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Part 1

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# THROTTLING AND SCALING STUDY FOR ADVANCED STORABLE ENGINE

Report 68-C-0008-F

Part 1 of Two Parts

S. R. Andrus
H. L. Bishop
R. E. Duckering
J. A. Gibb
A. W. Nelson
V. H. Ransom

AEROJET-GENERAL CORPORATION
Advanced Storable Engine Program Division
Liquid Rocket Operations
Sacramento, California

Final Report AFRPL-TR-68-2, Part 1
January 1968

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Edwards, California



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## FOREWORD

This is the final report documenting the technical accomplishments of the ARES (Advanced Rocket Engine Storable) Throttling-Scaling Design Study Program under Contract F04611-68-C-0008. Included also in this report are the results of an Aerojet-General Corporation-sponsored design of a throttlable-restartable 100K ARES engine which was used as the baseline engine for this design study. The period of performance covered by this report is from 10 July 1967 through 10 October 1967.

The throttling and scaling study was conducted by the Advanced Systems Division of the Liquid Rocket Operations, Aerojet-General Corporation, Sacramento, California under the direction of Mr. R. Beichel. Technical and managerial control was provided by Mr. J. A. Gibb. Mr. S. R. Andrus was the project engineer.

This report contains classified information extracted from the ARES Final Report, Phase I, AFRPL-TR-67-75 dated August 1967, Confidential, Group 4, Contract AF 04(611)-10830.

This report was prepared in two separate parts. Part 1 contains the technical accomplishments while Part 2 (Appendix I) contains ARES Thrust Scaling Data.

This technical report has been reviewed and is approved.

C. D. Penn
Program Manager, Liquid Rocket Division,
Air Force Rocket Propulsion Laboratory
Edwards, California

UNCLASSIFIED ABSTRACT

(U) This is the final report documenting the technical accomplishments of the ARES (Advanced Rocket Engine Storable) Throttling and Scaling Study Program under Contract F04611-68-C-0008. Included also in this report are the results of an Aerojet-General Corporation-sponsored design of a throttlable-restartable 100K ARES engine which was used as the baseline engine for this design study.

(U) Throttlable, restartable ARES (Advanced Rocket Engine Storable) engine designs are presented at 25,000, 100,000, and 500,000 lb rated thrust levels. On the basis of these designs, engine thrust scaling parametric data are presented over a thrust range of 25,000 to 500,000 lb with nozzle expansion ratios of 50:1 and 150:1.

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Part 1

TABLE OF CONTENTS (cont.)

## TABLE LIST

### Part 1



## FIGURE LIST

### Part 1

FIGURE LIST (cont.)

# I.

## INTRODUCTION

(U) This report documents the technical accomplishments of the ARES (Advanced Rocket Engine Storable) Throttling-Scaling Design Study Program, Contract F04611-68-C-0008, from 10 July 1967 through 10 October 1967. A design for a 100K throttlable-restartable ARES prepared under an Aerojet-General-sponsored program was used as the base-line engine design for this design study. This throttlable engine design was evolved from the ARES fixed-thrust engine, designed under Contract AF 04(611)-10830, reported in Reference 1, and described at the end of this section.

(U) The program had five basic objectives (Tasks) as listed and described:

### Task I--Integrated Auxiliary Power Package

(U) Prepare layout designs of an Integrated Auxiliary Power Package (IAPP). The IAPP shall include engine roll control, gimbal actuator for thrust vector control, and propellant tank pressurization systems for the base-line 100K ARES.

### Task II--Low Frequency Analysis

(U) Ascertain the suitability of the base-line 100K throttlable ARES to operate at discrete throttling points and identify system changes to establish satisfactory operation.

### Task III--Design 25K Thrust Engine

(U) Establish the thrust chamber operating pressure value and prepare a layout design of a throttlable-restartable 25K engine based on the established thrust chamber pressure and on the 100K base-line engine cycle, component design, and control approaches.

I, Introduction (cont.)

Task IV--Design 500K Thrust Engine

(U) Prepare a layout design of a throttlable-restartable 500K engine based on the 100K base-line engine cycle, component design, and control approaches.

Task V--Engine Thrust Scaling

(U) Establish engine thrust scaling parametric data over a thrust range of 25K to 500K using design data from the 100K base-line engine and from the 25K and 500K engine designs generated from Tasks III and IV.

(U) The fixed-thrust ARES engine from Contract AF 04(611)-10830, from which the throttlable base-line engine for this contract (F04611-68-C-0008) was derived, is described briefly below to properly orient the reader to the evolutionary process leading into this report.

(C) The fixed-thrust ARES engine is turbopump fed, using a staged combustion cycle, and operates at high thrust chamber pressure (2800 psia). In this staged combustion cycle, the turbopump turbine is driven by oxidizer-rich gas consisting of nearly all of the oxidizer ($N_2O_4$) and sufficient fuel (AeroZINE 50) to raise the temperature of the mixture to 1200°F. The turbine then exhausts through the secondary injector into the thrust chamber where this gas is used to burn the remaining engine fuel to create a maximum energy gas. Pump discharge pressures are approximately 6000 psia and the primary combustor operates at a pressure of 4700 psia.

(U) This engine, shown in Figure I-1, consists of a turbopump assembly, primary combustor assembly, secondary combustor (thrust chamber) assembly, suction valves, and engine control valves. The turbopump assembly houses the pumps, the turbine, and the primary combustor assembly and is the main structural component of the engine.

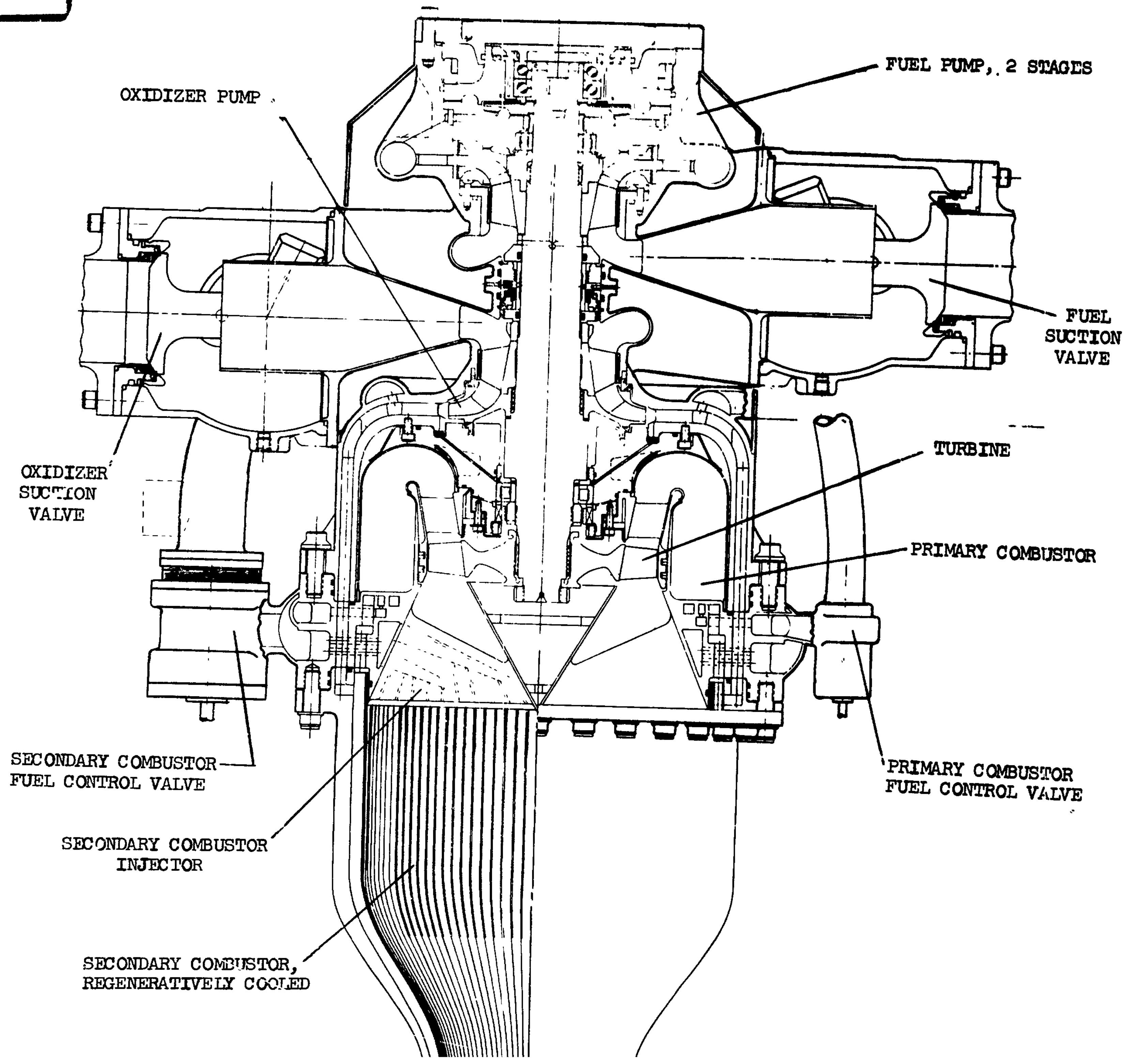
I, Introduction (cont.)

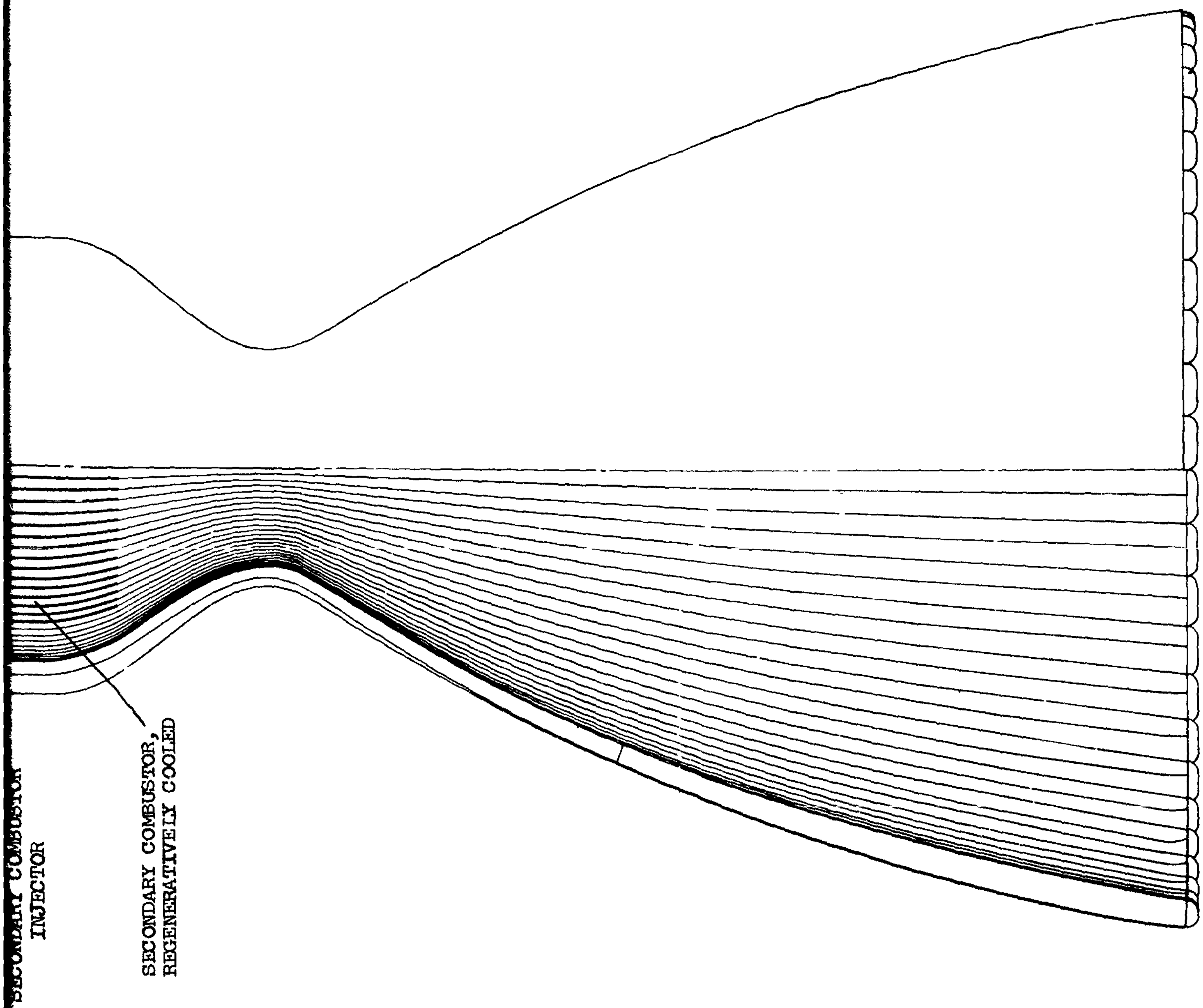
(U) The turbopump is located on top of the thrust chamber; engine thrust is transmitted through the turbopump housing to the airframe. The single-stage turbine, oxidizer pump and fuel pump are all attached to a single shaft, which is oriented along the engine thrust axis and supported in the housing by propellant-lubricated bearings. Rotating speed is 30,000 rpm. Propellants enter the main pumps through inlets located on the side of the turbopump. Hydraulically driven boost pumps (not shown), driven by propellant recirculated from the main pump discharge, are attached to the bottom of the propellant tanks. Suction valves, which are used to isolate the engine from the propellants during storage, are attached to the inlets of the main pumps.

(U) The primary combustor, also located within the TPA housing, utilizes an annular 180-element pentad injector. The primary combustor fuel control valve is mounted at the inlet to the primary injector fuel manifold.

(U) The thrust chamber is regeneratively cooled with $N_2O_4$ from the injector face to the design area ratio of 20:1. $N_2O_4$ film cooling is used in the cylindrical and converging section of the thrust chamber to control the wall surface temperature.

(U) The secondary injector is sandwiched between the turbopump and the thrust chamber; the secondary combustor fuel control valve is located at the inlet to the secondary injector fuel manifold.


OXIDIZER PUMP
FUEL PUMP, 2 STAGES
FUEL SUCTION VALVE
OXIDIZER SUCTION VALVE
TURBINE
PRIMARY COMBUSTOR
SECONDARY COMBUSTOR FUEL CONTROL VALVE
PRIMARY COMBUSTOR FUEL CONTROL VALVE
SECONDARY COMBUSTOR INJECTOR
SECONDARY COMBUSTOR, REGENERATIVELY COOLED




ARES Engine, 100K, Fixed Thrust (u)

Figure I-1

# II.

## SUMMARY

(U) All objectives of the program were accomplished and are summarized in the following paragraphs of this section and are described in detail in their respective sections. In addition to specific contract objectives, improvements were made to the 100K base-line engine based on test results from ARES thrust chamber testing under Contract AF 04(611)-10830. The updated configuration of this 100K base-line engine is described in Section III.

### Task I--Integrated Auxiliary Power Package (IAPP)

(U) Functional requirements of an IAPP including roll control, thrust vector control, and propellant tank pressurization were surveyed for Titan, Apollo Service Module, and Transtage engines. From these requirements, requirements were established for the 100K base-line engine. Approaches to achieving the required IAPP were evaluated and a system concept was selected which offered the greatest compatibility with an engine-vehicle system that has the requirement of being throttlable and restartable. The selected concept includes bipropellant small thrustors for roll control and propellant settling rockets, high pressure fuel-actuated (fuel from engine) gimbal actuators for thrust vector control, and main tank injection for tank pressurization. Detail description of the IAPP system and subsystems is presented in Section IV of this report.

### Task II--Low Frequency Analysis

(U) The cycle stability of the ARES 100K base-line engine incorporating both turbulent and laminar injectors was analyzed. The results indicated a general destabilization as the engine is throttled and becoming unstable at thrust levels between 15 to 20% of full thrust. Cycle stability at the low thrust level can be achieved by adjusting the slope of the oxidizer pump characteristics head-capacity curve and increasing oxidizer injector pressure drop values. Detail description of the low frequency analysis is presented in Section V of this report.

Task III--Design 25K Thrust Engine

(U) Thrust chamber pressure value was established based on engine performance and payload considerations for a space vehicle. Results of this analysis indicated that the operating chamber pressure value of the base-line 100K engine is optimum for the 25K engine. On the basis of this established pressure, and the 100K base-line engine, a 25K engine design was prepared. The engine design included an engine layout, engine envelope, predicted performance and an estimated weight breakdown by major components. Detail description of the 25K engine design is presented in Section VI of this report.

Task IV--Design 500K Thrust Engine

(U) A 500K engine design was prepared on the basis of the 100K base-line engine which includes an engine layout, engine envelope, predicted performance and an estimated weight breakdown by major components. A detail description of the 500K engine is presented in Section VII of this report.

Task V--Engine Thrust Scaling

(U) Engine thrust scaling data were established over a thrust range of 25K to 500K. Scaling data were based on the calculated performance, envelope, and weight values generated from the 100K base-line engine and the 25K and 500K engines designed in this program. Estimated development and

II, Summary (cont.)

production cost data based on 1967 dollars are also given. The technical approach to compiling the thrust scaling data is presented in Section VIII of this report. Thrust scaling data are presented in Part 2 of this report as Appendix I.

# III.

# 100K THROTTLABLE-RESTARTABLE BASE-LINE ENGINE

## A. GENERAL

(U) The throttlable and restartable ARES engine, which is the base-line engine for this throttling and scaling study, is described below. The changes, incorporated to convert the ARES fixed-thrust engine to this throttlable-restartable base-line engine, are also described.

## B. DESCRIPTION

### 1. Performance Rating

(C) The throttlable-restartable ARES base-line engine utilizes the same staged combustion cycle with an oxidizer-rich primary combustor as did the fixed-thrust engine. The design performance ratings of the fixed-thrust and throttlable ARES engines are tabulated below.

| | ARES Fixed-Thrust Engine, Contract AF 04(611)-10830 | ARES Throttlable Engine | |
|---|---|---|---|
| | Sea Level | Vacuum | Sea Level |
| Thrust, lbf | 100,000 | 111,066 | 95,500 |
| Specific impulse, predicted, sec | 285 | 316.5 | 271.8 |
| Specific impulse, efficiency, % | 91.7 | 91.7 | 91.7 |
| Nozzle area expansion (80% bell) | 20:1 | 50:1 | 50:1 |
| Propellants | | $N_2O_4$/AeroZINE 50 | |
| Chamber pressure, psia | | 2800 | |
| Mixture ratio, Injector | | 2.2 | |
| NPSH, fuel, ft | | 20 | |
| NPSH, oxidizer, ft | | 20 | |

III, B, Description (cont.)

(U) The basic change in performance rating of the throttlable engine compared to the original fixed-thrust engine resulted from the increased nozzle expansion ratio. The $I_s$ efficiency (percent of theoretical) and chamber pressure remained the same. The engine basic flows were not changed, since the nominal chamber throat area (21.35 sq in.) was retained.

2. Throttling Design Changes

(U) The Phase I ARES engine undergoing component testing under Contract AF 04(611)-10830 was designed to achieve specified performance at full thrust. As designed, the engine could be throttled to 80% of full thrust while maintaining constant engine mixture ratio by adjusting the primary and secondary combustor fuel-control valves. As part of an Aerojet-General-sponsored design study effort, system changes were defined that would provide the engine with 10:1 throttling and restart capability. The engine system requirements to evolve throttlable-restartable engines and the physical and functional changes to accomplish these requirements are shown in Table III-I. It can be seen from this table that the major changes to make the fixed-thrust engine throttlable were the inclusion of throttlable thrust chamber components and the increase of the first-stage fuel pump discharge pressure. The first-stage fuel pump discharge pressure selected permits throttling at fixed-engine mixture ratio by use of the primary combustor fuel control valve only. A HIPERTHIN* primary injector was incorporated because 10:1 throttling has been demonstrated on this type of injector. The transpiration-cooled chamber was incorporated because this chamber was selected over the regeneratively cooled chamber in the ARES test program. The transpiration-cooled chamber is also better adaptable to throttling than the regeneratively cooled chamber. The suction valves were moved upstream of the boost pumps to provide more positive shutoff for space coast periods. All other desirable features of the fixed-thrust ARES were retained.

*Aerojet General designation denoting High Performance Throttlable Injector.

III, B, Description (cont.)

3. Layout Design

(U) A layout design of the 100K throttlable ARES in shown in Figure III-1. The engine consists of a turbopump assembly, primary combustor assembly, secondary combustor (thrust chamber) assembly, fuel and oxidizer suction valves, and boost pumps. The turbopump assembly includes the main pumps, the turbine, the primary injector and combustor assembly, and the primary combustor fuel control valve, and forms the central structure of the module. The turbopump is mounted on top of the thrust chamber assembly, with thrust being transmitted through the turbopump housing to the gimbal and airframe. The thrust chamber assembly includes the combustion chamber, nozzle, secondary injector, and the secondary combustor fuel control valve. The entire engine is gimbaled from a gimbal assembly which is attached to the engine's thrust takeout pad.

(U) The turbine, oxidizer pump, and fuel pump are on a single shaft which is in line with the engine thrust axis and is supported in the housing by propellant-lubricated bearings. The single-stage turbine is on the lower end of the shaft and exhausts directly into the thrust chamber. The single-stage oxidizer pump is on the center of the shaft, with the two-stage fuel pump on the top end of the shaft. An interpropellant seal is located between the suction sides of the oxidizer pump and first-stage fuel pump to separate the propellants. The seal includes provisions for the introduction of an inert purge fluid if needed. Fuel and oxidizer enter the engine through vertical inlets on each side of the turbopump. In each suction inlet, a hydraulically driven boost pump is mounted with its shaft horizontal. A suction prevalve is integrated upstream of each boost pump.

(U) The primary combustor uses a radial inflow HIPERTHIN injector consisting of a stack of thin platelet washers, with fuel and oxidizer fed between and metered by alternate washers. HIPERTHIN injectors of radial inflow

III, B, Description (cont.)

and axial flow configurations have been tested. The axial flow type has demonstrated high performance with low L* chamber (15 in.) and has been throttled at constant mixture ratio over a 10:1 thrust range. The results of a test series to evaluate throttlability of this injector are shown in Figure III-2.

(C) The platelet injector concept currently being tested on the ARES 100K program was selected for the secondary combustor and is shown in Figure III-3. The fuel is introduced through platelets fabricated from pairs of photoetched plates; the oxidizer-rich turbine exhaust gas passes between the platelets. Injector parameters for the 100K design are as follows:

| | |
|---|---|
| $\dot{w}_F$, lb/sec | 84.1 |
| Injector blade length, total, in. | 240.0 |
| $\dot{w}_F$/blade length, lb/sec/in. | 0.35 |
| $\dot{w}_{gas}$ injector, lb/sec | 248.0 |
| Net gas area, $in.^2$ | 42.5 |
| Average gas flow, lb/sec/$in.^2$ | 5.84 |
| Gross area, $in.^2$ | 72.5 (ref) |
| Blade area, total, $in.^2$ | 30.0 (ref) |

(U) The secondary combustor, or thrust chamber, shown in Figure III-1, is transpiration-cooled to the throat and downstream to the point where static pressure is 30 psia; from that point an extension nozzle is cooled by the coolant-carryover boundary layer and radiation. The basis for selecting 30-psia pressure for the interface between the transpiration-cooled chamber and the nozzle extension is described in Section VI,B. The transpiration-cooled thrust chamber uses platelet washers for metering the required amounts of oxidizer into the thrust chamber wall. Experimental configurations of the platelet injector and the transpiration-cooled chamber are currently being tested at 100K thrust under ARES Contract AF 04(611)-10830. The nozzle extension is similar in design to the nozzle on the Apollo service module engine, which is shown in Figure III-4.

III, B, Description (cont.)

(U) All of the engine's key load-carrying structural parts are cooled by the liquid propellants flowing through the structure. The warm internal components and hot gas (1200°F) are thermally isolated from the structural portion of the housing by the high volume oxidizer flow. The fuel pump circuits are isolated from hot parts; this eliminates heat soak-back to these components on shutdown.

(U) An external envelope drawing of the engine is shown in Figure III-5. The integrated auxiliary power package (IAPP) shown in this figure is discussed in Section IV.

(U) A list showing the parts breakdown and materials considered for this engine design is shown in Table III-II. Included in this table are component environmental temperature values and the type of fluid exposure.

4. Cycle

(C) The ARES engine staged-combustion cycle with its oxidizer-rich primary combustor can best be described with the use of the schematic in Figure III-6. Propellants enter the engine through the suction valves, and are pumped by the 8000-rpm boost pumps to a pressure of 85 psia and 160 psia, fuel and oxidizer, respectively, which is required for the 30,000-rpm main pumps. All of the oxidizer ($N_2O_4$) is then pumped to 4960 psia in the main oxidizer pump with most of it continuing to the primary combustor injector and the remainder flowing to three low-flow circuits. All of the fuel is pumped to 5050 psia in the first-stage fuel pump. Twenty percent of the engine fuel then enters the second-stage fuel pump where it is pumped to 5550 psia and passes through the primary combustor fuel control valve to the primary injector. The oxidizer and fuel enter the primary combustor where they combine hypergolically to form a 1185°F hot gas. This oxidizer-rich hot gas passes through the turbine, and then is exhausted into the thrust chamber. The major portio of the fuel flow from the first-stage pump is ducted through the secondary combustor fuel control valve to the main injector where it is injected into the thrust chamber. This fuel burns with the oxidizer-rich turbine exhaust in the thrust chamber.

(U) In addition to the major flow circuits, the engine has several low-flow circuits. Each boost pump is hydraulically driven by approximately 8% of the propellant that is bled from the main pump discharge and ducted to the boost pump drive turbine, which then exhausts into the boost pump discharge. In the main turbopump, oxidizer for bearing coolant is bled from the pump discharge, passed through the oxidizer bearings, and discharged into the turbine inlet where it provides some turbine cooling. High pressure fuel from the first-stage pump is used to cool the fuel pump bearings. Secondary combustor transpiration coolant flow ($N_2O_4$) is tapped from the oxidizer circuit at the primary injector.

(U) The engine's two fuel control valves perform three functions: (1) propellant phasing is controlled during start and shutdown by sequencing both the primary and secondary fuel control valves, (2) engine throttling is achieved by actuation of the primary combustor fuel control valve (PCFCV) to obtain the desired thrust, and (3) engine mixture ratio is established by the preset open position of the secondary combustor fuel control valve (SCFCV). No oxidizer control valve is required.

### 5. Design Point Operation

(U) The predicted engine and component operating characteristics at design point and at various thrust points down to 10% are shown in Table III-III. Engine throttling performance is discussed in Section III, C. The parameter symbols listed at the left of the columns are defined in Table III-IV. This operating point is based on predicted component performances, on allocated pressure drops or passage friction loss characteristics throughout the system, and on the required thrust chamber transpiration oxidizer coolant flow rate. A computerized steady-state mathematical model of the engine was used to calculate this operating point. The two fuel control valves are adjusted to their noted $K_w$ values to attain the operating point.

6. Engine Start and Shutdown

(U) The engine is started with propellant tank pressure, the predicted start and shutdown sequence being shown graphically in Figure III-7. Initially, all valves are in the closed position. At the start command signal, the oxidizer and fuel suction valves are sequenced open in that order to admit propellants to the engine and assure an oxidizer lead. The primary combustor fuel control valve (PCFCV) is then opened to its 5% open position to admit fuel into the primary combustor. Primary combustor ignition occurs and the turbopump starts to accelerate. When first-stage fuel pump discharge pressure rises to 150 psi, it actuates the secondary combustor fuel control valve (SCFCV) open and secondary ignition occurs. The primary combustor fuel control valve is then sequenced further open to accelerate the engine, at a controlled rate, to steady-state operation at 10% thrust. The primary combustor fuel control valve can then be opened to the position of desired thrust at a rapid, controlled rate such that maximum allowable turbopump acceleration is not exceeded.

(U) Steady-state mixture ratio is maintained by an adjustable stop on the secondary combustor fuel control valve, which is preset at engine acceptance testing. Thrust is set simply by the position of the primary combustor fuel control valve.

III, B, Description (cont.)

(U) Engine shutdown is initiated by the shutdown command signal, which closes the primary combustor fuel control valve. When first-stage fuel pump discharge pressure drops below 150 psi, the secondary combustor fuel valve and both suction valves close.

7. Vacuum Start, Restart and Shutdown

(U) The throttlable-restartable ARES, as a space engine, is designed to start at sea level or in a vacuum, then to shutdown and coast for a few seconds or several weeks, and then to restart. It is assumed for vacuum restart that the vehicle will provide propellants to the engine by settling rockets or some other means. Vacuum starting and restarting of the engine have been studied for two systems of propellant tank pressurization as discussed in Section IV of this report. Engine starting sequence would be as shown in Figure III-7 for the case where sufficient tank pressure exists and vehicle settling rockets are used. The engine starting sequence for the main tank injection system involves the flowing of propellant from the vehicle-mounted accumulators to pressurize the propellant tanks and settle propellants prior to an otherwise typical start.

(U) It is anticipated that the vacuum engine overall start duration may be reduced as compared to the sea-level start plot shown because the downstream pressure in a vacuum is zero during fill. Since all propellants are gaseous before the development of back pressure, propellants will reach the primary combustor sooner and an earlier ignition can be expected. The pressure ratio across the turbopump turbine will be higher resulting in a relatively higher turbine torque, thus making greater utilization of the turbopump to accelerate the engine fill. The existence of vaporized oxidizer in the engine will result in oxidizer vapor entering the fuel manifolds prior to fuel fill. This condition exists in all engines started at altitude, including Apollo and Transtage engines which use the same propellants. Neither of these engines require altitude purging.

III, B, Description (cont.)

(U) Propellant freezing can occur if the propellant expands over a very large pressure ratio from a small opening. This occurs when the valves are first opened; however, experience has shown that the amount of frozen propellants formed during start are insignificant because the flow rate of propellant causes a rapid rise in back pressure. Ignition of propellants in the primary combustor at high mixture ratio will remove any frozen oxidizer from the secondary combustor (thrust chamber) injector and transpiration coolant washers prior to fuel flow to the secondary combustor.

(U) The vacuum shutdown of the engine will be essentially the same as the sea-level case shown in Figure III-7 except that the propellants will vaporize and leave the engine without requiring a purge. The high vapor pressure of the $N_2O_4$ will result in its dissipation first. This early dissipation due to vaporization will cool the warm turbine rotor and primary combustor walls, to minimize engine heat soak-back. For sea-level testing, the ARES thrust chamber utilizes a shutdown purge in the oxidizer system to clear the system of oxidizer followed by a purge of the fuel circuits. The vacuum shutdown procedure described above would be similar to the current sea-level test experience. The fuel will eventually leave the engine without re-opening the fuel control valves. This shutdown sequence is also consistent with a minimum tailoff impulse since most residual propellant leaves the engine without burning.

(U) Engine restarting after a short space coast period does not require the engine to be completely drained and cold at the time of restart; however, fuel must not be introduced against parts that are hot enough to cause spontaneous decomposition. The secondary injector is the only place where this can occur. The maximum temperature predicted for the secondary injector after shutdown is approximately 700°F if no cooling benefit is derived from the propellants expelled from the engine. Laboratory test experience at Aerojet-General has shown that a temperature in excess of 1400°F is required to initiate the decomposition of AeroZINE 50 under these conditions. Therefore, no problem is foreseen in fuel decomposition on restart.

C. ENGINE THROTTLING PERFORMANCE

(U) The actual mechanism by which the primary combustor fuel valve controls the thrust is as follows. Increasing the resistance in this valve reduces the fuel flow to the primary combustor. This in turn reduces turbine temperature because of the higher mixture ratio and, to a lesser extent, reduces the turbine mass flow; the reduction in turbine drive energy results in decreased turbopump speed, pump discharge pressures, propellant flow rate, and thrust. The engine maintains nearly constant engine mixture ratio during throttling, because the designed relationship between fuel and oxidizer pump heads almost exactly compensates for the other factors that influence engine mixture ratio.

(U) Some of the engine performance parameters are plotted over a 10:1 throttle range in Figure III-8. Vacuum specific impulse drops at the lower thrust levels mainly because of the increase in recombination (kinetic), friction and combustion losses. (A breakdown of these and other losses in the thrust chamber is included under Performance Scaling in Section VIII,B.) Thrust chamber pressure drops nearly linearly with thrust as the engine is throttled.

(U) A comprehensive tabulation of engine and component performance and operating parameters at rated thrust and several throttle points down to 10% thrust is shown in Table III-III. Symbols are defined in Table III-IV. Referring to Table III-III, some of the more important engine and component requirements and characteristics are explained in the following paragraphs.

(C) On Sheet 2 of Table III-III in the group of secondary combustor parameters, WOFC and WFC/WT indicate the oxidizer film coolant flow and its ratio to total flow. At rated thrust, the coolant flow value is 23.2 lb/sec, or 6.6% of the total engine flow. This value corresponds to an $I_s$ performance loss of 13.7 sec for a conical chamber, and was selected to meet the specified engine performance level of 91.7% of theoretical (see Table VIII-I for the performance loss breakdown). This transpiration coolant flow value gives a calculated wall temperature of 1625°F for the cylindrical chamber configuration now undergoing testing. The conical chamber was adopted to achieve better compatibility between the injector and the cooled chamber. The ratio of coolant flow to engine flow is kept constant during throttling and provides a slight reduction in wall temperature at throttled conditions, on the basis of preliminary heat analysis. The analytical means of holding this constant percentage in the computer was with the expedient of a variable valve to represent the turbulent/ laminar flow characteristic of the entire transpiration circuit. The equivalent flow factor for this circuit is shown as KWFCV (Sheet 1 of Table III-III); it decreases approximately 50% and defines the criteria required to maintain a constant percentage of coolant during throttling.

(U) This variation in $K_w$ can be designed into a transpiration chamber, without the aid of a valve, by proportioning the appropriate amount of laminar-flow ΔP versus turbulent-flow ΔP. In fact, the fixed-thrust transpiration chambers with their 12 coolant flow compartments in the current ARES test program (Contract AF 04(611)-10830) have approximately the desired characteristic, even though they were not designed for a specific throttling characteristic. Predicted coolant flow characteristics are shown in Figure III-9 for the fixed-thrust chamber when exposed to predicted engine pressure values over the throttling range, where the solid line in the figure represents a constant coolant to engine flow ratio. Each compartment flow and/or the total coolant flow could be adjusted by proper design criteria to provide the desired throttling characteristic.

(U) The ΔP's assumed for the three liquid injector circuits in the engine are shown on Sheet 1 of Table III-III. (DPFJSC, DPOJPC, and DPFJPC). Each ΔP is relatively low to accommodate a laminar flow (low velocity), platelet injector design. The laminar flow characteristic enhances the throttlability of the engine by sustaining a reasonable ratio of ΔP injector to chamber pressure (see DP/PSF, DP/PPO, and DP/PPF on Sheet 2 of the table) at low flow, throttled condition. If additional hardness is desired in the oxidizer circuit, substantial power margin is available in the turbine to accommodate future increase of the pump pressures.

(U) On Sheet 3 of Table III-III in the group of turbopump parameters, it can be seen that the pump flow parameter (Q/N) decreases to only 50% of design; this occurs at the low shaft speed of 7040 rpm which is 23% of design speed. Pump off-design operation has been limited to the negative slope portion of their H-Q curves.

(U) Turbine and pump efficiencies (see ETAT, ETAOM, ETAFM1 and ETAFM2 on Sheet 3 of the table) are well within Aerojet and industry demonstrated values for the conditions of turbine velocity ratio (U/C-GT on Sheet 3) and pump specific speeds and flows (NSO, NSF-1, NSF-2, QOSM, QFSM1, and QFSM2 on Sheet 3).

## D. WEIGHT BREAKDOWN

(U) Calculated dry and wet weights and gimbal moment of inertia values for the 100K base-line engine are shown by component in Table III-V. Values for a lower-weight production prototype engine are shown in Table III-VI. The lower weight of this production prototype engine is achieved by utilizing two interface joints between the thrust chamber and the turbopump in place of the three joints shown in Figure III-1, which is a development engine design. Other weight reductions could also be achieved with a detailed weight reduction effort.

(U) The throttlable-restartable ARES engine is characteristically heavier than the fixed-thrust version described in Section I from Contract AF 04(611)-10830. This heavier weight results from the relatively higher fuel pump pressure required for deep throttling, the radial inflow HIPERTHIN primary combustor injector desirable for throttling, and the integrated suction valve boost/pump assembly which improves restart. The total additive weight from these items is 115 lb.

(U) Also included in this summary is the calculated weight for the four valve actuators, which adds 27 lb, and the gimbal, which adds 19 lb. The propellant inlets for this engine are oriented vertically and integrated with the suction valves, which adds 41 lb but reduces the vehicle interface requirements and the vehicle suction line weight. This arrangement also reduces the amount of propellant that is trapped in the engine at the end of each firing, reducing the shutdown impulse and the loss of propellants in a multiple restart mission. The total weight of these additive items is 87 lb. The total of all of the items above amounts to 202 lb, which is included in the weight summary of Table III-V.

(U) The difference between the weights of engines with 50:1 and 150:1 nozzle extensions at a given thrust is relatively small and amounts to only 14 lb for the 100K size. The reason for this is that the contours of the 80% bell and the RAO nozzle contour are considerably different immediately downstream of the throat in the transpiration-cooled region. The 50:1 bell nozzle has a smaller included angle and is much longer in the downstream portion up to the point where the static pressure is 30 $lb/in.^2$; whereas the 150:1 RAO contour flares out more rapidly and obtains the required pressure ratio to get 30 psia in a shorter distance. Consequently, the transpiration-cooled section of the expansion nozzle is relatively light on the 150:1 nozzle and almost compensates for the larger overall size of the nozzle. Thus, the difference in area ratio between the 50:1 bell and the 150:1 RAO has little weight effect.

