AD-A276 954

NASA CR-190754
RI/RD88-291

FINAL REPORT

ORBITAL TRANSFER ROCKET ENGINE TECHNOLOGY 7.5K-LB THRUST ROCKET ENGINE PRELIMINARY DESIGN

By

T. J. HARMON AND E. ROSCHAK

Rocketdyne Division
Rockwell International Corporation

Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

October, 1993

NASA-Lewis Research Center
Cleveland, Ohio 44135

Contract No. NAS3-23773
Task B.7 and D.5

7.5KLB THRUST ROCKET ENGINE PRELIMINARY DESIGN

FOREWORD

6633 Canoga Avenue, Canoga Park, CA 91303

The work reported herein was conducted by the Advanced Programs and Engineering Personnel of Rocketdyne, a Division of Rockwell International Corporation, under Contract NAS3-23773 from December 1987 to October 1988. D. D. Sheer, Lewis Research Center, was the NASA Project Manager. Mr. R. Pauckert was the Rocketdyne Project Manager, and Mr. T. J. Harmon, as the Study Manager, was responsible for the technical direction of the program.

Important contributions to the conduct of the program, and to the preparation of the material, were made by the following Rocketdyne personnel:

Engine Systems Analysis	C. Erickson
Engine Design	C. Reed, J. Raymond, P. Schilhany
Combustion Devices	W. Brown
Aerothermal Analysis	C. Laren
Turbomachinery	R. Beatty, H. Clausen, A. Eastland, N. Gulbrandsen, E. Jackson, B. Murphy, L. Nielson, J. Scharrer, K. Tran

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

The 7.5Klb Rocket Engine Preliminary Design Study, Task D.5, is a successive iteration of previous engine system design tasks under contract NAS3-23773. In Tasks D.1/D.3 of the space-based engine study, the first iteration of the engine design was completed. That design was driven by space maintenance requirements and by a Failure Mode and Effects Analysis (FEMA). Incorporated in the baseline design was the latest OTV vehicle study findings and the latest component technology advancements. In Task D.4, the Phase I FEMA-Maintenance driven engine design, preliminary maintenance plan, and concepts for space operable disconnects were further developed.

Task D.5 updates the baseline engine by integrating technology improvements, from this and other technology tasks, into a viable preliminary design of a 7.5Klb thrust Orbital Transfer Vehicle engine. The 7.5Klb engine High Pressure Fuel Turbopump Preliminary Design Task work, Task B.7, is included in this report.

2.0 OBJECTIVES

The overall program objective is to define and demonstrate advanced technology for LO_2/LH_2 engines for orbit transfer vehicles. The task objective is to accurately define the characteristics of the components and the engine by conducting preliminary design analyses and design studies at the 7.5Klb thrust level. The designs are for a flight engine.

3.0 APPROACH

A systematic approach was followed wherein the baseline engine, as defined by previous "Preliminary Design Tasks" (Tasks D.1 through D.4), were reviewed to assure the configuration was compatible with engine requirements stated in the work statement. An engine systems analysis performance appraisal was made as a guide to component trade and optimization analysis. In addition, design data from other complementary technology tasks ongoing within the

NAS3-23773 contract were incorporated into the engine design. Table 1 lists the ongoing technology tasks.

Table 1. OTV Rocket Engine Technology Tasks, NAS3-23773

Task Number	Task Description	Task Start Date
B.2	High-Velocity Diffusing Crossover	01/84
B.3/B.5	Soft-Wear Ring Seals	05/84
B.6	High-Speed Turbopump Bearings	06/87
B.7	Hydrogen Turbopump Rotordynamic Simulator	09/87
C.1/C.5	Enhanced Heat-Load Thrust Chamber	01/84
D.5	7.5Klb Thrust Rocket Engine Preliminary Design	12/87
E.3/E.5	Integrated Control and Health Monitoring	07/84

The results of Task B.7, the High-Pressure Turbopump Preliminary Design task, are included in this report. Component trade studies and preliminary analysis were synthesized in layout drawings to define the components. Integration of the above task technologies into an engine design defines the engine system.

