<br>2.30 | 200.5<br>2.20<br>2.33 | 197.5<br>2.14<br>2.38 |
| NPSH = 27/9 Engine Weight lb<br>F/O Suction Line dia in. Fuel<br>0x  |         | 199<br>2.33<br>1.90   | 199<br>2.20<br>1.90   | 197<br>2.14<br>1.95   |
| NPSH = 60/16 Engine Weight lb<br>F/O Suction Line dia in. Fuel<br>0x |         | 198<br>2.33<br>1.90   | 198<br>2.20<br>1.90   | 196<br>2.14<br>1.95   |

TABLE XVIII (cont.)

| Nozzle Concept                                                       | Fixed   |       |       |        | Retractable |       |      |      |
|----------------------------------------------------------------------|---------|-------|-------|--------|-------------|-------|------|------|
|                                                                      | 15      | 15    | 15    | 15     | 15          | 15    | 15   | 15   |
| Thrust                                                               | 1000 lb |       |       |        |             |       |      |      |
| Mixture Ratio                                                        |         | 5     | 6     | 7      |             |       |      |      |
| Chamber Pressure                                                     | psia    | 1450  | 1450  | 1450   | 1450        | 1450  | 1450 | 1450 |
| Area Ratio                                                           |         | 295   | 350   | 390    | 500         | 500   | 500  | 500  |
| Specific Impulse                                                     | sec     | 467.0 | 466.0 | 460.20 |             |       |      |      |
| Engine Length                                                        | in.     | 82    | 82    | 82     | 106         | 100   | 93   |      |
| Maximum Diameter                                                     | in.     | 45    | 49    | 51     | 59          | 61    | 60   |      |
| Suction Line Orientation in.                                         |         | 18    | 18    | 13     | 18          | 18    | 18   |      |
|                                                                      |         |       |       |        |             |       |      |      |
| NPSH = 15/2 Engine Weight lb<br>F/O Suction Line dia in. Fuel<br>Ox  | 271     | 275   | 291   |        | 365         | 345   | 335  |      |
|                                                                      | 3.06    | 2.90  | 2.80  |        | 3.06        | 2.90  | 2.80 |      |
|                                                                      | 3.13    | 3.18  | 3.24  |        | 3.13        | 3.18  | 3.24 |      |
| NPSH = 27/9 Engine Weight lb<br>F/O Suction Line dia in. Fuel<br>Ox  | 267.5   | 271.5 | 287.5 |        | 361.5       | 341.5 | 330  |      |
|                                                                      | 3.60    | 2.90  | 2.80  |        | 3.60        | 2.90  | 2.80 |      |
|                                                                      | 2.60    | 2.60  | 2.67  |        | 2.60        | 2.60  | 2.60 |      |
| NPSH = 60/16 Engine Weight lb<br>F/O Suction Line dia in. Fuel<br>Ox | 266     | 270   | 286   |        | 360         | 340   | 330  |      |
|                                                                      | 3.06    | 2.90  | 2.80  |        | 3.06        | 2.90  | 2.80 |      |
|                                                                      | 2.60    | 2.60  | 2.67  |        | 2.60        | 2.60  | 2.67 |      |

TABLE XVIII (cont.)

| Nozzle Concept               | Fixed |       |       |       | Retractable |       |       |       |
|------------------------------|-------|-------|-------|-------|-------------|-------|-------|-------|
|                              | 25    | 25    | 25    | 25    | 25          | 25    | 25    | 25    |
| Thrust                       | 5     | 6     | 7     | 7     | 5           | 6     | 7     | 7     |
| Mixture Ratio                | 1800  | 1800  | 1800  | 1800  | 1800        | 1800  | 1800  | 1800  |
| Chamber Pressure             | 260   | 280   | 315   | 315   | 500         | 500   | 500   | 500   |
| Area Ratio                   | 466.2 | 465.3 | 460.2 | 460.2 | 471.0       | 469.8 | 463.7 | 463.7 |
| Specific Impulse             | 82    | 82    | 82    | 82    | 120         | 110   | 104   | 104   |
| Engine Length                | 46.3  | 50.5  | 53.0  | 53.0  | 68          | 68    | 68    | 68    |
| Maximum Diameter             | 24    | 24    | 24    | 24    | 24          | 24    | 24    | 24    |
| Suction Line Orientation in. |       |       |       |       |             |       |       |       |
| PSH = 15/2 Engine Weight lb  | 394   | 389   | 379   | 379   | 549         | 599   | 484   | 484   |
| Suction Line dia in. Fuel Ox | 3.80  | 3.60  | 3.46  | 3.46  | 3.80        | 3.60  | 3.46  | 3.46  |
|                              | 4.05  | 4.10  | 4.18  | 4.18  | 4.05        | 4.10  | 4.18  | 4.18  |
| PSH = 27/9 Engine Weight lb  | 387   | 382   | 372   | 372   | 542         | 492   | 477   | 477   |
| Suction Line dia in. Fuel Ox | 3.80  | 3.60  | 3.46  | 3.46  | 3.80        | 3.60  | 3.46  | 3.46  |
|                              | 3.35  | 3.40  | 3.44  | 3.44  | 3.35        | 3.40  | 3.44  | 3.44  |
| PSH = 60/16 Engine Weight lb | 385   | 380   | 370   | 370   | 540         | 490   | 475   | 475   |
| Suction Line dia in. Fuel Ox | 3.80  | 3.60  | 3.46  | 3.46  | 3.80        | 3.60  | 3.46  | 3.46  |
|                              | 2.90  | 3.12  | 3.17  | 3.17  | 2.90        | 3.12  | 3.17  | 3.17  |