## TABLE III-I

### ENGINE CHANGES FOR THROTTLING CAPABILITY

| SYSTEM REQUIREMENTS \ ENGINE CHANGES | Increase first-stage fuel pump discharge pressure | Adjust pump H-Q slope to system requirement | Utilize Hiperthin primary injector | Utilize transpiration TCA wall cooling | Adjust laminar-turbulent resistance of TCA transpiration system | Adjust turbine pressure ratio | Relocate engine suction valves upstream of boost pumps | Engine mounted integrated boost pump and poppet suction valves | Relocate PC injector to provide self drain through TPA turbine |
|---|---|---|---|---|---|---|---|---|---|
| Throttle range to 10:1 | X | | X | | | | | | |
| Throttle engine at fixed mixture ratio with single valve | X | X | | | X | | | | |
| Maintain engine stiffness | X | X | X | | | | | | |
| Maintain combustor stability | X | | X | | | | | | |
| Maintain TCA wall compatibility | | | | X | X | | | | |
| Maintain turbine temperature under 1250°F | | | | | | X | | X | |
| Limit pump operation to negative slope portion of H-Q curve | | X | | | | | | | |
| Eliminate check valves from boost pump turbine drive line | | | | | | | X | | |
| Minimize propellant wet volume downstream of engine start-stop valves | | | | X | | | | X | |
| Provide aft direction self drain of trapped engine propellant | | | | | | | | | X |

TABLE III-II

MATERIAL LIST, ENGINE MODULE ASSEMBLY, 100K ARES

| Part | Material Surface Environment (Wall Temp. °F) Fuel | Oxid | Gas | Material (Alternates Shown in Parentheses) |
|---|---|---|---|---|
| 1. Turbopump Housing | 200°F | 200°F | 600°F | INCO 718 |
| 2. Turbopump Shaft | 77° | 600° | 1000° | INCO 718 (AM 355) |
| 3. Turbine Nozzle | - | - | 1200° | Haynes 25 (713 C) |
| 4. Turbine Rotor | - | 600° | 1200° | Forged Udimet 700 (Waspalloy) |
| 5. Turbine Shaft Labyrinth | - | 500° | - | AM 355 |
| 6. Turbine Disc Nut | - | - | 1000° | AM 355 |
| 7. Turbine Exhaust Flow Distribution Plate | - | - | 1200° | Udimet 700 (Waspalloy) |
| 8. Thrust Takeout Plate | 77° | - | - | AM 355 |
| 9. Fuel Pump, 1st Stage Impeller | 77° | - | - | 17-4PH Cast, LC-1 Flame Plated |
| 10. Fuel Pump, 1st Stage Backplate | 77° | - | - | AM 355, LC-1 Flame Plated Land |
| 11. Fuel Pump, 1st Stage Inducer | 77° | - | - | Titanium 6Al-4Va |
| 12. Fuel Pump, 1st Stage Inducer Hsg | 77° | - | - | SS 347, LC-1 Flame Plated Land |
| 13. Fuel Pump, 2nd Stage Impeller | 100° | - | - | AM 355 |
| 14. Fuel Pump, 2nd Stage Backplate & Retaining Nut | 100° | - | - | AM 355 |
| 15. Fuel Pump Labyrinth Inserts | 100° | - | - | Pressure Relieved Kynar |
| 16. Fuel Pump Radial Bearing | 200° | - | - | SS 440C Rollers & Races, Glass Filled Teflon Cages |
| 17. Fuel Pump Thrust Bearing Sleeve, Retainers, and Bolt | 100° | - | - | AM 355 |
| 18. Fuel Pump Thrust Bearings | 200° | - | - | SS 440C Races, K5H Balls, Glass Filled Teflon Cages |

TABLE III-II (cont.)

| Part | Material Surface Environment (Wall Temp. °F) Fuel | Oxid | Gas | Material (Alternates Shown in Parentheses) |
|---|---|---|---|---|
| 19. Fuel Bearing Shaft Retaining Nut | 77° | - | - | AM 355 |
| 20. Interpropellant Seal | 77° | 77° | - | Carbon Stationary Ring, LC-1 Flame Plated, 440C Rotating Ring |
| 21. Oxid Pump Impeller | - | 200° | - | 17-4 PH Cast, LC-1 Flame Plated Land |
| 22. Oxid Pump Impeller Hydrostatic Seal | - | 77° | - | LC-1 Flame Plated SS347 |
| 23. Oxidizer Pump Inducer | - | 77° | - | AM 355 |
| 24. Oxidizer Pump Inducer Nut | - | 77° | - | AM 355 |
| 25. Oxid Pump Radial Bearing | - | 200° | - | SS 440C Rollers & Races, Glass Filled Teflon Cages |
| 26. Oxid Pump Radial Bearing Retaining Nut | - | 500° | - | AM 355 |
| 27. Oxid Pump Inducer Insert | - | 77° | - | Graphite Filled Vespo SP-21 |
| 28. Fuel Boost Pump Inlet Housing | 77° | - | - | SS 347 |
| 29. Fuel Boost Pump Discharge Housing | 77° | - | - | Al A356 Cast |
| 30. Fuel Boost Pump Impeller | 77° | - | - | Al 7075-T73 |
| 31. Fuel Boost Pump Impeller Nut | 77° | - | - | Al 7075-T6 |
| 32. Fuel Boost Pump Shaft | 77° | - | - | AM 355 |
| 33. Fuel Boost Pump Bearing Housing | 77° | - | - | AM 355 |
| 34. Fuel Boost Pump Bearing | 200° | - | - | SS 440C Rolling Elements & Races, Glass Filled Teflon Cages |
| 35. Fuel Boost Pump Bearing Retaining Nuts | 77° | - | - | SS 347 |
| 36. Fuel Boost Pump Turbine Rotor | 77° | - | - | AM 355 |
| 37. Fuel Boost Pump Turbine Stators | 77° | - | - | AM 355 |

TABLE III-II (cont.)

| Part | Material Surface Environment (Wall Temp. °F) Fuel | Oxid | Gas | Material (Alternates Shown in Parentheses) |
|---|---|---|---|---|
| 38. Oxidizer Boost Pump | | 77° | - | Same materials as Fuel Boost Pump (Items 28-37) |
| 39. Fuel Suction Valve Body | 77° | - | - | SS-17-4PH |
| 40. Fuel Suction Valve Poppet | 77° | - | - | SS-17-4PH (AM 350) |
| 41. Fuel Suction Valve Springs | 77° | - | - | SS-17-7PH |
| 42. Fuel Suction Valve Poppet Seal | 77° | - | - | Teflon |
| 43. Fuel Suction Valve Static Seals | 77° | - | - | Teflon |
| 44. Fuel Suction Valve Shear Seal (Optional, Long Term Storage) | 77° | - | - | SS304L |
| 45. Oxid Suction Valve | - | 77° | - | Same materials as Fuel Suction Valve (Items 39-44) |
| 46. Primary Fuel Valve Body | 100° | - | - | Integral part of primary injector |
| 47. Primary Fuel Valve Shaft | 100° | - | - | AM 350 (17-4PH) |
| 48. Primary Fuel Valve Sleeve | 100° | - | - | SS-17-4PH (AM 350) |
| 49. Primary Fuel Valve Bearings | 100° | - | - | 440C |
| 50. Primary Fuel Valve Dyn. Seals | 100° | - | - | Teflon |
| 51. Primary Fuel Valve Static Statics | 100° | - | - | AS 4004 (Butyl) |
| 52. Secondary Fuel Valve | 200° | - | - | Same materials as Primary Fuel Valve except: valve body is integral part of Secondary Injector |
| 53. Primary Fuel Feed Line | 100° | - | - | Mil-T-6845 304 |
| 54. Secondary Fuel Feed Line | 100° | - | - | Mil-T-6845 304 |
| 55. Fuel Boost Pump Turbine Feed Line | 100° | - | - | Mil-T-6845 304 |
| 56. Oxid Boost Pump Turbine Feed Line | 100° | - | - | Mil-T-6845 304 |
| 57. Primary Injector | 200° | 200° | 1200° | SS 347 |

TABLE III-II (cont.)

| | Part | Material Surface Environment (Wall Temp. °F) Fuel | Oxid | Gas | Material (Alternates Shown in Parentheses) |
|---|---|---|---|---|---|
| 58. | Adapter, Turbopump/Combustors | - | - | 1200° | INCO 718 (Hast X) |
| 59. | Primary Combustor Liner | - | - | 1200° | Hast X (René 62, INCO 718) |
| 60. | Secondary Injector | 600° | - | 1200° | SS 347 |
| 61. | Secondary Combustor Washers | - | 1625° | - | SS 347 (Nickel) |
| 62. | Secondary Combustor Housing | - | 300° Soak-back | - | Maraging Steel - 18% Nickel (Titanium) |
| 63. | Nozzle Extension, First Section | - | - | 2200° | Columbium (10 HF, 1 Ti) |
| 64. | Nozzle Extension, Second Section | - | - | 1100° | Titanium (5 Al, 2.5 Sn) |

TABLE III-III

THROTTLING PERFORMANCE, 100K ARES (u)

| [illegible] | 100% F CASE 1 | 75% F CASE 2 | 50% F CASE 3 | 37.5% F CASE 4 | 25% F CASE 5 | 20% F CASE 6 | 15% F CASE 7 | 10% F CASE 8 |
|---|---|---|---|---|---|---|---|---|
| F | [illegible] | [illegible] | [illegible] | [illegible] | 27817.05640 | 22237.34961 | 16620.88950 | [illegible] |
| PCSC | 2799.99997 | 2100.24261 | 1401.40048 | 1051.63223 | 703.91291 | 564.23190 | 424.66772 | 284.63477 |
| MR-ENG | 2.42686 | 2.43726 | 2.43379 | 2.42136 | 2.40423 | 2.39706 | 2.42689 | 2.57159 |
| IS | 316.20216 | 315.00113 | 313.52773 | 312.50895 | 310.67545 | 309.82823 | 307.92838 | 302.78642 |
| W-ENG | 350.94994 | 264.71243 | 177.51248 | 133.46335 | 89.47974 | 71.77316 | 54.20379 | 36.77511 |
| WOT | 248.53823 | 187.69531 | 125.83686 | 94.46991 | 63.21524 | 50.65951 | 38.38612 | 26.47999 |
| WFT | 102.41192 | 77.01085 | 51.70402 | [illegible] | 26.29338 | 21.13405 | 15.81699 | [illegible] |
| NT | 29999.98584 | 24509.11841 | 18648.90576 | 15488.41687 | 12059.48218 | 10545.11145 | 8906.09119 | 7040.03552 |
| TTIT | 1183.79366 | 973.95750 | 744.58759 | 619.14153 | 480.65434 | 454.86489 | 421.68653 | 368.60951 |
| RPT | 1.50000 | 1.40983 | 1.31917 | 1.27107 | 1.22009 | 1.19819 | 1.17518 | 1.14933 |
| PODTM | 4959.77515 | 3479.75107 | 2150.38809 | 1547.26973 | 989.19426 | 776.96892 | 572.72816 | 375.85987 |
| DPOH1 | 49.97809 | 28.68552 | 12.96173 | 7.31837 | 3.27855 | 2.10456 | 1.20676 | .57283 |
| DPORG | 49.99976 | 28.69434 | 12.96033 | 7.31377 | 3.27412 | 2.10098 | 1.20535 | .57390 |
| DPOH2 | 50.00647 | 28.69070 | 12.95618 | 7.31091 | 3.27267 | 2.10002 | 1.20479 | .57363 |
| DPOJPC | 199.51154 | 155.33307 | 106.68791 | 80.85899 | 54.55013 | 43.81783 | 33.31223 | 23.07445 |
| PCPC | 4610.27930 | 3238.34744 | 2004.82195 | 1444.46768 | 924.81880 | 726.84553 | 535.79903 | 351.06506 |
| PFDTM1 | [illegible] | 3624.72647 | 2156.93021 | [illegible] | 971.16956 | 757.77448 | 552.69997 | 356.64542 |
| DPSCVI | 104.06677 | 62.58630 | 30.18283 | 17.83939 | 8.44511 | 5.53825 | 3.1539 | 1.36641 |
| DPFSCV | 1655.91580 | 991.90726 | 476.87932 | 281.52615 | 133.15479 | 87.29803 | 49.70358 | 21.52985 |
| DPSCVO | 105.17450 | 62.98425 | 30.27496 | 17.87152 | 8.45230 | 5.54134 | 3.15495 | 1.36660 |
| DPFJSC | 299.86606 | 243.24866 | 175.65009 | 137.29797 | 95.83567 | 78.03648 | 59.12809 | 39.10709 |
| PCFACE | 2885.00000 | 2164.00000 | 1443.94301 | 1083.55679 | 725.28170 | 581.36037 | 437.55942 | 293.27547 |
| PFDTM2 | 5555.58765 | 4007.07770 | 2493.62054 | 1789.93076 | 1134.25877 | 885.52163 | 646.18475 | 416.67546 |
| DPFPCV | 499.99921 | 502.29871 | 351.85965 | 256.29875 | 158.65073 | 120.55981 | 83.71251 | 50.12529 |
| DPPCVO | 49.99908 | 21.64407 | 6.83258 | 3.07364 | 1.02628 | .58473 | .28181 | .09554 |
| DPFJPC | 295.30548 | 198.81027 | 115.03273 | 78.34889 | 46.03835 | 34.99419 | 24.47266 | 14.35952 |
| PCPC | 4610.27930 | 3238.34744 | 2004.82195 | 1444.46768 | 924.81880 | 726.84553 | 335.79903 | 351.06506 |
| PTIT | 4485.00000 | 3150.34891 | 1950.34311 | 1405.21587 | 899.68787 | 707.09430 | 521.23928 | 341.52526 |
| PTET | 3039.37921 | 2260.29251 | 1494.30356 | 1115.81560 | 742.97144 | 594.21120 | 446.23633 | 298.30809 |
| PGJT | 3009.07071 | 2241.31439 | 1484.33107 | 1109.41182 | 739.43971 | 591.64870 | 444.48010 | 297.29919 |
| PCFACE | 2885.00000 | 2164.00000 | 1443.94301 | 1083.55679 | 725.28170 | 581.36037 | 437.55942 | 293.27547 |
| KWFSCV | 2.14467 | 2.14467 | 2.14467 | 2.14467 | 2.14467 | 2.14467 | 2.14467 | 2.14467 |
| KWFPCV | .93048 | .61085 | .41009 | .32227 | .23669 | .20495 | .17075 | .12848 |
| KWOPCV | 26.07429 | 26.07429 | 26.07429 | 26.07429 | 26.07429 | 26.07429 | 26.07429 | 26.07429 |
| KWFCV | .42286 | .39824 | .36165 | .33383 | .29459 | .27342 | .24720 | .21356 |
| KWRGV | | | | | | | | |

**NOTE:** Values less than unity have their decimal location noted by prefix. Example: "-5" indicates decimal point is 5 places to the left of first digit. No prefix and no decimal point indicate decimal precedes first digit.

## TABLE III-III (cont.)

| | 100% F CASE 1 | 75% F CASE 2 | 50% F CASE 3 | 37.5% F CASE 4 | 25% F CASE 5 | 20% F CASE 6 | 15% F CASE 7 | 10% F CASE 8 |
|---|---|---|---|---|---|---|---|---|
| F | 110971.12091 | 83384.71387 | 55655.08846 | 41788.49219 | 27817.05640 | 22237.34961 | 16690.88550 | 11135.00330 |
| DP/PSF | .10394 | .11241 | .12165 | .12671 | .13214 | .13423 | .13513 | .13335 |
| DP/PPO | .04328 | .04797 | .05322 | .05598 | .05898 | .06028 | .06217 | .06573 |
| DP/PPF | .06405 | .06139 | .05738 | .05424 | .04978 | .04815 | .04568 | .04090 |
| PCSC | 2799.99997 | 2100.24261 | 1401.40048 | 1051.63223 | 703.91291 | 564.23190 | 424.66772 | 284.63477 |
| MRSC | 2.20000 | 2.20976 | 2.20674 | 2.19499 | 2.17868 | 2.17208 | 2.20012 | 2.33829 |
| AE/AT | 50.00000 | 50.00000 | 50.00000 | 50.00000 | 50.00000 | 50.00000 | 50.00000 | 50.00000 |
| ETAC | .96247 | .96052 | .95864 | .95766 | .95671 | .95632 | .95587 | .95550 |
| ETAN | .95104 | .94986 | .94715 | .94449 | .93975 | .93665 | .93221 | .92532 |
| C*SC | 5480.44446 | 5458.01959 | 5422.95862 | 5412.58582 | 5403.77332 | 5400.05927 | 5381.73749 | 5316.63899 |
| CF | 1.85633 | 1.85960 | 1.86014 | 1.85765 | 1.85095 | 1.84598 | 1.84091 | 1.83233 |
| WGJSC | 245.07470 | 183.16362 | 121.37972 | 90.52572 | 60.11693 | 48.04106 | 36.28007 | 24.90782 |
| WFJSC | 82.64199 | 64.01555 | 44.40720 | 34.12257 | 23.46671 | 19.00056 | 14.33594 | 9.43479 |
| WOFC | 23.23307 | 17.52699 | 11.75395 | 8.83691 | 5.92497 | 4.75195 | 3.58711 | 2.43449 |
| WFC/WT | .06620 | .06621 | .06621 | .06621 | .06622 | .06621 | .06618 | .06620 |
| WORG | 223.39591 | 168.64908 | 112.96678 | 84.72823 | 56.60737 | 45.31943 | 34.31001 | 23.66387 |
| DPFJSC | 299.86606 | 243.24866 | 175.65009 | 137.29797 | 95.83567 | 78.03648 | 59.12809 | 39.10709 |
| DPOFC | 2109.79709 | 1350.82294 | 736.02588 | 488.31912 | 282.00280 | 210.63245 | 146.85368 | 90.65226 |
| DPORG | 49.99976 | 28.69434 | 12.96033 | 7.31377 | 3.27412 | 2.10098 | 1.20535 | .57390 |
| DTORG | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 |
| D*FJSC | 55.81637 | 55.94488 | 56.03026 | 56.05598 | 56.07095 | 56.07546 | 56.07439 | 56.07640 |
| D*OFC | 89.28149 | 89.4783[illegible] | 89.55243 | 89.54214 | 89.51030 | 89.48876 | 89.47041 | 89.45314 |
| D*ORG | 91.60972 | 90.97688 | 90.37414 | 90.08944 | 89.82781 | 89.72341 | 89.63647 | 89.55887 |
| MRPC | 11.30001 | 12.97770 | 15.48165 | 17.31721 | 20.02618 | 21.24187 | 23.16590 | 27.44196 |
| WOJPC | 223.39591 | 168.64908 | 112.96678 | 84.72823 | 56.60737 | 45.31943 | 34.31001 | 23.66387 |
| WFJPC | 19.76953 | 12.99530 | 7.29682 | 4.89272 | 2.82667 | 2.13349 | 1.48106 | .86232 |
| D*OJPC | 91.32734 | 90.76811 | 90.23810 | 89.98908 | 89.76192 | 89.67107 | 89.59711 | 89.5289[illegible] |
| D*FJPC | 56.22080 | 56.14999 | 56.10677 | 56.08906 | 56.07829 | 56.07482 | 56.07325 | 56.073[illegible] |
| POT | 37.14000 | 37.14000 | 37.14000 | 37.14000 | 37.14000 | 37.14000 | 37.14000 | 37.14000 |
| PFT | 17.51000 | 17.51000 | 17.51000 | 17.51000 | 17.51000 | 17.51000 | 17.51000 | 17.51000 |
| NPSPOB | 12.32524 | 15.42207 | 17.68499 | 18.49127 | 19.06631 | 19.23313 | 19.36065 | 19.48076 |
| NPSPFB | 7.87835 | 10.85374 | 12.99186 | 13.75348 | 14.30894 | 14.47480 | 14.60986 | 14.71156 |
| NPSPOM | 140.32589 | 114.89201 | 84.69921 | 68.70476 | 52.43550 | 45.69152 | 38.86765 | 31.96481 |
| NPSPFM | 79.38197 | 65.47814 | 49.30939 | 40.76928 | 32.21791 | 28.70059 | 25.14813 | 21.86553 |

TABLE III-III (cont.)

| | 100% F CASE 1 | 75% F CASE 2 | 50% F CASE 3 | 37.5% F CASE 4 | 25% F CASE 5 | 20% F CASE 6 | 15% F CASE 7 | 10% F CASE 8 |
|---|---|---|---|---|---|---|---|---|
| F | [illegible] | 83384.71387 | 55695.08845 | 41700.49219 | 27817.05640 | 22237.34961 | 16690.88550 | 11135.00330 |
| ETAT | .75251 | .75483 | .75544 | .75308 | .74457 | .73672 | .72401 | .70485 |
| WTI | 243.16545 | 181.64438 | 120.26360 | 89.62095 | 59.43403 | 47.45292 | 35.79197 | 24.52620 |
| U/C-GT | .57084 | .55468 | .52786 | .50711 | .47545 | .45675 | .4[illegible]349 | .40610 |
| SHPT | [illegible] | 5187.92456 | 2196.07315 | 1219.26901 | 551.34734 | 360.87043 | 211.82208 | 100.61366 |
| SHPOW | 5605.78693 | 2974.89731 | 1257.41791 | 698.36266 | 315.55230 | 205.97629 | 120.54671 | 57.47976 |
| SHPFN1 | 4034.81987 | 2138.83929 | 905.73206 | 504.49001 | 228.96583 | 149.84857 | 87.67490 | 41.47088 |
| SHPFN2 | 150.06828 | 83.41859 | 33.97315 | 18.42054 | 8.18700 | 5.36830 | 3.17991 | 1.55791 |
| POSTN | 159.19666 | 133.45985 | 103.01003 | 86.90087 | 70.51531 | 63.72723 | 56.84384 | 49.86876 |
| PODTN | 4959.77515 | 3479.75107 | 2150.38809 | 1547.26973 | 989.19426 | 776.96892 | 572.72816 | 375.85987 |
| HOWNC | 7735.18115 | 5389.84479 | 3296.18570 | 2351.11426 | 1478.92296 | 1148.21532 | 830.55935 | 524.73406 |
| OOSN | 1380.56190 | 1035.63263 | 704.24910 | 535.33562 | 365.67800 | 296.86575 | 228.85861 | 161.65018 |
| HOW/N2 | -5 85946536 | -5 89726530 | -5 94777436 | -5 98007580 | -4 10169234 | -4 10325735 | -4 10471198 | -4 10587405 |
| Q/QCOM | 1.00863 | .93976 | .83987 | .76870 | .67439 | .62611 | .57150 | .51067 |
| ETAOM | .67970 | .67959 | .66695 | .65306 | .62107 | .59969 | .57136 | .53483 |
| NSO | 1341.60854 | 1253.85834 | 1137.64780 | 1061.36525 | 966.98335 | 921.11479 | 870.84895 | 816.41048 |
| SOM | 18978.19727 | 15720.36536 | 12400.46875 | 10506.10535 | 8280.41516 | 7233.66083 | 6056.24298 | 4659.19165 |
| D*OSN | 89.36878 | 89.40164 | 89.42406 | 89.43247 | 89.44107 | 89.44396 | 89.44948 | 89.45718 |
| PFSTN1 | 82.21128 | 68.28024 | 52.08643 | 43.53434 | 34.97104 | 31.44855 | 27.89168 | 24.30368 |
| PFDTN1 | 5050.02313 | 3524.72647 | 2156.93021 | 1538.09183 | 971.16956 | 757.77448 | 552.69997 | 356.64542 |
| HFNNC1 | 12761.85132 | 8882.82642 | 5404.46552 | 3837.92584 | 2403.03937 | 1862.58856 | 1347.71507 | 853.08259 |
| QFSN1 | 877.34677 | 665.91604 | 454.53913 | 348.09841 | 240.85467 | 197.11771 | 151.86007 | 104.55882 |
| HF1/N2 | -4 14179848 | -4 14787535 | -4 15539822 | -4 15998619 | -4 16523558 | -4 16749991 | -4 16991190 | -4 17212397 |
| Q/QDF1 | .98357 | .91379 | .81974 | .75588 | .67171 | .62868 | .57347 | .49951 |
| ETAFN1 | .63030 | .62816 | .61613 | .60163 | .57433 | .55670 | .53040 | .48873 |
| NSF-1 | 740.06779 | 691.23248 | 630.77505 | 592.63282 | 545.30013 | 522.18737 | 493.41282 | 456.04945 |
| SFN1 | 16467.05493 | 13543.36230 | 10533.09265 | 8829.72058 | 6823.33093 | 5888.67365 | 4818.50684 | 3546.73975 |
| D*FSN1 | 56.05492 | 56.06536 | 56.07446 | 56.07868 | 56.08291 | 56.08478 | 56.08627 | 56.08826 |
| PFSTN2 | 4708.27094 | 3329.44113 | 2067.30972 | 1486.21825 | 946.87284 | 741.72217 | 543.36437 | 352.37083 |
| PFDTN2 | 5555.58765 | 4007.07770 | 2493.62054 | 1789.93076 | 1134.25877 | 885.52163 | 646.18475 | 416.67546 |
| HFN2 | 2160.14523 | 1731.12361 | 1091.27489 | 778.19993 | 480.56744 | 368.90047 | 263.86979 | 165.06884 |
| QFSN2 | 166.84950 | 113.33755 | 68.16526 | 49.04911 | 32.58487 | 27.05426 | 21.84439 | 16.89987 |
| HF2/N2 | -5 24001636 | -5 28815587 | -5 31378158 | -5 32439722 | -5 33044335 | -5 33174688 | -5 33267134 | -5 33305457 |
| Q/QDF2 | .99888 | .83033 | .65605 | .56827 | .48481 | .46030 | .44008 | .43071 |
| ETAFN2 | .55012 | .53749 | .49916 | .47183 | .43508 | .42274 | .41204 | .40693 |
| NSF-2 | 1222.98569 | 972.22910 | 810.93182 | 736.21435 | 6[illegible]0.68864 | [illegible]51.60906 | 635.79173 | 628.44570 |
| NT | 29999.98584 | 24509.11841 | 18648.90576 | 15488.41687 | 12059.48218 | 10545.11145 | 8906.09119 | 7040.03552 |

## TABLE III-III (cont.)

| | 100% F CASE 1 | 75% F CASE 2 | 50% F CASE 3 | 37.5% F CASE 4 | 25% F CASE 5 | 20% F CASE 6 | 15% F CASE 7 | 10% F CASE 8 |
|---|---|---|---|---|---|---|---|---|
| F | 110971.12891 | 83384.71387 | 55655.08548 | 41708.49219 | 27817.05640 | 22237.34961 | 16690.88550 | 11135.00330 |
| NTOB | 7999.99622 | 6606.78082 | 5129.81055 | 4333.90674 | 3464.16617 | 3069.87723 | 2620.72546 | 2085.57736 |
| WOSB | 248.53823 | 187.69531 | 125.83685 | 94.46991 | 63.21524 | 50.65951 | 38.38612 | 26.47999 |
| TOSB | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 |
| POSTB | 29.95064 | 33.03974 | 35.29702 | 36.10130 | 36.67490 | 36.84131 | 36.96850 | 37.05839 |
| PODTB | 162.05130 | 135.11408 | 103.77498 | 87.34287 | 70.72154 | 63.86314 | 56.92462 | 49.90906 |
| HOBNC | 215.56866 | 164.39586 | 110.17898 | 82.44530 | 54.77907 | 43.47647 | 32.10810 | 20.67588 |
| QOSB | 1246.41046 | 941.24828 | 631.02435 | 473.72612 | 316.99501 | 254.03334 | 192.48779 | 132.78419 |
| HOB/N2 | -5 33682635 | -5 37662668 | -5 41869337 | -5 43894164 | -5 45647522 | -5 46133058 | -5 46748921 | -5 47534759 |
| Q/QDOB | 1.00632 | .92019 | .79453 | .70601 | .59104 | .53448 | .47440 | .41123 |
| ETAOB | .64094 | .64223 | .60417 | .56351 | .50201 | .46670 | .42450 | .37561 |
| SHPOB | 149.86251 | 87.27235 | 41.72391 | 25.13035 | 12.54173 | 8.58052 | 5.27890 | 2.65022 |
| SOB | 30054.04590 | 18231.38970 | 10459.76831 | 7404.96908 | 4731.86090 | 3729.37924 | 2757.66458 | 1816.37572 |
| PTITOB | 4760.66858 | [illegible] | 2065.80109 | 1487.00906 | 951.33641 | 747.59368 | 551.49314 | 362.44847 |
| DPTOB | 4648.37262 | 3234.47021 | 1974.78105 | 1406.85489 | 883.83533 | 685.79875 | 495.75599 | 313.10450 |
| TTITOB | 92.61465 | 88.08217 | 84.35461 | 82.76491 | 81.23660 | 80.70773 | 80.01860 | 79.30638 |
| WTOB | 22.38617 | 18.60429 | 14.48582 | 12.20654 | 9.66051 | 8.50459 | 7.22726 | 5.74097 |
| ETATOB | .50453 | .50411 | .50367 | .50364 | .50396 | .50418 | .50430 | .50433 |
| NTFB | 7999.99622 | 6595.86176 | 5112.74512 | 4311.61426 | 3442.14606 | 3049.89435 | 2604.01895 | 2074.04327 |
| WFSB | 102.41152 | 77.01085 | 51.70402 | 39.01529 | 26.29338 | 21.13405 | 15.81699 | 10.29711 |
| TFSB | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 |
| PFSTB | 10.59303 | 13.56751 | 15.70499 | 16.46638 | 17.02167 | 17.18748 | 17.32250 | 17.42417 |
| PFDTB | 84.78544 | 69.76341 | 52.77752 | 43.93968 | 35.16510 | 31.57853 | 27.96883 | 24.34026 |
| HFBNC | 191.50767 | 144.25056 | 95.16113 | 70.52063 | 46.57184 | 36.93994 | 27.32770 | 17.75265 |
| QFSB | 819.33191 | 616.10563 | 413.63949 | 312.12641 | 210.34907 | 169.07392 | 126.53695 | 82.37749 |
| HFB/N2 | -5 29923100 | -5 33156937 | -5 30404183 | -5 37934677 | -5 39306539 | -5 39712438 | -5 40300898 | -5 41269340 |
| Q/QDFB | .98477 | .89815 | .77792 | .69608 | .58759 | .53304 | .46724 | .38191 |
| ETAFB | .64651 | .63814 | .59723 | .55844 | .49999 | .46574 | .41918 | .35156 |
| SHPFB | 54.85158 | 31.65142 | 14.97899 | 8.95796 | 4.45289 | 3.04769 | 1.87483 | .94540 |
| SFB | 24012.64380 | 13501.03625 | 7493.21545 | 5259.61401 | 3346.21109 | 2635.25897 | 1932.98317 | 1235.77107 |
| PTITFB | 4900.03033 | 3420.51047 | 2093.56537 | 1493.13864 | 943.03803 | 735.95866 | 536.94444 | 346.67346 |
| DPTFB | 4855.95502 | 3373.95071 | 2051.41129 | 1455.34123 | 910.74702 | 706.27833 | 510.07912 | 322.83834 |
| TTITFB | 92.54557 | 88.07590 | 84.21469 | 82.50410 | 80.90839 | 80.24703 | 79.72275 | 79.05420 |
| WTFB | 5.91870 | 4.92727 | 3.83750 | 3.23048 | 2.55428 | 2.24898 | 1.91087 | 1.52001 |
| ETATFB | .41220 | .41017 | .40896 | .40907 | .41054 | .41154 | .41227 | .41244 |
| SEAL S/ | | | | | | | | |
| WOTS | 1.90925 | 1.51924 | 1.11612 | .90477 | .68290 | .58813 | .48900 | .38163 |
| WOBOS | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 |
| WFBOS | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 |
| WFRTS | 1.25000 | 1.25000 | 1.25000 | 1.25000 | 1.25000 | 1.25000 | 1.25000 | 1.25000 |

TABLE III-IV

SYMBOL LIST FOR THROTTLING COMPUTER STUDY

| | | |
|---|---|---|
| AE/AT | - | Area Exit/Area Throat |
| CF | - | Nozzle Coefficient |
| C*SC | - | Throat Velocity--Secondary Combustor |
| D*FJPC | - | Density Fuel Injector Primary Combustor |
| D*FJSC | - | Density Fuel Injector Secondary Combustor |
| D*$FSM_1$ | - | Density Fuel Suction Main Pump First Stage |
| D*$FSM_2$ | - | Density Fuel Suction Main Pump Second Stage |
| D*OFC | - | Density Oxidizer Transpiration or Film Cooling |
| D*OJPC | - | Density Oxidizer Injector Primary Combustor |
| D*ORG | - | Density Oxidizer Regenerative Coolant Exit |
| D*OSM | - | Density Oxidizer Suction Main Pump |
| DPFJPC | - | ΔP Fuel Injector Primary Combustor |
| DPFJSC | - | ΔP Fuel Injector Secondary Combustor |
| DPFPCV | - | ΔP Fuel Primary Combustor Valve |
| DPFPCP | - | ΔP Fuel Primary Combustor Pilot System |
| DPFSC | - | ΔP Fuel Secondary Combustor Valve |
| DPFSCP | - | ΔP Fuel Secondary Combustor Pilot System |
| DPOFC | - | ΔP Oxidizer Transpiration or Film Coolant System |
| $DPOH_1$ | - | ΔP Oxidizer Housing First Passage |
| $DPOH_2$ | - | ΔP Oxidizer Housing Second Passage |
| DPOJPC | - | ΔP Oxidizer Injector Primary Combustor |
| DPOPCP | - | ΔP Oxidizer Primary Combustor Pilot System |
| DPORG | - | ΔP Oxidizer Regenerative Coolant Coolant Circuit (or Oxidizer Housing Orifice) |
| DPPCVO | - | ΔP Primary Combustor Valve Outlet |
| DPSCVI | - | ΔP Secondary Combustor Valve Inlet |
| DPSCVO | - | ΔP Secondary Combustor Valve Outlet |
| DPTOB | - | ΔP Turbine Oxidizer Boost Pump |

Table III-IV
Sheet 1 of 6

TABLE III-IV (cont.)

| | | |
|---|---|---|
| DP/PPF | - | ΔP Fuel Injector ÷ Pressure Primary Combustor |
| DP/PPO | - | ΔP Oxidizer Injector ÷ Pressure Primary Combustor |
| DP/PSF | - | ΔP Fuel Injector ÷ Pressure Secondary Combustor |
| DTORG | - | Temperature Regenerative Coolant Circuit |
| ETAC | - | Efficiency Secondary Combustor Combustion |
| ETAFB | - | Efficiency Fuel Boost Pump |
| $ETAFM_1$ | - | Efficiency Fuel Main Pump First Stage |
| $ETAFM_2$ | - | Efficiency Fuel Main Pump Second Stage |
| ETAN | - | Efficiency Secondary Combustor Nozzle |
| ETAOB | - | Efficiency Oxidizer Boost Pump |
| ETAOM | - | Efficiency Oxidizer Main Pump |
| ETAT | - | Efficiency Turbine |
| ETATFB | - | Efficiency Turbine Fuel Boost |
| ETATOB | - | Efficiency Turbine Oxidizer Boost Pump |
| F | - | Thrust |
| HFBNC | - | Head Fuel Boost Pump, Noncavitating |
| HFB/N2 | - | Head Fuel Boost Pump ÷ $(Speed)^2$ |
| $HFM_2$ | - | Head Fuel Main Pump Second Stage |
| $HF_2/N2$ | - | Head Fuel Main Pump Second Stage ÷ $(Speed)^2$ |
| $HFMNC_1$ | - | Head Fuel Main Pump First Stage, Noncavitating |
| $HF_1/N2$ | - | Head Fuel Main Pump First Stage, Noncavitating ÷ $(Speed)^2$ |
| HOBNC | - | Head Oxidizer Boost Pump, Noncavitating |
| HOB/N2 | - | Head Oxidizer Boost Pump, Noncavitating |
| HOMNC | - | Head Oxidizer Main Pump, Noncavitating |
| HOM/N2 | - | Head Oxidizer Main Pump, Noncavitating ÷ $(Speed)^2$ |
| $I_s$ | - | Specific Impulse |

TABLE III-IV (cont.)

| | | |
|---|---|---|
| KwFCV | - | Film Coolant Valve Flow Admittance Factor |
| KwFPCV | - | Fuel Primary Combustor Valve Flow Admittance Factor |
| KwFSCV | - | Fuel Secondary Combustor Valve Flow Admittance Factor |
| KwOPCV | - | Oxidizer Primary Combustor Valve Flow Admittance Factor |
| KwRGV | - | Regenerative Coolant Valve Flow Admittance Factor |
| NT | - | Turbine Speed |
| NTFB | - | Turbine Speed Fuel Boost Pump |
| NTOB | - | Turbine Speed Oxidizer Boost Pump |
| MRENG | - | Engine Mixture Ratio |
| MRPC | - | Primary Combustor Mixture Ratio |
| MRSC | - | Secondary Combustor Mixture Ratio |
| NPSPFB | - | Net Positive Suction Pressure Fuel Boost Pump |
| NPSPFM | - | Net Positive Suction Pressure Fuel Main Pump |
| NPSPOB | - | Net Positive Suction Pressure Oxidizer Boost Pump |
| NPSPOM | - | Net Positive Suction Pressure Oxidizer Main Pump |
| NSF-1 | - | Specific Speed Fuel Pump First Stage |
| NSF-2 | - | Specific Speed Fuel Pump Second Stage |
| NSO | - | Specific Speed Oxidizer Pump |
| PA | - | Ambient Pressure |
| PCFACE | - | Primary Combustor Injector Face Pressure |
| PCPC | - | Primary Combustor Chamber Pressure |
| PCSC | - | Secondary Combustor Chamber Pressure |
| PFDTB | - | Pressure Fuel Discharge (total) Boost Pump |
| $PFDTM_1$ | - | Pressure Fuel Discharge (total) Main Pump First Stage |
| $PFDTM_2$ | - | Pressure Fuel Discharge (total) Main Pump Second Stage |
| PFSTB | - | Pressure Fuel Suction (total) Fuel Boost Pump |
| $PFSTM_1$ | - | Pressure Fuel Suction (total) Fuel Main Pump First Stage |
| $PFSTM_2$ | - | Pressure Fuel Suction (total) Fuel Main Pump Second Stage |