4.0 SUMMARY OF ACCOMPLISHMENTS

The objective of developing a preliminary design of a space-based, 7.5Klb thrust engine for an Orbital Transfer Vehicle application was successfully completed. The resulting design built upon the foundation of previous preliminary design tasks, Tasks D.1/D.3 and D.4, and incorporates advanced technology.

The baseline engine system analysis was reviewed to assure requirements and goals could be met. Off-design studies were conducted to assess the severity of the ranges of required operation of the components. Results of this effort indicated engine requirements and performance goals could be met. Computer models are described and model outputs are presented.

Component analyses include studies to optimize the configuration. The injector/igniter configuration has strong historical precedence and demonstrated high performance. Updated heat transfer analysis defined regenerative cooling requirements for the thrust chamber and nozzle. The resultant coolant passage geometry indicates safe engine operation over the engine design life of 500 cycles.

A preliminary design analysis was completed to define the design and off-design performance of the fuel high-pressure turbopump. Major design technologies were identified and remaining issues and concerns were listed. This effort was completed under a different task order, Task B.7, but is included in this report for completeness. The design and analyses of the boost pumps have been conducted to the extent necessary to assure the validity of the interface with the high-pressure fuel and oxidizer turbopumps. Cross-sectional design layouts were completed showing the primary design features, basic dimensions critical clearances and materials.

Valve, control and health monitoring advances were reviewed and updated. Design improvements for accommodating deep throttling were developed and documented.

5.0 TECHNICAL DISCUSSION

The overall approach followed (` Task D.5 is presented in Figure 1. Outputs from previous preliminary design task (References 1 and 2) include FMEA maintenance driven engine design/layout, a preliminary space maintenance plan, several preliminary concepts for space operable disconnects, and an engine design update.