TABLE XIX

## EFFECT OF TURBOMACHINERY DESIGN

Engine MR = 7      NPSH = 60 ft

| Fuel Circuit           |        | Thrust    |            |            |
|------------------------|--------|-----------|------------|------------|
|                        |        | <u>8K</u> | <u>15K</u> | <u>25K</u> |
| Boost Pump             |        |           |            |            |
| Shaft Speed            | rpm    | 31428     | 25714      | 22857      |
| Suction Specific Speed | -      | 9232      | 10348      | 11884      |
| Main Pump              |        |           |            |            |
| Number Stages          | -      | 2         | 2          | 3          |
| Shaft Speed            | rpm    | 11000     | 90000      | 80000      |
| Impeller Tip Speed     | ft/sec | 1787      | 1726       | 1515       |
| Specific Speed         | -      | 462       | 465        | 652        |
| Efficiency             | %      | 49.8      | 52.6       | 59.7       |
| Discharge Pressure     | psia   | 3388      | 3907       | 4494       |
| Volume Flow            | gpm    | 225       | 421        | 704        |
| Turbine                |        |           |            |            |
| Inlet Temperature      | °R     | 1860      | 1860       | 1860       |
| Mean Blade Speed       | ft/sec | 1300      | 1300       | 1300       |
| Number Stages          | -      | 2         | 2          | 2          |
| Nozzle Admission       | %      | 100       | 100        | 100        |
| Efficiency             | %      | 64.1      | 62.7       | 62.1       |
| Shaft Power            | HP     | 929       | 1904       | 3225       |

TABLE XIX (cont.)

Engine MR = 7      NPSH = 16 ft

| Oxidizer Circuit       |        | Thrust    |            |            |
|------------------------|--------|-----------|------------|------------|
|                        |        | <u>8K</u> | <u>15K</u> | <u>25K</u> |
| Boost Pump             |        |           |            |            |
| Shaft Speed            | rpm    | 20000     | 16000      | 14286      |
| Suction Specific Speed | -      | 20727     | 22717      | 26207      |
| Main Pump              |        |           |            |            |
| Number Stages          | -      | 1-1/2     | 1-1/2      | 1-1/2      |
| Shaft Speed            | rpm    | 70000     | 56000      | 50000      |
| Impeller Tip Speed     | ft/sec | 490       | 534        | 593        |
| Specific Speed         | -      | 1552      | 1458       | 1428       |
| Efficiency             | %      | 57.9      | 61.4       | 64.1       |
| Discharge Pressure*    | psia   | 2062      | 2491       | 3092       |
| Volume Flow            | gpm    | 96.1      | 180        | 301        |
| Turbine                |        |           |            |            |
| Inlet Temperature      | °R     | 1860      | 1860       | 1860       |
| Mean Blade Speed       | ft/sec | 1100      | 1100       | 1100       |
| Number Stages          | -      | 1         | 1          | 1          |
| Nozzle Admission       | %      | 24        | 23.7       | 27.7       |
| Efficiency             | %      | 46.6      | 45.3       | 44.7       |
| Shaft Power            | HP     | 235       | 506        | 1012       |

\* Main Stage

TABLE XIX (cont.)

Engine MR = 5      NPSH = 60 ft

| Fuel Circuit           |        | Thrust |       |       |
|------------------------|--------|--------|-------|-------|
|                        |        | 8K     | 15K   | 25K   |
| Boost Pump             |        |        |       |       |
| Shaft Speed            | rpm    | 31428  | 25714 | 22857 |
| Suction Specific Speed | -      | 10584  | 11855 | 13605 |
| Main Pump              |        |        |       |       |
| Number Stages          | -      | 2      | 2     | 3     |
| Shaft Speed            | rpm    | 11000  | 90000 | 80000 |
| Impeller Tip Speed     | ft/sec | 1549   | 1640  | 1503  |
| Specific Speed         | -      | 559    | 575   | 807   |
| Efficiency             | %      | 53.9   | 57.0  | 63.6  |
| Discharge Pressure     | psia   | 3170   | 3559  | 4090  |
| Volume Flow            | gpm    | 295    | 553   | 922   |
| Turbine                |        |        |       |       |
| Inlet Temperature      | °R     | 1860   | 1860  | 1860  |
| Mean Blade Speed       | ft/sec | 1300   | 1300  | 1300  |
| Number Stages          | -      | 2      | 2     | 2     |
| Nozzle Admission       | %      | 100    | 100   | 100   |
| Efficiency             | %      | 71.1   | 70.6  | 70.3  |
| Shaft Power            | HP     | 1056   | 2102  | 3614  |

TABLE XIX (cont.)