Table III-IV
Sheet 3 of 6

TABLE III-IV (cont.)

| | | |
|---|---|---|
| PFT | - | Pressure Fuel Tank (Bottom) |
| PGJT | - | Pressure Gas Injector Total (Inlet) |
| PODTM | - | Pressure Oxidizer Discharge (Total) Main Pump |
| PODTB | - | Pressure Oxidizer Discharge (Total) Boost Pump |
| PORGDT | - | Pressure Oxidizer Regen. Coolant Discharge Total |
| POSTB | - | Pressure Oxidizer Suction (Total) Boost Pump |
| POSTM | - | Pressure Oxidizer Suction (Total) Main Pump |
| POT | - | Pressure Oxidizer Tank (Bottom) |
| PTET | - | Pressure Turbine Exit Total |
| PTIT | - | Pressure Turbine Inlet (Total) |
| PTITFB | - | Pressure Turbine Inlet (Total) Fuel Boost Pump |
| PTITOB | - | Pressure Turbine Inlet (Total) Oxidizer Boost Pump |
| QFSB | - | Volume Flow Fuel Suction Boost Pump |
| $QFSM_1$ | - | Volume Flow Fuel Suction Main Pump First Stage |
| $QFSM_2$ | - | Volume Flow Fuel Suction Main Pump Second Stage |
| QOSB | - | Volume Flow Oxidizer Boost Pump |
| QOSM | - | Volume Flow Oxidizer Main Pump |
| $Q/QDF_1$ | - | Flow Parameter Ratio Fuel Pump First Stage* |
| $Q/QDF_2$ | - | Flow Parameter Ratio Fuel Pump Second Stage* |
| Q/QDFB | - | Flow Parameter Ratio Fuel Boost Pump* |
| Q/QDOB | - | Flow Parameter Oxidizer Boost Pump* |
| Q/QDOM | - | Flow Parameter Oxidizer Main Pump* |
| RPT | - | Pressure Ratio Turbine |
| SFB | - | Suction Specific Speed Fuel Boost Pump |
| $SFM_1$ | - | Suction Specific Speed Fuel Main Pump First Stage |
| SHPFB | - | Shaft Horsepower Fuel Boost Pump |

*Q/QD represents (Q/N) Actual/(Q/N)Design

Table III-IV
Sheet 4 of 6

TABLE III-IV (cont.)

| | | |
|---|---|---|
| $SHPFM_1$ | - | Shaft Horsepower Fuel Main Pump First Stage |
| $SHPFM_2$ | - | Shaft Horsepower Fuel Main Pump Second Stage |
| SHPOB | - | Shaft Horsepower Oxidizer Boost Pump |
| SHPOM | - | Shaft Horsepower Oxidizer Main Pump |
| SHPT | - | Shaft Horsepower Turbine |
| SOB | - | Suction Specific Speed Oxidizer Boost Pump |
| SOM | - | Suction Specific Speed Oxidizer Main Pump |
| TFSB | - | Temperature Fuel Suction Boost Pump |
| TOSB | - | Temperature Oxidizer Suction Boost Pump |
| TTIT | - | Temperature Turbine Inlet (Total) |
| TTITFB | - | Temperature Turbine Inlet (Total) Fuel Boost Pump |
| TTITOB | - | Temperature Turbine Inlet (Total) Oxidizer Boost Pump |
| U/C-GT | - | Tip Velocity ÷ Spouting Velocity Gas Turbine |
| W-ENG | - | Weight Flow Total Engine |
| WFBOS | - | Weight Flow Fuel Burn-Off Seal |
| WFC/WT | - | Ratio Weight Flow Film Coolant*/Weight Flow Total Engine Propellant |
| WFJPC | - | Weight Fuel Primary Combustor |
| WFJSC | - | Weight Flow Fuel Secondary Combustor |
| WFPCP | - | Weight Flow Fuel Primary Combustor Pilot |
| WFRTS | - | Weight Flow Fuel Pump Return to Suction |
| WFSB | - | Weight Flow Fuel Suction Boost Pump |
| WFT | - | Weight Flow Fuel Total (Engine) |
| WFSCP | - | Weight Flow Fuel Secondary Combustor Pilot |
| WGJSC | - | Weight Flow Gas Injector Secondary Combustor |
| WOBOS | - | Weight Flow Oxidizer Burn-Off Seal |
| WOFC | - | Weight Flow Oxidizer Transpiration or Film Coolant |

*Film Coolant and/or Transpiration Coolant

Table III-IV
Sheet 5 of 6

TABLE III-IV (cont.)

| | | |
|---|---|---|
| WOJPC | - | Weight Flow Oxidizer Injector Primary Combustor |
| WOPCP | - | Weight Flow Oxidizer Primary Combustor Pilot |
| WORG | - | Weight Flow Oxidizer Regenerative Coolant |
| WOSB | - | Weight Flow Oxidizer Suction Boost Pump |
| WOT | - | Weight Flow Oxidizer Total (Engine) |
| WOTS | - | Weight Flow Oxidizer Turbine Seal |
| WTFB | - | Weight Flow Turbine Fuel Boost Pump |
| WTOB | - | Weight Flow Turbine Oxidizer Boost Pump |
| WTI | - | Weight Flow Turbine Inlet |

TABLE III-V

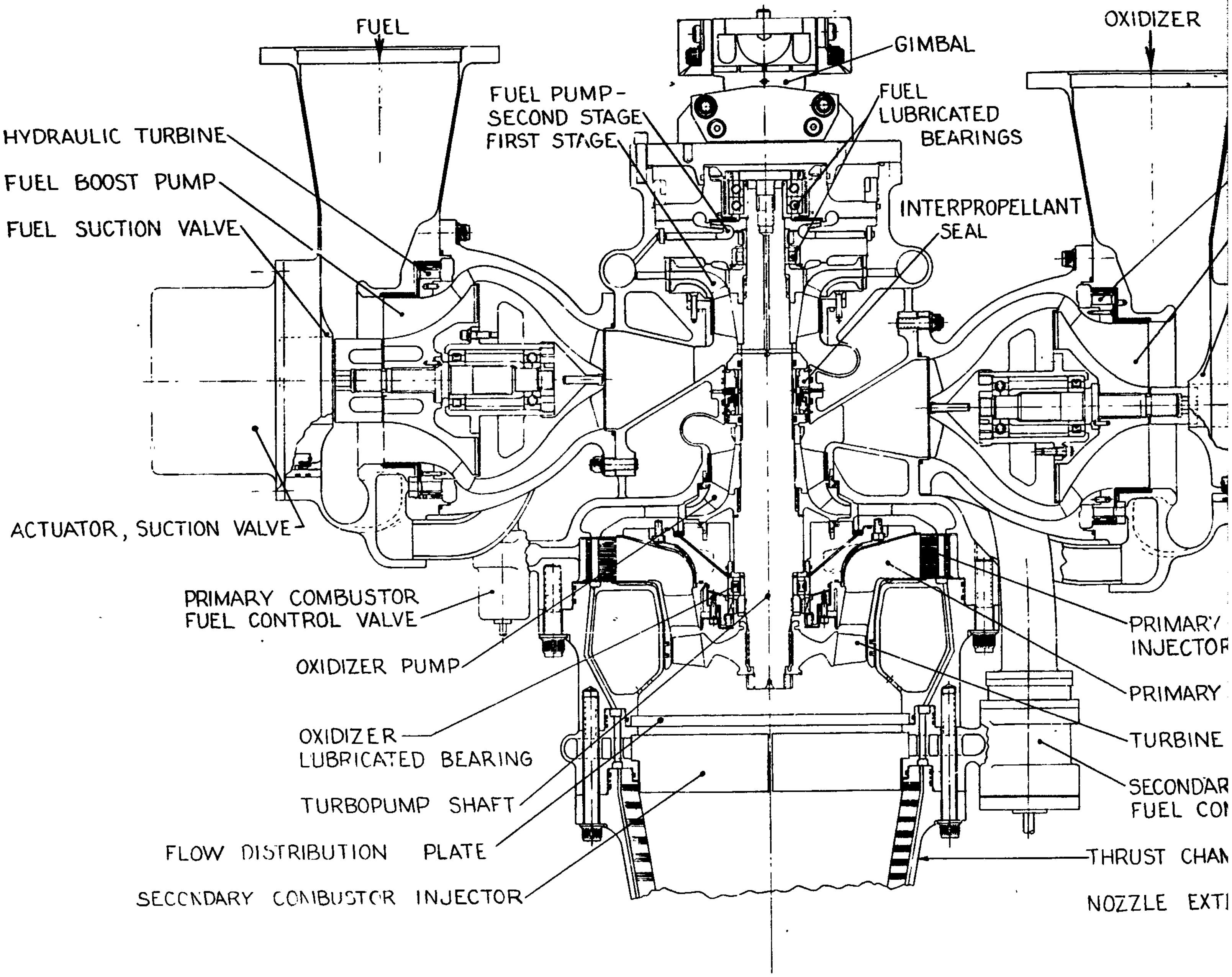
100K ARES WEIGHT AND INERTIA SUMMARY

| COMPONENT ASSEMBLY | Weight Pound | Moment of Inertia About Gimbal Slug Ft$^2$ |
|---|---|---|
| TURBOPUMP - INCL. PRIM. COMB & PCFCV HSG ADAPTER & LINE (W/O GIMBAL) | 337.1 | 17.75 |
| SECONDARY INJECT. SUB-ASS'Y & SCFCV | 85.6 | 10.04 |
| TPA SUB-TOTAL | 422.7 | 27.79 |
| $\epsilon$ = 150 THRUST CHAMBER ASSEMBLY AND NOZZLE EXTENSION | 345.9 | 211.37 |
| $\epsilon$ = 50 THRUST CHAMBER ASSEMBLY AND NOZZLE EXTENSION | 332.2 | 137.64 |
| SUB-TOTAL BASIC ENGINE $\epsilon$ = 150 | 768.6 | 239.16 |
| SUB-TOTAL BASIC ENGINE $\epsilon$ = 50 | 754.9 | 165.43 |
| BOOST PUMPS (2) | 36.0 | 1.705 |
| PROPELLANT INLET HOUSINGS (2) | 62.0 | 4.030 |
| SUCTION VALVES & ACTUATORS (2) | 40.0 | 4.280 |
| GIMBAL | 19.5 | .001 |
| PCFCV ACTUATOR | 4.0 | .301 |
| SCFCV ACTUATOR | 3.0 | .399 |
| ADDITIONAL ITEMS SUB-TOTAL | 164.5 | 10.716 |
| GRAND TOTAL - | | |
| $\epsilon$ = 150 DRY ENGINE ASSEMBLY | 993.1 | 249.876 |
| $\epsilon$ = 50 DRY ENGINE ASSEMBLY | 919.4 | 176.146 |
| $\epsilon$ = 150 WET ENGINE ASSEMBLY | 996.1 | 254.236 |
| $\epsilon$ = 50 WET ENGINE ASSEMBLY | 983.4 | 180.376 |

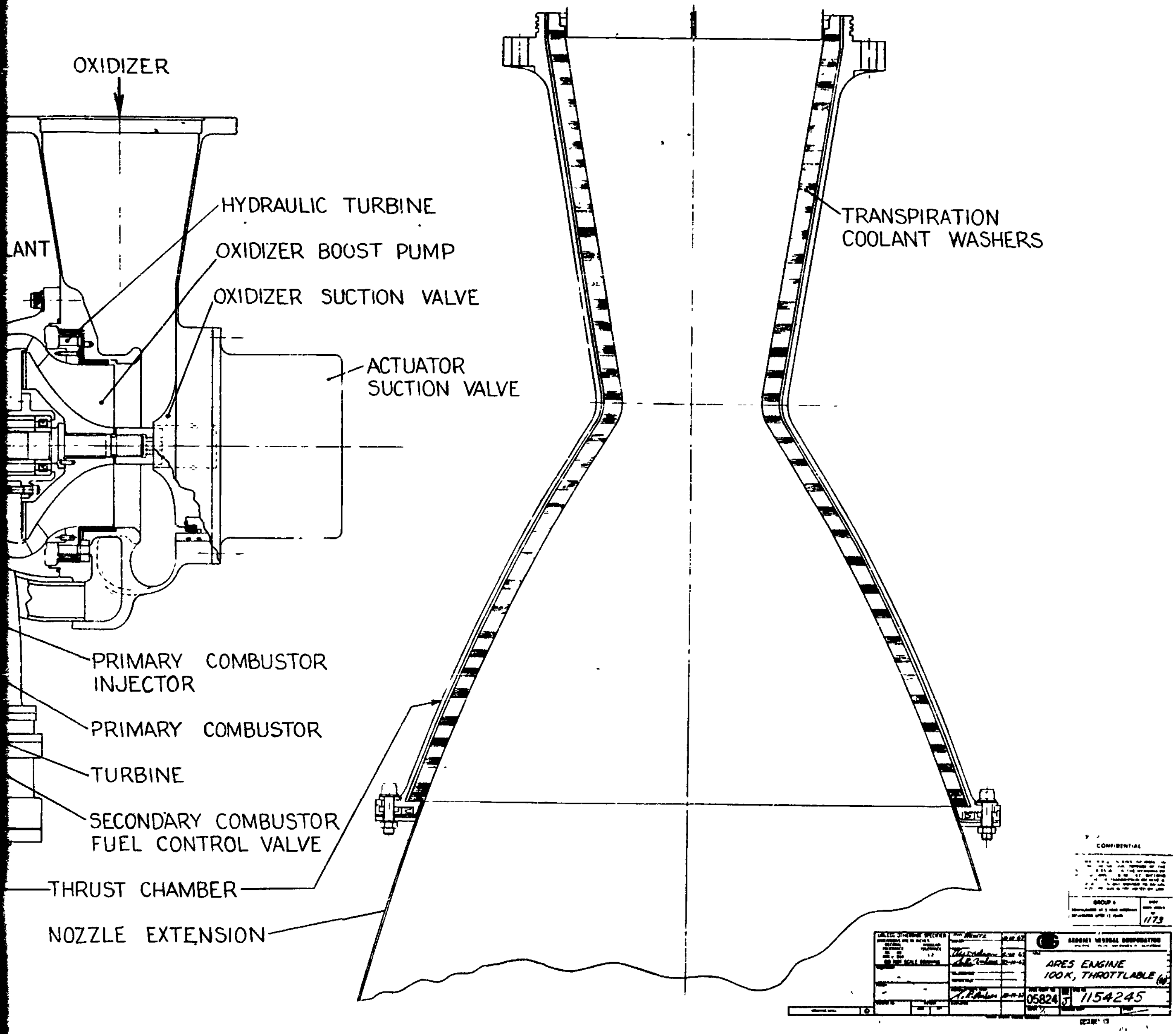
TABLE III-VI

100K PROTOTYPE PRODUCTION ARES WEIGHT AND INERTIA SUMMARY

| | Nozzle Expansion Ratio € | Weight Pound | Moment of Inertia About Gimbal Slug $Ft^2$ |
|---|---|---|---|
| DRY ENGINE | 150:1 | 883. | 246. |
| | 50:1 | 869. | 172. |
| ADDITIVE EFFECT | 150:1 | 63. | 4.36 |
| OF PROPELLANTS | 50:1 | 64. | 4.23 |
| WET ENGINE | 150:1 | 946. | 250.36 |
| | 50:1 | 933. | 176.23 |

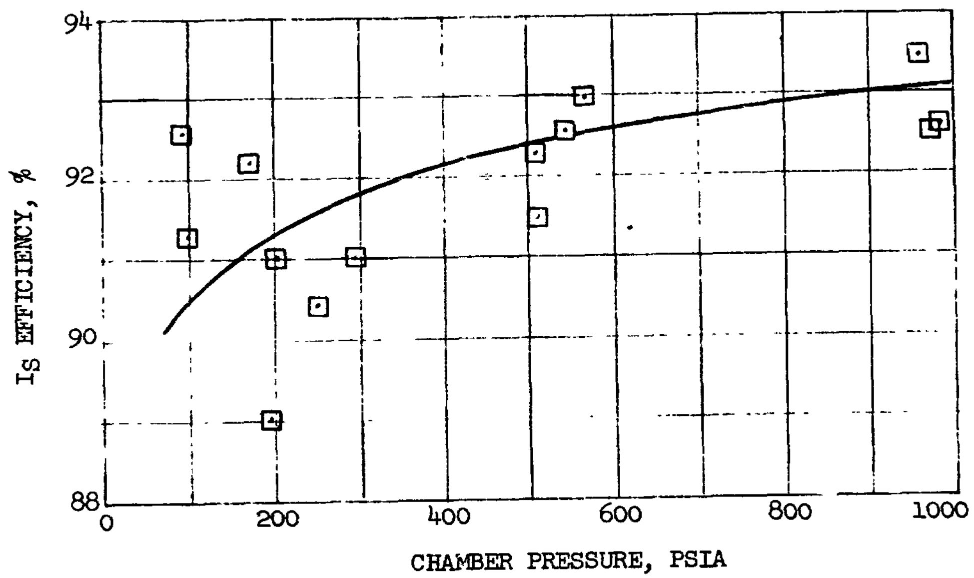

FUEL
OXIDIZER
GIMBAL
FUEL PUMP-
SECOND STAGE
FIRST STAGE
FUEL
LUBRICATED
BEARINGS
INTERPROPELLANT
SEAL
HYDRAULIC TURBINE
FUEL BOOST PUMP
FUEL SUCTION VALVE
ACTUATOR, SUCTION VALVE
PRIMARY COMBUSTOR
FUEL CONTROL VALVE
OXIDIZER PUMP
OXIDIZER
LUBRICATED BEARING
TURBOPUMP SHAFT
FLOW DISTRIBUTION PLATE
SECONDARY COMBUSTOR INJECTOR
PRIMARY
INJECTOR
PRIMARY
TURBINE
SECONDAR
FUEL CO
THRUST CHAN
NOZZLE EXT

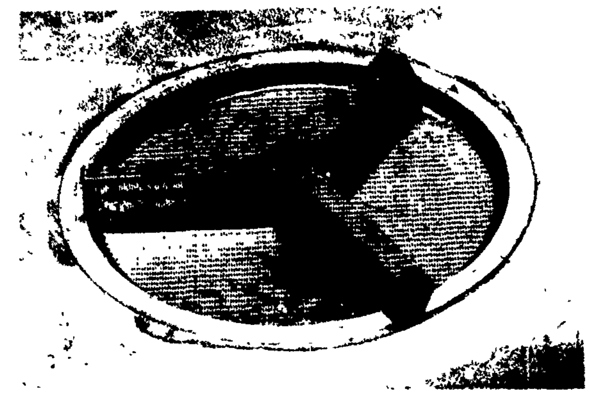
1




ARES Engine, 100K, Throttlable (u)

Figure III-1



HIPERTHIN INJECTOR
IR&D PROGRAM 8709-53

PROPELLANTS: $N_2O_4$/A-50

MAXIMUM THRUST: 1000 LBS

THROTTLE RANGE: 10:1

CHAMBER L*: 15 IN.

MIXTURE RATIO: 2.0

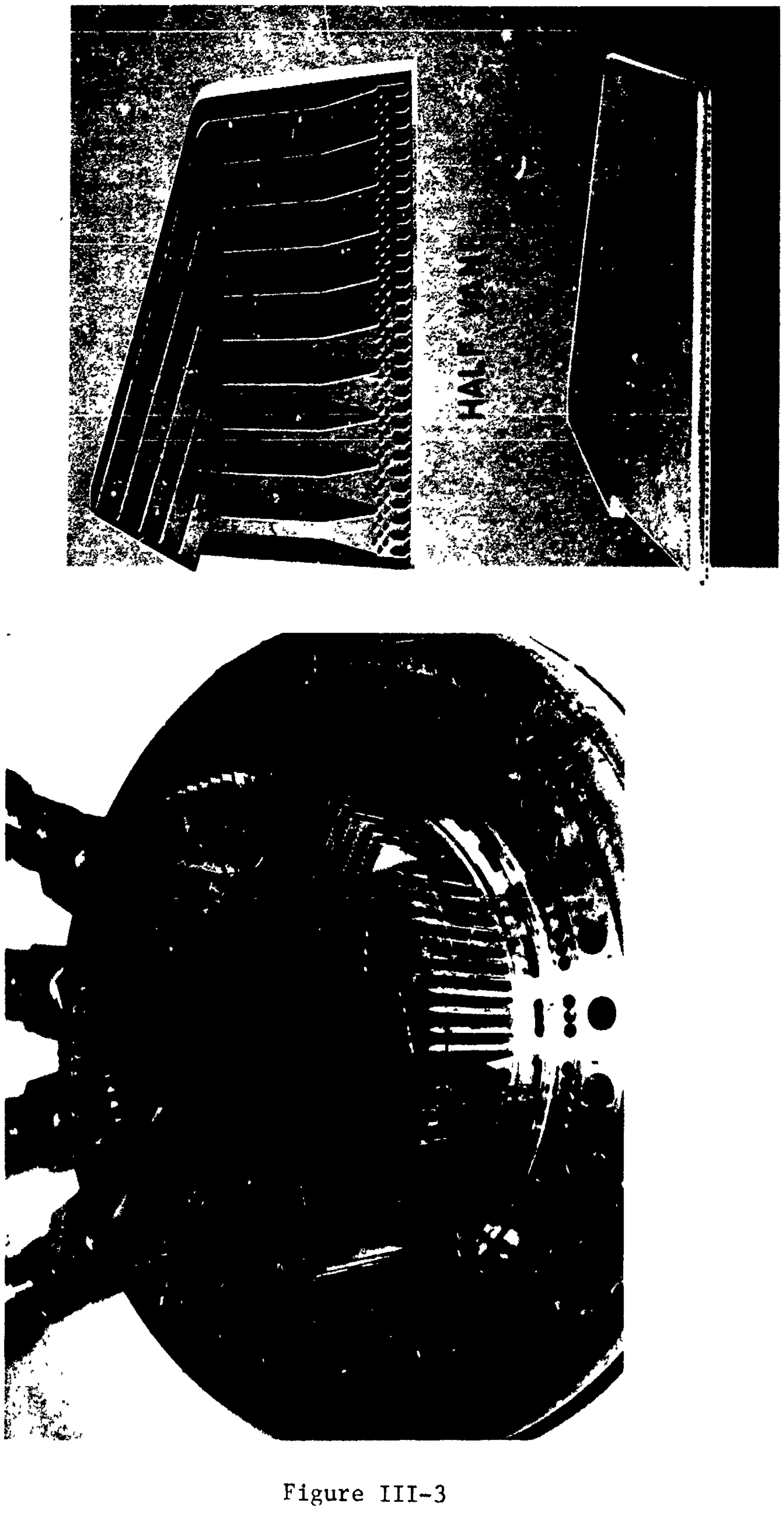
NUMBER OF TESTS: 15

STEADY STATE DURATION (MAX): 2.4 SEC

NOTE: TESTS WERE CONDUCTED WITH VARIOUS INJECTORS AND CHAMBERS, AND A SHORT NOZZLE ($\epsilon$ = 1.4:1). DATA SHOWN IS CORRECTED TO AN ASSUMED TYPICAL NOZZLE EFFICIENCY OF 96%.

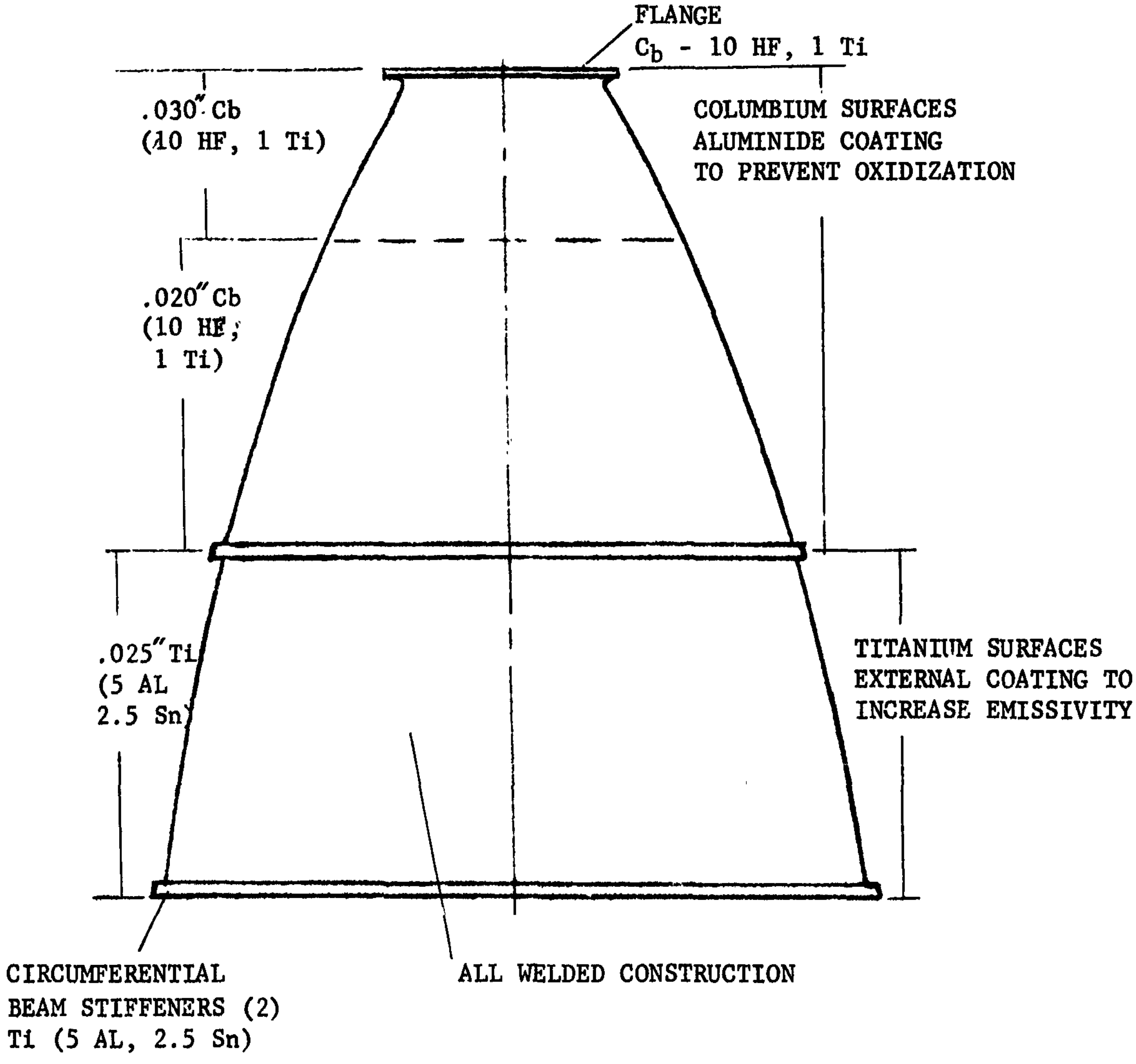
HIPERTHIN Injector Throttling Characteristics

Figure III-2



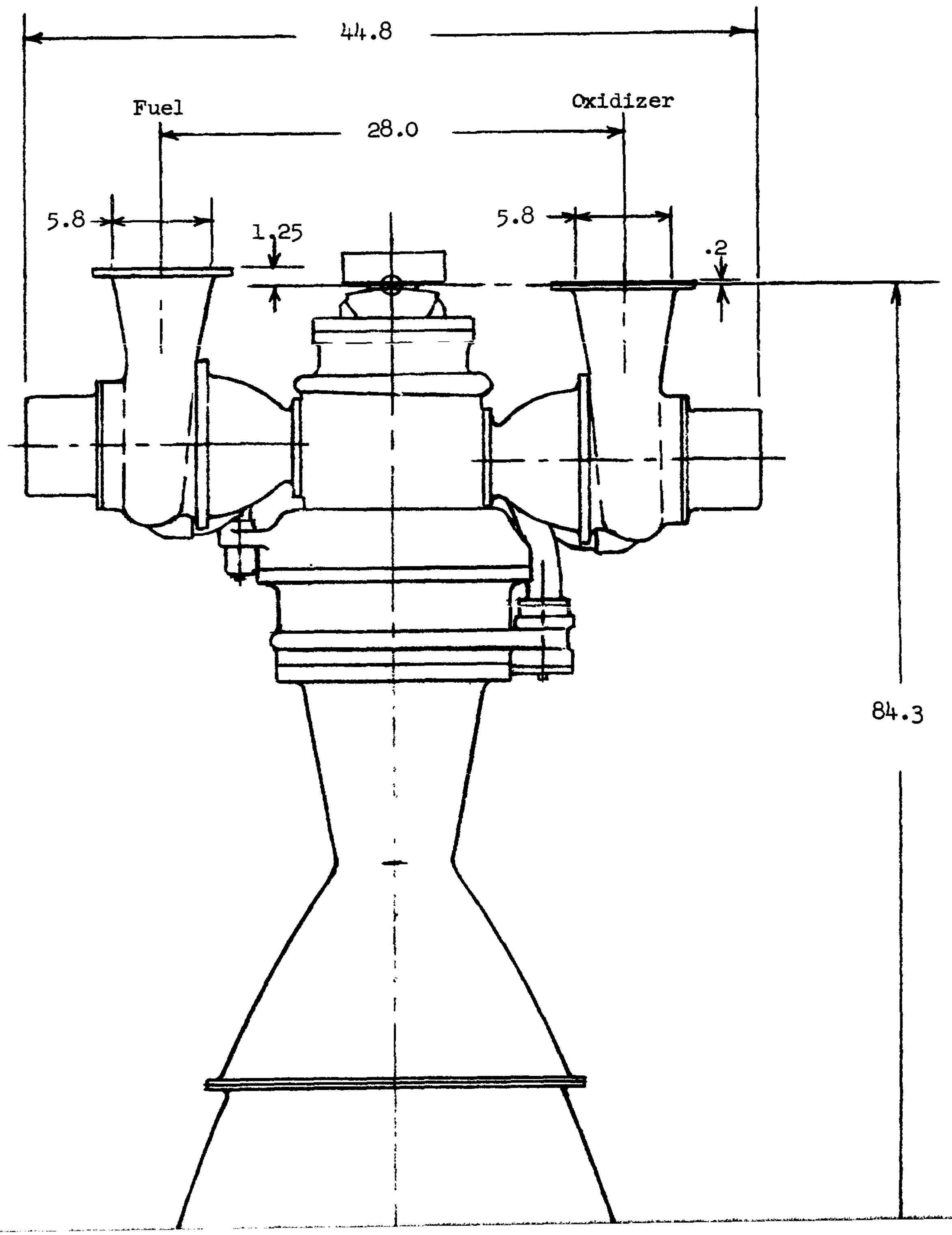
Secondary Combustor Injector (u)