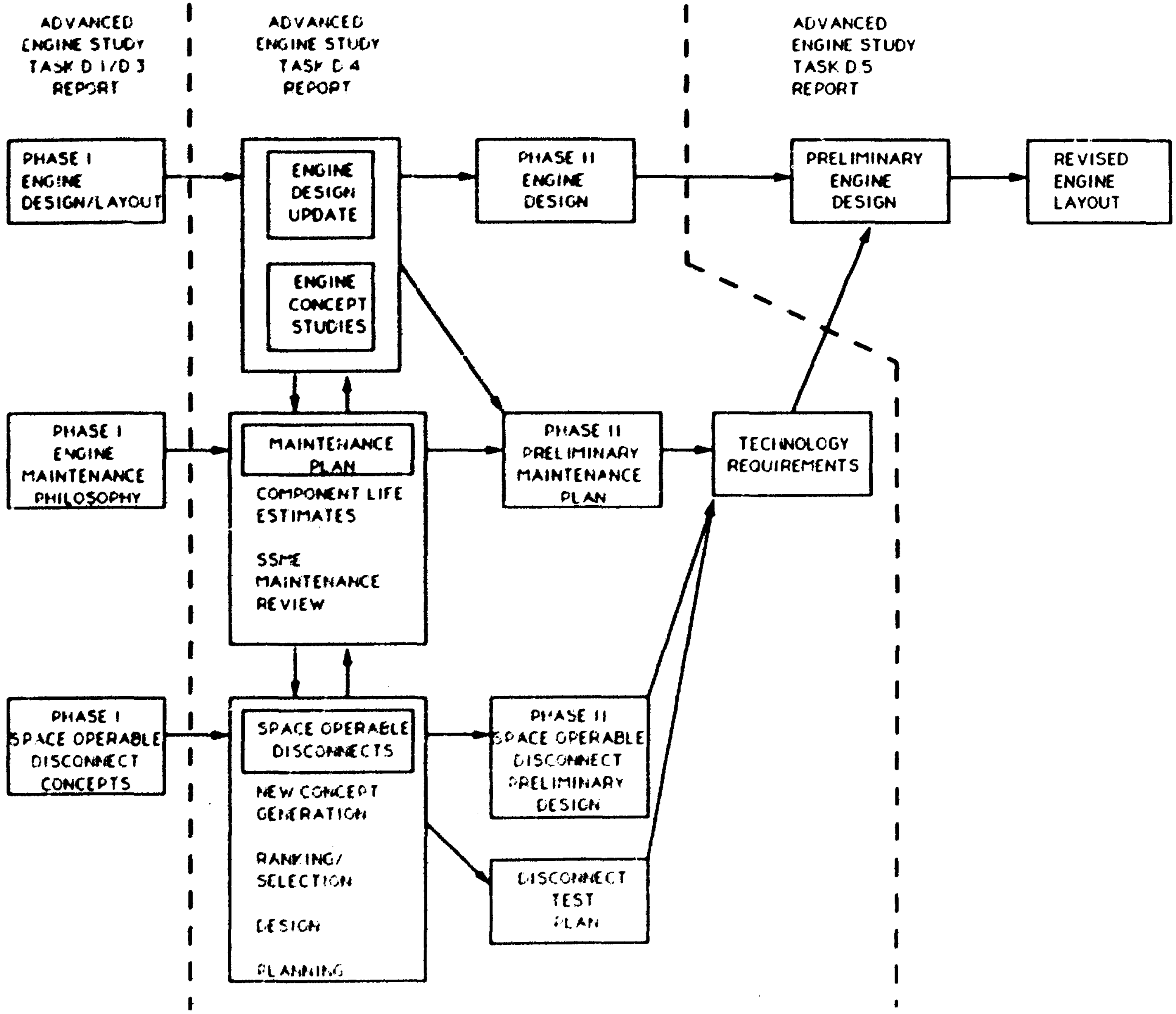


FIGURE 1
ADVANCED ENGINE STUDY LOGIC DIAGRAM

6.0 PROGRAM WORK PLAN

The D.5 Task Order was approved in March 1987 and a task work plan was approved in May 1987. The task results are presented in the same order described in the work plan (i.e., engine analysis, component analysis, technology level, engine layout, component layout, and support).

6.1 Engine Analysis

There are two primary computer programs used for preliminary design and analysis of the engine. These are the Expander Cycle Engine Steady-State and Optimization Code and the Expander Cycle Rocket Engine Steady-State Off-Design Code. The steady-state design model is a comprehensive mathematical model of an expander cycle engine with standard converging/diverging nozzle. Numerous component and design options are included in the model. The generality of the program is greatly enhanced by its ability to model a wide range of different expander cycle schematic configurations which include or omit certain components. This "variable schematic" feature is achieved by the use of powerful routines which analyze schematic topology, which is specified by a data set read by the program. These routines then establish all component interconnections and flow paths implied by the data description of the desired engine schematic diagram. Bookkeeping of propellant thermodynamic properties, including pressure, temperature, density, enthalpy, and entropy is performed throughout the system.

A modified multidimensional Box Complex optimization algorithm is used to optimize selected key independent engine variables. First, determination is made if a steady-state system balance can be obtained within the specified maximum and minimum component limits. Once a solution is found the variable being optimized is maximized by variation of a user-specified set of independent variables. An example of a typical balance run would be the maximization of engine specific impulse with 10 independent variables, as listed in Table 2. The optimum combination of these variables determines th allowable ranges as dictated by technology limits. The output from this balance includes the engine performance and dimensions in addition to many specific details such as T/P efficiencies, impeller diameters, pressure schedules, etc.

Table 2. Engine Balance

Independent Variables
Chamber pressure
Nozzle area ratio
Fuel turbopump (T/P) RPM
Oxidizer T/P RPM
Fuel turbine pressure ratio
Oxidizer turbine pressure ratio
Fuel turbine arc of admission
Oxidizer turbine arc of admission
Fuel turbine pitchline velocity
Oxidizer turbine pitchline velocity

The engine performance predicted by the Design and Optimization Code is the take off point used by the Expander Cycle Rocket Engine Steady-State Off Design Code. This code is designed to accept a numerical description from the Steady-State Design Code and perform a power balance at off-design operating points. Off-design mixture ratios of 5 and 7, and reduced thrust levels to 10% with mixture ratios from 4 to 7 were evaluated utilizing this code. Flow schematics showing flow, pressure and temperature at selected engine system locations are presented in Figures 2 through 8. Figure 2 presents the on-design case, mixture ratio 6.0, with a calculated Isp performance of 490.2 s. Figures 3 and 4 present full thrust off-design cases for mixture ratios of 5.0 and 7.0, respectively. Figures 5 through 8 present 10% thrust level off-design cases at mixture ratios of 4.0, 5.0, 6.0, and 7.0, respectively.