Engine MR = 5      NPSH = 16 ft

| Oxidizer Circuit       |        | Thrust    |            |            |
|------------------------|--------|-----------|------------|------------|
|                        |        | <u>8K</u> | <u>15K</u> | <u>25K</u> |
| Boost Pump             |        |           |            |            |
| Shaft Speed            | rpm    | 20000     | 16000      | 14286      |
| Suction Specific Speed | -      | 20084     | 21997      | 25356      |
| Main Pump              |        |           |            |            |
| Number Stages          | -      | 1-1/2     | 1-1/2      | 1-1/2      |
| Shaft Speed            | rpm    | 70000     | 56000      | 50000      |
| Impeller Tip Speed     | ft/sec | 487       | 531        | 590        |
| Specific Speed         | -      | 1493      | 1403       | 1372       |
| Efficiency             | %      | 57.3      | 60.8       | 63.5       |
| Discharge Pressure*    | psia   | 2062      | 2491       | 3092       |
| Volume Flow            | gpm    | 90.2      | 169        | 282        |
| Turbine                |        |           |            |            |
| Inlet Temperature      | °R     | 1860      | 1860       | 1860       |
| Mean Blade Speed       | ft/sec | 1100      | 1100       | 1100       |
| Number Stages          | -      | 1         | 1          | 1          |
| Nozzle Admission       | %      | 33        | 34         | 38.8       |
| Efficiency             | %      | 53.7      | 53.0       | 52.0       |
| Shaft Power            | HP     | 223       | 476        | 947        |

\* Main Stage

### III. A, Engine Design Parametric Study (Task IV) (cont.)

#### 11. Thermal Conditioning Requirements

##### a. Engine Chillover Analysis

An engine chillover study was made to estimate pump chillover requirements. The results are preliminary; however, they are sufficiently accurate to indicate the functional relationships. They should be scaled to actual empirical data and repeated for improved controlled chillover methods. In particular, improvements are required in the LO<sub>2</sub> pump chillover method.

The basic assumption of this analysis is that the pump discharge port is choked controlling the two phase flow. Obviously, improvements can be made by incorporating valve controlled chillover particularly toward the final stage of the chillover transient.

The parametric study was performed to determine the effect of thrust and chamber pressure on propellant pump chillover time and amount of propellant flowed. The effect of pump inlet pressure and pump initial temperature was also studied. The range of variables for which the study was made is:

|                           |                                        |
|---------------------------|----------------------------------------|
| Thrust:                   | 8000 - 50,000 lb                       |
| Chamber Pressure:         | 1000 - 4000 psia                       |
| Pump Inlet Pressure:      | 15 - 100 psia                          |
| Initial Pump Temperature: | $T_{\text{sat}} - 540^{\circ}\text{R}$ |

The pumps were assumed to be made of aluminum (Table XV). The results, presented in Figures 117 through 123 are intended to be relative and may be scaled directly to match available data.

##### (1) Method of Analysis

The analysis was performed to provide a simple method of calculation for use in the chillover analysis of the OOS engine. Attention was given to determination of functional relationships so that the final results could be scaled directly to available data.

The pump is modeled thermally as a one-dimensional plate, insulated on one side, with wetted area and mass equal to that of the pump. If chillover is defined to be accomplished when a given temperature is reached then the time may be determined as a function of pump flow passage geometry and material properties.