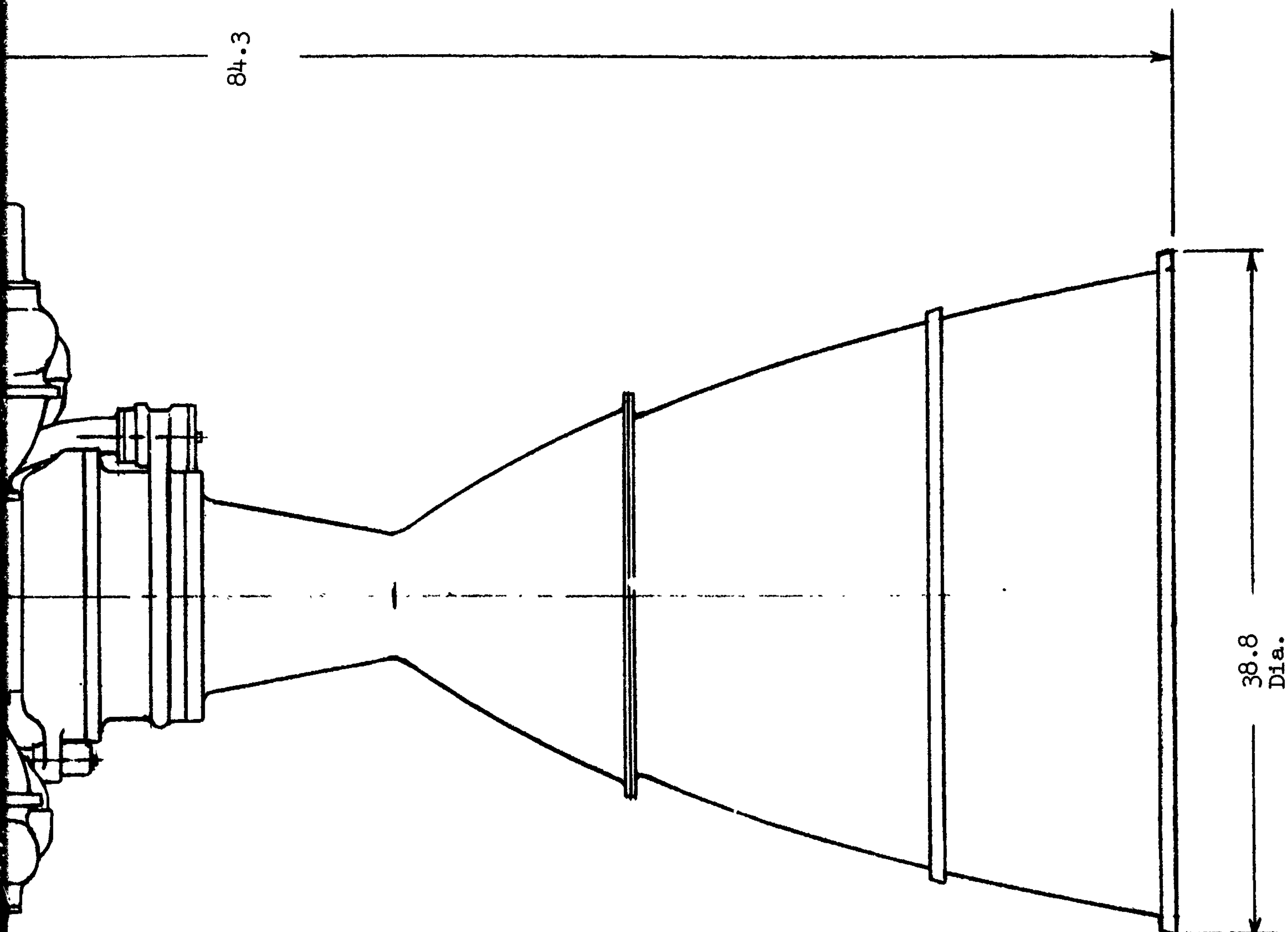
Figure III-3




Apollo Nozzle Extension

Figure III-4

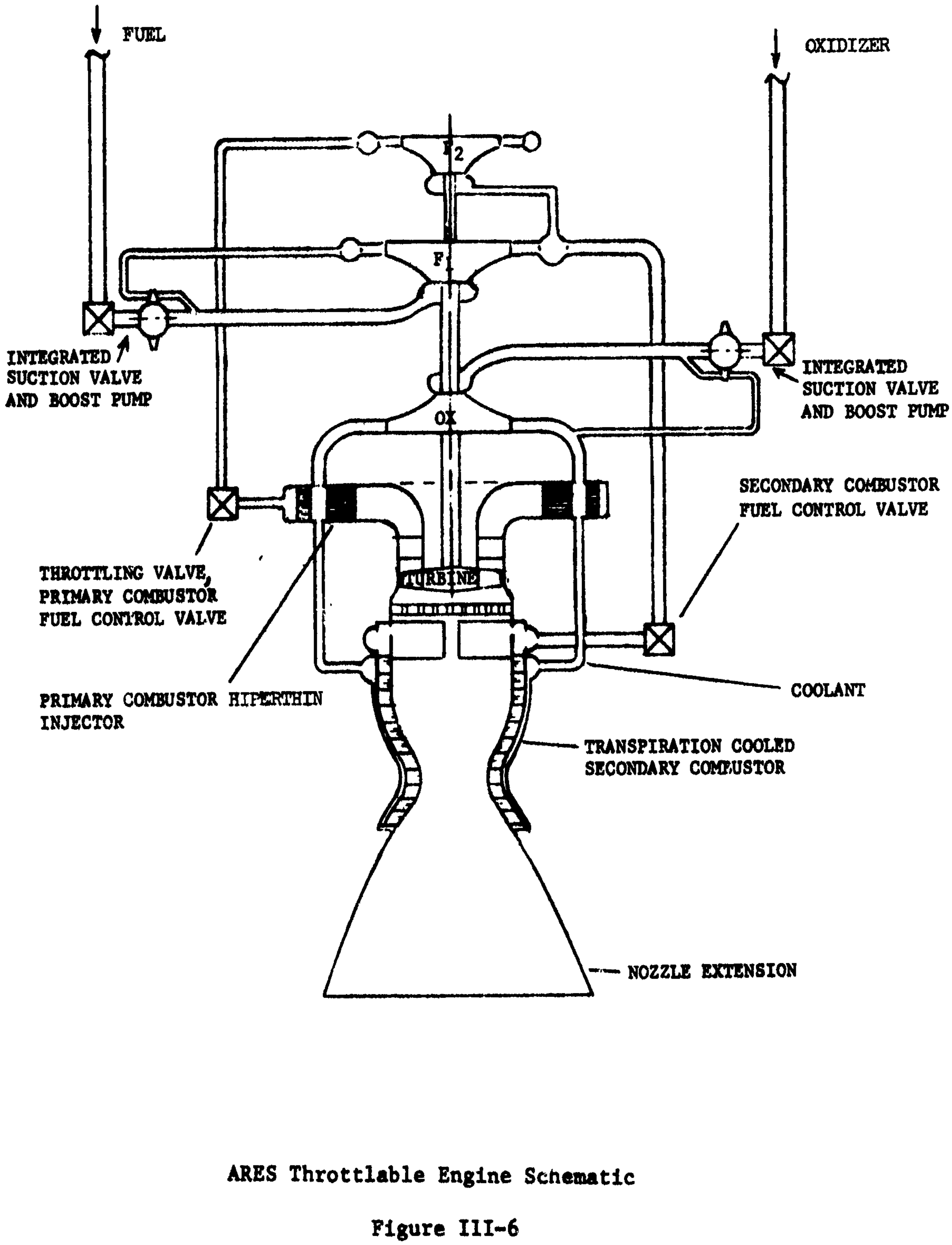

44.8
Fuel
Oxidizer
28.0
5.8
5.8
1.25
.2
84.3




2

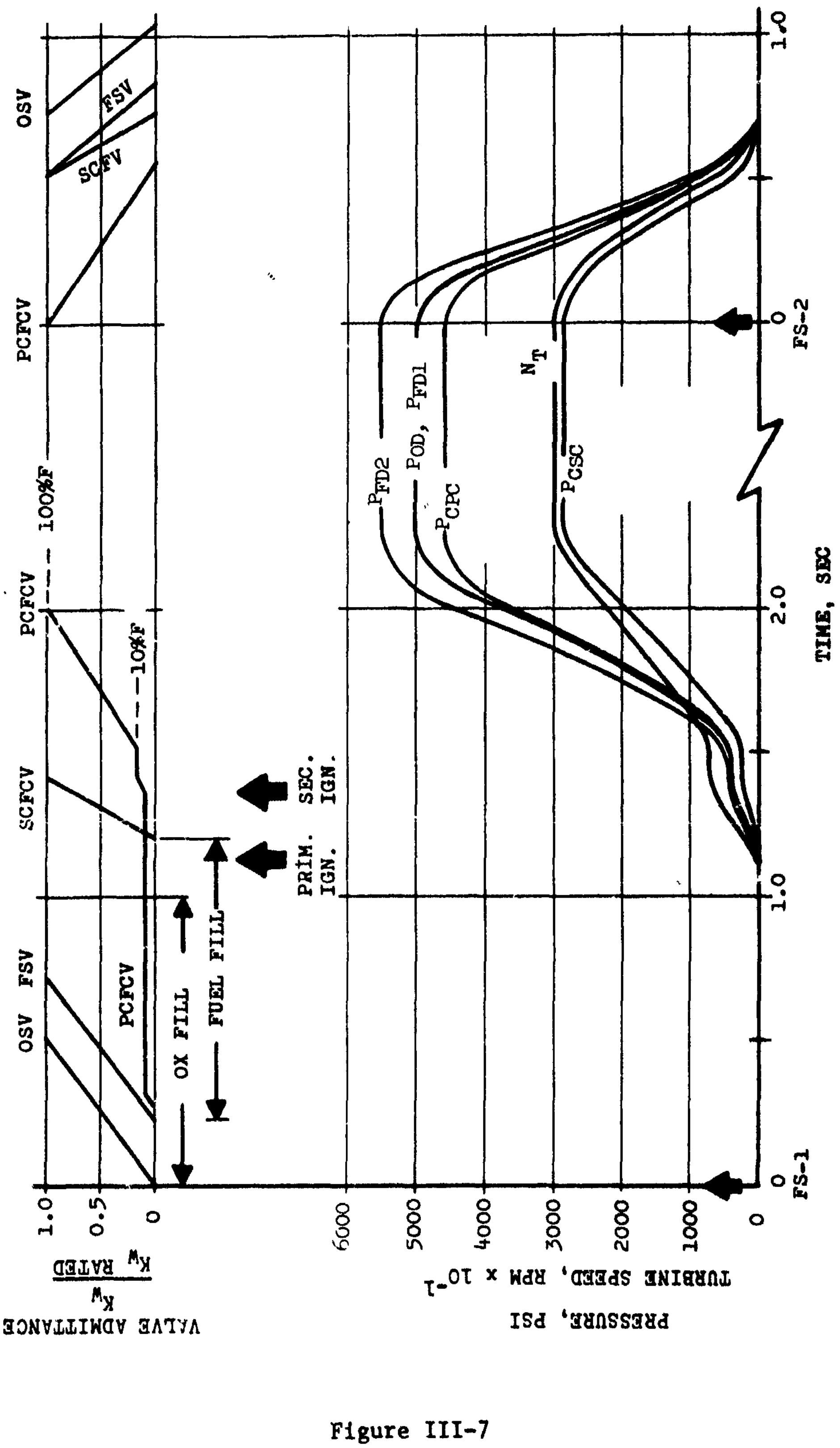
Envelope 100K Throttlable ARES

Figure III-5



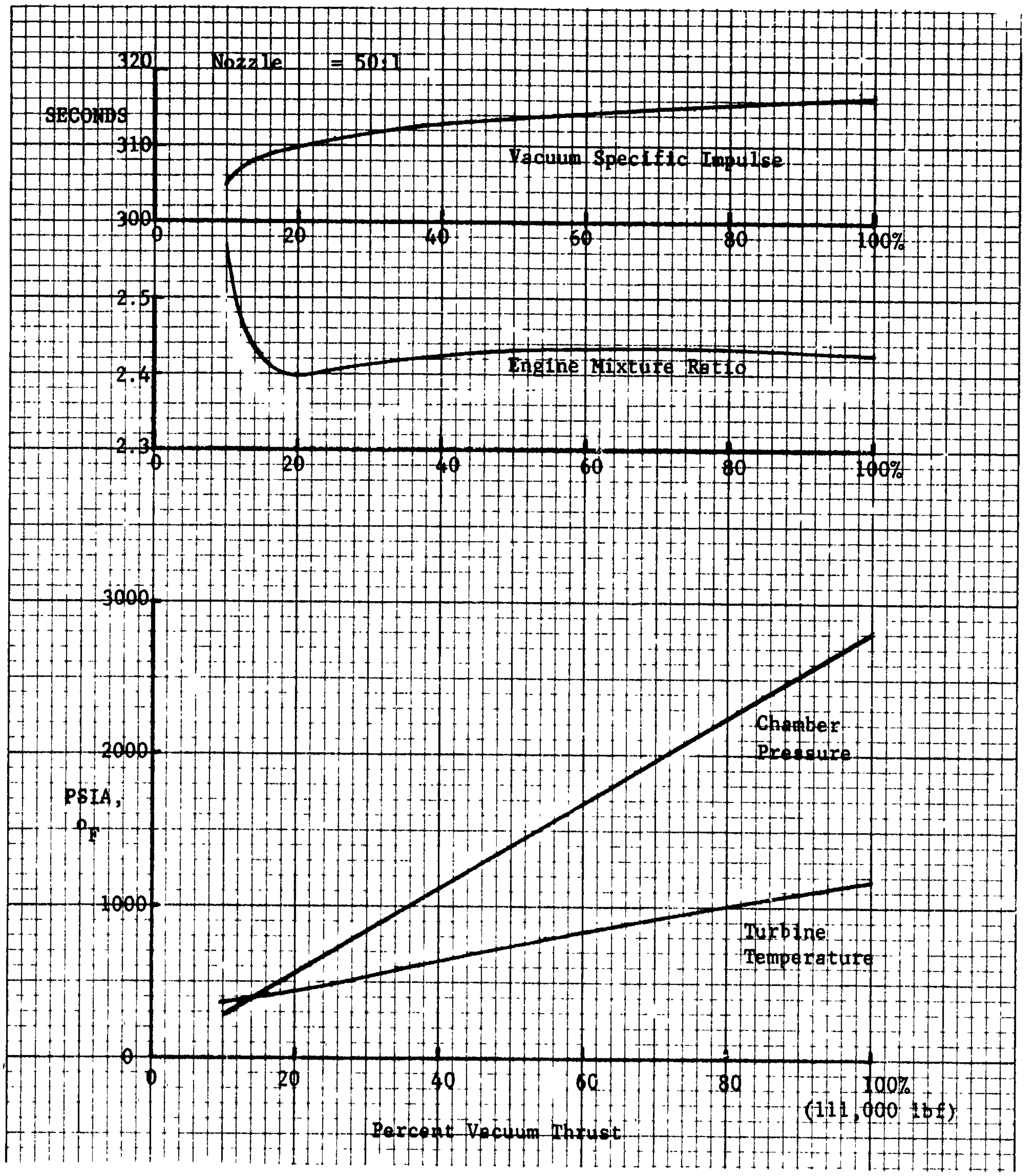

ARES Throttlable Engine Schematic

Figure III-6



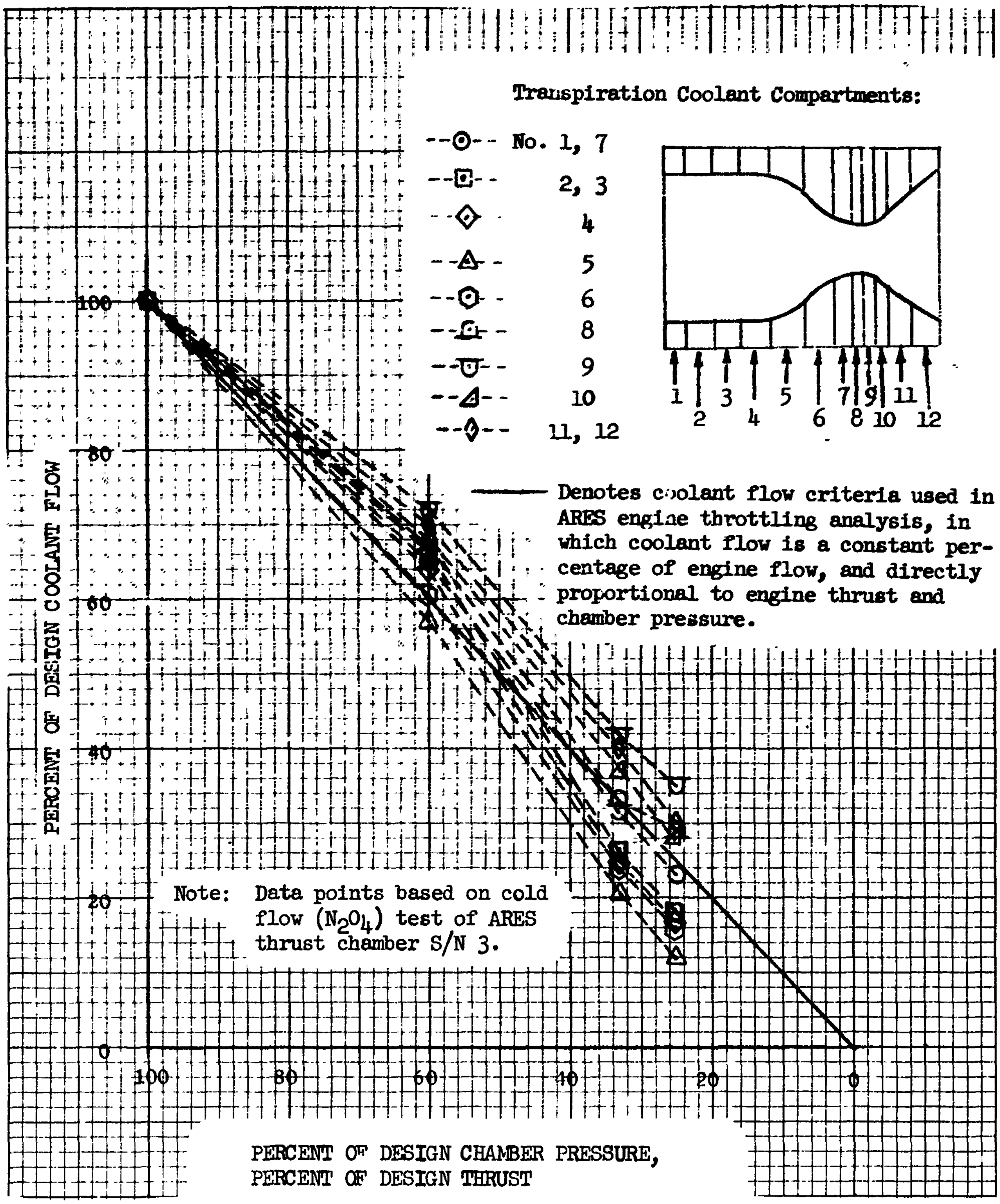

ARES Start and Shutdown (u)

Figure III-7




Throttling Performance, 100K ARES (u)

Figure III-8




Typical Transpiration Coolant Flow During Throttling

Figure III-9

# IV.

# INTEGRATED AUXILIARY POWER PACKAGE (TASK I)

## A. OBJECTIVES AND APPROACH

(U) The objectives of Task I of the work statement were to establish design requirements and a layout design of an Integrated Auxiliary Power Package (IAPP) for use with the throttlable-restartable 100K ARES engine. The IAPP includes roll control, thrust vector control (TVC), and propellant tank-pressurization systems.

(U) Typical functional requirements for the IAPP were established primarily on the basis of the Titan Stage II requirements because of the size similarity. Additional requirements were defined to permit operation of the IAPP prior to engine restart and during engine-throttled conditions.

(U) Using this typical set of functional requirements, a vehicle/engine IAPP system design was established. The engine-supplied system was designed to provide the vehicle with complete attitude control as well as roll control, with adequate thrust vector control, and with quick-response propellant tank pressurization. Through the use of propellant accumulators the system was designed for operation during vehicle coast periods and prior to engine restart, providing vehicle orientation, tank settling and pressurization, and engine gimbal orientation. The system was also designed to provide adequate pressure and flow regulation during engine throttling down to 10% thrust.

(U) The vehicle-located components of the IAPP system are defined in this report by means of a conceptual flow diagram and a table of predicted pressures and flows. The engine-located components are integrated physically and functionally to the basic 100K ARES engine and are defined in this report by means of an external engine drawing and tables of dimensions, weights, and flow requirements.

IV, A, Objectives and Approach (cont.)

(U) The functional requirements and conceptual design of the IAPP were then scaled and incorporated into the 25K and 500K thrust engines, as part of Tasks III and IV.

B. OPERATIONAL REQUIREMENTS

1. Titan, Apollo and Transtage IAPP Requirements

(U) Table IV-I lists the IAPP requirements and some of the operating parameters for the first- and second-stage engines of three Titan vehicles (Titan II, Gemini, and Titan IIIC) and for the upper-stage Apollo and Transtage engines.

(U) The Titan engines are pump-fed, with fixed thrust, and use solid start cartridges for their single start at altitude. The Apollo and Transtage engines are tank-fed, with fixed thrust, and have restart capability by means of their vehicle-supplied helium tank-pressurization systems.

2. Typical IAPP Requirements for 100K ARES

(U) The following basic IAPP requirements were established for the 100K ARES in a typical single-engine application.

100K ARES IAPP Requirements

TVC

| | |
|---|---|
| Gimbal control angle | $\pm 5$ deg |
| Maximum gimbal velocity | 25 deg/sec |
| Maximum acceleration | 18 rad/sec |

ROLL CONTROL

| | |
|---|---|
| Moment | 1600 ft-lb |

TANK PRESSURIZATION

| | Oxidizer Tank | Fuel Tank |
|---|---|---|
| Propellant | $N_2O_4$ | AeroZINE 50 |
| Engine NPSH, min | 20 ft | 20 ft |
| Tank top pressure | 40 ± 10 psia | 30 ± 10 psia |

3. General Requirements

(U) Engine throttling and restart requirements: The IAPP, including TVC, roll control, and tank-pressurization systems, shall also be operable at reduced rates, pressures, and flows, while supplied from the engine at any reduced-thrust condition down to and including 10% thrust. Also, with the engine shutdown, the IAPP shall be operable at reduced rates, pressures, and flows, while supplied from a separate pressure source, such as engine-supplied accumulators.

(U) The tank pressure requirements were selected to provide a minimum NPSH of 20 ft to the engine boost pumps during the worst condition; i.e., assuming full-thrust operation with empty tanks and relatively short suction lines, as in Titan Stage II. Selection criteria were as follows:

| 100% Thrust Conditions | Oxidizer | Fuel |
|---|---|---|
| Minimum tank dome pressure requirement, psia | 28 | 13 |
| Gravity head (3 g's, empty tanks), psi | +12 | +1 |
| Line loss, psi | - 7 | -3 |
| Minimum total pressure, engine suction, psia | 33 | 11 |
| Vapor pressure (at 80°F), psia | -20 | -3 |
| Minimum net positive suction pressure, psi (Equivalent to NPSH = 20 ft) | +13 | +8 |

IV, B, Operational Requirements (cont.)

(U) Nominal oxidizer and fuel tank dome pressures were selected at 40 and 30 psia, respectively, to assure operation exceeding the above-noted minimums, allowing for pressure regulation and system response.

C. THRUST VECTOR CONTROL DESIGN

(U) The TVC gimbaling requirements specified above for ARES permitted the selection of a conventional, hydraulic, gimbal actuator similar to the flight-qualified actuators used on the Titan Stage II engine.

(U) The selected 100K ARES gimbal actuator is servo-controlled with an actuation pressure of 3000 psi, weighs less than 15 lb, and is 18 in. in length. It has a maximum piston force of 7500 lb, a nominal stroke of 1.8 in. and a flow demand of 10 $in.^3$/sec at the maximum stroke velocity of 4 in./sec.

(U) Dimensions and layout of the TVC are shown in an external view of the ARES engine in Figure IV-1. The two actuators have been integrated as part of the engine rather than as part of the vehicle to use the high fluid pressure generated by the engine pumps. Engine fuel was selected as the actuating medium, because the conversion of seal materials from use with hydraulic oil to the use of AeroZINE 50 is less extensive than if $N_2O_4$ were used. A maximum momentary flow of 5 gpm or 0.6 lb/sec of engine fuel will be required during movement of both actuators. The source of fuel to the actuator is a tap-off from the engine's first-stage fuel pump discharge. The source pressure is dropped to 3000 psi at the actuator inlet by means of a continuous-flow bleed system described in Section IV,F as part of the overall IAPP system.

(U) The 100K ARES requires a smaller gimbal force than did the Titan because of the reduced weight and moment of inertia. However, since the ARES requires gimbaling at a 10% thrust condition and during vehicle coast periods, the piston area criteria of 2.55 sq in. used in the Titan actuator was retained for the ARES. This will provide high response at the 100% thrust, high pressure conditions and permit moderate response at the low pressure conditions (150 to 350 psia) available at 10% thrust or from the accumlator during coast periods.

D. ROLL CONTROL DESIGN

(U) The typical roll control requirement specified for ARES is 1600 ft-lb, again based on Titan Stage II. Two roll control systems were examined: (1) a system of hot-gas nozzles mounted on the engine, using turbine exhaust gas and therefore operable only during engine operation, and (2) a system of bipropellant rockets mounted on the vehicle skirt, using propellants supplied from the engine during engine operation, and from a pair of propellant accumulators in the vehicle between engine firings.

1. Engine-Mounted Roll Control System

(U) For booster applications where stage roll control is required during engine operation only, a pair of opposing nozzles can be mounted on an outboard structural portion of the ARES engine and supplied with hot gas bled from the turbine exhaust through a duct and a three-way valve.

(U) The schematic in Figure IV-2 shows such a system with redundant valves and nozzles on each side of the engine to provide reliability and to eliminate pitch and yaw moments. A practical location for the nozzles on the engine structure to provide the greatest moment arm is the mounting of a nozzle and valve assembly outboard of each boost pump; this results in a moment arm of 2 ft measured from the engine/vehicle centerline. Thus, a total thrust of 800 lb is required to produce the specified moment of 1600 ft-lb, or with two nozzles operating, a thrust of 400 lb in each nozzle. At a chamber pressure of 2700 psia, the nozzles will require a maximum weight flow from the engine of 7 lb/sec, on an intermittent (on-off) basis. As the main engine is throttled to 10% thrust, the roll control thrust will drop to less than 10%, which is a disadvantage of this system.

2. Vehicle-Mounted Roll Control System

(U) A more versatile system, particularly for upper-stage applications, is shown schematically in Figure IV-3, and utilizes small rockets mounted on the vehicle skirt. During engine operation, these rockets receive bipropellants bled from the main engine pumps. While the engine is shut down the rockets receive propellants from low-pressure (150 to 350 psi) storage accumulators that are recharged during engine firings.

(U) A pair of opposing rockets is mounted on each of two sides of the vehicle stage, at a moment arm of approximately 5 ft (typical). For the specified moment of 1600 ft-lb, a total thrust of 320 lb is required, or 160 lb each for two-rocket operation. (Standard 100-lb rockets could be used by using three pair instead of two.) A nominal chamber pressure of 100 psia was selected for the following reasons:

a. It is the standard pressure for most of the control rockets of this type either already developed or being developed.

b. Chamber and nozzle cooling requirements are less critical at low pressure.

c. If maximum available pressures were used in the rockets, they would be tapped directly off the main engine pumps, and the pressure would consequently decrease greatly, by a ratio of 5000/350 psi, during engine throttling; however, the low-pressure bleed system, described in Section IV,F, permits better pressure regulation. The chamber pressure of the roll control rockets will vary less than 50% with the latter system.

d. Low-pressure rockets permit use of relatively low-pressure accumulators as their source of propellant between engine firings; the low pressure permits accumulator recharge capability even at 10% thrust operation of the engine.

(U) From the discussion above, it is evident that a throttlable type of control rocket is required. Its control valves are on-off, but since the supply pressures will decrease at times, the injector and chamber must be capable of operating at reduced thrust and flow rates. A throttlable control rocket meeting these requirements is being developed by Aerojet under Contract NAS8-20795. By use of the Aerojet HIPERTHIN injector concept, the 100-lb-thrust rockets are throttlable 4:1, weigh 7.5 lb without valves, and deliver an $I_s$ vac of 290 to 300 sec at a mixture ratio of 1.6. The long life (25 hr) chamber is cooled by fuel-film cooling in combination with bimetallic regenerative conduction (Inconel lining, clad with copper). The nozzle has an expansion ratio of 50:1 and is radiation cooled. The controls are Moog bipropellant solenoid-operated valves.

(U) With adequate capacity in the propellant storage accumulators, additional rockets of the same type as above can be used for complete attitude control and as settling rockets prior to starting the ARES engine in space. These rockets are included in the ARES IAPP system shown in the flow diagram in Figure IV-3.

(U) A mixture ratio of 1.6 was selected for the control rockets in the ARES system. This permits a reasonable excursion of mixture ratio during changes in the supply pressures, without leaving the fuel-rich region of operation; this is desirable because of the fuel-film cooling. By proper design of the system pressure regulation, any large changes of the mixture ratio of the control rockets will only be momentary and confined to transient changes during engine starting and throttling; the heat-sink capability of the above-described rockets can absorb a momentary increase in gas temperature.

## E. TANK PRESSURIZATION DESIGN

(U) Two systems were examined for pressurizing the propellant tanks from the engine: (1) an autogenous system, and (2) main tank injection.

### 1. Autogenous Pressurization System

(U) The autogenous pressurization system uses oxidizer-rich gas bled from the engine turbine exhaust for oxidizer tank pressurization, and uses fuel-rich gas from a small auxiliary gas generator for fuel tank pressurization. A schematic of this system is shown in Figure IV-2.

(U) A monopropellant rather than bipropellant gas generator was considered for the fuel pressurant, but a major disadvantage is that AeroZINE 50 is a poor monopropellant. Decomposition could be initiated with the proper catalyst but coking of the catalyst bed would be a problem, particularly at reduced operating pressures.

(U) Pressurant gases are cooled to approximately 300°F by means of heat exchangers in the engine propellant lines, as shown in the schematic. As an alternate, the oxidizer gas can be cooled by injecting liquid $N_2O_4$ directly into the gas. This system as shown can be designed to operate under engine throttling conditions.

(U) The major disadvantage of this autogenous system is that pressurization between engine firings requires a separate gas make-up system on the vehicle.

IV, D, Roll Control Design (cont.)

d. Low-pressure rockets permit use of relatively low-pressure accumulators as their source of propellant between engine firings; the low pressure permits accumulator recharge capability even at 10% thrust operation of the engine.

(U) From the discussion above, it is evident that a throttlable type of control rocket is required. Its control valves are on-off, but since the supply pressures will decrease at times, the injector and chamber must be capable of operating at reduced thrust and flow rates. A throttlable control rocket meeting these requirements is being developed by Aerojet under Contract NAS8-20795. By use of the Aerojet HIPERTHIN injector concept, the 100-lb-thrust rockets are throttlable 4:1, weigh 7.5 lb without valves, and deliver an $I_s$ vac of 290 to 300 sec at a mixture ratio of 1.6. The long life (25 hr) chamber is cooled by fuel-film cooling in combination with bimetallic regenerative conduction (Inconel lining, clad with copper). The nozzle has an expansion ratio of 50:1 and is radiation cooled. The controls are Moog bipropellant solenoid-operated valves.

(U) With adequate capacity in the propellant storage accumulators, additional rockets of the same type as above can be used for complete attitude control and as settling rockets prior to starting the ARES engine in space. These rockets are included in the ARES IAPP system shown in the flow diagram in Figure IV-3.

(U) A mixture ratio of 1.6 was selected for the control rockets in the ARES system. This permits a reasonable excursion of mixture ratio during changes in the supply pressures, without leaving the fuel-rich region of operation; this is desirable because of the fuel-film cooling. By proper design of the system pressure regulation, any large changes of the mixture ratio of the control rockets will only be momentary and confined to transient changes during engine starting and throttling; the heat-sink capability of the above-described rockets can absorb a momentary increase in gas temperature.

IV, Integrated Auxiliary Power Package (Task I) (cont.)

## E. TANK PRESSURIZATION DESIGN

(U) Two systems were examined for pressurizing the propellant tanks from the engine: (1) an autogenous system, and (2) main tank injection.

### 1. Autogenous Pressurization System

(U) The autogenous pressurization system uses oxidizer-rich gas bled from the engine turbine exhaust for oxidizer tank pressurization, and uses fuel-rich gas from a small auxiliary gas generator for fuel tank pressurization. A schematic of this system is shown in Figure IV-2.

(U) A monopropellant rather than bipropellant gas generator was considered for the fuel pressurant, but a major disadvantage is that AeroZINE 50 is a poor monopropellant. Decomposition could be initiated with the proper catalyst but coking of the catalyst bed would be a problem, particularly at reduced operating pressures.

(U) Pressurant gases are cooled to approximately 300°F by means of heat exchangers in the engine propellant lines, as shown in the schematic. As an alternate, the oxidizer gas can be cooled by injecting liquid $N_2O_4$ directly into the gas. This system as shown can be designed to operate under engine throttling conditions.

(U) The major disadvantage of this autogenous system is that pressurization between engine firings requires a separate gas make-up system on the vehicle.

2. Main Tank Injection

(U) This system uses propellants injected directly into the propellant tanks—fuel into the oxidizer tank and oxidizer into the fuel tank. The system shown in Figure IV-3 uses propellants supplied from the propellant accumulators for tank pressurization. Therefore, the system can operate when the engine is off. This system was selected for the IAPP because it can operate when the engine is off, it is light in weight, it has fast response and it can operate with low supply pressures.

(U) Two safe methods of injector are available: Aerojet-General Corporation under a company-sponsored program has demonstrated a subsurface injection method, and The Martin Company has demonstrated a solid stream, surface injection method (Reference 2). The latter method was selected because it was conducted with both small- and large-scale equipment, including full size, flight-weight, Titan Stage II tankage, and thereby providing quantitative design data that can be directly applied to the 100K ARES system.

(U) The selected MTI system is shown schematically in Figure IV-3. During engine firings, an almost continuous flow of the liquid pressurants from the engine will be required, with the approximate values as indicated on the schematic for the 100 and 10% thrust conditions. Between engine firings, and prior to restart, a flow of liquid pressurants from rechargeable accumulators located in the vehicle will be required to make up the loss in tank pressure as the gases cool down and partially condense. Most of the tank gases generated by the MTI system are products of combustion and noncondensable; however, a small percentage of condensable vapors will also be formed and these will tend to condense as the gas cools. In sizing the system, it was assumed that the tank pressure will decay by 50% during coast periods, and require corresponding make-up from the accumulators.

IV, E, Tank Pressurization Design (cont.)

(U) Several potential problems in the MTI system were investigated and resolved in The Martin Company program. The temperature of the tank gas increased during the pressurization process, but the use of solid stream injection, as opposed to a spray, kept this rise to a safe minimum and well within the capabilities (300°F maximum wall temperature) of the thin aluminum tankage used in the tests. Also, effects on the main propellant caused by soluble inerts, entrained vapors, moisture, and temperature increase were investigated and found to be well within allowable limits.

(U) Tank pressure control within a 3% variation was attained in the full-scale, 150-sec duration tests, including start, restart, and throttling simulations. This precise pressure control was obtained with a pulse-mode injection system that varies the frequency of the pulses to control the flow rate of liquid pressurant. A pulse system of this type was also selected for the ARES system, because a wide range of flow variation required for throttling can be accomplished without seriously changing the $\Delta P$ across the pressurant injector. This will improve the performance of the system and simplify the injector design requirements.

(U) An unknown area that was not tested was the operation of the system during a zero-gravity condition, with the possible hazard and change in performance characteristics. Until tests are conducted and possibly unique equipment is developed for zero-gravity injection, it is necessary to assume the tank propellant will be properly oriented just prior to and during MTI operation. Propellant can be oriented with the small settling rockets shown on the schematic in Figure IV-3, and the tanks repressurized in approximately 5 sec preceding the engine start or restart.

F. INTEGRATED SYSTEM

(U) The functional IAPP system for the 100K ARES is shown in Figure IV-3, along with values for the predicted pressures and flows of each subsystem at 100 and 10% thrust conditions. In the figure, those components shown below the vehicle/engine interface line will be engine-mounted hardware; their physical integration with the 100K ARES is shown in the engine external view in Figure IV-1. These engine-mounted components include the two gimbal actuators with their high-pressure fuel supply lines and low-pressure return lines. The remainder of the engine-mounted IAPP components are the two pump discharge bleed lines (one fuel and one oxidizer) with check valves, orifices, and vehicle interface connections to supply propellants to the vehicle Attitude Control System (ACS) and Main Tank Injection (MTI) System, and to recharge the IAPP accumulators. The engine-mounted tubing and fitting sizes are tabulated in Figure IV-1.

(U) The attitude control and tank pressurization systems are located on the vehicle and are supplied with propellants directly from the engine or from the fuel and oxidizer accumulators located on the vehicle. In the schematic in Figure IV-3, a simple system of check valves are added to semi-regulate the IAPP system pressures and to minimize variations in the total flows bled from the engine. The fuel and oxidizer accumulators provide propellants during coast periods. The overall system operation and typical design parameters are described briefly in the following paragraphs.

(U) A major portion (about 75%) of the design flow in each supply line is not expended in the IAPP system, but is used for pressure and flow regulation and returns to the suction lines through a bypass check valve. Proper regulation requires that this check valve be designed to be full open at 500 psia, and full closed at 400 psia. By this means, as the system pressure drops below 400 psia, either because the accumulator is charging or the engine is throttled below full thrust, the bypass flow ceases and is diverted into the system where it is needed.

(U) An isolation valve is located at each accumulator and will be closed only during long coast periods. Upstream of this valve is a relief check valve that bypasses to the suction line and is set at 900 psia cracking pressure; its purpose is two-fold: (1) to limit the accumulator pressure during lock-up, and (2) to provide a back-up system for pressure regulation at a higher but safe level should the 500-psi bypass check valve fail to open. The 900-psia relief valve will remain closed under normal operation and can be designed with minimum leakage, or it can be preceded by a burst diaphragm if zero leakage is required.

(U) Selection of final accumulator sizes should follow establishment of vehicle and mission requirements, and a detailed analysis of recharging times as a function of the mission thrust schedule. A preliminary analysis indicates that oxidizer and fuel accumulators of 2.0 $ft^3$ each (1.15 $ft^3$ liquid volume) will provide IAPP requirements for 300 sec during a coast period, equivalent to a total impulse of 48,000 lb-sec in the ACS, which is the subsystem that determines most of the IAPP requirements. From the empty condition this size of accumulator will fully recharge in 40 sec at full thrust engine operation, or half-recharge in 100 sec at 10% thrust.

(U) Pressure regulation in the system will be sufficient to maintain the following supply pressures in psia, to each of the IAPP subsystems:

| Vehicle Subsystems | 100% Thrust | 10% Thrust | Coast Periods |
|---|---|---|---|
| Attitude control system (2 nozzles operating) | 200 to 500 | 200 to 350 | 200 to 350 |
| Tank pressurization system | 200 to 800* | 200 to 350 | 200 to 350 |
| Engine Subsystem | | | |
| TVC-gimbal actuators | 2500 to 3000 | 200 to 350 | 200 to 350 |

*800 psia can occur in the vehicle system when the ACS is not operating and the accumulators are fully charged.

IV, F, Integrated System (cont.)

(U) The nominal flow of approximately 3 lb/sec required by the IAPP system from the fuel and oxidizer circuits in the engine will require an initial control valve adjustment on the engine to maintain rated thrust and mixture ratio. This adjustment can be made during engine acceptance testing, and it will result in a turbine temperature increase of approximately 20°F, with minor changes in pump discharge pressures.

(U) The predicted variation in IAPP flow from the nominal would be $\pm$ 0.5 lb/sec at the 100% thrust condition, with negligible effect (less than 0.5%) on engine thrust and mixture ratio.