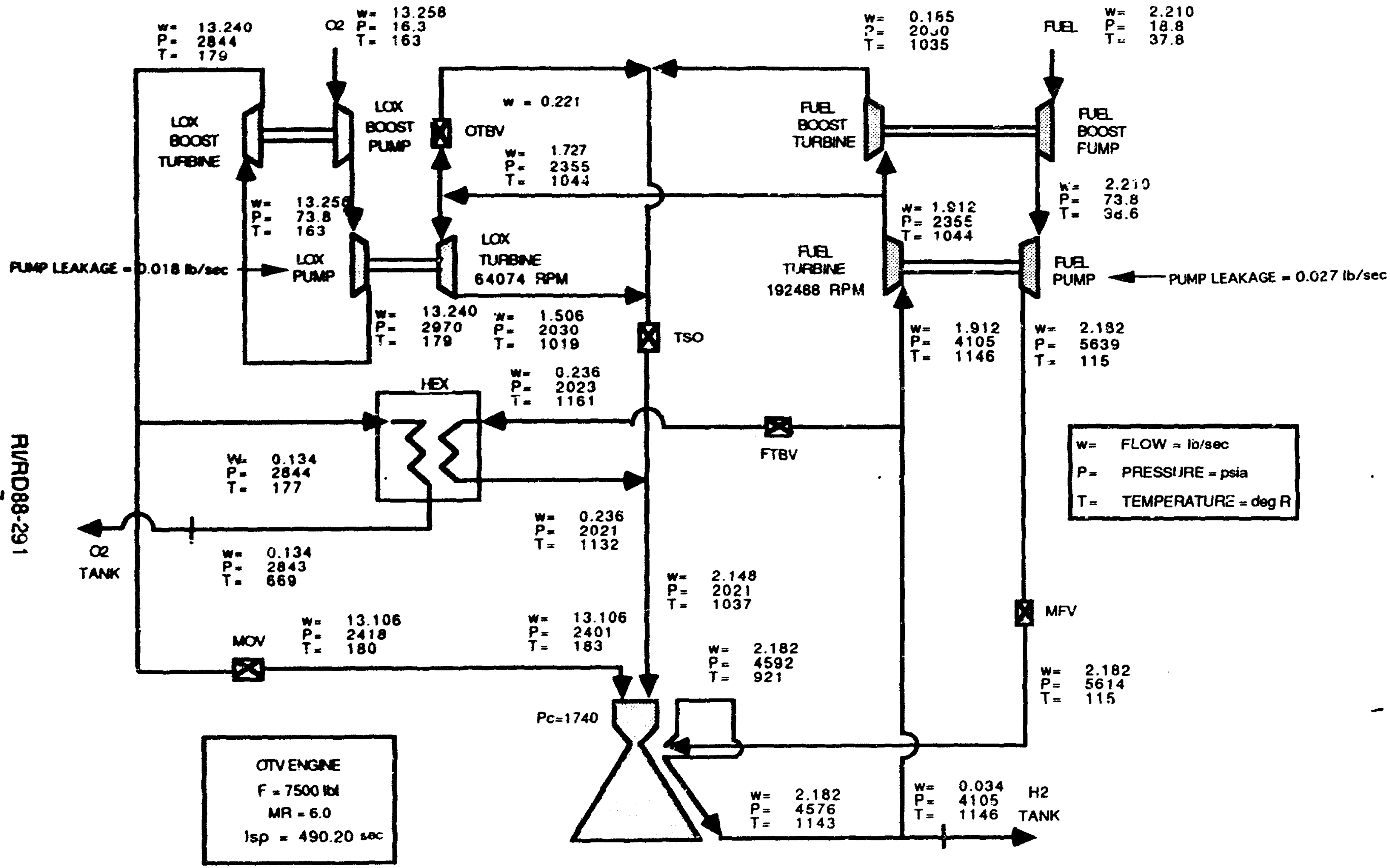


FIGURE 2
DESIGN POINT ENGINE PERFORMANCE
A[illegible] FULL THRUST & MR = 6.0