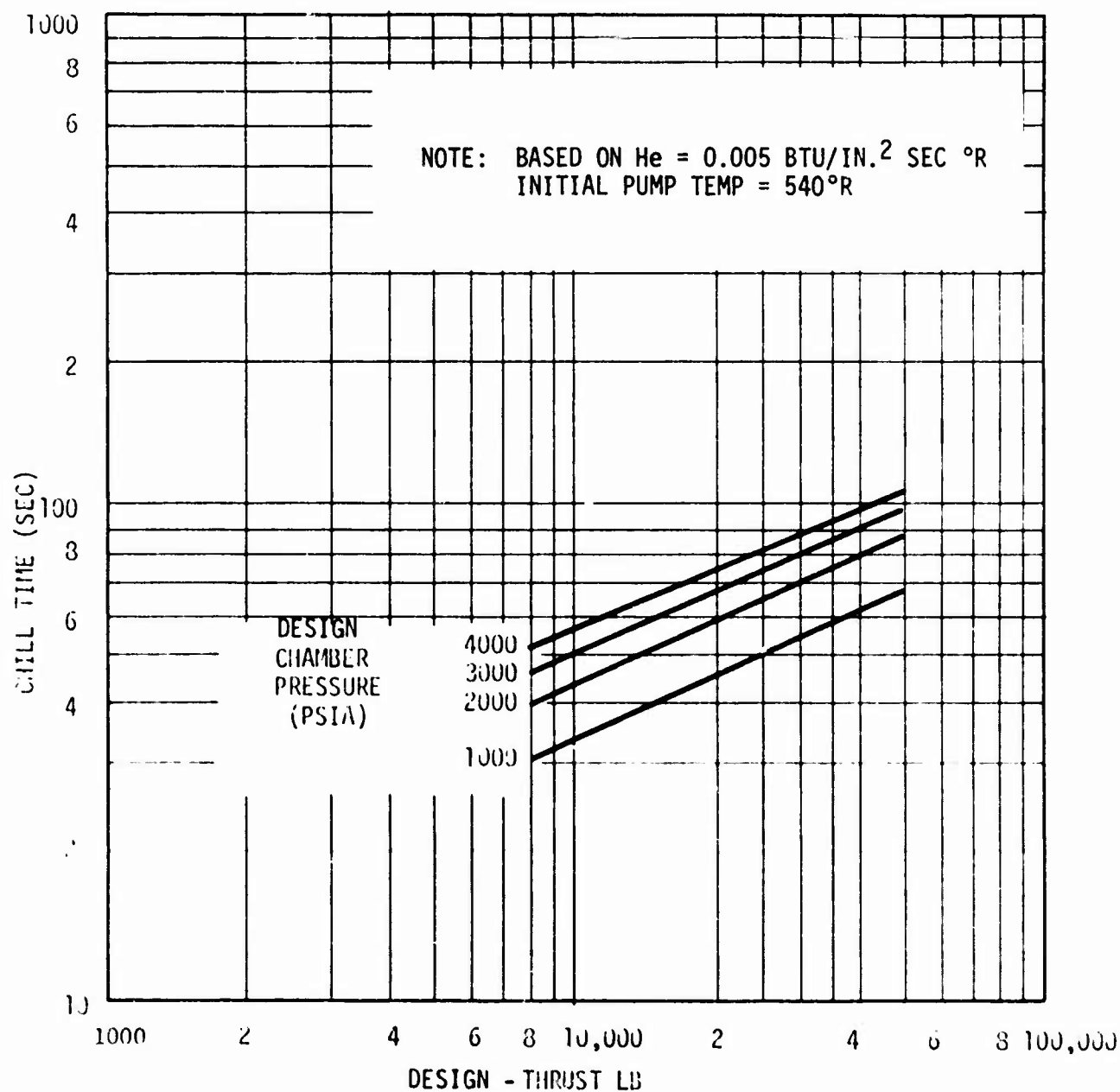


Figure 117. Hydrogen Pump Chilledown Time

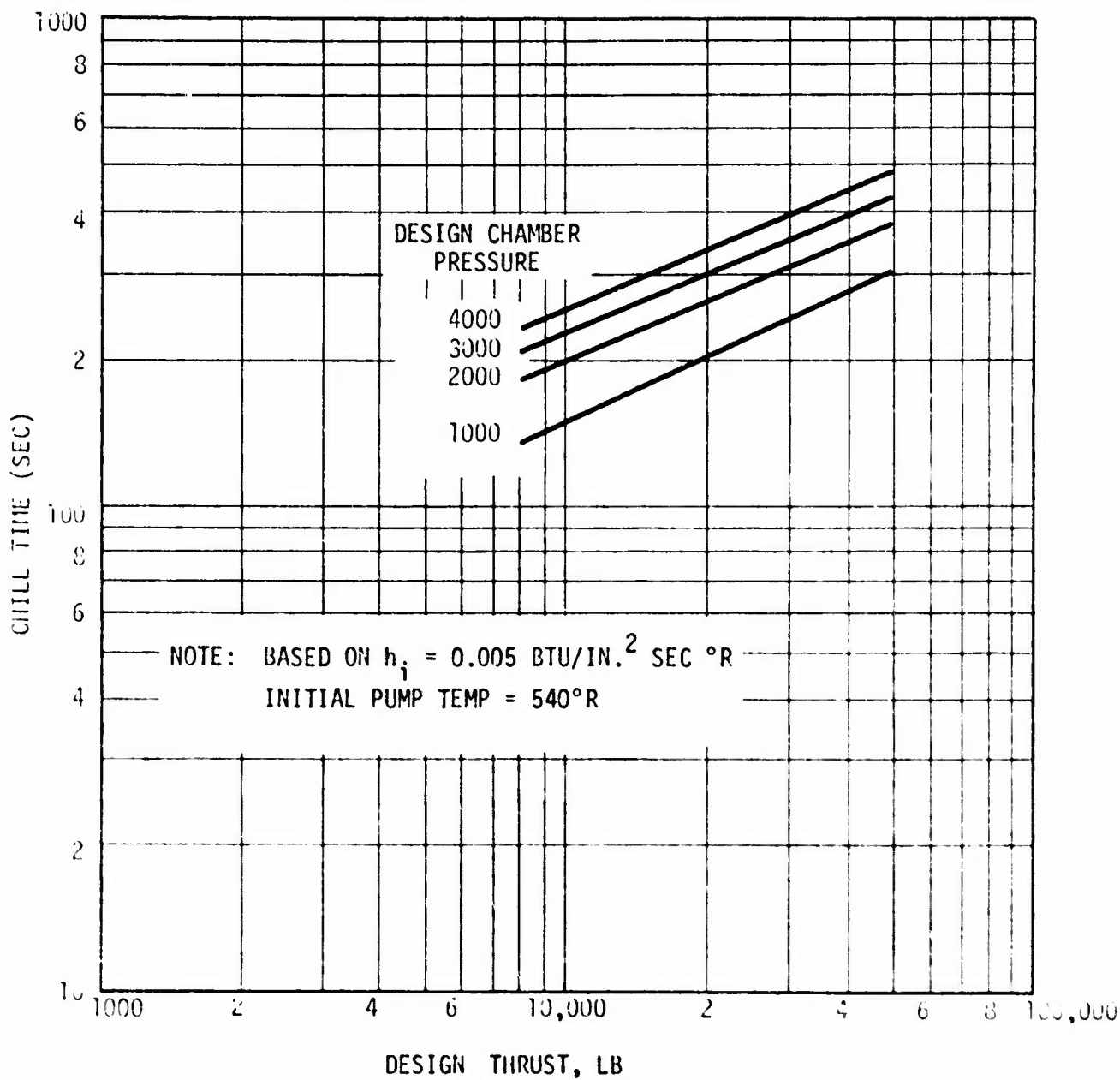


Figure 118. Oxygen Pump Chillydown Time

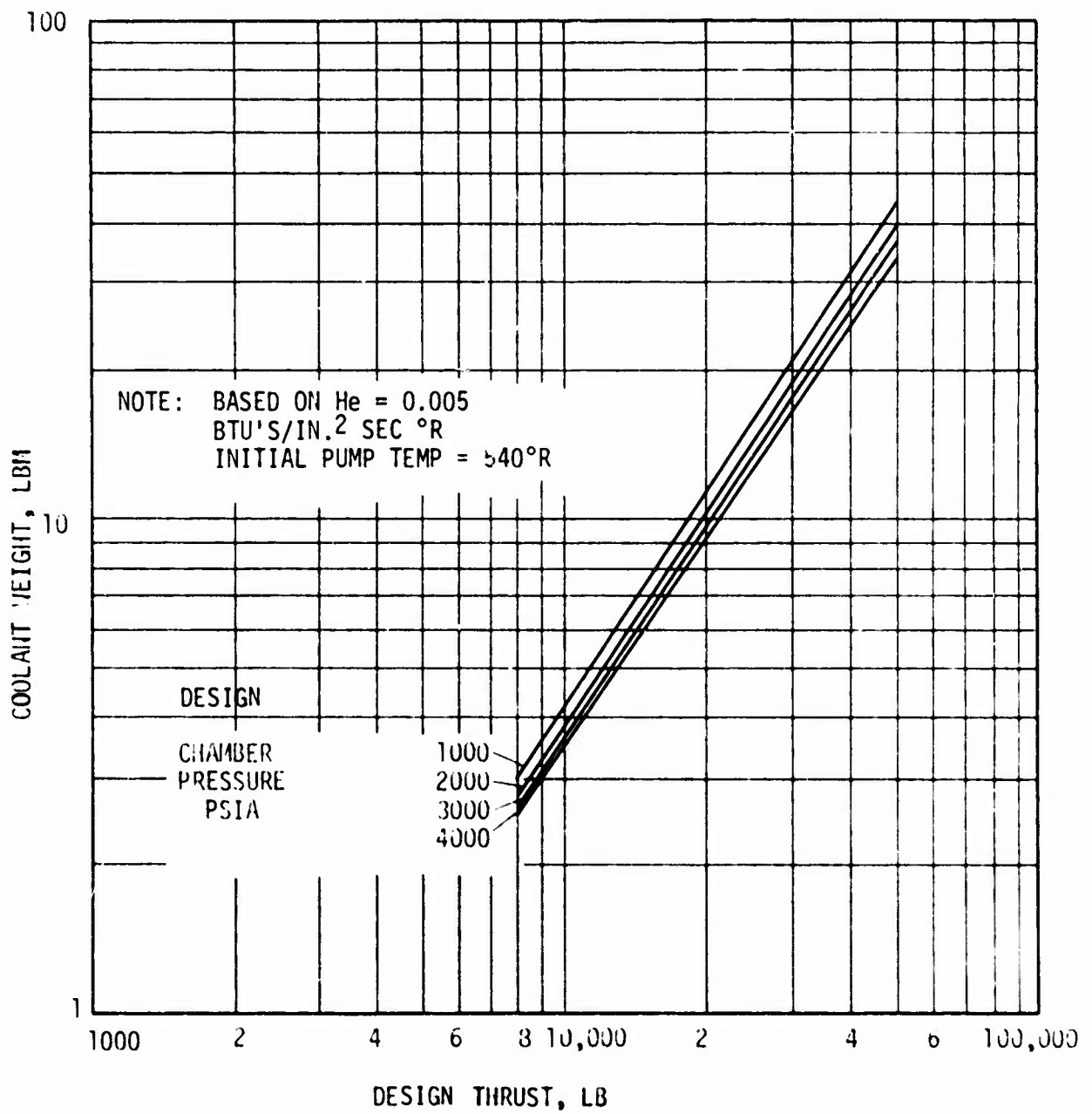


Figure 119. Hydrogen Pump Chilledown Flow

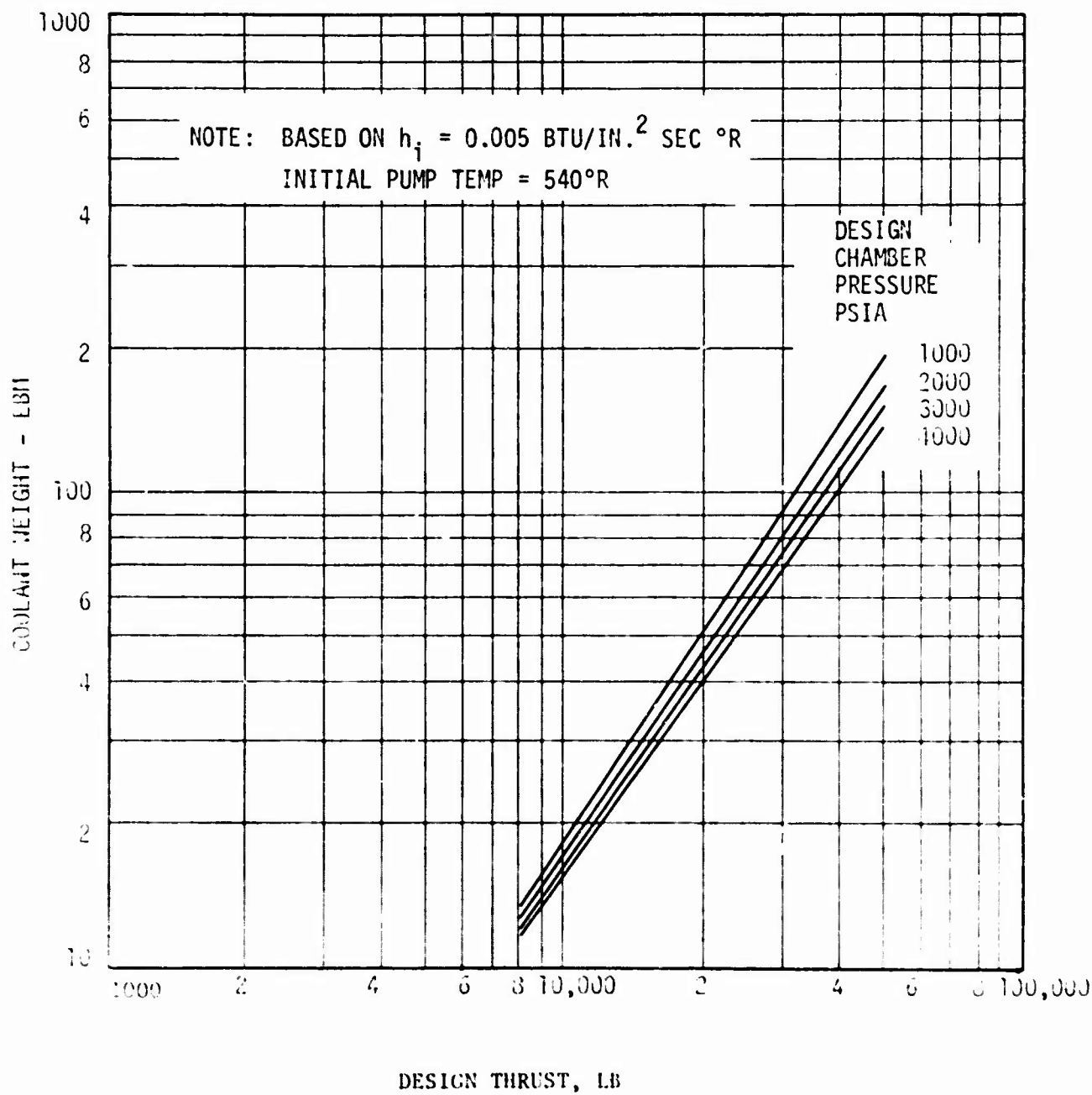


Figure 120. Oxygen Pump Chilldown Flow

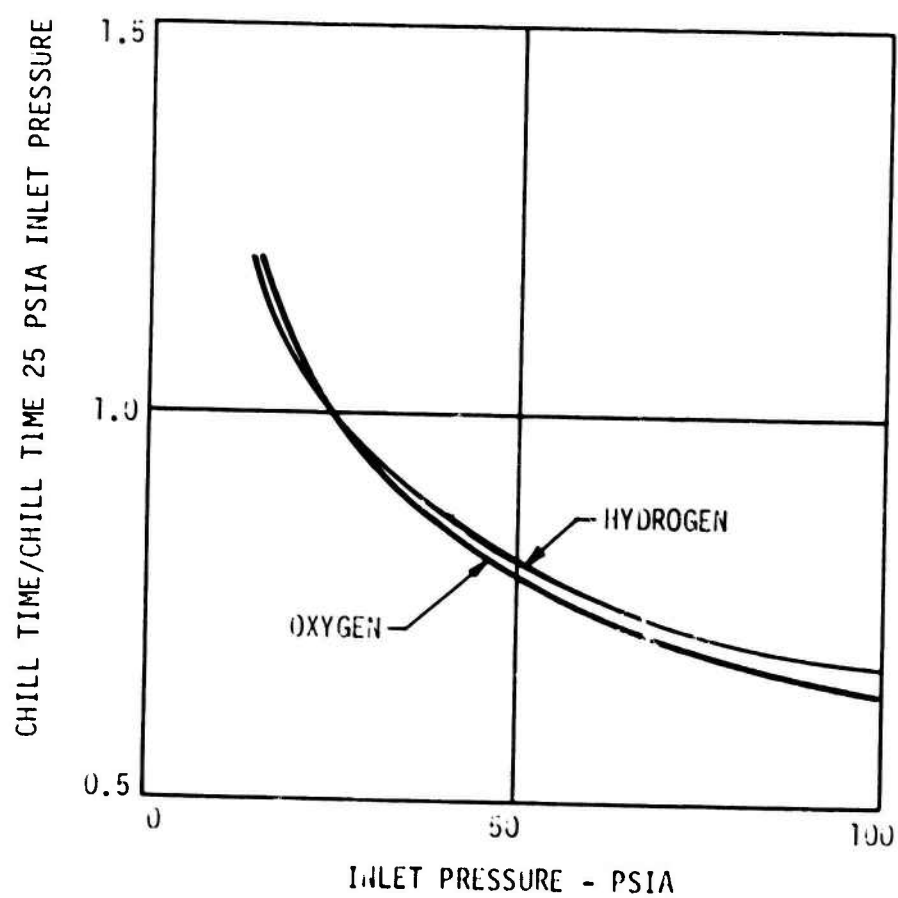


Figure 121. Effect of Inlet Pressure on Pump Chilldown Time

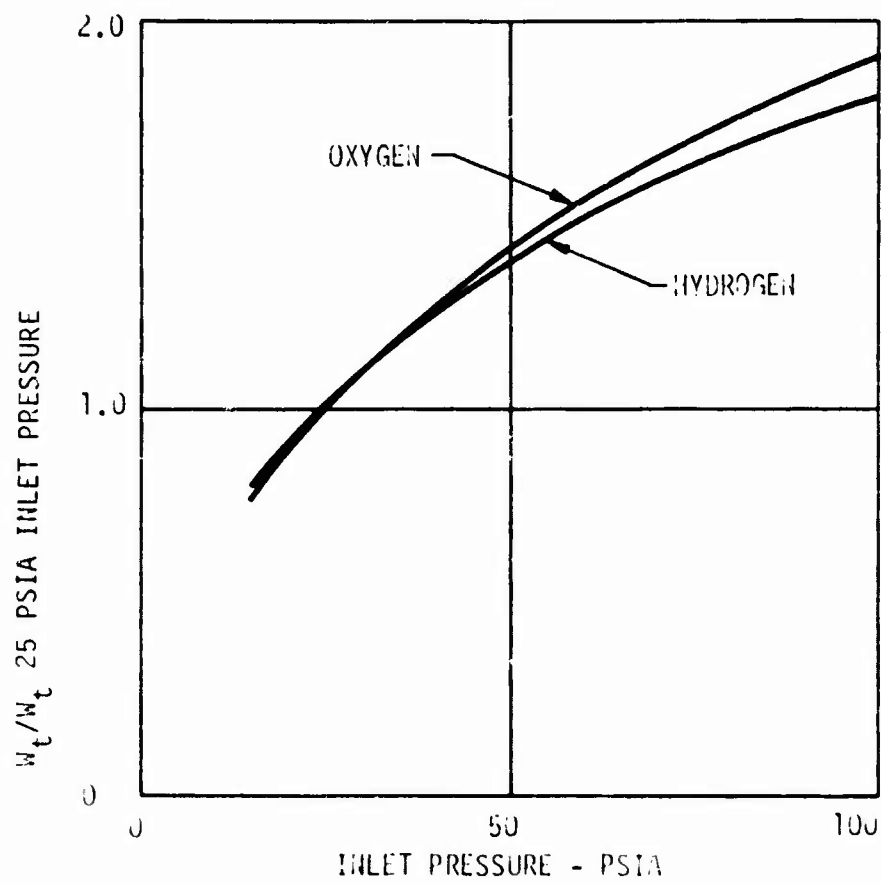


Figure 122. Effect of Inlet Pressure on Pump Chillover Coolant Weight

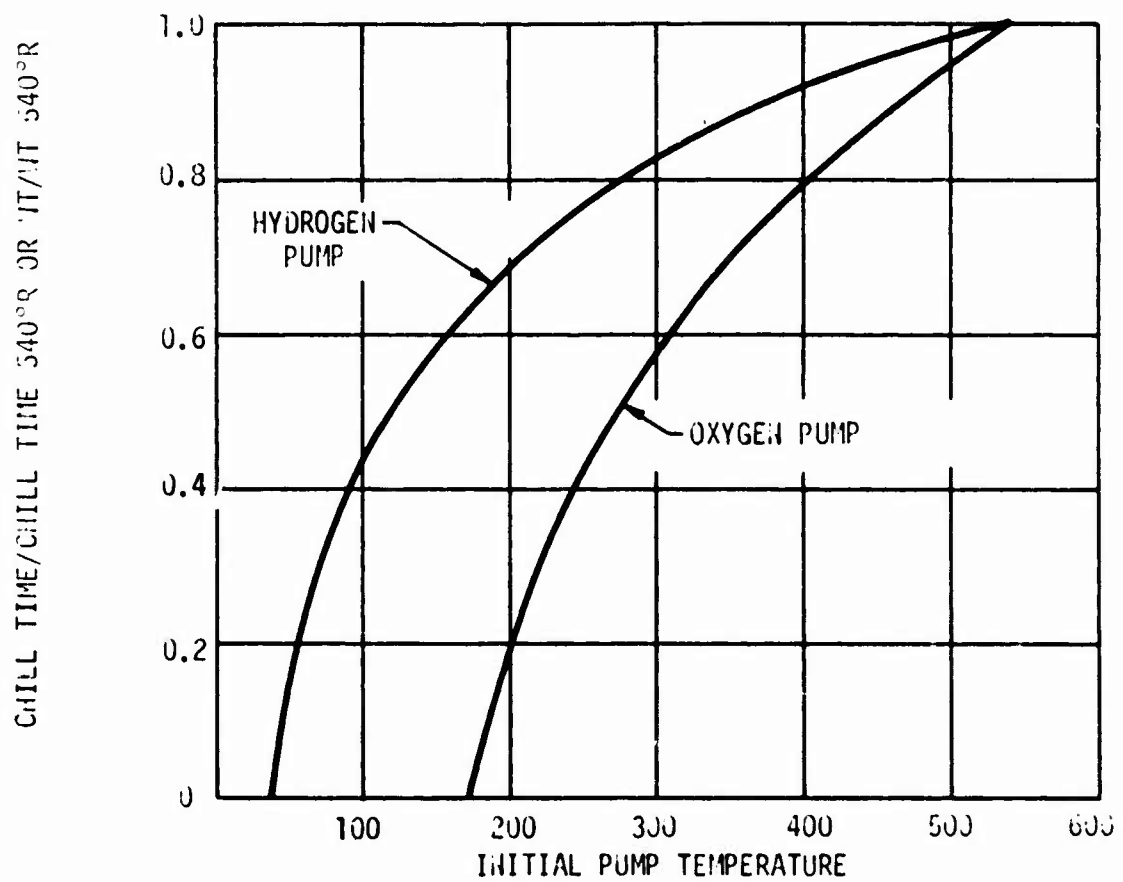


Figure 123. Effect of Initial Temperature on Pump Chillover Rate and Coolant Weight

# 111. A, Engine Design Parametric Study (Task IV) (cont.)

The pump geometry is given in equation form as:

Weight:

$$W_{t_{\text{pump}}} = \text{Const} \times \left[ \frac{\sqrt{2F/P_c}}{\sqrt{1 + MR} \cdot S \cdot (NPSH + TSH)^{3/4} \sqrt{N}} \right]^{2.5}$$

$$H_2:\text{Const} = 1.99 \times 10^8 \quad O_2:\text{Const} = 5.77 \times 10^5$$

Wetted Area:

$$A_{\text{wetted}} = \text{Const} \times \left[ \frac{\sqrt{2F/P_c}}{\sqrt{1 + MR} \cdot S \cdot (NPSH + TSH)^{3/4} \sqrt{N}} \right]^{2.0}$$

$$H_2:\text{Const} = 5.18 \times 10^7 \quad O_2:\text{Const} = 1.23 \times 10^5$$

Port Area:

$$A_{\text{port}} = \text{Const} \times \frac{F\sqrt{N}}{(1 + MR) \sqrt{2 P_c}}$$

$$H_2:\text{Const} = 0.0136 \quad O_2:\text{Const} = 0.01215$$

In addition it was assumed that film boiling takes place in the passages and that the film coefficient,  $h_1$  could be expressed as:

$$h_1 \sim \text{Reynolds}^{0.8} \sim 1/D^{0.2}$$