## TABLE IV-I

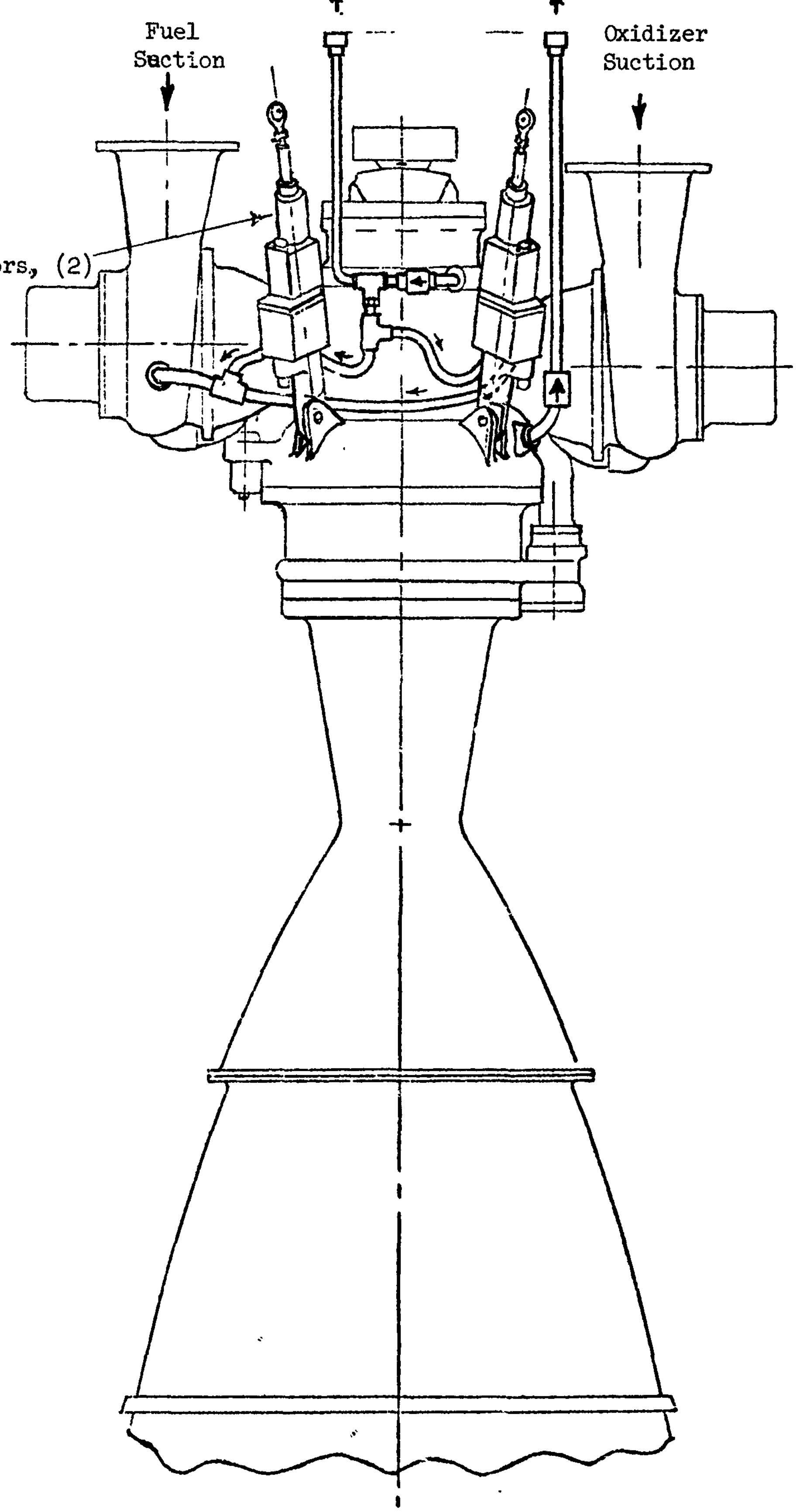
### IAPP REQUIREMENTS, CURRENT OPERATIONAL VEHICLES

| | | Titan II | | Gemini | | Titan IIIC | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1st Stg | 2nd Stg | 1st Stg | 2nd Stg | 1st Stg | 2nd Stg | Apollo | Transtage |
| Engine | | LR87AJ-5 | LR91AJ-5 | LR87AJ-7 | LR91AJ-7 | LR87AJ-9 | LR91AJ-9 | AJ10-137 | AJ10-138 |
| Thrust | lb | 430,000 | 100,000 | 430,000 | 100,000 | 430,000 | 100,000 | 20,000 | 16,000 |
| Nozzle Expansion Ratio | | 8:1 | 49:1 | 8:1 | 49:1 | 8:1 | 49:1 | 60:1 | 40:1 |
| TVC (all are gimbal type) | | | | | | | | | |
| Total Angle | deg | $\pm 5\frac{1}{2}$ | $\pm 4\frac{1}{2}$ | $\pm 5\frac{1}{2}$ | $\pm 4\frac{1}{2}$ | $\pm 5\frac{1}{2}$ | $\pm 4\frac{1}{2}$ | $\pm 9\frac{1}{2}$ | $\pm 9$ |
| Control Angle | deg | $\pm 4\frac{1}{2}$ | $\pm 3\frac{1}{2}$ | $\pm 4\frac{1}{2}$ | $\pm 3\frac{1}{2}$ | $\pm 4\frac{1}{2}$ | $\pm 3\frac{1}{2}$ | $\pm 8\frac{1}{2}$ | $\pm 5$ |
| Angular Acceleration | rad/sec$^2$ | 65 | 18 | 65 | 18 | 65 | 18 | 3 | 7.5 |
| Angular Velocity | deg/sec | 30 | 25 | 30 | 25 | 30 | 25 | 23 | 50 |
| Roll Control | | | | | | | | | |
| Method | | Gimbal | Swivel Nozzle | Gimbal | Swivel Nozzle | Gimbal | Swivel Nozzle | Fixed Thrusters | Fixed Thrusters |
| Source of Thrust | | Main Engines | Turbine Exhaust | Main Engines | Turbine Exhaust | Main Engines | Turbine Exhaust | $N_2O_4$/A-50 Rockets | Hydrazine Rockets |
| Roll Thrust | lb | 33,800 | 440 | 33,800 | 440 | 33,800 | 440 | 400 | 50 |
| Moment Arm | in. | 29.2 | 44 | 29.2 | 44 | 29.2 | 44 | 80 | 60 |
| Moment | ft-lb | 82,000 | 1,612 | 82,000 | 1,612 | 82,000 | 1,612 | 2,670 | 250 |

TABLE IV-I (cont.)

| | | Titan II | | Gemini | | Titan IIIC | | Apollo | Transtage |
|---|---|---|---|---|---|---|---|---|---|
| | | 1st Stg | 2nd Stg | 1st Stg | 2nd Stg | 1st Stg | 2nd Stg | | |
| **Tank Pressurization - Fuel** | | | | | | | | | |
| Method | | Autogenous | Autogenous | Autogenous | Autogenous | Autogenous | Autogenous | Blow down | Blow down |
| Gas Source | | Turbine Inlet | Turbine Inlet | Turbine Inlet | Turbine Inlet | Turbine Inlet | Turbine Inlet | Bottle | Bottle |
| Gas | | Fuel Rich A-50/$N_2O_4$ | Fuel Rich A-50/$N_2O_4$ | Fuel Rich A-50/$N_2O_4$ | Fuel Rich A-50/$N_2O_4$ | Fuel Rich A-50/$N_2O_4$ | Fuel Rich A-50/$N_2O_4$ | Helium | Helium |
| Gas Flow Rate | lb/sec | .681 | .299 | .650 | .291 | .717 | .333 | N/A | N/A |
| Gas/Propellant Ratio, $\dot{W}(gas)/\dot{W}(fuel)$ | | .00120 | .00259 | .00115 | .00254 | .00126 | .00291 | N/A | N/A |
| Gas Temp. | °F | 215 | 220 | 216 | 220 | 230 | 220 | N/A | N/A |
| Press. To Sonic Orifice | psia | 270 | 400 | 250 | 390 | 345 | 390 | N/A | N/A |
| Tank Top Pressure | psia | 26-23 | 45-50 | 26-23 | 45-50 | 27-24 | 51-56 | N/A | N/A |
| **Tank Pressurization - Oxidizer** | | | | | | | | | |
| Method | | Autogenous | Blow down | Autogenous | Blow down | Autogenous | Autogenous | Blow down | Blow down |
| Gas Source | | Ox.Pump | Bottle | Ox.Pump | Bottle | Ox.Pump | Ox.Pump | Bottle | Bottle |
| Gas | | $N_2O_4$ Vapor | Helium | $N_2O_4$ Vapor | Helium | $N_2O_4$ Vapor | $N_2O_4$ Vapor | Helium | Helium |
| Gas Flow Rate | lb/sec | 1.712 | N/A | 2.099 | N/A | 3.233 | .923 | N/A | N/A |
| Gas/Propellant Ratio, $\dot{W}(gas)/\dot{W}(oxid.)$ | | .00156 | N/A | .00191 | N/A | .00295 | .00443 | N/A | N/A |
| Gas Temp. | °F | 376 | N/A | N/A | N/A | 350 | 350 | N/A | N/A |
| Press. To Orifice, | psia | 450 | N/A | N/A | N/A | 600 | 450 | N/A | N/A |
| Tank Top Pressure | psia | 27-18 | 55-10 | 27-18 | 55-10 | 31-19 | 46-48 | N/A | N/A |

1




Thrust lbf

Engine gimbal
wet
Max. gimbal a
Max. gimbal v
Gimbal contro
Gimbal moment

Actuation pre
Actuator pist
Actuator cont
Actuator max.
snubbing,
Actuator leng

Weight, actua
Weight, total
lines & fit
Tubing & fitt
Actuator li
Vehicle IAI

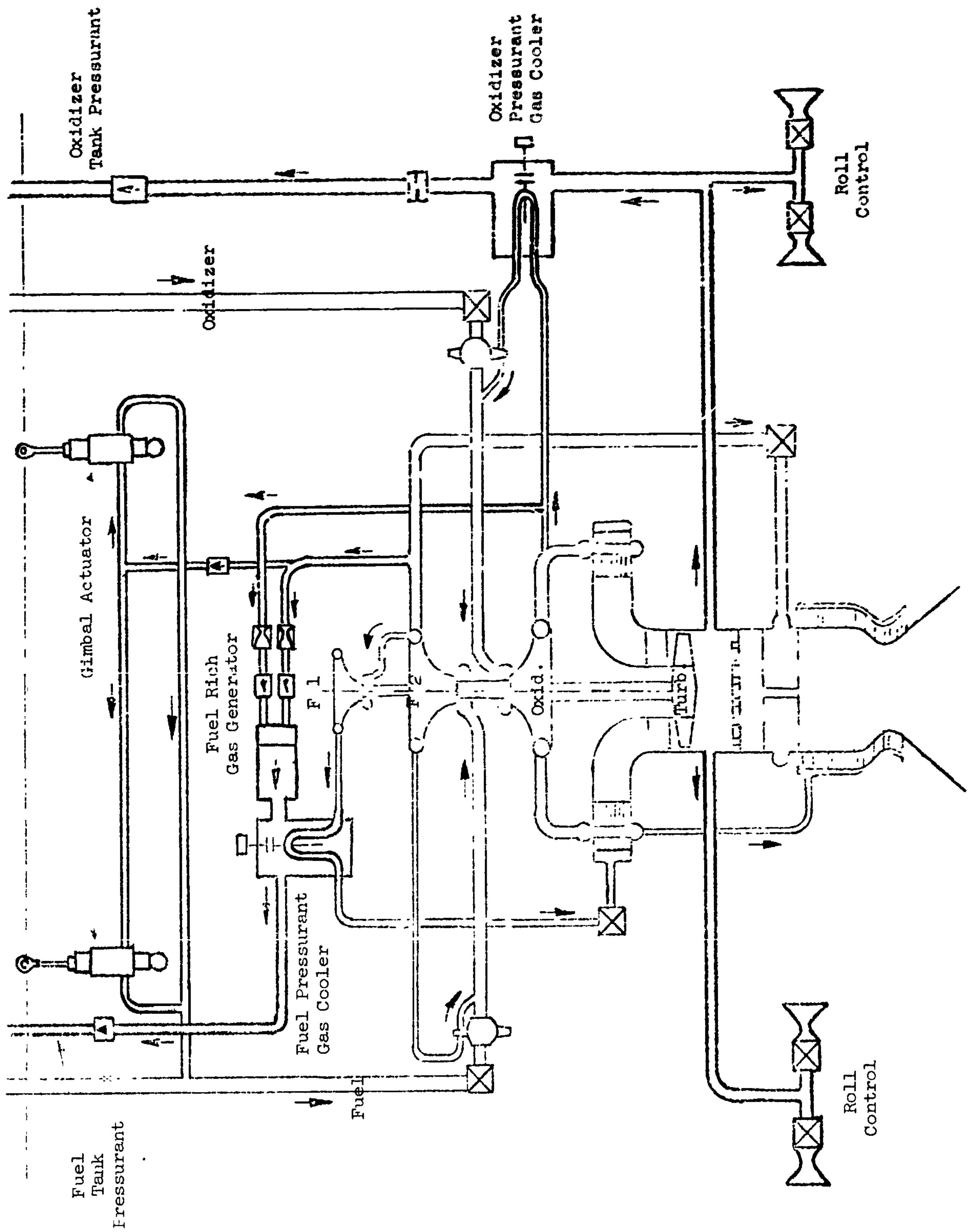
Actuator max.
flow demand
One actuato
Both actuat
Vehicle IAPP
sustained f
Fuel
Oxidizer

ARES ENGINE IAPP SPECIFICATION

| Thrust lbf | | 25K | 100K | 500K |
|---|---|---|---|---|
| Engine gimbal moment of inertia, wet | slug ft$^2$ | 13.9 | 176 | 4531 |
| Max. gimbal accel., | rad/sec$^2$ | 18 | 18 | 18 |
| Max. gimbal velocity, | deg/sec | 25 | 25 | 25 |
| Gimbal control angle, | deg | ±8 | ±5 | ±5 |
| Gimbal moment arm, | in | 5 | 10 | 24 |
| Actuation pressure, | psia | 3000 | 3000 | 3000 |
| Actuator piston area, net, | in$^2$ | 0.4 | 2.55 | 14.2 |
| Actuator control stroke, | in | 1.4 | 1.8 | 4.2 |
| Actuator max. stroke including snubbing, | in | 1.6 | 2.2 | 5.0 |
| Actuator length, | in | 12 | 18 | 36 |
| Weight, actuators (2) | lb | 16 | 30 | 230 |
| Weight, total engine IAPP lines & fittings | lb | 3 | 5 | 30 |
| Tubing & fitting size: | | | | |
| Actuator lines | in | 1/4 | 1/4 | 1/2 |
| Vehicle IAPP supply lines | in | 1/4 | 3/8 | 1 |
| Actuator max. momentary flow demand, fuel: | | | | |
| One actuator | lb/sec | .03 | .4 | 5.0 |
| Both actuators, | lb/sec | .04 | .6 | 7.0 |
| Vehicle IAPP interface, max. sustained flow demand: | | | | |
| Fuel | lb/sec | 1.2 | 2.6 | 28.5 |
| Oxidizer | lb/sec | 1.9 | 2.9 | 33.5 |

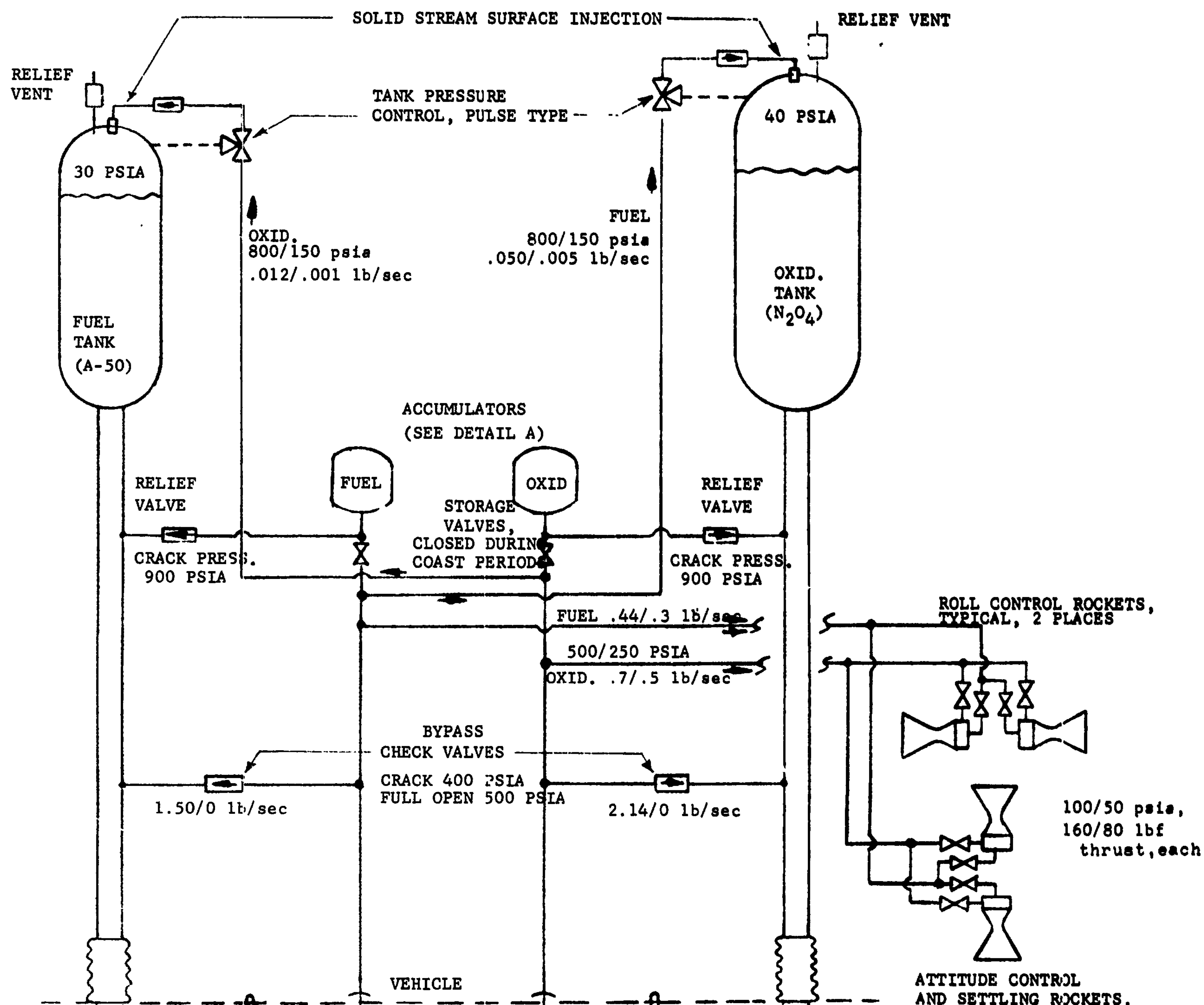
ARES External View with IAPP Specification

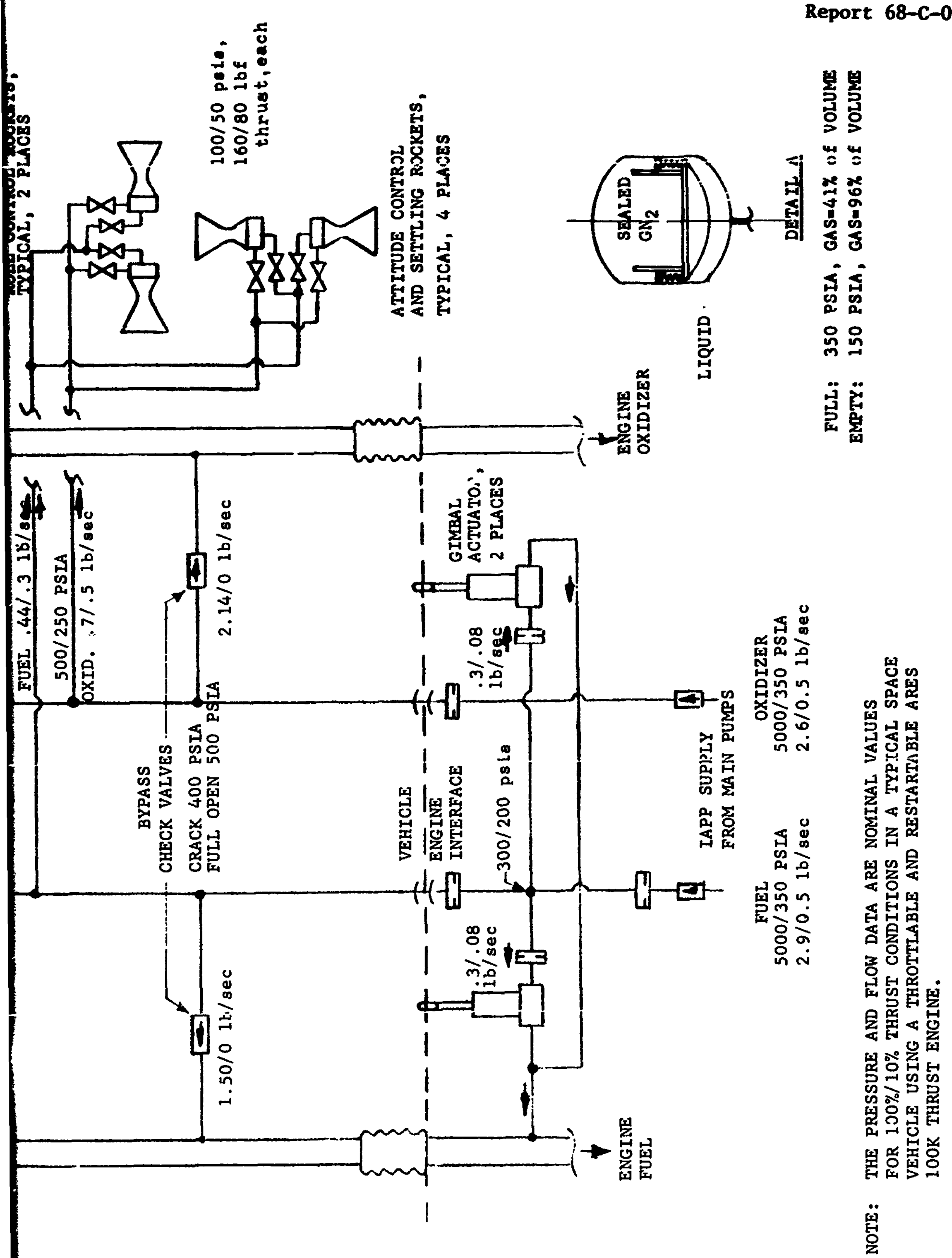
Figure IV-1




IAPP System Using Engine Gas

Figure IV-2


SOLID STREAM SURFACE INJECTION
RELIEF VENT
RELIEF VENT
TANK PRESSURE CONTROL, PULSE TYPE
30 PSIA
40 PSIA
OXID. 800/150 psia .012/.001 lb/sec
FUEL 800/150 psia .050/.005 lb/sec
FUEL TANK (A-50)
OXID. TANK ($N_2O_4$)
ACCUMULATORS (SEE DETAIL A)
FUEL
OXID
RELIEF VALVE
RELIEF VALVE
STORAGE VALVES, CLOSED DURING COAST PERIODS
CRACK PRESS. 900 PSIA
CRACK PRESS. 900 PSIA
ROLL CONTROL ROCKETS, TYPICAL, 2 PLACES
FUEL .44/.3 lb/sec
500/250 PSIA
OXID. .7/.5 lb/sec
BYPASS CHECK VALVES
CRACK 400 PSIA
FULL OPEN 500 PSIA
1.50/0 lb/sec
2.14/0 lb/sec
100/50 psia, 160/80 lbf thrust, each
VEHICLE
ATTITUDE CONTROL AND SETTLING ROCKETS.




IAPP System Using Engine Liquids

Figure IV-3

# V.

# LOW FREQUENCY ANALYSIS (TASK II)

## A. OBJECTIVES AND APPROACH

(U) A lumped-parameter low frequency stability analysis was conducted for the 100K ARES throttlable-restartable engine at eight throttle ratios for the turbulent injector configurations and at four throttle ratios for the laminar flow injector configurations. The analysis was conducted using the basic dynamic model and low frequency analysis computer program which was developed during the ARES Phase I effort on Contract AF 04(611)-10830. A new computer program was written for calculation of the coefficients of the system of ordinary differential equations which are used to represent the dynamic behavior of the engine system. This program takes as input the pressure and flow schedules for the engine and other characterizing parameters such as pump head curves, efficiencies and pump rotor moments of inertia, and as output, it punches the cards to be used with the stability analysis program.

## B. MATHEMATICAL MODEL

(U) A lumped-parameter mathematical model was used to describe the engine system. The system components are closely coupled and distributed characteristics, such as hydraulic line transmission delay, are assumed to be adequately approximated by lumped-parameter models for the frequency range of 0 to 500 cycles per second. Lumped-parameter elements are described mathematically by systems of ordinary differential equations. The general differential equations are nonlinear; however, the nonlinearities are removed by application of perturbation methods, resulting in a system of simultaneous linear differential equations with constant coefficients.

(U) The component arrangement is simulated by means of 75 simultaneous equations (33 differential equations and 42 algebraic relations). These equations represent the dynamic characteristics of the pumps, lines, valves, injectors, and combustors.

## C. STABILITY ANALYSIS

(U) The system of equations which represent the ARES engine are solved by Laplace transformation of the equations and subsequent use of Matrix methods, programed for digital computer, to obtain the "solution" in terms of the Laplace operator. Stability or instability of the system is easily determined at this point. The solution has the form of a ratio of two real and factored polynomials in the Laplace operator. The real-time solution, which can be obtained by inverse Laplace transformation for known input parameters, will be in the form of a sum of exponential terms formed from the roots of the denominator polynomial. The roots of the real polynomial are either real or appear as complex conjugate pairs. The real roots yield exponential terms in the transient while the complex conjugates produce sine and cosine terms multiplied by exponential decaying factors. The exponential factors in both cases will only decay if the real part of the roots of the denominator polynomial have negative real part. Hence, the stability criterion reduces to requiring that all roots of the denominator polynomial have a negative real part which is readily determined by inspection of the stability program output.

## D. RESULTS

(U) Stability analyses were made for the engine with turbulent injectors at eight throttle points: 100, 75, 50, 37.5, 25, 20, 15, and 10%, and for the laminar injector system at four throttle points: 100, 37.5, 20, and 10% of full thrust. Both engines were found to be stable at the design thrust; however, the turbulent injector system was found to be unstable at 15 and 10% of design thrust and the laminar injector system was found to be unstable at 10% of design thrust. The laminar injector system was only slightly more stable (compared to turbulent); the laminar system was estimated to become unstable at 15% of full thrust while the turbulent injector system was estimated to become unstable at 18% of full thrust.

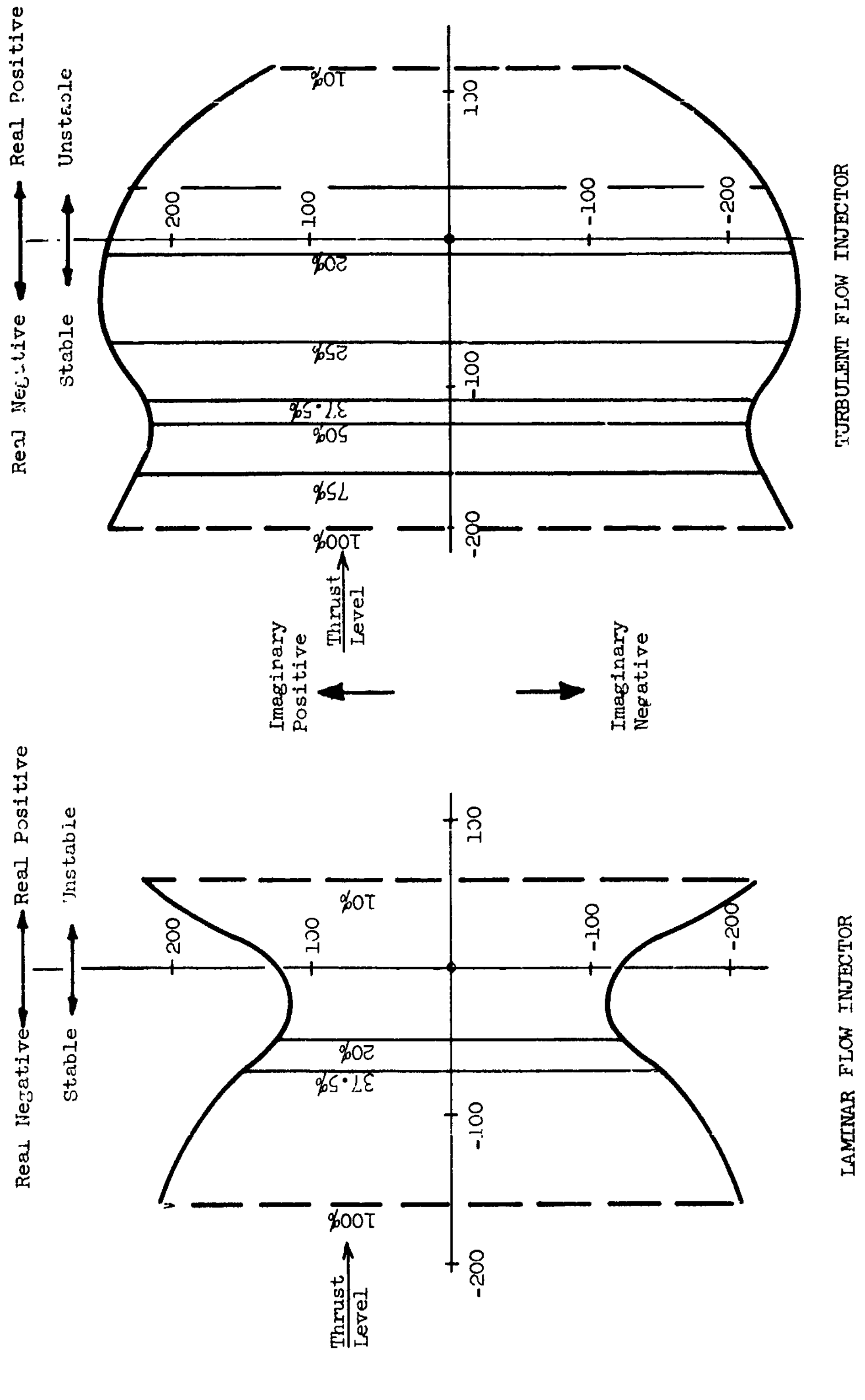
E. ENGINE SYSTEM CHANGES

(U) Several engine parameters were varied in attempts to obtain a stable configuration at the 10% thrust point. The following modifications were tried: increased hydraulic resistances in boost pump drive lines, primary fuel and oxidizer injectors, and secondary fuel and oxidizer injectors; increased boost pump and main pump rotor moments of inertia; eliminated the volume of turbine exhaust duct; eliminated unburned propellant storage terms in primary and secondary combustors; and increased the negative slopes of pump characteristics for the first-stage main fuel pump, second-stage fuel pump, and oxidizer main stage. The only changes that had a significant stabilizing effect were increasing the primary combustor oxidizer injector pressure drop and increasing the oxidizer pump characteristic slope. Doubling of the primary combustor oxidizer injector pressure drop was not sufficient to stabilize the engine. The oxidizer pump characteristic slope at the 10% thrust point was steepened from the design value of 0.0 to -0.1, -0.44, and -0.73. The change to -0.73 was sufficient to stabilize the system while the changes to -0.1 and -0.44 were not. It should be noted that the variation of this slope was from -0.65 at full thrust to -0.33 at 20% thrust to 0.0 at 10% originally. Thus, the change from 0.0 to -0.73 at the 10% thrust point is substantial and would probably be difficult to achieve physically. A better solution would be to increase pressure drops throughout the system in addition to changes to the pump characteristic. The necessary change in pump characteristic slope could be achieved by a bypass or recirculation arrangement for the oxidizer pump such that the operating point at low thrust is shifted to higher flow rate.

(U) The real and imaginary parts of the root that produced the instability are plotted in Figure V-1 as a function of the operating thrust level. The point at which the real part of the root becomes positive can be clearly determined.

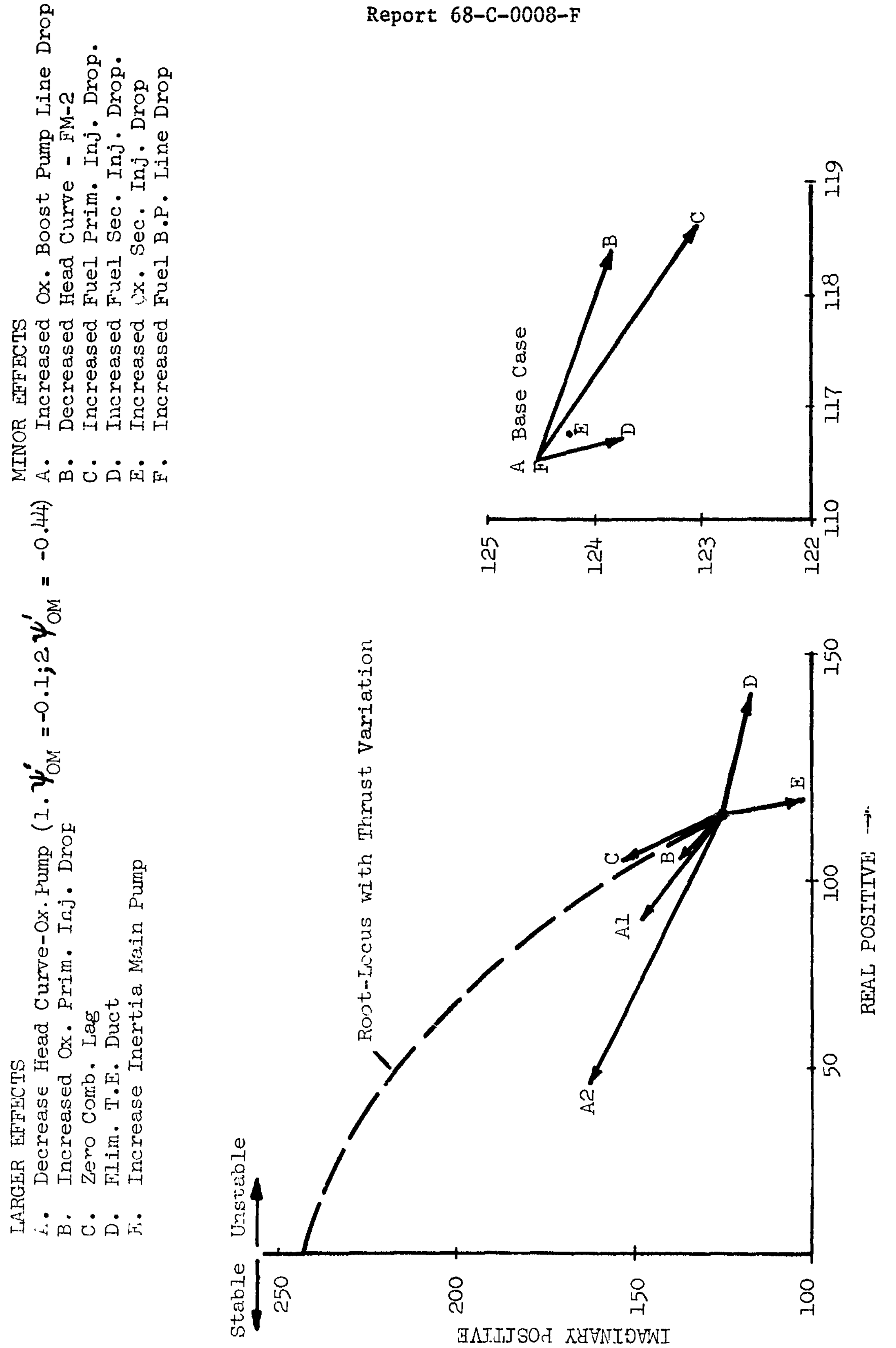
V, E, Engine System Changes (cont.)

(U) The results of the various changes which were made at the 10% thrust point for the turbulent injector configuration are shown in Figure V-2. The arrows indicate the effect which the identified change had on the real and imaginary parts of the offending denominator root. Each change also produced effects in other roots, but in all cases the real parts of all other roots remained negative so that stability was not affected. Some of the changes produced destabilizing effects while the change in the oxidizer pump head curve had the most significant effect and was the only change which resulted in a stable system.




ARES Throttling Stability

Figure V-1




Stabilizing Effects of Engine Changes

Figure V-2

# VI.

# 25K ENGINE DESIGN (TASK III)

## A. OBJECTIVES AND APPROACH

(U) The objectives of Task III were to establish the thrust chamber pressure and establish an engine design based on the established pressure for a throttlable, restartable engine having a throttle range of 10:1 and a vacuum thrust of 25,000 lbf using a nozzle with a 150:1 area expansion ratio.

(U) The approach to accomplishing these objectives was to (1) analyze the heat transfer, performance and payload effects of thrust chamber pressure to establish the chamber pressure; (2) use the established pressure and establish design criteria and operating characteristics over the throttling range; and (3) prepare a 25K thrust (vacuum) engine design on the basis of these criteria, and similar to the 100K base-line design. The results of this task are described in the following paragraphs.

## B. CHAMBER PRESSURE OPTIMIZATION

(U) To maximize the performance potential of a 25K engine design it was desirable to consider a range of chamber pressures, particularly because of the inherent increase in cooling requirements associated with the smaller chamber geometry. In recognition of the relative importance of performance factors other than cooling losses, such as energy release and recombination or kinetic losses, the study took into account the variation of all performance factors with chamber pressure and geometry. Additionally, the effects of chamber length and weight on vehicle payload were considered.

(C) The analysis was performed at each of three chamber pressures: 500, 1600, and 2800 psia. The basic chamber design approach adhered to at all pressures was to determine the throat diameter for an estimated performance level and then establish a family of cylindrical chambers of various contraction ratios ($A_{inj}/A_{throat}$), each with varying cylindrical length, and blend radii equal to the throat diameter connected by a 30-degree convergence angle.

(U) Minimum-length RAO nozzle contours were similar for each pressure and were established at an expansion ratio of 150:1 by Aerojet computer program 1025. Nozzle geometrical efficiencies were also determined with this same program.

(U) Cooling requirements for each chamber were computed using a one-dimensional fin conduction model in association with the Stollery & El-Ehwany boundary layer mixing model for film cooling (Reference 3). This is the same technique presently used on all transpiration cooling analyses on the ARES chambers. All remaining chamber design and analysis followed the same ground rules as does the ARES chamber, including the use of 0.021-in. platelets at area ratios (chamber and nozzle) greater than 2.3, and 0.011-in. platelets at all other points. Because of the variation in chamber pressure and, hence, the nozzle cooling requirements, each nozzle was assumed to be cooled to a point where the gas pressure was 30 psia. Consequently, each chamber has a different cooled length. The selection of this nozzle extension attachment point is based on experience with the Transtage nozzle and the ARES transpiration-cooled chamber. The ARES nozzle extension is similar in design to the nozzle on the Apollo service module engine, which is shown in Figure III-4. The upper portion of the Apollo nozzle is columbium alloy C-103 with a ceramic-aluminide coating to inhibit oxidation. This upper portion of the nozzle operates with a wall temperature of 1950°F at a static pressure of 2.4 psia. A similar nozzle configuration for the Transtage engine has demonstrated an accumulative duration of 4397 sec with 205 restarts without failure at a wall temperature of 2200°F and static pressure of 2.2 psia.

(U) The ARES nozzle extension is film cooled by the carry-over from the transpiration-cooled chamber and nozzle. Testing experience on the ARES program has shown that this coolant carry-over significantly lowers the extension nozzle temperature. This permits attachment of the nozzle extension at a higher static pressure. The value of static pressure where the nozzle extension can be attached must be determined experimentally. For this study, it was assumed that the nozzle extension could be attached at a static pressure of 30 psia.

(U) The boundary layer losses were calculated by Aerojet computer program E-25202 and include the effects of shear drag, heat transfer, and displacement thickness.

(U) The energy release loss calculation for each injector/chamber combination assumed that injector and propellant conditions could be achieved which equal those of the ARES chamber. These conditions include injection density, propellant atomization characteristics, and transport properties. With all of these effects constant, the energy release loss becomes only a function of changes in chamber geometry and chamber pressure.

(U) The kinetic or finite rate performance losses were calculated using the Kushida sudden freezing criteria (Reference 4) and were only a function of chamber pressure with the nozzles and gas condition being similar.

VI, B, Chamber Pressure Optimization (cont.)

(C) The effect on weight of changes in chamber geometry was also considered in the optimization as the basic performance of the thrust chamber is only important to the extent that it contributes to the overall vehicle performance. Changes in weight from a nominal chamber used in previous scaling studies were calculated assuming 1-in.-thick chamber walls of stainless steel. The nominal chamber at each pressure was a 40L* cylindrical chamber with a 30-degree convergent section and a cylindrical length such that a chamber L/D (length-to-throat/chamber diameter) of 1.5 was achieved. Weight changes were converted to equivalent $I_s$ using 30 lb of payload per second of $I_s$ exchange ratio. Nozzle length was converted to payload at the rate of 1 lb/in. These numbers are representative of a synchronous equatorial orbit with a pump-fed engine powered Transtage.

(U) The analysis at each chamber pressure was carried out in the following manner. Three values of chamber contraction ratio were selected and the sum of cooling, energy release, and weight losses determined as a function of cylindrical length. Examination of this result together with the optimum cylindrical length versus contraction ratio and the sum of the losses at the optimum length versus contraction ratio led to the selection of a large contraction ratio, zero cylindrical length chamber at each chamber pressure. It must be recognized that for physical reasons, these chamber configurations would not be the ones selected for actual design. For the purpose of optimizing chamber pressure, however, while not evaluating absolute performance level, any group of chambers consistant with each other is adequate.

(C) The individual losses and the resulting delivered specific impulses are shown in Figure VI-1 as a function of thrust chamber pressure. This figure shows an optimum pressure at some point between 1500 and 2000 psia. The advantage, however, is sufficiently small that other factors must be considered. For this reason, the overall engine weight and length were taken into account to determine the effect of chamber pressure on vehicle payload. The changes in weight and length for the selected geometries were based on the same nominal design described above and used the engine lengths and weights from the engine scaling studies. Again, the validity of those weights and lengths is not critical to the optimization. Length and weight were converted to payload on the basis of one-pound-payload/pound-engine and one-pound-payload/inch-engine (interstage structure). The results of this study are shown in Figure VI-2, which shows an advantage for the higher chamber pressures. The advantage is 47 lb of payload over the 1600-psia chamber pressure while the nominal payload for the aforementioned mission is approximately 3700 lb.

(C) Evaluation of the effect of throttling on engine performance is represented by Figure VI-3 which shows that delivered specific impulse is reduced as the engine is throttled; however, the magnitude of this reduction is less for the engine designed to operate at 2800 psia.