88-0418RP3/TE
OTVM 6

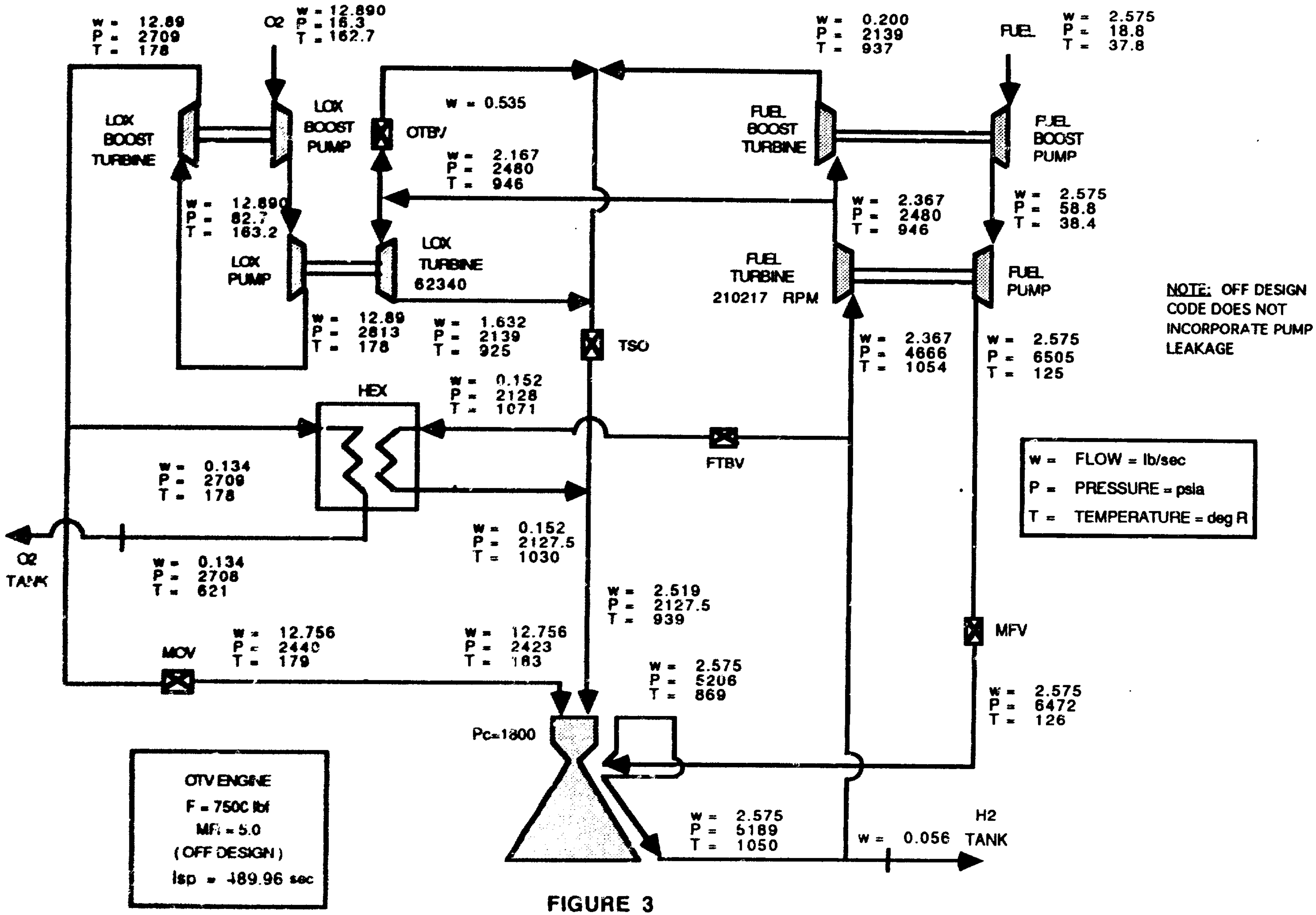


FIGURE 3
OFF-DESIGN ENGINE