A chart solution of the plate problem was utilized, necessitating determination of both the Biot ( $h L/k$ ) and Fourier ( $\alpha t/L^2$ ) numbers. Combining the above relationships into an expression for Biot number we have:

$$Bi = \text{Const} P_c^{0.3} F^{0.15}$$

$$H_2:\text{Const} = 0.066 \quad O_2:\text{Const} = 0.226$$

and likewise for Fourier number, solving for time:

$$T_{\text{chill}} = \text{Const} \times F_{\text{chill}} \sqrt{F/P_c}$$

$$H_2:\text{Const} = 0.00306 \quad O_2:\text{Const} = 0.036$$

Assuming chilldown is complete when the wall temperature is within 5 degrees of the saturation temperature, the Biot numbers calculated from the above equation are used in conjunction with Chart 25, of P. J. Schneiders' Temperature Response Charts published by John Wiley and Sons, Inc., New York, 1963, to determine the Fourier number and thus chilldown time.

### III, A, Engine Design Parametric Study (Task IV) (cont.)

The coolant flow rates, and thus weight for chill-down, were determined assuming choaked vapor flow. The actual flow rates may differ somewhat from those calculated. It is felt, however, that the trends predicted represent reality.

Since the reference values of importance to both chill time and coolant weight appear without powers, both time and coolant weight may be directly proportioned to available data.

#### (2) Discussion of Results

Chiltdown time is presented in Figures 117 and 118. The time increases both with thrust and chamber pressure, reflecting the need for larger pumps port size. It should be noted that the oxygen pump chiltdown times are longer than the hydrogen, a result of the much higher hardware mass to wetted surface area ratio given for those pumps.

Figures 119 and 120 show the effect of thrust and chamber pressure on coolant weight used during cooldown. Although coolant weight increases with thrust, it decreases with chamber pressure, reflecting the decrease in port area that occurs as the pump is designed for higher pressure.

Figures 121 and 122 show the effect of pump inlet pressure on chiltdown rate and coolant weight respectively. The primary effect is to change the flow rate, thus heat transfer rate.

Figure 123 shows the effect of pump initial temperature on both chiltdown time and coolant weight. The time and thus coolant weight decrease sharply with initial temperature.