(C) On the basis of this study, the engine was designed to operate with a 2800-psia chamber pressure, since this resulted in the highest payload, minimum throttling performance degradation, and near maximum delivered specific impulse.

## C. DESCRIPTION

### 1. Performance Rating

(C) The 25K engine operating parameters are tabulated below.

| | |
|---|---|
| Thrust, vacuum, lbf | 25,000 |
| Specific impulse, predicted, sec | 324.6 |
| Specific impulse efficiency, % | 90.5 |

VI, C, Description (cont.)

| | |
|---|---|
| Nozzle area expansion ratio (RAO) | 150:1 |
| Propellants | $N_2O_4$/AeroZINE 50 |
| Chamber pressure, psia | 2800 |
| Mixture ratio, injector | 2.2 |
| NPSH, fuel, ft | 20 |
| NPSH, oxidizer, ft | 20 |

(U) The specific impulse efficiency (percent of theoretical) of the 25K engine is less than that of the 100K engine, for a given development level because the losses in the smaller nozzle are higher and a higher proportion of coolant is required to maintain the same wall temperature in the smaller chamber.

2. Layout Design

(C) A layout design of the 25K thrust engine with a 150:1 area ratio RAO contour nozzle is shown in Figure VI-4.

(U) Engine and component design criteria were established such that critical design parameters would reflect a similar degree of conservatism as in the 100K base-line engine design; e.g., similar values for primary combustor gas temperature, bearing seal velocity, shaft stress, and chamber wall temperatures were used. The 25K engine functional operation and its start and shutdown sequence are identical to those of the 100K base-line engine.

(C) The platelet injector concept currently being tested in the ARES program, and already described in Section III,B,3 and Figure III-3, was selected for the 25K engine. Injector parameters for the 25K design are as follows:

VI, C, Description (cont.)

| | |
|---|---|
| $\dot{w}_F$, lb/sec | 84.1 |
| Injector blade length, total, in. | 240.0 |
| $\dot{w}_F$/blade length, lb/sec/in. | 0.35 |
| $\dot{w}_{gas}$ injector, lb/sec | 248. |
| Net gas area, $in.^2$ | 42.5 |
| Average gas flow, lb/sec/$in.^2$ | 5.84 |
| Gross area, $in.^2$ | 72.5 (ref) |
| Blade area, total, $in.^2$ | 30.0 (ref) |

(U) An external envelope drawing of the engine is shown in Figure VI-5. The engine portion of the IAPP for the 25K design is defined in Figure IV-1, in which the dimensions for the gimbal actuators, etc., were scaled from the 100K design.

D. ENGINE THROTTLING PERFORMANCE

(U) Engine thrust is controlled in the same manner as the 100K baseline engine. Some of the engine and component performance parameters are plotted in Figure VI-6, with a major list of the operating parameters shown in Table VI-I. The format of Table VI-I is the same as for the 100K engine, with the symbols defined in Table III-IV.

(U) The throttling characteristics of the 25K thrust engine are also similar to those already described for the 100K engine. As in the 100K engine, the laminar flow characteristics designed into the transpiration film coolant circuit maintain the coolant flow at a constant percentage of total flow during throttling. Also, the injector $\Delta P$'s stay at a reasonable percentage of chamber pressure, due to laminar flow design of the injectors.

VI, D, Engine Throttling Performance (cont.)

(U) The pump design efficiencies are six points lower, and the turbine efficiency three points lower, than those of the 100K baseline ARES, due to the smaller size and flows of the 25K engine. The turbine operating temperature was maintained at the 100K engine range (1200°F) by increasing the turbine pressure ratio and the pump discharge pressures.

## E. WEIGHT BREAKDOWN

(U) Calculated dry weight and gimbal moment of inertia values for the 25K engine are shown by component in Table VI-II. Wet weight and inertia values are also shown. Estimated weight and gimbal moment of inertia values for a lower weight production prototype engine are shown in Table VI-III. The lower weight of this production prototype engine, as in the 100K engine, is achieved by using two interface joints between the thrust chamber and turbopump in place of the three as shown in Figure VI-4.

## TABLE VI-I

### THROTTLING PERFORMANCE, 25K ARES (u)

| | 100% F CASE 1 | 75% F CASE 2 | 50% F CASE 3 | 37.5% F CASE 4 | 25% F CASE 5 | 20% F CASE 6 | 15% F CASE 7 | 10% F CASE 8 |
|---|---|---|---|---|---|---|---|---|
| F | [illegible] | [illegible] | [illegible] | [illegible] | 4261.75000 | 5012.58085 | 3787.64575 | [illegible] |
| PCSC | 2799.99997 | 2100.24261 | 1401.45580 | 1051.85179 | 705.24529 | 566.33497 | 426.63737 | 286.49327 |
| MR-ENG | 2.46508 | 2.48408 | 2.48732 | 2.47888 | 2.46218 | 2.46362 | 2.46645 | 2.58003 |
| IS | 324.82632 | 323.29837 | 321.38039 | 320.08736 | 318.02296 | 316.60640 | 314.60619 | 309.57193 |
| W-ENG | [illegible] | [illegible] | 38.97689 | 29.31575 | 19.68962 | 15.83253 | 11.94397 | 8.09774 |
| WOT | [illegible] | 41.41180 | 27.79567 | 20.09211 | 14.00370 | 11.26053 | 8.49772 | [illegible] |
| WFT | [illegible] | 16.87092 | 11.17493 | 8.42804 | 5.68793 | 4.57073 | 3.44532 | [illegible] |
| NT | 64000.16211 | 52084.92725 | 39482.32471 | 32700.99707 | 25417.01929 | 22211.36450 | 18748.43994 | 14815.31970 |
| TTIT | 1200.15847 | 973.73698 | 730.65012 | 595.90288 | 471.18681 | 441.21733 | 405.73026 | 349.70808 |
| RPT | 1.66596 | 1.54410 | 1.42288 | 1.36134 | 1.29669 | 1.27018 | 1.24041 | 1.20952 |
| PODTM | | | | | | | | |
| PODTM | [illegible] | 3770.51590 | 2305.63733 | 1647.48199 | 1048.45432 | 821.85120 | 605.21882 | 396.42069 |
| DPOH1 | [illegible] | [illegible] | 13.22488 | 7.48274 | 3.36203 | 2.17236 | 1.23508 | [illegible] |
| DPORG | 48.84790 | 28.12534 | 12.72684 | 7.19711 | 3.23013 | 2.08730 | 1.18645 | .55946 |
| DPOH2 | 49.50122 | 28.49414 | 12.89124 | 7.28957 | 3.27145 | 2.11398 | 1.20159 | .56660 |
| DPOJPC | 197.22449 | 156.45999 | 109.20441 | 83.38278 | 56.65196 | 45.77853 | 34.70306 | 23.97437 |
| PCPC | [illegible] | 3628.21099 | 2187.58997 | 1842.12979 | 981.93872 | 769.69904 | 566.89263 | 376.72829 |
| PFDTM1 | [illegible] | 2875.15875 | 2232.42721 | 1865.48826 | 997.69914 | 777.69170 | 567.70531 | [illegible] |
| DPSCVI | 116.83649 | 70.09412 | 33.74326 | 19.95631 | 9.46913 | 6.21798 | 3.60512 | 1.59624 |
| DPFSCV | 1880.60275 | 1123.07040 | 538.74269 | 318.19859 | 190.83096 | 99.01344 | 57.39256 | 25.40689 |
| DPSCVO | 117.06381 | 69.88873 | 33.51860 | 19.79550 | 9.38278 | 6.15923 | 3.57011 | 1.58042 |
| DPFJSC | [illegible] | [illegible] | 182.42276 | 143.79402 | 181.36175 | 82.77376 | 63.54866 | [illegible] |
| PCFACE | [illegible] | [illegible] | 1444.00000 | 1083.78302 | 726.65482 | 583.52728 | 439.56886 | 295.19039 |
| PFDTM2 | 6008.36731 | 4318.92096 | 2667.89813 | 1905.74225 | 1202.02121 | 936.70424 | 683.46577 | 440.28264 |
| DPFPCV | 499.98291 | 532.97052 | 367.04153 | 269.88712 | 168.61777 | 127 15430 | 89.88260 | 54.16312 |
| DPPCVO | 46.38031 | 17.22122 | 5.33405 | 2.35493 | .78186 | .43670 | .20399 | .06561 |
| DPFJPC | [illegible] | [illegible] | 120.39502 | 83.01884 | 48.60405 | 36.69305 | 25.35863 | [illegible] |
| PCPC | [illegible] | [illegible] | 2187.58997 | 1842.12979 | 981.93872 | 769.69904 | 566.89263 | [illegible] |
| PTIT | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| PTET | 3023.01273 | 2249.67050 | 1488.52507 | 1112.19835 | 741.76292 | 594.30793 | 446.80759 | 299.33551 |
| PGJT | 3009.29245 | 2240.78519 | 1483.6494[illegible] | 1108.87325 | 740.20250 | 593.28600 | 446.05981 | 298.89373 |
| PCFACE | 2865.00000 | 2164.00000 | 1444.00000 | 1083.78302 | 726.65482 | 583.52728 | 439.56886 | 295.19039 |
| KWFSCV | [illegible] | .43736 | .43736 | .43736 | .43736 | .43736 | .43736 | [illegible] |
| KWFPCV | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | .04186 | [illegible] | [illegible] |
| KWOPCV | 5.72140 | 5.72140 | 5.72140 | 5.72140 | 5.72140 | 5.72140 | 5.72140 | 5.72140 |
| KWFCV | .09710 | .09174 | .08341 | .07722 | .06828 | .06351 | .05726 | .04949 |
| KWRGV | | | | | | | | |

NOTE: Values less than unity have their decimal location noted by prefix. Example: '-5' indicates decimal point is 5 places to the left of first digit. No prefix and no decimal point indicate decimal precedes first digit.

TABLE VI-I (cont.)

| | 100% F CASE 1 | 75% F CASE 2 | 50% F CASE 3 | 37.5% F CASE 4 | 25% F CASE 5 | 20% F CASE 6 | 15% F CASE 7 | 10% F CASE 8 |
|---|---|---|---|---|---|---|---|---|
| F | [illegible] | 18779.78809 | 18126.40710 | 9283.60610 | 6261.78000 | 5612.68085 | 3757.64578 | 2506.[illegible] |
| DP/PSF | .10396 | .11465 | .12633 | .13264 | .13949 | .14185 | .14476 | .14438 |
| DP/PPO | .03874 | .04435 | .05061 | .05407 | .05769 | .05948 | .06122 | .06467 |
| DP/PPF | .05893 | .05820 | .05580 | .05319 | .04950 | .04767 | .04473 | .03923 |
| PCSC | [illegible] | [illegible].24861 | 1401.45580 | 1131.65179 | 768.24829 | 666.33497 | 426.63737 | 286.49387 |
| MRJC | [illegible] | 2.21790 | 2.22085 | 2.21299 | 2.19744 | 2.19892 | 2.26186 | 2.30672 |
| AE/AT | 150.00000 | 150.00000 | 150.00000 | 150.00000 | 150.00000 | 150.00000 | 150.00000 | 150.00000 |
| ETAC | .95472 | .95278 | .95081 | .94993 | .94894 | .94851 | .94813 | .94782 |
| ETAN | .94870 | .94693 | .94339 | .94007 | .93425 | .93047 | .92493 | .91601 |
| C*SC | [illegible] | [illegible].60237 | 5372.96363 | 5361.88017 | 5352.29128 | 5345.14880 | 5337.61328 | 5284.[illegible] |
| CF | [illegible] | 1.92626 | 1.92449 | 1.92088 | 1.91172 | 1.90575 | 1.89658 | 1.8[illegible] |
| WGJSC | [illegible] | 35.77048 | 26.37399 | 19.68818 | 13.09296 | 10.49768 | 7.88936 | 5.39638 |
| WFJSC | 17.92542 | 13.87375 | 9.61866 | 7.39412 | 5.09176 | 4.125-9 | 3.14100 | 2.08987 |
| WOFC | 8.88779 | 4.43854 | 2.97795 | 2.24086 | 1.50651 | 1.20989 | .91269 | .61948 |
| WFC/WT | .07660 | .07641 | .07640 | .07644 | .07651 | .07642 | .07641 | .07650 |
| WORG | [illegible] | 36.60893 | 24.85046 | 18.43488 | 12.33338 | 9.90923 | 7.46745 | 5.12581 |
| DPFJSC | [illegible] | 246.18850 | 182.42276 | 143.78482 | 101.38175 | 82.77376 | 63.[illegible] | 42.[illegible] |
| DPOFC | [illegible] | 541.95885 | 890.95645 | 468.14746 | 339.64760 | 263.34387 | 177.34637 | 109.[illegible] |
| DPORG | 48.84790 | 28.1253 | 12.72684 | 7.19711 | 3.23013 | 2.08730 | 1.18646 | .55946 |
| DTORG | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 |
| D*FJSC | 55.59731 | 55.80315 | 56.94952 | 55.99657 | 56.03644 | 56.04824 | 56.05553 | 56.06413 |
| D*OFC | [illegible] | [illegible] | 89.27879 | 89.38618 | 89.38470 | 89.38927 | 89.39255 | [illegible] |
| D*ORG | [illegible] | [illegible].83982 | 90.27734 | 90.06940 | 69.76835 | 69.47866 | 69.58343 | 69.[illegible] |
| MRPC | 11.29412 | 13.08787 | 15.77525 | 17.82992 | 20.70170 | 22.25586 | 24.53813 | 29.69833 |
| WOJPC | 48.46632 | 36.60893 | 24.55046 | 18.43458 | 12.33338 | 9.90923 | 7.46745 | 5.12581 |
| WFJPC | 4.28597 | 2.79717 | 1.55626 | 1.03391 | .59577 | .44524 | .30432 | .17260 |
| D*OJPC | [illegible] | [illegible] | [illegible] | [illegible] | 89.70088 | 89.62107 | 89.55248 | [illegible] |
| D*FJPC | [illegible] | [illegible].63414 | 56.02867 | 56.02820 | 56.04144 | 56.04385 | 56.08084 | 56.[illegible] |
| POT | [illegible] | [illegible] | 37.14[illegible] | 37.[illegible] | 37.14000 | 37.14000 | 37.14000 | 37.[illegible] |
| PFT | [illegible] | 17.81[illegible] | 17.81000 | 17.81000 | 17.81000 | 17.81000 | 17.81000 | 17.81[illegible] |
| NPSPOB | [illegible] | [illegible] | 17.79199 | 18.49838 | 19.04793 | 19.23213 | 19.36147 | 19.48[illegible] |
| NPSPFB | 7.79128 | 10.81904 | 12.98166 | 13.74866 | 14.30542 | 14.47259 | 14.60607 | 14.70851 |
| NPSPON | 123.00678 | 100.75850 | 80.27665 | 65.20826 | 49.99606 | 43.83071 | 37.84519 | 31.13608 |
| NPSPFN | 80.97785 | 64.26750 | 49.58131 | 40.85861 | 32.24320 | 28.71460 | 25.16275 | 21.57667 |

TABLE VI-I (cont.)

| | 100% F CASE 1 | 75% F CASE 2 | 50% F CASE 3 | 37.5% F CASE 4 | 25% F CASE 5 | 20% F CASE 6 | 15% F CASE 7 | 10% F CASE 8 |
|---|---|---|---|---|---|---|---|---|
| F | [illegible] | 16771.78809 | 12526.40710 | 9383.60610 | 6261.78000 | 5012.68065 | 3767.64578 | 504.83174 |
| ETAT | .72564 | .72549 | .72231 | .71711 | .70468 | .69508 | .67969 | .65541 |
| WTI | 51.69230 | 39.40610 | 26.10672 | 19.46849 | 12.92915 | 10.35447 | 7.77177 | 5.29841 |
| U/C-GT | .54328 | .52763 | .50209 | .48166 | .45078 | .43311 | .40985 | .38006 |
| SHPT | [illegible] | 1369.09427 | 564.96818 | 311.72626 | 140.23905 | 91.70989 | 63.55290 | 25.84937 |
| SHPDM | [illegible] | 786.06451 | 329.13715 | 181.53409 | 81.66267 | 53.27802 | 31.09936 | 14.80223 |
| SHPFM1 | [illegible] | 539.12665 | 225.96450 | 124.93926 | 56.47811 | 36.90675 | 21.61047 | 10.24848 |
| SHPFM2 | 45.54796 | 25.05564 | 10.07529 | 5.41076 | 2.39484 | 1.56513 | .92408 | .45181 |
| POSTM | 153.10170 | 127.62150 | 96.77939 | 83.54851 | 68.18425 | 61.95529 | 55.60124 | 49.10312 |
| PODTM | [illegible] | 3776.81590 | 2305.63733 | 1647.48199 | 1048.45432 | 821.85120 | 605.21882 | 396.42869 |
| HOMNC | [illegible] | 5471.12610 | 3555.09409 | 2518.93682 | 1578.46461 | 1223.60725 | 884.93159 | 659.13147 |
| QOSM | [illegible] | 229.13076 | 158.91356 | 118.61384 | 81.13690 | 66.05902 | 50.75557 | 35.73257 |
| HOM/N2 | -5 20803337 | -5 21641994 | -5 22805818 | -5 23555604 | -5 24433496 | -5 24802277 | -5 25175576 | -5 25471971 |
| Q/QDOM | .99990 | .93606 | .84026 | .77181 | .67925 | .63283 | .57604 | .51318 |
| ETAOM | .62000 | .61947 | .60956 | .59613 | .56804 | .54965 | .52329 | .48911 |
| NSD | [illegible] | 1178.47230 | 1070.79558 | 1001.65128 | 914.23475 | 872.58921 | 823.23677 | 770.23361 |
| SOM | [illegible] | 16364.94153 | 12855.94922 | 10856.20740 | 8510.26367 | 7413.96539 | 6161.14349 | 4701.31836 |
| D*OSM | [illegible] | 89.34751 | 89.38512 | 89.40491 | 89.42075 | 89.42736 | 89.43476 | 89.44866 |
| PFSTM1 | 83.86246 | 69.11011 | 52.38549 | 43.64533 | 35.01152 | 31.47621 | 27.91660 | 24.32261 |
| PFDTM1 | 5299.42944 | 3675.15875 | 2232.42731 | 1585.48825 | 997.69914 | 777.69170 | 567.70531 | 366.39335 |
| HFMNC1 | [illegible] | [illegible].10352 | 5597.48114 | 3955.64978 | 2471.42181 | 1915.30916 | 1385.15124 | 870.11916 |
| QFSM1 | [illegible] | 145.96775 | 99.62384 | 76.34619 | 52.98798 | 43.41138 | 33.70320 | 23.42496 |
| HF1/N2 | [illegible] | [illegible] | -5 35907648 | -5 36990980 | -5 38255625 | -5 38822936 | -5 39466417 | -5 40003874 |
| Q/QDF1 | 1.00012 | .93164 | .83899 | .77629 | .69319 | .64987 | .59773 | .52872 |
| ETAFM1 | .57000 | .56932 | .56048 | .54904 | .52675 | .51182 | .49080 | .45630 |
| NSF-1 | 712.73129 | 666.56663 | 608.96159 | 572.85065 | 527.84116 | 505.47300 | 479.37772 | 444.52902 |
| SFM1 | [illegible] | [illegible] | 10395.22839 | 8715.04504 | 6740.69806 | 5816.14618 | 4776.23468 | 3831.41[illegible] |
| D*FSM1 | [illegible] | 86.04613 | 86.06159 | 86.06816 | 86.07580 | 86.07611 | 86.08123 | 86.08[illegible] |
| PFSTM2 | 4953.82733 | 3478.56097 | 2142.54196 | 1533.52570 | 973.30561 | 761.86163 | 558.21326 | 361.98236 |
| PFDTM2 | 6008.36731 | 4318.92096 | 2667.89813 | 1905.74225 | 1202.02121 | 936.90424 | 683.46577 | 440.28264 |
| HFM2 | 2694.83807 | 2150.28159 | 1346.13214 | 954.46477 | 586.83280 | 449.96353 | 321.82092 | 201.03004 |
| QFSM2 | [illegible] | [illegible].44971 | 14.86431 | 10.42237 | 6.92416 | 5.72106 | 4.59636 | 3.[illegible] |
| HF2/N2 | [illegible] | [illegible]3128 | -6 86363950 | -6 89256100 | -6 90837491 | -6 91206717 | -6 91470058 | -6 91581687 |
| Q/QDF2 | [illegible] | .[illegible]840 | .55180 | .56213 | .48048 | .45436 | .43231 | .42168 |
| ETAFM2 | .49010 | .47859 | .44364 | .41820 | .38572 | .37387 | .36332 | .35806 |
| NSF-2 | 1030.43640 | 815.60048 | 678.46886 | 614.78660 | 560.94762 | 543.63215 | 529.31983 | 522.27174 |
| NT | 64060.16211 | 52084.92725 | 39482.32471 | 32700.99707 | 28417.01929 | 22211.36450 | 16748.43994 | 14815.81970 |

TABLE VI-I (cont.)

| | 100% F CASE 1 | 75% F CASE 2 | 50% F CASE 3 | 37.5% F CASE 4 | 25% F CASE 5 | 20% F CASE 6 | 15% F CASE 7 | 10% F CASE 8 |
|---|---|---|---|---|---|---|---|---|
| F | [illegible] | 18779.78809 | 12526.40710 | 9383.60010 | 6261.75000 | 5012.68085 | 3787.64575 | [illegible] |
| NTOB | [illegible] | 13946.21033 | 10752.71692 | 9041.58716 | 7194.34827 | 6377.14795 | [illegible] | 4344.09955 |
| WOSB | 54.75289 | 41.41186 | 27.79567 | 20.89211 | 14.00370 | 11.26053 | 8.49772 | 5.83724 |
| TOSB | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 |
| POSTB | 38.08461 | 33.08679 | 35.31399 | 36.10839 | 36.67652 | 36.84031 | 36.96933 | 37.08947 |
| PODTB | [illegible] | 129.35648 | 99.88290 | 84.01358 | 68.40187 | 62.09985 | 55.66640 | 49.14834 |
| HOBNC | [illegible] | 155.83289 | 103.40673 | 77.07722 | 51.04425 | 40.64065 | 30.11487 | [illegible] |
| QOSB | 274.58344 | 207.67070 | 139.38475 | 104.76498 | 70.22204 | 56.46619 | 42.61194 | 29.27088 |
| HOB/N2 | -6 71133687 | -6 79709741 | -6 89436000 | -6 94283712 | -6 98619752 | -6 99932463 | -5 10129762 | -5 10304253 |
| Q/QDOB | 1.02542 | .94536 | .82295 | .73561 | .61967 | .56213 | .49616 | .42777 |
| ETAOB | [illegible] | .88669 | .85940 | .82469 | .46923 | .43980 | .39966 | .38293 |
| SHPOB | [illegible] | 19.87953 | 9.35868 | 6.88013 | 2.76977 | 1.89189 | 1.16418 | [illegible] |
| SOB | [illegible] | [illegible] | 10296.99840 | 7262.81857 | 4484.95538 | 3662.64746 | 2699.34665 | [illegible] |
| PTITOB | 5209.73175 | 3614.05054 | 2211.03592 | 1580.51791 | 1006.53512 | 789.37332 | 581.74134 | 381.59288 |
| DPTOB | 5105.28162 | 3514.23453 | 2124.76129 | 1504.02286 | 941.51119 | 729.45794 | 527.29974 | 333.03478 |
| TTITOB | 99.06723 | 92.49846 | 86.98738 | 84.68819 | 82.52931 | 81.72102 | 80.86133 | 79.90439 |
| WTOB | [illegible] | 4.20370 | 3.25798 | 2.73681 | 2.16235 | 1.90232 | 1.61662 | 1.28428 |
| ETATOB | [illegible] | .46721 | .46631 | .46614 | .46649 | .46699 | .46736 | [illegible] |
| NTFB | [illegible] | [illegible] | 10780.34985 | 9069.22913 | 7228.72101 | 6403.91677 | 5471.73395 | [illegible] |
| WFSB | 22.21140 | 16.67092 | 11.17493 | 8.42804 | 5.68753 | 4.57073 | 3.44532 | 2.26246 |
| TFSB | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 |
| PFSTB | 10.50599 | 13.53293 | 15.69479 | 16.46156 | 17.01815 | 17.18527 | 17.31871 | 17.42112 |
| PFDTB | [illegible] | 73.63783 | 53.09728 | 44.06339 | 35.21292 | 31.61139 | 27.99809 | 24.36190 |
| HFBNC | [illegible] | 146.86420 | 96.00809 | 70.85055 | 46.70362 | 37.02994 | 27.41292 | [illegible] |
| QFSB | [illegible] | [illegible] | 89.40101 | 67.42519 | 45.50068 | 36.86417 | 27.86276 | [illegible] |
| HFB/N2 | -6 67887937 | -6 75187552 | -6 82611604 | [illegible] | [illegible] | [illegible] | -6 91558581 | [illegible] |
| Q/QDFB | .98720 | .90211 | .78321 | .70213 | .59446 | .53926 | .47573 | [illegible] |
| ETAFB | .58692 | .58007 | .54414 | .50970 | .45748 | .42649 | .38621 | [illegible] |
| SHPFB | [illegible] | 7.65961 | 3.58493 | 2.13004 | 1.05870 | .72156 | .44462 | [illegible] |
| SFB | [illegible] | [illegible] | 7349.58917 | 5143.31898 | 3248.91980 | 2573.56589 | 1896.03427 | [illegible] |
| PTITFB | [illegible] | [illegible] | 2146.14256 | [illegible] | 960.54823 | 748.90483 | 546.69087 | [illegible] |
| DPTFB | 5051.74194 | 3488.20126 | 2105.68121 | 1408.00710 | 928.21423 | 719.19554 | 520.01332 | 329.36840 |
| TTITFB | 98.20616 | 91.80148 | 86.39091 | 84.14728 | 81.86144 | 81.12515 | 80.26596 | 79.41399 |
| WTFB | 1.56083 | 1.28753 | .99948 | .83982 | .66308 | .58357 | .49617 | .39484 |
| ETATFB | [illegible] | .36702 | .36871 | .36877 | .36737 | .36849 | .36933 | [illegible] |
| SEALS/ WOTS | [illegible] | .26438 | .25786 | .21665 | .16381 | .14141 | .11787 | [illegible] |
| WOBOS | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 |
| WFBOS | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 |
| WFRTS | .27000 | .27000 | .27000 | .27000 | .27000 | .27000 | .27000 | .27000 |

Table VI-I, Page 4 of 4

TABLE VI-II

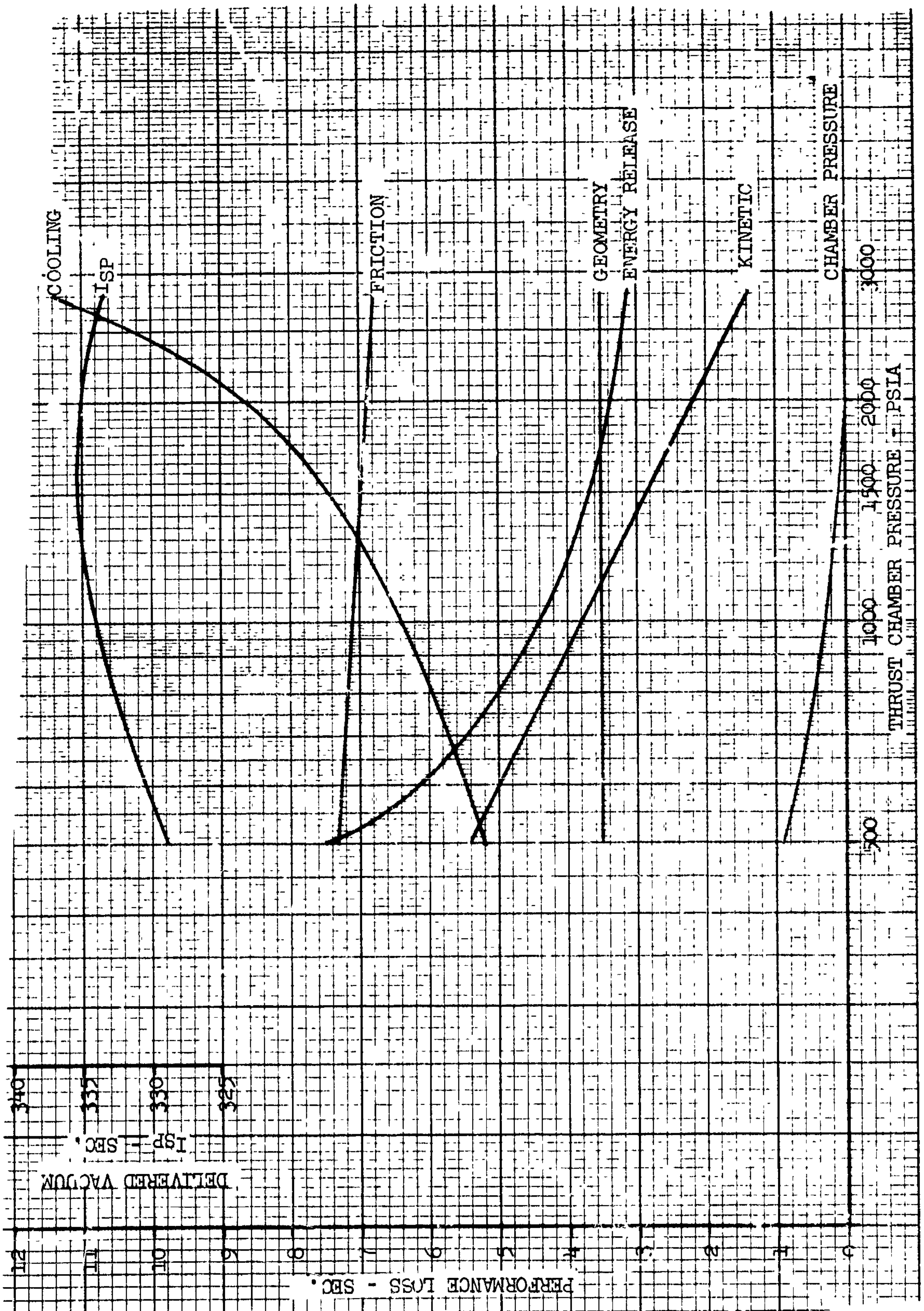
25K ARES WEIGHT AND INERTIA SUMMARY

| COMPONENT ASSEMBLY | Weight Pound | Moment of Inertia About Gimbal Slug Ft$^2$ |
|---|---|---|
| TURBOPUMP - INCL. PRIM. COMB & PCFCV HSG ADAPTER & LINE (W/O GIMBAL) | 73.62 | 1.153 |
| SECONDARY INJECT. SUB-ASS'Y & SCFCV | 31.27 | .931 |
| TPA SUB-TOTAL | 104.89 | 2.084 |
| $\epsilon = 150$ THRUST CHAMBER ASSEMBLY AND NOZZLE EXTENSION | 92.45 | 13.770 |
| $\epsilon = 50$ THRUST CHAMBER ASSEMBLY AND NOZZLE EXTENSION | 90.05 | 9.958 |
| SUB-TOTAL BASIC ENGINE $\epsilon = 150$ | 197.34 | 15.854 |
| SUB-TOTAL BASIC ENGINE $\epsilon = 50$ | 194.94 | 12.042 |
| BOOST PUMPS (2) | 5.0 | .0575 |
| PROPELLANT INLET HOUSINGS (2) | 8.0 | .1465 |
| SUCTION VALVES & ACTUATORS (2) | 6.0 | .1585 |
| GIMBAL | 2.54 | .0003 |
| PCFCV ACTUATOR | 1.30 | .0261 |
| SCFCV ACTUATOR | 1.00 | .0394 |
| ADDITIONAL ITEMS SUB-TOTAL | 23.84 | .4283 |
| GRAND TOTAL - | | |
| $\epsilon = 150$ DRY ENGINE ASSEMBLY | 221.18 | 16.2823 |
| $\epsilon = 50$ DRY ENGINE ASSEMBLY | 218.78 | 12.4703 |
| $\epsilon = 150$ WET ENGINE ASSEMBLY | 229.58 | 16.4693 |
| $\epsilon = 50$ WET ENGINE ASSEMBLY | 227.28 | 12.6483 |

TABLE VI-III

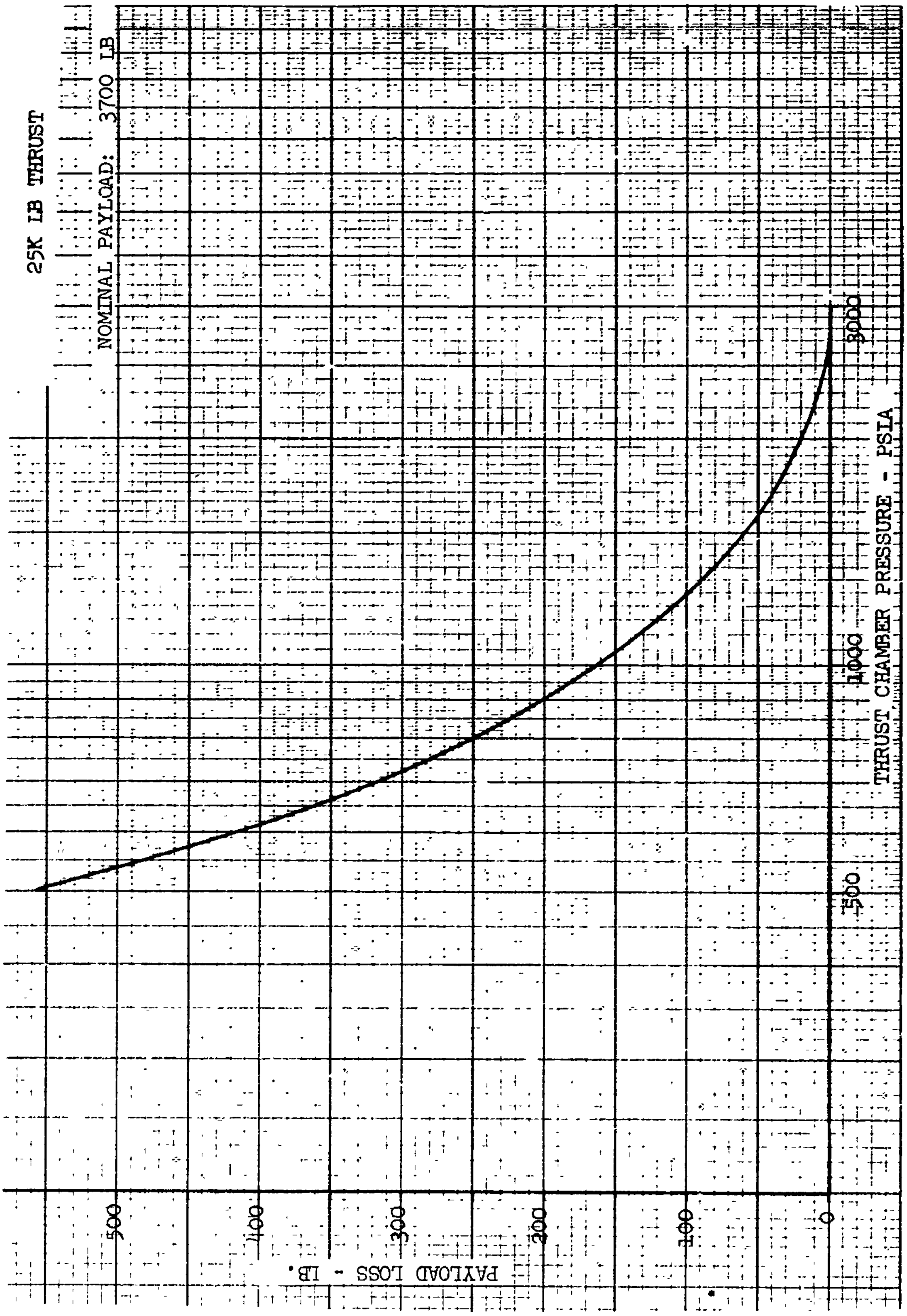
25K PROTOTYPE PRODUCTION ARES WEIGHT AND INERTIA SUMMARY

| | Nozzle Expansion Ratio $\epsilon$ | Weight Pound | Moment of Inertia About Gimbal Slug $Ft^2$ |
|---|---|---|---|
| DRY ENGINE | 150:1 | 209. | 13.7 |
| | 50:1 | 207. | 9.9 |
| ADDITIVE EFFECT OF PROPELLANTS | 150:1 | 8.4 | .187 |
| | 50:1 | 8.5 | .178 |
| WET ENGINE | 150:1 | 217.4 | 13.887 |
| | 50:1 | 215.5 | 10.078 |