PERFORMANCE AT FULL THRUST & MR = 5.0

88-0418RP1/TE
OTVM 5

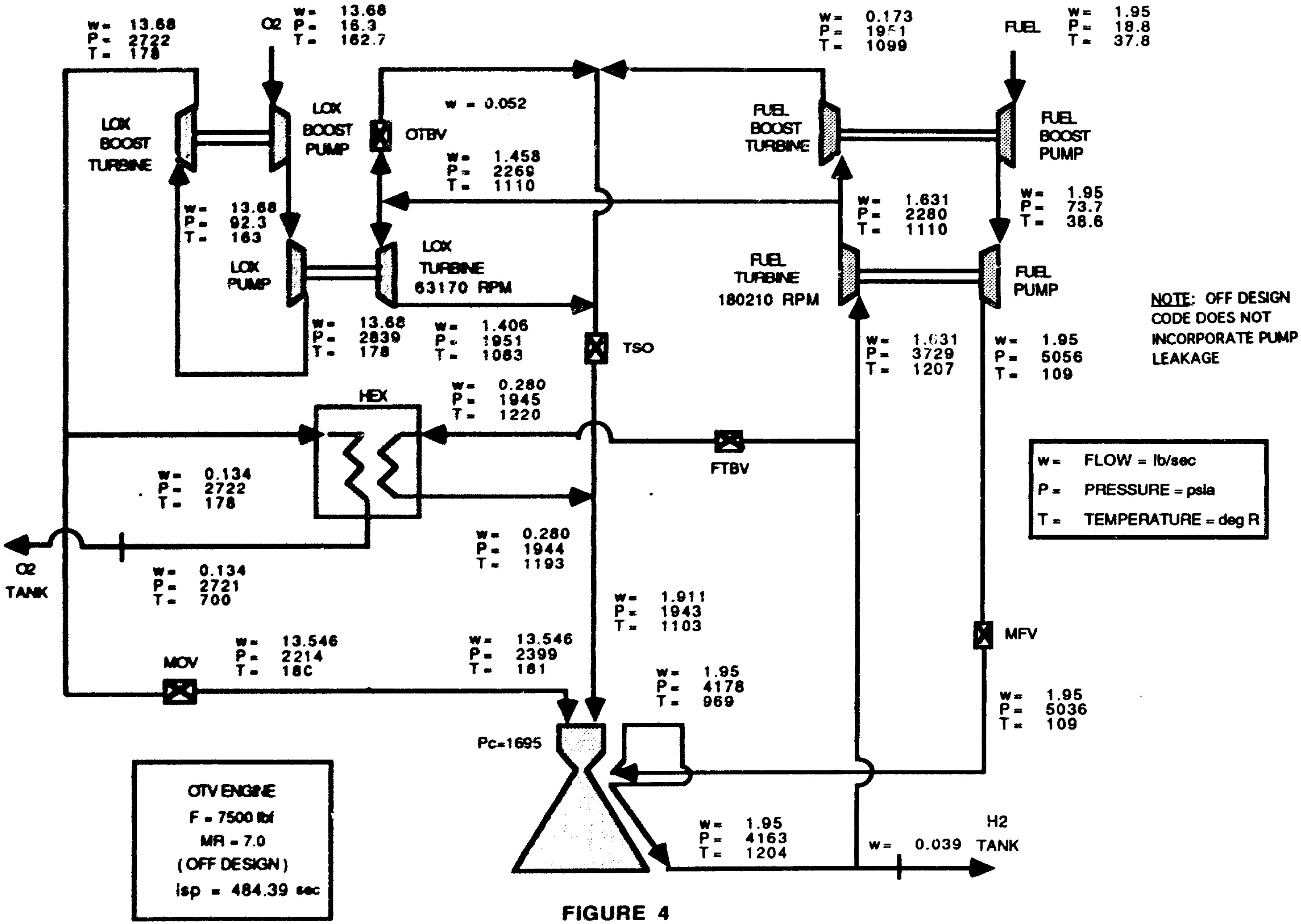


FIGURE 4