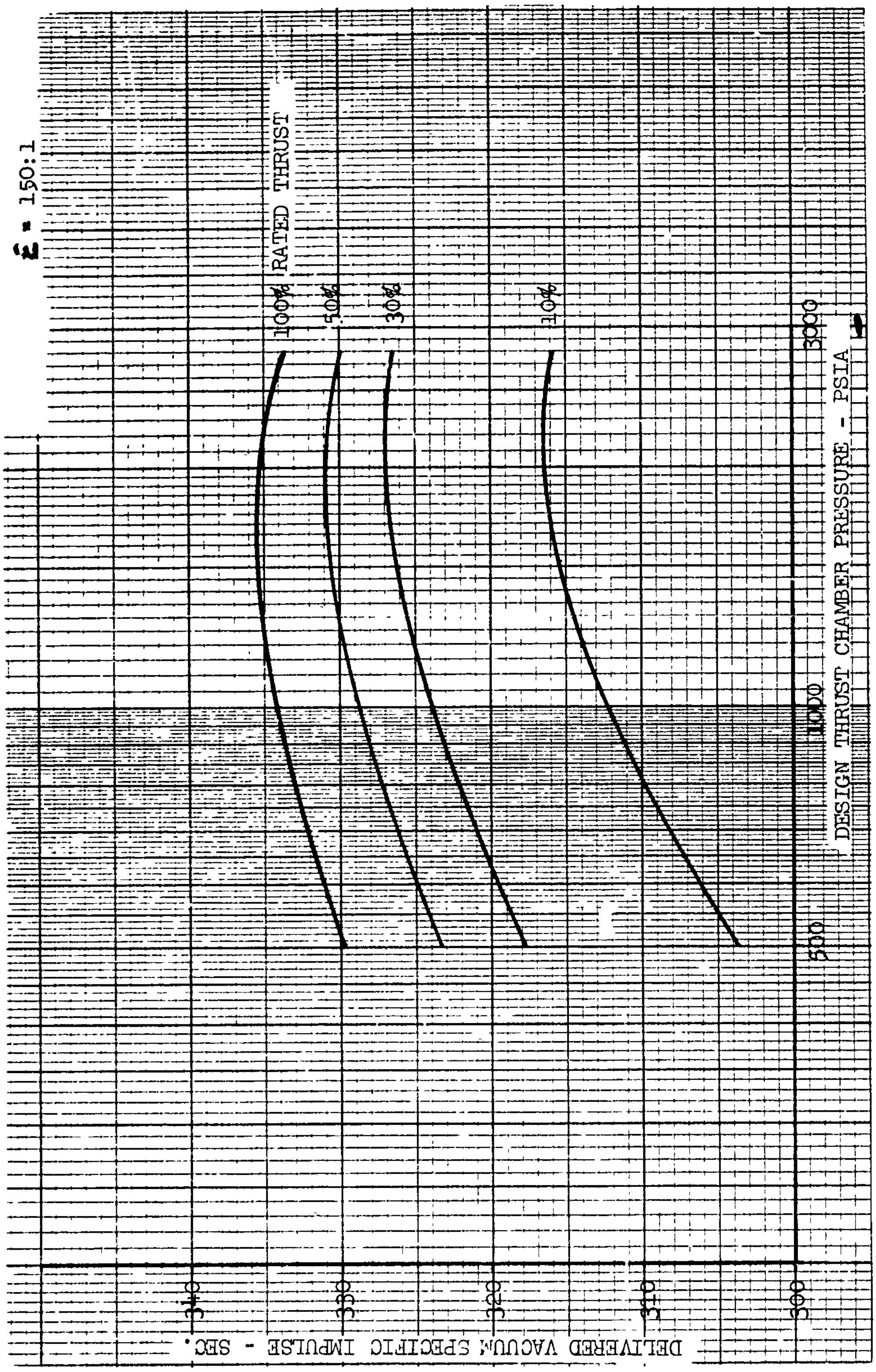

Performance Loss Summary for Different Design Pressures (u)

Figure VI-1



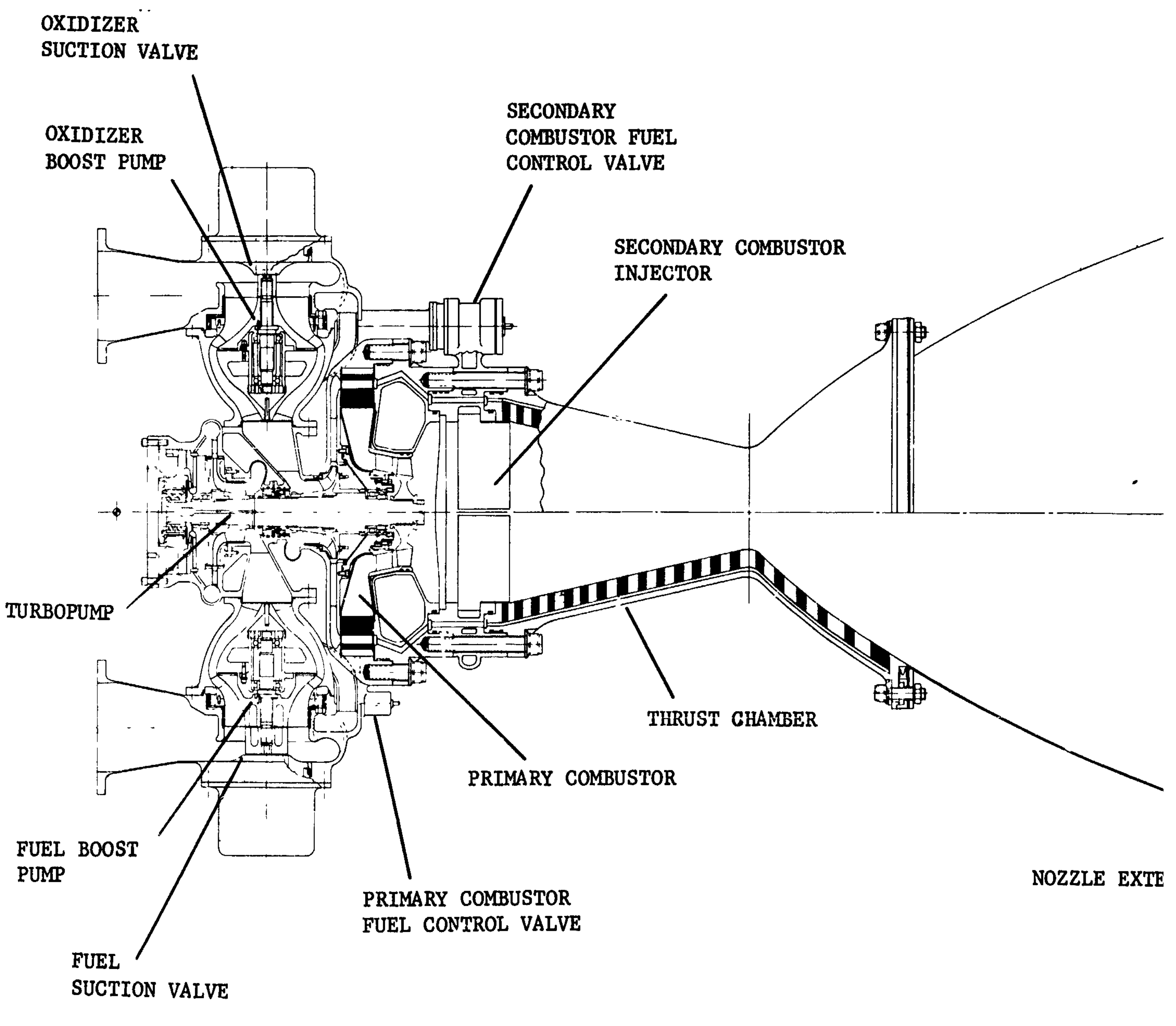

Vehicle Payload Loss for Different Design Pressures (u)

Figure VI-2

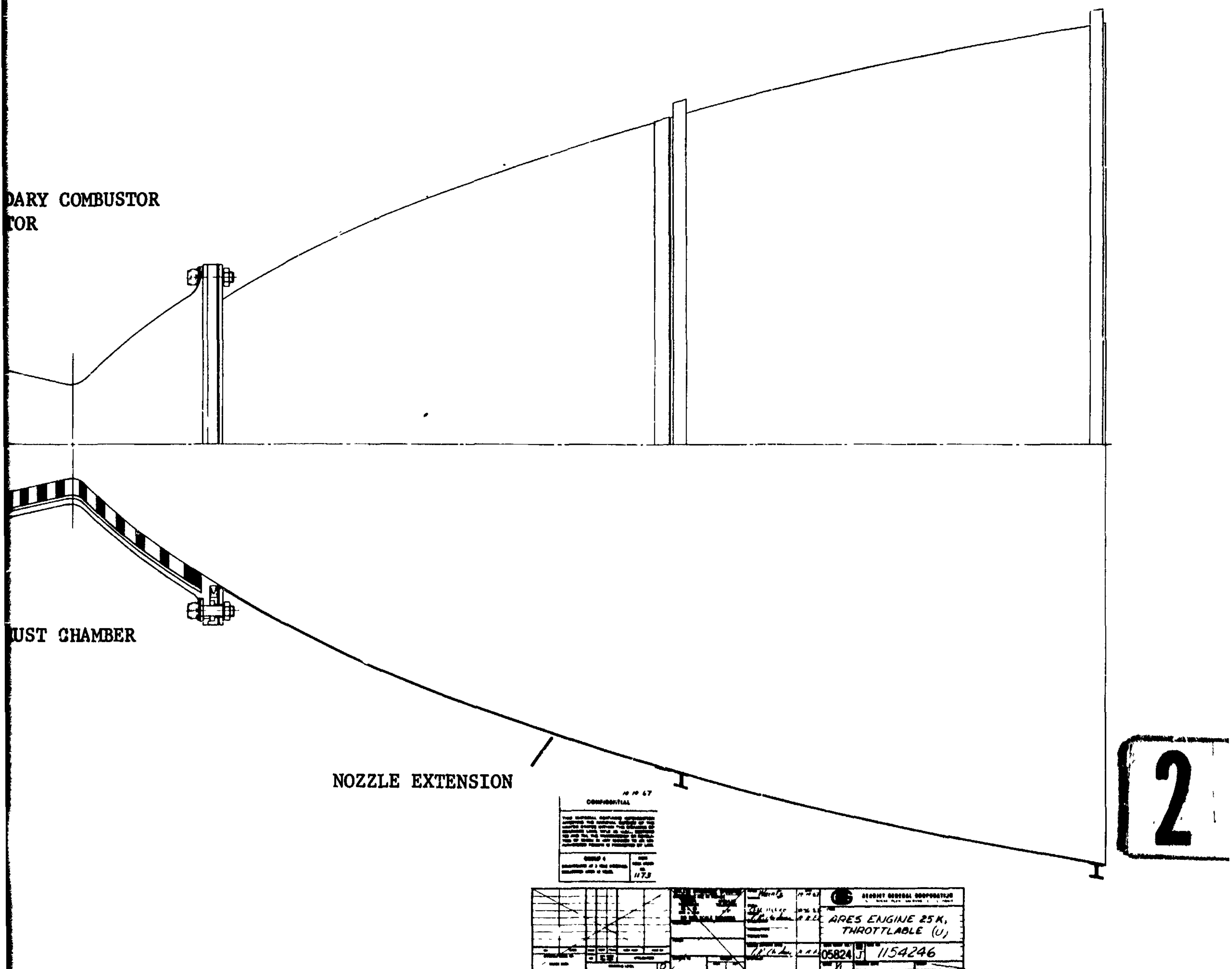



Throttling Performance for Different Design Pressures (u)

Figure VI-3

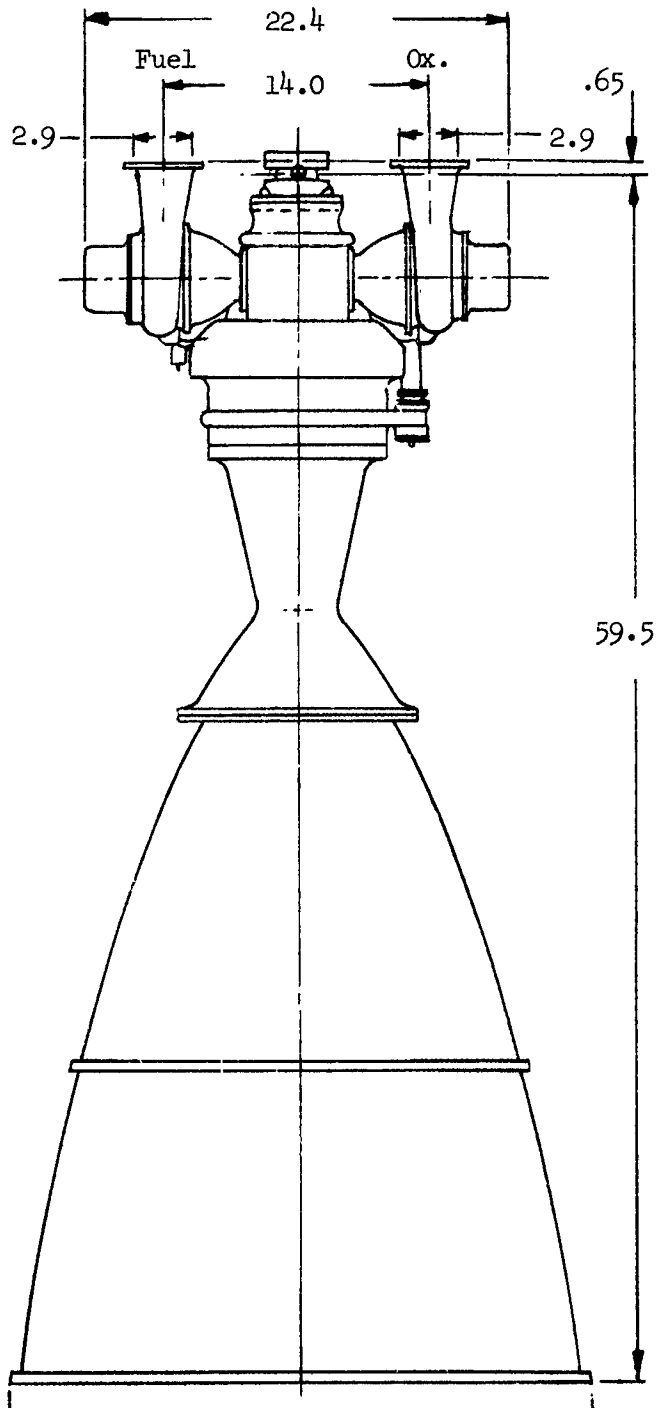

OXIDIZER
SUCTION VALVE
OXIDIZER
BOOST PUMP
SECONDARY
COMBUSTOR FUEL
CONTROL VALVE
SECONDARY COMBUSTOR
INJECTOR
TURBOPUMP
THRUST CHAMBER
PRIMARY COMBUSTOR
FUEL BOOST
PUMP
PRIMARY COMBUSTOR
FUEL CONTROL VALVE
NOZZLE EXTE
FUEL
SUCTION VALVE

1



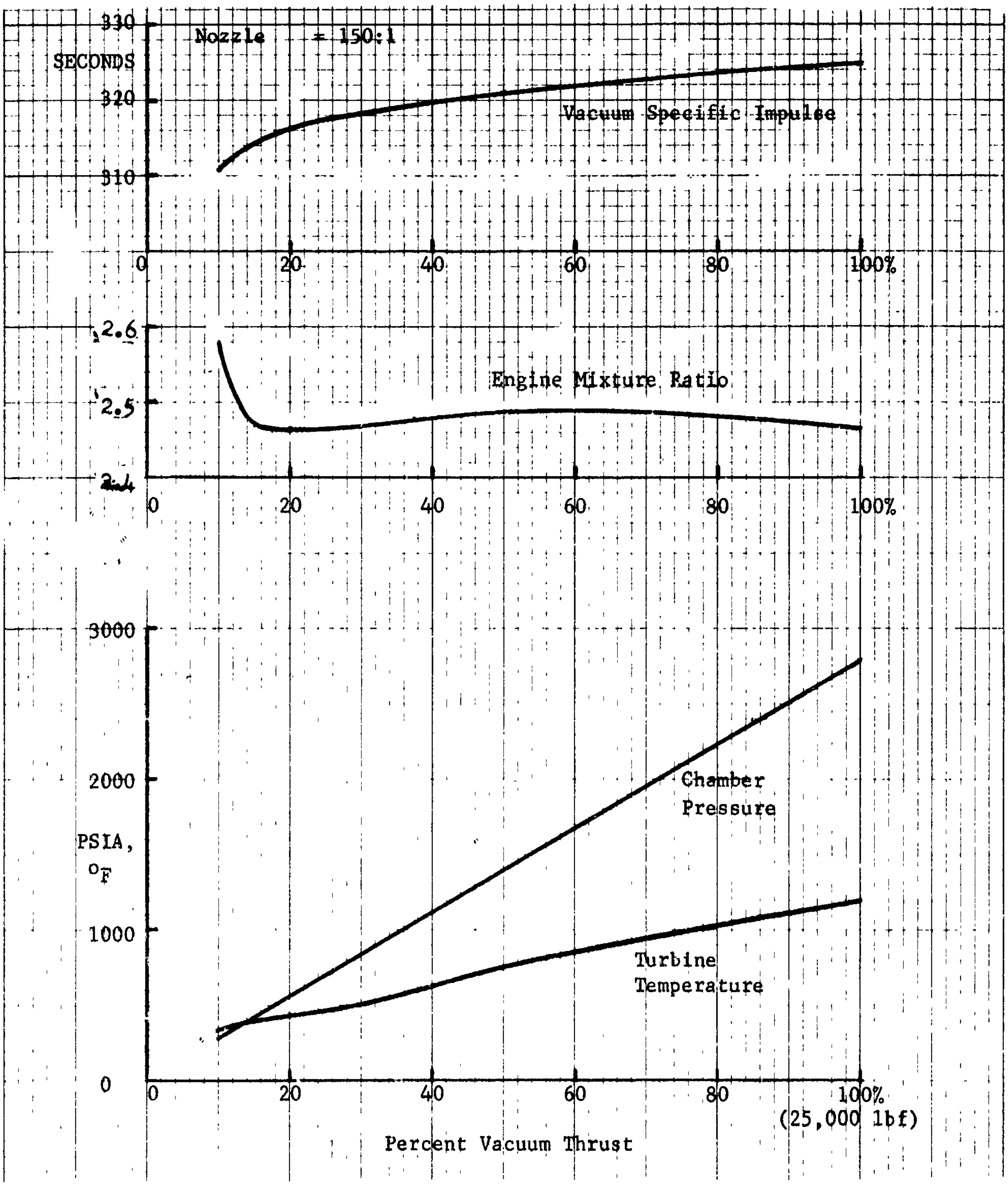

ARES Engine, 25K, Throttlable (u)

Figure VI-4




Envelope 25K Throttlable ARES

Figure VI-5




Throttling Performance, 25K ARES (u)

Figure VI-6

# VII.

# 500K ENGINE DESIGN (TASK IV)

## A. OBJECTIVE AND APPROACH

(U) The objective of Task IV was to establish an engine design for a throttlable, restartable engine having a throttle range of 5:1 and a thrust of 500,000 lbf using a nozzle with a 50:1 area expansion ratio.

(U) The approach to accomplishing this objective was to (1) establish design criteria and operating characteristics over the throttling range; and (2) prepare a 500K thrust engine design that was based on these criteria. The 500K engine design (Task IV) was completed, and the results are described in the following paragraphs.

## B. DESCRIPTION

### 1. Performance Rating

(C) The 500K engine operating parameters are as follows:

| | Sea Level | Vacuum |
|---|---|---|
| Thrust, vacuum, lbf | 500,000 | 582,200 |
| Specific impulse, predicted, sec | 271.8 | 316.5 |
| Specific impulse efficiency, % | 91.7 | 91.7 |
| Nozzle area expansion ratio (RAO) | 50:1 | 50:1 |
| Propellants | $N_2O_4$/AeroZINE 50 | |
| Chamber pressure, psia | 2800 | |
| Mixture ratio, injector | 2.2 | |
| NPSH, fuel, ft | 20 | |
| NPSH, oxidizer, ft | 20 | |

VII, B, Description (cont.)

(U) Specific impulse efficiency for the 500K engine was assumed to be equal to that of the 100K engine. This is a conservative assumption in that the specific impulse efficiency for the 500K engine would be slightly higher than for the 100K engine for a given development level (i.e., maintain chamber wall temperature of 1625°F), because of the reduced cooled area per unit propellant flow.

2. Layout Design

(U) A layout design of the 500K thrust engine with a 50:1 area ratio 80% bell contour nozzle is shown in Figure VII-1.

Engine and component design criteria were established so that critical design parameters would reflect a similar degree of conservatism as in the 100K base-line engine design; e.g., similar values for primary combustor gas temperature bearing DN, seal velocity, shaft stress and chamber wall temperatures were used. The 500K engine functional operation and its start and shutdown sequence are identical to those of the 100K base-line engine.

(C) The platelet injector concept currently being tested in the ARES program, and already described in Section III,B,3 and Figure III-3, was selected for the 500K engine. Injector parameters for the 500K design are as follows:

| | |
|---|---|
| $\dot{w}_F$, lb/sec | 447.7 |
| Injector blade length, total, in. | 950.0 |
| $\dot{w}_F$/blade length, lb/sec/in. | 0.471 |
| $\dot{w}_{gas}$ injector, lb/sec | 1297.2 |
| Net gas area, in.$^2$ | 164.3 |
| Average gas flow, lb/sec/in.$^2$ | 7.9 |
| Gross area, in.$^2$ | 283.0 (ref) |
| Blade area, total, in.$^2$ | 118.7 (ref) |

VII, B, Description (cont.)

(U) An external envelope drawing of the engine is shown in Figure VII-2. The engine portion of the IAPP for the 500K design is shown in Figure IV-1. The dimensions for the gimbal actuators were scaled from the 100K design.

C. ENGINE THROTTLING PERFORMANCE

(U) Engine thrust is controlled as in the 100K base-line engine by means of the primary combustor fuel control valve. Some of the engine and component performance parameters are plotted in Figure VII-3 with a major list of the operating parameters shown in Table VII-I. The format of the table is the same as described for the 100K engine and shows predicted throttle performance up to 10:1 which is greater than the specified value of 5:1. Symbols are defined in Table III-IV.

(U) The throttling characteristics of the 500K thrust engine are also similar to those already described for the 100K engine. As in the 100K thrust engine, the laminar flow characteristics designed into the transpiration film coolant circuit maintain the coolant flow at a constant percentage of total flow during throttling. Also, the injector ΔP's stay at a reasonable percentage of chamber pressure, due to laminar flow design of the injectors.

(U) The pump and the turbine design efficiencies are three percentage points higher than those of the 100K base-line ARES, due to the larger size and flow of the 500K engine.

D. WEIGHT BREAKDOWN

(U) Calculated dry weight and gimbal moment of inertia values for the 500K engine are shown by component in Table VII-II. Wet weight and inertia values are also shown. Estimated weight and gimbal moment of inertia values for a lower weight production prototype engine are shown in Table VII-III. The lower weight of this production prototype engine, as in the 100K engine, is achieved by using two interface joints between the thrust chamber and turbopump in place of the three as shown in Figure VII-1

## TABLE VII-I

### THROTTLING PERFORMANCE, 500K ARES (u)

| | CASE 1 100% F | CASE 2 75% F | CASE 3 50% F | CASE 4 37.5% F | CASE 5 25% F | CASE 6 20% F | CASE 7 15% F | CASE 8 10% F |
|---|---|---|---|---|---|---|---|---|
| F | 582175.71875 | 436393.41016 | 291303.36719 | 218724.27930 | 145703.50000 | 116733.66699 | 87454.32031 | 58228.16406 |
| PCSC | 2799.99997 | 2095.02441 | 1398.10883 | 1051.15350 | 702.68279 | 564.36742 | 424.12478 | 283.80345 |
| MR-ENG | 2.42687 | 2.43866 | 2.43554 | 2.42334 | 2.40918 | 2.40679 | 2.42816 | 2.60470 |
| IS | 316.20212 | 314.97744 | 313.49121 | 312.48079 | 310.80572 | 309.73687 | 307.93599 | 301.91268 |
| W-ENG | 1841.15057 | 1385.47511 | 929.22338 | 699.96073 | 468.79285 | 376.88012 | 284.00162 | 192.86425 |
| WOT | 1303.88412 | 982.51686 | 658.83408 | 495.56194 | 331.34175 | 266.33807 | 201.22631 | 139.38197 |
| WFT | 537.27044 | 402.89266 | 270.50888 | 204.49549 | 137.53282 | 110.66133 | 82.87178 | 53.51163 |
| NT | 13150.00049 | 10718.14661 | 8162.47955 | 6789.44916 | 5283.97412 | 4628.41663 | 3907.74713 | 3086.47961 |
| TTIT | 1096.88783 | 891.87547 | 673.60403 | 554.19474 | 458.39038 | 430.89723 | 395.79627 | 337.11308 |
| RPT | 1.50000 | 1.40884 | 1.31679 | 1.26909 | 1.21816 | 1.19658 | 1.17280 | 1.14790 |
| PODTM | 4960.00867 | 3461.58109 | 2141.72131 | 1544.60005 | 985.90945 | 776.19733 | 571.52953 | 374.22039 |
| DPOH1 | 51.30066 | 29.33545 | 13.25617 | 7.52068 | 3.36472 | 2.17314 | 1.23904 | .59309 |
| DPORG | 48.74561 | 27.89004 | 12.59988 | 7.13927 | 3.19181 | 2.06130 | 1.17577 | .56473 |
| CPOH2 | 49.53845 | 28.32620 | 12.79910 | 7.25162 | 3.24188 | 2.09361 | 1.19418 | .57357 |
| OPOJPC | 200.14465 | 155.58401 | 106.93620 | 81.23877 | 54.77515 | 44.16512 | 33.47173 | 23.29794 |
| PCPC | 4610.27930 | 3220.45538 | 1996.11995 | 1441.44972 | 921.33598 | 725.70417 | 534.44881 | 349.19107 |
| PFDTM1 | 4949.95093 | 3449.48401 | 2117.51849 | 1516.91713 | 958.48387 | 750.75097 | 548.39295 | 353.59954 |
| DPSCVI | 109.93328 | 65.53540 | 31.45087 | 18.61525 | 8.73144 | 5.74174 | 3.28084 | 1.40235 |
| DPFSCV | 1544.96600 | 917.13364 | 438.87842 | 259.49547 | 121.61027 | 79.95016 | 45.67428 | 19.51979 |
| OPSCVO | 109.99136 | 65.27618 | 31.23039 | 18.46344 | 8.65256 | 5.68834 | 3.24961 | 1.38877 |
| DPFJSC | 300.01028 | 242.91541 | 175.40739 | 137.28944 | 95.47537 | 77.87074 | 59.18822 | 38.86982 |
| PCFACE | 2885.00000 | 2158.62338 | 1440.55142 | 1083.06352 | 724.01424 | 581.50000 | 437.00000 | 292.41891 |
| PFDTM2 | 5560.38672 | 4014.14615 | 2506.31531 | 1806.68343 | 1144.71716 | 896.84180 | 654.95000 | 421.75500 |
| CPFPCV | 499.11737 | 524.26910 | 370.27890 | 273.92432 | 170.63549 | 130.50314 | 93.56789 | 57.89022 |
| OPPCVO | 48.74609 | 20.91409 | 6.60452 | 2.97223 | 1.00756 | .56664 | .26402 | .08313 |
| DPFJPC | 300.97406 | 203.13034 | 118.36900 | 80.80164 | 47.91116 | 36.22704 | 24.90013 | 14.08244 |
| PCPC | 4610.27930 | 3220.45538 | 1996.11995 | 1441.44972 | 921.33588 | 725.70417 | 534.44881 | 349.19107 |
| PTIT | 4485.00000 | 3132.94305 | 1941.87758 | 1402.27991 | 896.29959 | 705.03396 | 519.92575 | 339.70218 |
| PTET | 3035.20193 | 2251.78281 | 1489.29012 | 1114.33362 | 741.04685 | 593.90454 | 445.27525 | 297.20539 |
| PGJT | 2998.15683 | 2228.72607 | 1477.19843 | 1106.56026 | 736.80888 | 590.80270 | 443.20989 | 296.01189 |
| PCFACE | 2885.00000 | 2158.62338 | 1440.55142 | 1083.06352 | 724.01424 | 581.50000 | 437.00000 | 292.41891 |
| KWFSCV | 11.82109 | 11.82109 | 11.82109 | 11.82109 | 11.82109 | 11.82109 | 11.82109 | 11.82109 |
| KWFPCV | 4.56421 | 2.91727 | 1.95078 | 1.52154 | 1.12244 | .96251 | .77592 | .55355 |
| KWOPCV | 138.41774 | 138.41774 | 138.41774 | 138.41774 | 138.41774 | 138.41774 | 138.41774 | 138.41774 |
| KWFCV | 2.21685 | 2.09056 | 1.89927 | 1.75425 | 1.54902 | 1.43810 | 1.29732 | 1.12576 |

NOTE: Values less than unity have their decimal location noted by prefix. Example: "-5" indicates decimal point is 5 places to the left of first digit. No prefix and no decimal point indicate decimal precedes first digit.

## TABLE VII-I (cont.)

| | CASE 1 100% F | CASE 2 75% F | CASE 3 50% F | CASE 4 37.5% F. | CASE 5 25% F | CASE 6 20% F | CASE 7 15% F | CASE 8 10% F |
|---|---|---|---|---|---|---|---|---|
| F | 582175.71875 | 436393.41016 | 291303.36719 | 218724.27930 | 145703.50000 | 116733.66699 | 87454.32031 | 58228.16406 |
| DP/PSF | .10399 | .11253 | .12176 | .12676 | .13187 | .13391 | .13544 | .13293 |
| DP/PPO | .04341 | .04831 | .05357 | .05636 | .05945 | .06086 | .06263 | .06672 |
| DP/PPF | .06528 | .06308 | .05930 | .05606 | .05200 | .04992 | .04659 | .04033 |
| | | | | | | | | |
| PCSC | 2799.99997 | 2095.02441 | 1398.10883 | 1051.15350 | 702.[illegible]8279 | 564.36742 | 42[illegible].12478 | 283.80345 |
| MRSC | 2.20000 | 2.21147 | 2.20830 | 2.19690 | [illegible].18365 | 2.18141 | 2.20150 | 2.36594 |
| AE/AT | 50.00000 | 50.00000 | 50.00000 | 50.00000 | 50.00000 | 50.00000 | 50.00000 | 50.00000 |
| ETAC | .96247 | .96053 | .95862 | .95756 | .95669 | .95634 | .95597 | .95550 |
| ETAN | .95104 | .94986 | .94713 | .94448 | .93972 | .93665 | .93220 | .92526 |
| C*SC | 5480.44446 | 5449.25854 | 5422.10474 | 5411.77234 | 5401.63696 | 5396.42023 | 5381.70496 | 5302.89453 |
| CF | 1.85633 | 1.85972 | 1.86021 | 1.85776 | 1.85127 | 1.84668 | 1.84097 | 1.83178 |
| WGJSC | 1278.94670 | 954.33784 | 632.93587 | 473.10936 | 314.20258 | 251.82322 | 189.55[illegible]26 | 130.59899 |
| WFJSC | 440.32151 | 339.46437 | 234.89168 | 180.60997 | 123.62963 | 100.23557 | 75.75590 | 49.51881 |
| WOFC | 121.88640 | 91.60735 | 61.51545 | 46.33802 | 31.04238 | 24.94062 | 18.78295 | 12.77581 |
| WFC/WT | .06620 | .06612 | .05620 | .06620 | .06622 | .06618 | .06614 | .06624 |
| WORG | 1172.04927 | 883.01973 | 591.52771 | 444.52381 | 296.75581 | 238.34072 | 179.907[illegible]7 | 124.62481 |
| DPFJSC | 300.01028 | 242.91541 | 175.40739 | 137.28944 | 95.47537 | 77.87074 | 59.18822 | 38.86982 |
| DPOFC | 2108.70804 | 1337.22122 | 730.34631 | 485.92537 | 279.86194 | 209.65678 | 146.16571 | 89.82385 |
| DPORG | 46.74561 | 27.88004 | 12.59988 | 7.13927 | 3.19181 | 2.06130 | 1.17577 | .56473 |
| DTORG | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 |
| D*FJSC | 55.90041 | 56.00396 | 56.06870 | 56.08322 | 56.08430 | 56.08872 | 56.08768 | 56.08277 |
| D*OFC | 89.45516 | 89.60197 | 89.62940 | 89.59944 | 89.54392 | 89.51778 | 89.48966 | 89.46956 |
| D*ORG | 91.78193 | 91.08536 | 90.44482 | 90.14410 | 89.85905 | 89.75434 | 89.65495 | 89.57135 |
| | | | | | | | | |
| MRPC | 12.08935 | 13.92154 | 16.60792 | 18.61060 | 21.34444 | 22.86075 | 25.28251 | 31.21216 |
| WOJPC | 1172.04927 | 883.01973 | 591.52771 | 444.52381 | 296.75581 | 238.34072 | 179.90737 | 124.62481 |
| WFJPC | 96.94893 | 63.42829 | 35.61721 | 23.88552 | 13.90319 | 10.42576 | 7.11588 | 3.99283 |
| D*OJPC | 91.49957 | 90.87681 | 90.30871 | 90.04339 | 89.79294 | 89.70161 | 89.61542 | 89.54412 |
| D*FJPC | 56.28949 | 56.19021 | 56.13473 | 56.10970 | 56.09104 | 56.08863 | 56.08153 | 56.07864 |
| | | | | | | | | |
| POT | 37.14000 | 37.14000 | 37.14000 | 37.14000 | 37.14000 | 37.14000 | 37.14000 | 37.14000 |
| PFT | 17.51000 | 17.51000 | 17.51000 | 17.51000 | 17.51000 | 17.51000 | 17.51000 | 17.51000 |
| NPSPOB | 12.42943 | 15.49935 | 17.71904 | 18.50652 | 19.07387 | 19.23620 | 19.36339 | 19.45140 |
| NPSPFB | 7.79128 | 10.82617 | 12.97925 | 13.74256 | 14.30586 | 14.47217 | 14.60816 | 14.71208 |
| NPSPOM | 138.42462 | 112.89127 | 83.43994 | 67.91281 | 51.86063 | 45.30461 | 38.56002 | 31.73561 |
| NPSPFM | 81.25537 | 66.91592 | 50.38577 | 41.70399 | 32.85805 | 29.28052 | 25.58043 | 21.84070 |

TABLE VII-I (cont.)

| | CASE 1 100% F | CASE 2 75% F | CASE 3 50% F | CASE 4 37.5% F | CASE 5 25% F | CASE 6 20% F | CASE 7 15% F | CASE 8 10% F |
|---|---|---|---|---|---|---|---|---|
| F | 582175.71875 | 436393.41016 | 291303.35715 | 218724.27930 | 145703.50000 | 116733.66699 | 87754.32031 | 58228.16406 |
| ETAT | .77487 | .77927 | .78366 | .78433 | .78050 | .77592 | .76633 | .75112 |
| WTI | 1268.99825 | 946.44805 | 627.14494 | 469.40934 | 310.65902 | 248.76649 | 187.02326 | 128.61765 |
| U/C-GT | .59526 | .57919 | .55308 | .53230 | .50119 | .48300 | .46011 | .43207 |
| SHPT | 48438.86377 | 25518.50806 | 10807.84692 | 6034.88060 | 2721.20715 | 1788.69569 | 1043.82521 | 495.91229 |
| SHPOM | 27897.45386 | 14697.93286 | 6224.85284 | 3472.40668 | 1565.19290 | 1027.45432 | 600.90326 | 285.57560 |
| SHPFM1 | 19743.55786 | 10390.11340 | 4407.94061 | 2465.83414 | 1110.67703 | 734.32286 | 429.25761 | 202.12499 |
| SHPFM2 | 786.37576 | 434.48064 | 177.62588 | 96.82753 | 43.16621 | 29.42632 | 16.80270 | 8.20289 |
| PQSTM | 157.06396 | 131.28146 | 101.64463 | 86.00657 | 69.86436 | 63.26987 | 56.48166 | 49.59287 |
| PQDTM | 4960.00867 | 3461.58109 | 2141.72131 | 1544.60005 | 985.90945 | 776.19713 | 571.52953 | 374.22039 |
| HOMNC | 7735.72900 | 5362.37317 | 3283.81116 | 2347.82974 | 1474.43765 | 1147.80597 | 829.51756 | 522.63060 |
| QOSM | 7069.18433 | 5364.72314 | 3643.80295 | 2771.54666 | 1987.81558 | 1534.91690 | 1178.25801 | 833.06094 |
| HOM/N2 | -4 44735232 | -4 46678580 | -4 49287178 | -4 50932795 | -4 52808647 | -4 53584709 | -4 54321615 | -4 54861549 |
| Q/QDOM | 1.00005 | .93112 | .83044 | .75939 | .66462 | .61692 | .56091 | .50210 |
| ETAOM | .71000 | .70912 | .69664 | .67916 | .64426 | .62132 | .59004 | .55244 |
| NSD | 1340.40051 | 1252.78238 | 1135.83698 | 1059.73129 | 964.87425 | 919.49220 | 867.81580 | 814.99649 |
| SUM | 19163.11133 | 15358.12317 | 12480.77307 | 10571.96216 | 8312.88135 | 7266.32843 | 6065.98145 | 4662.53876 |
| D*DSM | 89.40607 | 89.43027 | 89.44477 | 89.449 9 | 89.45380 | 89.45587 | 89.45872 | 89.46815 |
| PFSTM1 | 84.06952 | 69.70639 | 53.15444 | 44.46239 | 35.60648 | 32.02465 | 28.32009 | 24.57683 |
| PFDTM1 | 4949.95093 | 3449.48401 | 2117.51849 | 1516 91713 | 958.49387 | 750.79097 | 549.39298 | 353.59964 |
| HFMNC1 | 12498.40942 | 8676.57349 | 5301.18945 | 3780.40692 | 2369.27271 | 1844.19328 | 1334.34163 | 844.33856 |
| QFSM1 | 4590.47052 | 3474.22467 | 2370.83172 | 1818.37242 | 1255.26331 | 1028.10345 | 792.15079 | 541.41938 |
| HF1/N2 | -4 72277513 | -4 75528195 | -4 79560288 | -4 82010500 | -4 84858173 | -4 86087785 | -4 87380418 | -4 88631945 |
| Q/QDF1 | 1.00001 | .92857 | .83206 | .76723 | .68353 | .63632 | .58071 | .50251 |
| ETAFM1 | .66000 | .65904 | .64770 | .63338 | .60514 | .58868 | .55952 | .51392 |
| NSF-1 | 753.72581 | 702.72819 | 639.72658 | 600.51265 | 551.27722 | 527.34654 | 498.17298 | 458.50379 |
| SFM1 | 16225.95105 | 13310.58215 | 10360.53845 | 8697.62646 | 6725.49121 | 5813.02795 | 4767.53461 | 3504.94846 |
| D*FSM1 | 56.06253 | 56.07125 | 56.07872 | 56.08201 | 56.08513 | 56.08677 | 56.08826 | 56.08948 |
| PFSTM2 | 4608.19171 | 3255.22385 | 2028.35455 | 1465.12433 | 934.32221 | 734.75762 | 539.08336 | 349.40041 |
| PFDTM2 | 5560.38672 | 4014.14615 | 2506.31531 | 1906.69343 | 1144.71716 | 896.84180 | 654.95000 | 421.75800 |
| HFM2 | 2425.38522 | 1937.56052 | 1222.91722 | 874.85883 | 539.44623 | 415.72739 | 297.28697 | 185.71429 |
| QFSM2 | 820.14299 | 555.87757 | 335.69593 | 242.50753 | 153.03230 | 135.29910 | 108.88396 | 83.93766 |
| HF2/N2 | -4 14025850 | -4 16866147 | -4 18354935 | -4 18978806 | -4 19320975 | -4 19406345 | -4 19468073 | -4 19494766 |
| Q/QDF2 | 1.00019 | .83142 | .65898 | .57218 | .49417 | .46818 | .44024 | .43888 |
| ETAFM2 | .58011 | .56695 | .52721 | .49916 | .46760 | .45006 | .43801 | .43193 |
| NSF-2 | 1089.64511 | 965.30241 | 723.19170 | 657.26989 | 602.74896 | 584.745[illegible] | 569.84309 | 562.09261 |
| NT | 13150.00349 | 10718.14661 | 8162.47955 | 6789.44916 | 5283.97412 | 4628.41663 | 3907.74713 | 3086.47961 |