OFF-DESIGN ENGINE PERFORMANCE AT FULL THRUST & MR = 7.0

88-0418RP2/TE
OTVM 7

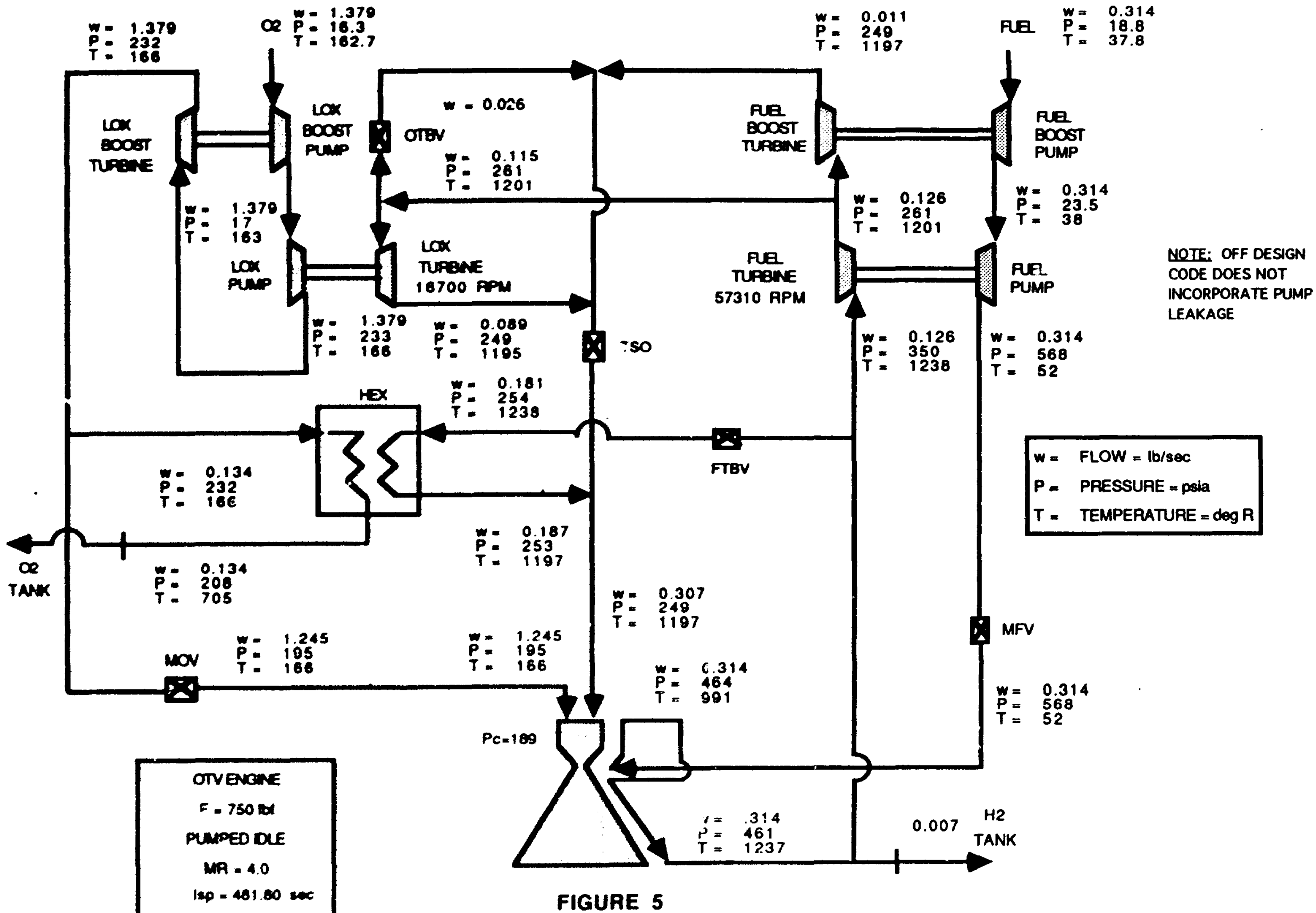