## TABLE VII-I (cont.)

| | CASE 1 100% F | CASE 2 75% F | CASE 3 50% F | CASE 4 37.5% F | CASE 5 25 % F | CASE 6 20% F | CASE 7 15% F | CASE 8 10% F |
|---|---|---|---|---|---|---|---|---|
| F | 582175.71875 | 436393.41016 | 291303.36719 | 218724.27930 | 145703.59000 | 116733.66699 | 87454.32031 | 58224.16406 |
| NTOP | 3499.99985 | 2383.09244 | 2240.40137 | 1895.04913 | 1513.37851 | 1342.86269 | 1149.52696 | 910.41880 |
| WOSB | 1303.88412 | 982.51686 | 658.83408 | 495.56184 | 331.34175 | 266.33807 | 201.22631 | 139.38197 |
| TOSB | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 |
| POSTB | 30.05457 | 33.11683 | 35.33099 | 36.11651 | 36.68245 | 36.84437 | 36.97124 | 37.05903 |
| PODTB | 159.86940 | 132.89723 | 102.42997 | 86.43775 | 70.06439 | 63.40210 | 56.55988 | 49.63177 |
| HOBNC | 211.79222 | 160.69383 | 107.96020 | 80.96452 | 53.70360 | 42.72976 | 31.51637 | 20.22870 |
| COSB | 6538.92426 | 4927.08856 | 3303.80310 | 2485.02982 | 1661.57460 | 1335.55864 | 1009.05256 | 698.93230 |
| HOB/N2 | -4 17289162 | -4 19332235 | -4 21503593 | -4 22545185 | -4 23450752 | -4 23695575 | -4 24017374 | -4 24405373 |
| Q/QDOB | 1.00695 | .92109 | .77480 | .70677 | .53174 | .53604 | .47476 | .41377 |
| ETAOB | .67065 | .67208 | .63217 | .58992 | .52561 | .48932 | .44438 | .39509 |
| SHPOB | 738.38632 | 426.73829 | 204.57047 | 123.66301 | 61.56060 | 42.29679 | 29.94812 | 12.97528 |
| SOB | 29926.94019 | 18134.72339 | 10437.68335 | 7411.35016 | 4731.28131 | 3740.09395 | 2759.52490 | 1819.08997 |
| PTITOB | 4798.47528 | 3349.77283 | 2073.37610 | 1495.79399 | 955.29849 | 752.38719 | 554.33801 | 363.39041 |
| DPTOB | 4688.30713 | 3245.09680 | 1983.63573 | 1416.53569 | 898.44530 | 691.05991 | 498.96279 | 314.32687 |
| TTITOB | 90.40896 | 86.53133 | 83.37176 | 82.03994 | 80.30665 | 80.30189 | 79.77089 | 79.09313 |
| WTOB | 104.37793 | 86.48632 | 67.36715 | 56.82997 | 44.93338 | 39.60519 | 33.63432 | 26.68292 |
| ETATOB | .52960 | .52936 | .52904 | .52900 | .52924 | .52940 | .52947 | .52949 |
| NTFB | 3499.99985 | 2881.93088 | 2237.02579 | 1891.27490 | 1510.74384 | 1341.73653 | 1145.70647 | 911.64976 |
| WFSB | 537.27044 | 402.89266 | 270.59889 | 204.49549 | 137.53292 | 110.66133 | 82.87178 | 53.51163 |
| TFSB | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 | 77.00000 |
| PFSTB | 10.50599 | 13.53995 | 15.60238 | 16.45546 | 17.01360 | 17.18485 | 17.32080 | 17.42469 |
| PFDTB | 86.63424 | 71.17560 | 53.8386 | 44.86510 | 35.79930 | 32.15332 | 28.39649 | 24.61222 |
| HFBNC | 196.55954 | 147.94633 | 97.91739 | 72.92410 | 48.20507 | 38.42209 | 28.42979 | 18.44940 |
| QFSB | 4299.37427 | 3223.24051 | 2164.10962 | 1615.98552 | 1100.27341 | 885.29848 | 662.97957 | 428.09624 |
| HFB/N2 | -4 16045678 | -4 17313000 | -4 19566710 | -4 20387397 | -4 21120834 | -4 21342562 | -4 21658430 | -4 22198636 |
| Q/QDFB | .98587 | .89782 | .77659 | .59439 | .58464 | .52987 | .46452 | .37696 |
| ETAFB | .67619 | .66751 | .62419 | .58331 | .53125 | .48488 | .43640 | .36347 |
| SHPFB | 282.31024 | 162.35846 | 77.15441 | 46.48269 | 23.12564 | 15.94726 | 9.81596 | 4.93861 |
| SFB | 24263.85915 | 13518.43188 | 7504.64520 | 5285.08301 | 3359.42410 | 2653.20917 | 1946.86848 | 1238.23518 |
| PTITFB | 4824.89033 | 3362.74323 | 2064.62189 | 1479.22108 | 934.88103 | 732.37735 | 535.10414 | 345.19727 |
| DPTFB | 4778.95319 | 3314.63574 | 2021.34456 | 1440.48341 | 901.93805 | 702.11332 | 507.80700 | 321.08073 |
| TTITFB | 90.39298 | 86.52395 | 83.15890 | 81.74394 | 80.40964 | 79.86502 | 79.31976 | 78.85933 |
| WTFB | 29.65510 | 24.66287 | 19.23520 | 16.22819 | 12.87406 | 11.36128 | 9.62635 | 7.65306 |
| ETATFB | .43062 | .42814 | .42669 | .42687 | .42863 | .42987 | .43062 | .43071 |
| WJTS | 9.94847 | 7.88979 | 5.79093 | 4.70002 | 3.54357 | 3.05674 | 2.53600 | 1.98138 |
| WOBOS | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 |
| WFBOS | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 | .00000 |
| WFRTS | 6.50000 | 6.50000 | 6.50000 | 6.50000 | 6.50000 | 6.50000 | 6.50000 | 6.50000 |

## TABLE VII-II

### 500K ARES WEIGHT AND INERTIA SUMMARY

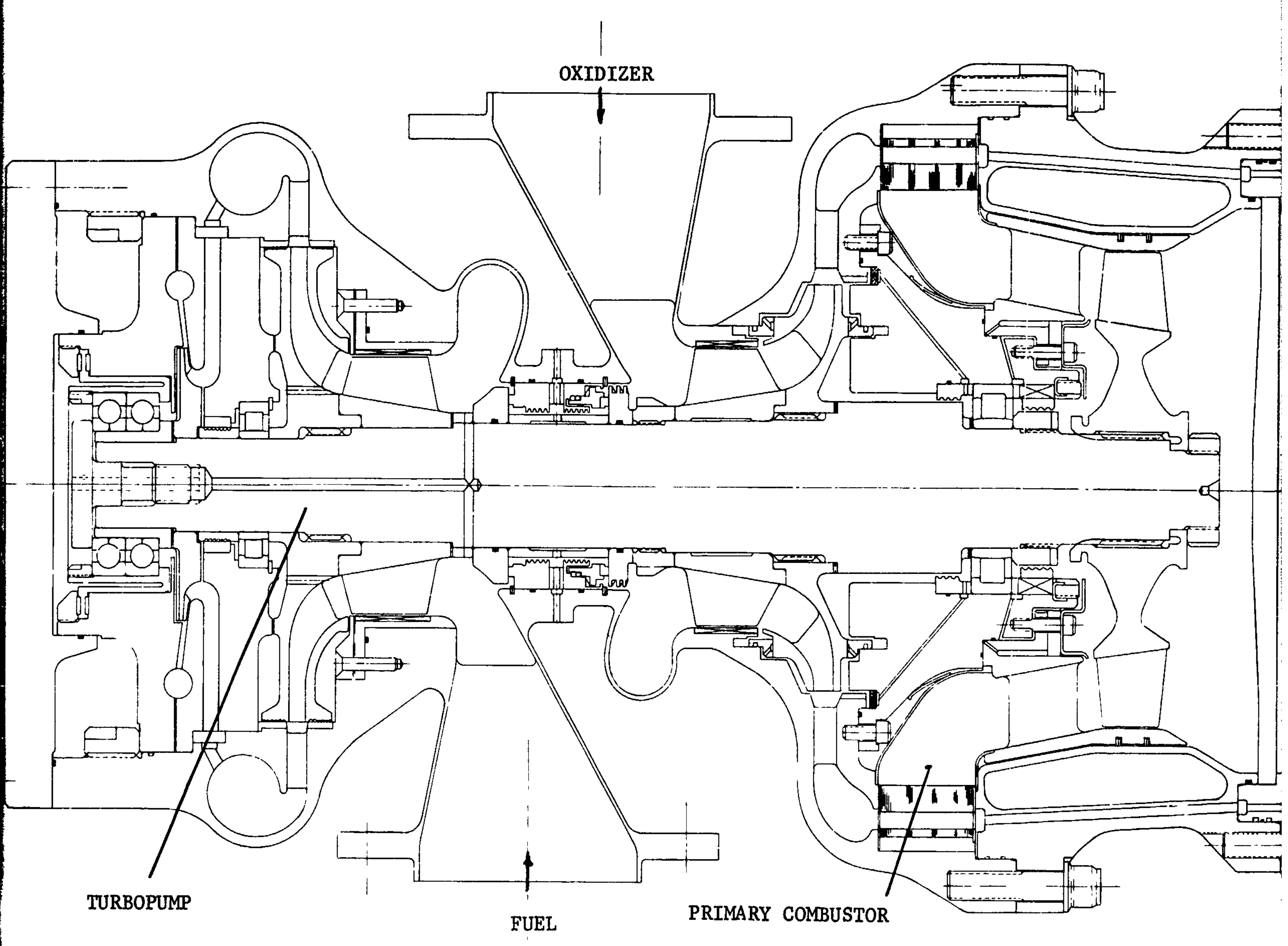
| COMPONENT ASSEMBLY | Weight Pound | Moment of Inertia About Gimbal Slug $Ft^2$ |
|---|---|---|
| TURBOPUMP - INCL. PRIM. COMB & PCFCV HSG ADAPTER & LINE (W/O GIMBAL) | 2614.0 | 603.8 |
| SECONDARY INJECT. SUB-ASS'Y & SCFCV | 578.0 | 382.6 |
| TPA SUB-TOTAL | 3192.0 | 986.4 |
| $\epsilon = 150$ THRUST CHAMBER ASSEMBLY AND NOZZLE EXTENSION | 1681.0 | 4984.5 |
| $\epsilon = 50$ THRUST CHAMBER ASSEMBLY AND NOZZLE EXTENSION | 1662.0 | 2955.1 |
| SUB-TOTAL BASIC ENGINE $\epsilon = 150$ | 4873.0 | 5970.9 |
| SUB-TOTAL BASIC ENGINE $\epsilon = 50$ | 4854.0 | 3941.5 |
| BOOST PUMPS (2) | 390.0 | 96.0 |
| PROPELLANT INLET HOUSINGS (2) | 670.0 | 224.0 |
| SUCTION VALVES & ACTUATORS (2) | 320.0 | 185.5 |
| GIMBAL | 211.0 | .57 |
| PCFCV ACTUATOR | 12.0 | 4.30 |
| SCFCV ACTUATOR | 9.0 | 5.17 |
| ADDITIONAL ITEMS SUB-TOTAL | 1612.0 | 515.54 |
| GRAND TOTAL - | | |
| $\epsilon = 150$ DRY ENGINE ASSEMBLY | 6485.0 | 6486.44 |
| $\epsilon = 50$ DRY ENGINE ASSEMBLY | 6466.0 | 4457.04 |
| $\epsilon = 150$ WET ENGINE ASSEMBLY | 7183.0 | 6708.44 |
| $\epsilon = 50$ WET ENGINE ASSEMBLY | 7167.0 | 4676.04 |

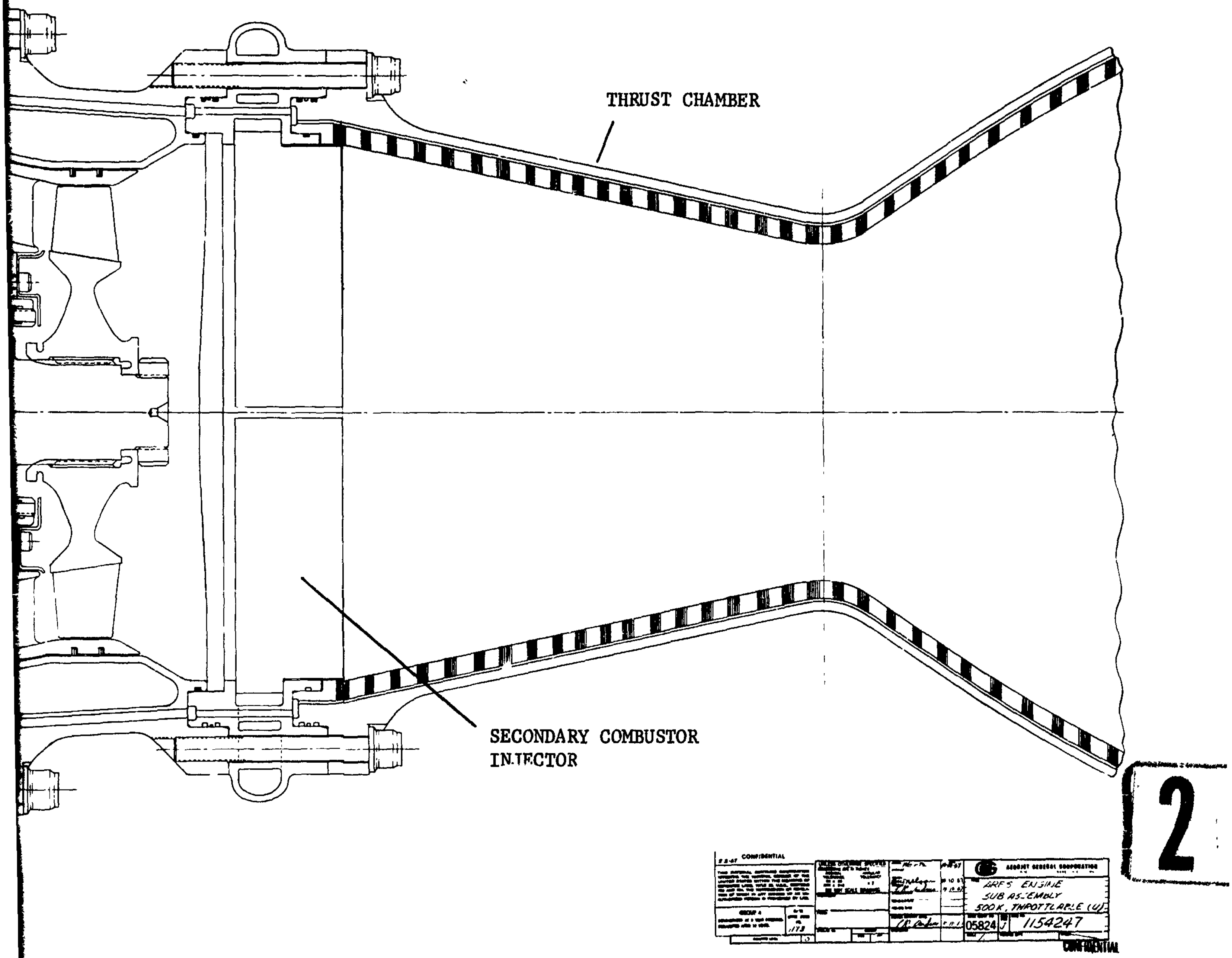
TABLE VII-III

500K PROTOTYPE PRODUCTION ARES WEIGHT AND INERTIA SUMMARY

| | Nozzle Expansion Ratio $\epsilon$ | Weight Pound | Moment of Inertia About Gimbal Slug $Ft^2$ |
|---|---|---|---|
| DRY ENGINE | 150:1 | 6130. | 6341. |
| | 50:1 | 6110. | 4312. |
| ADDITIVE EFFECT OF PROPELLANTS | 150:1 | 698. | 222. |
| | 50:1 | 701. | 219. |
| WET ENGINE | 150:1 | 6828. | 6563. |
| | 50:1 | 6811. | 4531. |

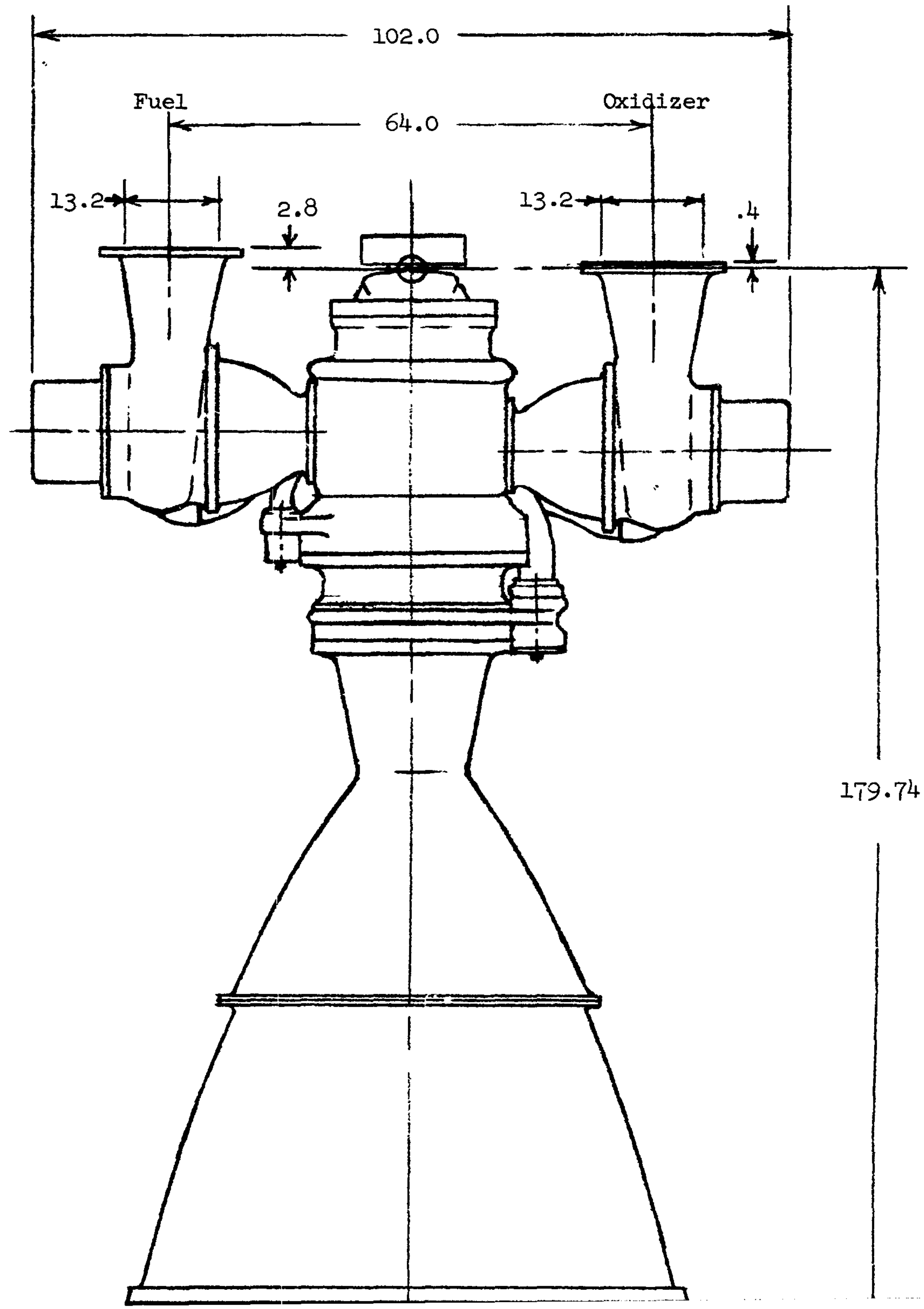
1

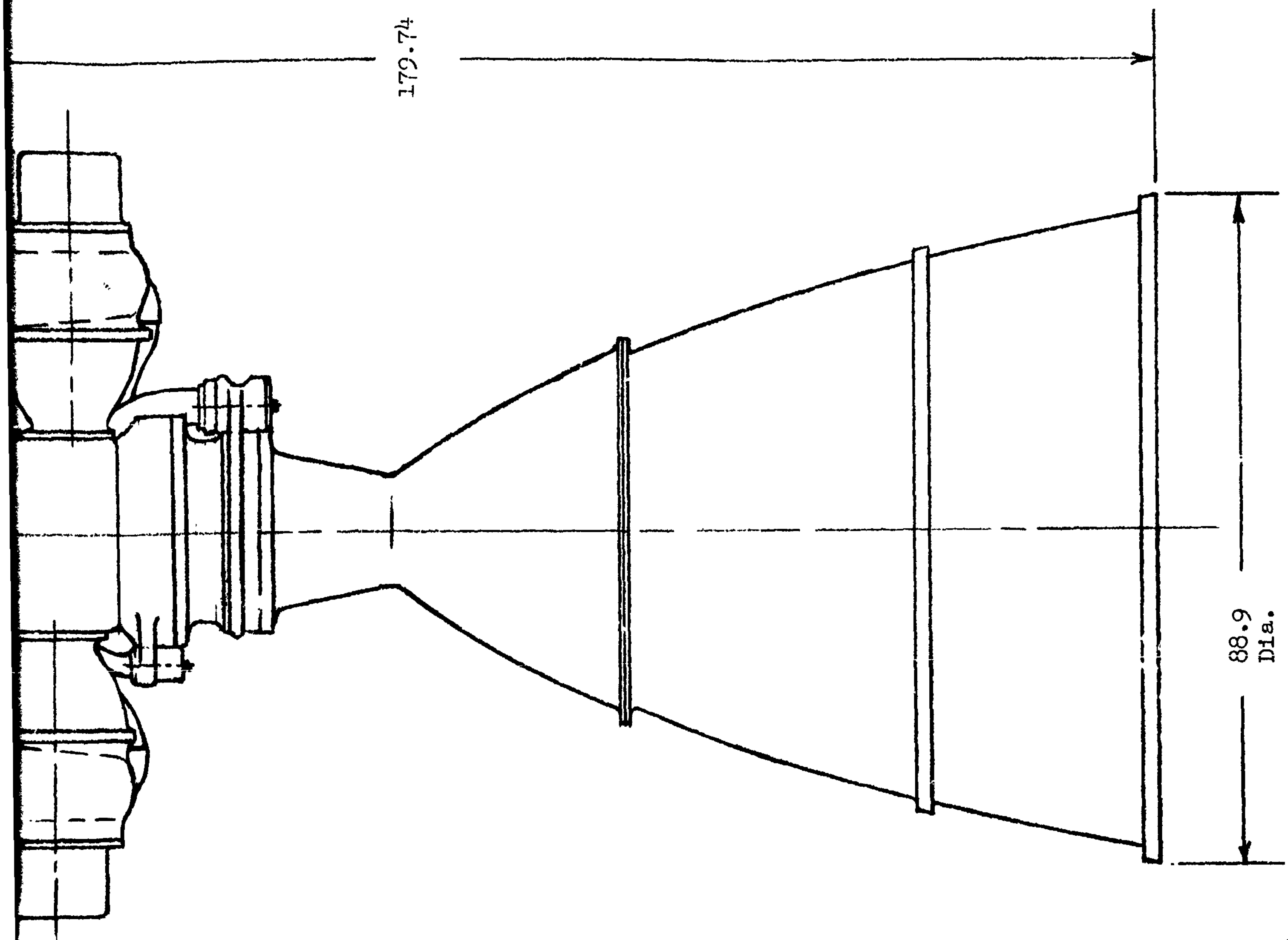





ARES Engine, 500K, Throttlable (u)

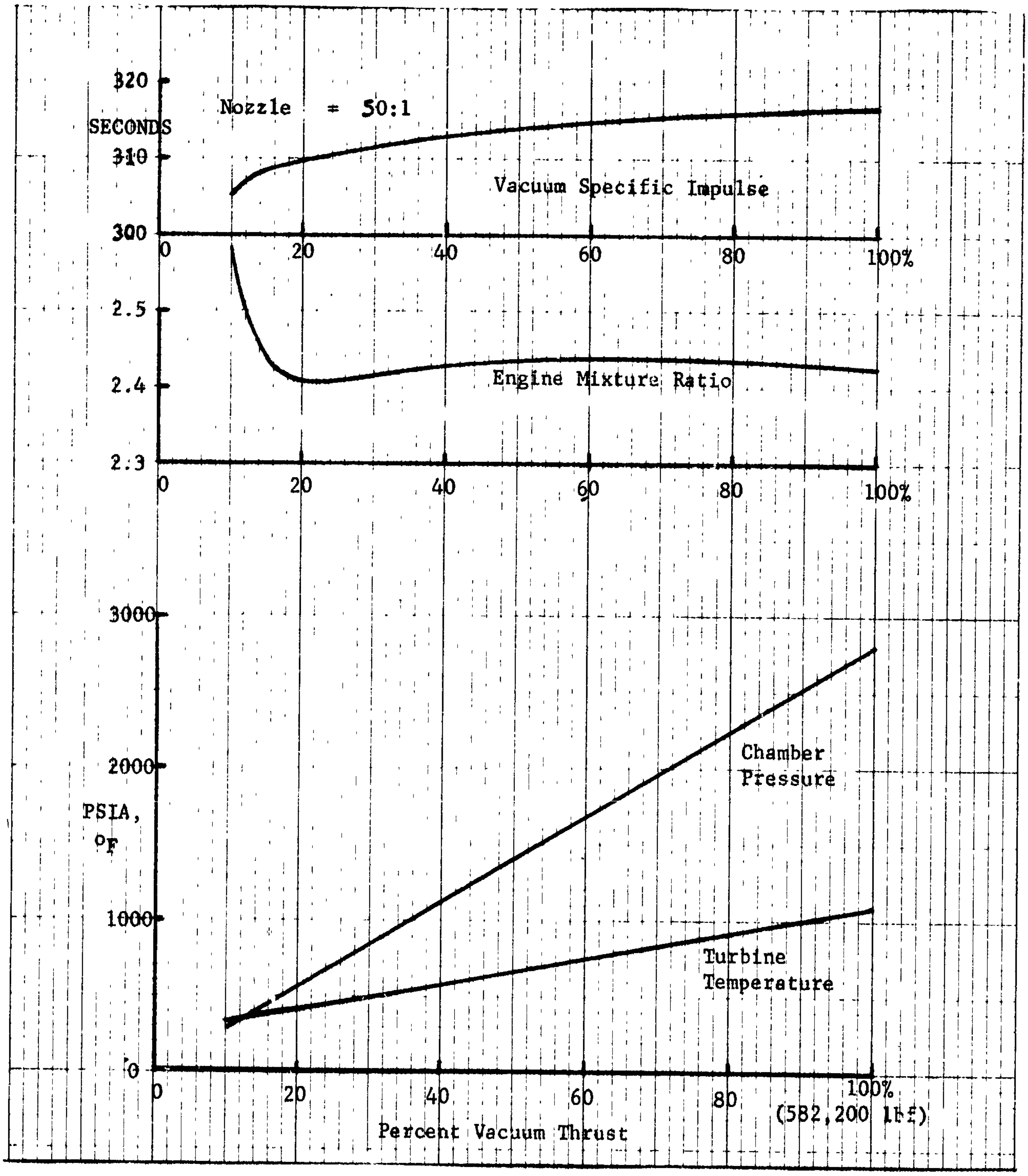
Figure VII-1


102.0
Fuel
Oxidizer
64.0
13.2
13.2
2.8
.4
179.74




Envelope, 500K, Throttlable ARES

Figure VII-2




Throttling Performance, 500K ARES (u)

Figure VII-3

# VIII.

# ENGINE THRUST SCALING (TASK V)

## A. OBJECTIVE AND APPROACH

(U) The objective of Task V was to establish engine thrust scaling data for ARES cycle engines over a range of design point thrust values of 25,000 to 500,000 lbf. The scaling data are presented in Appendix I and include engine weight, length, diameter, specific impulse, development and production costs. Data for this thrust scaling task were obtained from the 100K, 25K and 500K engine designs described in Sections III, VI, and VII, respectively. The technical approach to defining performance of these engines with various area ratio nozzles and under throttled conditions is described in Section VIII,B. Engine weight figures are based on the estimated values for the production prototype ARES configuration. Engine development and production cost figures have been estimated for a man-rated ARES with cost figures in terms of the 1967 dollar. Cost figures are based on estimated component costs for experimental production quantities. These component cost figures are used in the development program cost estimate where the development program was assumed to be of four years duration involving three years through PFRT and one year for qualification. Production cost figures were established from experimental component costs by applying cost adjustment factors obtained from Aerojet-General Corporation experience on Titan programs. The man-rated engine cost is priced a factor of 1.6 higher than an unmanned utilization, this factor being based on cost data from Titan IIIB and Gemini engine production deliveries. Fee is not included in the cost estimate.

## B. PERFORMANCE SCALING

(C) All engine performance scaling starts from the basic contract AF 04(611)-10830 ARES engine with an 80% bell nozzle and an expansion ratio of 20:1. The target performance of this engine is 91.7% of theoretical sea-level specific impulse. The performance loss breakdown of this engine together with the rather detailed analysis conducted on the 25K design as part of Task III (see Section VI,B) provide the design information necessary to scale the individual losses to the various area ratios and thrust levels.

(U) Performance of the 500K engine is defined as being equal to that of the 100K; therefore, the performance curves compiled are based on 25K and 100K each with RAO nozzles of 20, 50, 150, and 300:1 area ratios and 80% bell nozzles of 20 and 50:1 area ratios. The performance breakdown of the base-line engine differs from that of the ARES engine in that the cooling losses are consistent with the conical chamber design, and the nozzle is transpiration cooled to the 30-psia point in the nozzle. Similarly, the energy release loss has been calculated for the conical chamber and the remaining combustion loss attributed to mixture ratio distribution.

(U) The individual performance losses were calculated in the same manner as described in Section VI,B. Conversion of the 80% bell nozzle at 20:1 area ratio to a RAO nozzle of the same area ratio requires only determination of the new nozzle friction and geometry losses. Conversion of either of these, then, to larger area ratios involves referencing the percents of energy release and mixture ratio distribution losses to the higher theoretical $I_s$ values. This is an approximation necessitated by the fact that the exact nature of the injector which determines this loss is unknown. The nozzle friction or boundary layer and geometry losses can be calculated for changes in area ratio. Scaling of this loss was done on the basis of the data presented in Reference (5). Cooling losses are assumed to be constant with changes in area ratio. Kinetic or finite rate losses were scaled with the use of Reference (5).

VIII, B, Performance Scaling (cont.)

(U) Scaling for changes in thrust was done in the following manner. Mixture ratio distribution, nozzle geometry, and kinetic losses were all taken to be constant with changes in thrust. Cooling and energy release losses were calculated for the particular chamber geometry, and boundary layer losses were scaled using Reference (5).

(U) The results of this performance scaling effort can be seen in Figure III-2 in Appendix I which shows the vacuum and sea-level delivered specific impulse as a function of area ratio for two thrust levels, 25K lb and 100K lb. Table VIII-I shows the loss breakdown summary for the 100K engine at three area ratios and the 25K at two area ratios. The 500K delivered impulse is shown equal to the 100K; consequently, no loss breakdown is shown. Finally, Figure III-3 in Appendix I shows the vacuum performance of both 150:1 and 300:1 RAO nozzle engines during throttling. Also shown is the performance of the 100K and 500K thrust engine with a 50:1 bell nozzle. To arrive at these curves the individual performance loss changes with thrust and chamber pressure were handled as follows: mixture ratio distribution was assumed constant; energy release loss was calculated for changes in $P_c$; boundary layer and kinetic losses were scaled with $P_c$; geometry losses are constant; and the cooling loss was taken to be constant on the basis of studies previously performed on the ARES engine Contract AF 04(611)-10830.

## REFERENCES

1. Advanced Rocket Engine--Storable (U), Phase I Interim Final Report, Volume III Appendix, Section 9, "Backup Turbopump Assembly," AFRPL-TR-67-75, Contract AF 04(611)-10830, Aerojet-General Corporation, August 1967, Confidential.

2. Kenny, R. M., Freedman, P., Lane, A. P., and Bingham, P., Development and Demonstration of Main Tank Injection (MTI) Pressurization System, Final Report, Technical Documentary Report No. RTD-TDR-63-1123, December 1963; prepared for Air Force Flight Test Center, Edwards AFB, California, under Contract AF 04(611)-8198, by The Martin Company, Denver Division.

3. Stollery, J. L., and El-Ehwany, A. A. M., "A Note on the Use of a Boundary-Layer Model for Correlating Film Cooling Data"; Int. Journal of Heat-Mass Transfer, Vol. 8, pp 55-65, 1965.

4. Kushida, R., "Nonequilibrium Chemical Recombination Effects in Exhaust Nozzle Flow, an Approximate Method," Liquid Rockets and Propellants, Vol. 18, July 1960.

5. Performance Evaluation Methods for Liquid Propellant Rocket Thrust Chambers, Chemical Propulsion Information Agency Publication No. 132, November 1966.



3

TABLE VIII-I

ARES THRUST CHAMBER PERFORMANCE SUMMARY (u)

| Engine Rating, lbf | 100K | 100K | 100K | 25K | 25K | 500K | 500K |
|---|---|---|---|---|---|---|---|
| Area Ratio | 20:1 | 50:1 | 150:1 | 50:1 | 150:1 | 50:1 | 150:1 |
| Nozzle Contour | 80% Bell | 80% Bell | RAO | 80% Bell | RAO | 80% Bell | RAO |
| Loss Breakdown, sec (for conical chamber) | | | | | | | |
| Mixture Ratio Dist. | 5.2 | 5.5 | 5.7 | 5.5 | 5.7 | | |
| Combustion | 1.0 | 1.1 | 1.1 | 1.1 | 1.1 | | |
| Nozzle Friction | 3.1 | 4.4 | 5.8 | 3.6 | 6.8 | | |
| Nozzle Geometry | 2.9 | 3.1 | 3.5 | 3.1 | 3.5 | | |
| Transpiration Cooling | 13.7 | 13.7 | 13.7 | 16.5 | 16.5 | | |
| Kinetic (Recombination) | 0.0 | 0.9 | 1.4 | 0.9 | 1.4 | | |
| Total Losses | 25.9 | 28.7 | 31.2 | 30.7 | 35.0 | | |
| Sea Level Performance | | | | | | | |
| Thrust, lbf | 100,000* | 94,760 | | 20,625 | | 500,000* | |
| $I_s$ theo, sec | 310.9 | 298.7 | | 298.7 | | 298.7 | |
| $I_s$ act., sec | 285.0 | 270.0 | | 268.0 | | 271.8 | |
| $\eta_{IS(SL)}$, % | 91.67 | 90.4 | | 89.7 | | 91.0 | |
| Vacuum Performance | | | | | | | |
| Thrust, lbf | 106,550 | 111,065 | 115,250 | 24,200 | 25,000* | 582,200 | 604,100 |
| $I_s$ theo, sec | 329.5 | 345.2 | 359.6 | 345.2 | 359.6 | 345.2 | 359.6 |
| $I_s$ act, sec | 303.6 | 316.5 | 328.4 | 314.5 | 324.6 | 316.5 | 328.4 |
| $\eta_{IS(vac)}$, % | 92.0 | 91.[illegible] | 91.2 | [illegible].1 | 90.3 | 91.7 | 91.2 |

*Rated Thrust

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13 ABSTRACT

This is the final report documenting the technical accomplishments of the ARES (Advanced Rocket Engine Storable) Throttling and Scaling Study Program under Contract F04611-68-C-0008. Included also in this report are the results of an Aerojet-General Corporation-sponsored design of a throttlable-restartable 100K ARES engine which was used as the baseline engine for this design study.

Throttlable, restartable ARES (Advanced Rocket Engine Storable) engine designs are presented at 25,000, 100,000, and 500,000 lb rated thrust levels. On the basis of these designs, engine thrust scaling parametric data are presented over a thrust range of 25,000 to 500,000 lb with nozzle expansion ratios of 50:1 and 150:1.

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| 14 KEY WORDS | LINK A ROLE | LINK A WT | LINK B ROLE | LINK B WT | LINK C ROLE | LINK C WT |
|---|---|---|---|---|---|---|
| Staged Combustion | | | | | | |
| Storable Propellants | | | | | | |
| High Chamber Pressure | | | | | | |
| Throttlable Engine | | | | | | |
| Restartable Engine | | | | | | |
| Thrust Scaling Data | | | | | | |
| Transpiration Cooling | | | | | | |
| Gas-Liquid Injection | | | | | | |
| Platelet Injector | | | | | | |
| Integrated Turbopumps | | | | | | |
| Propellant Lubricated Bearing | | | | | | |

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