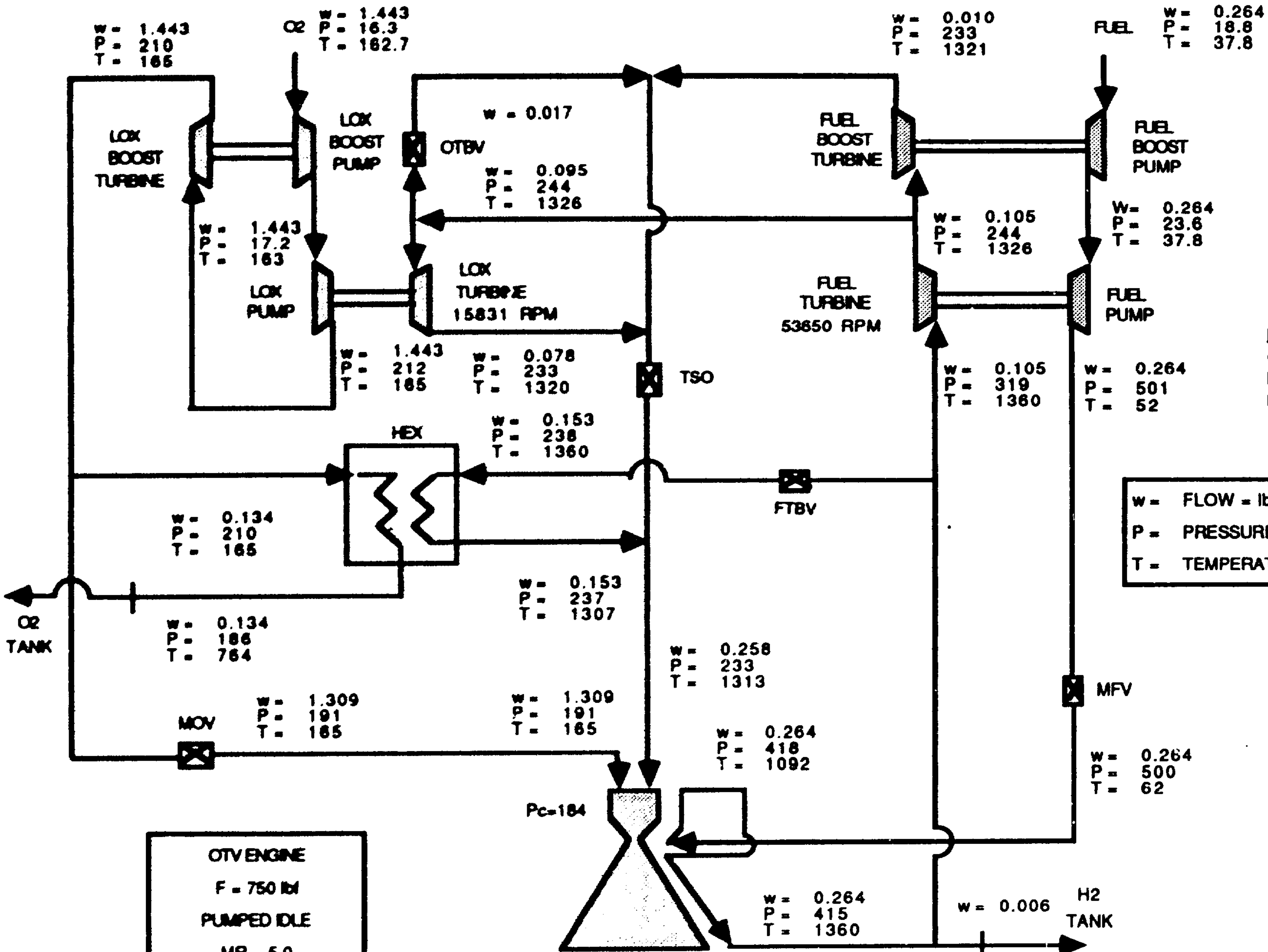


FIGURE 5
OFF-DESIGN ENGINE PERFORMANCE
AT 10% THRUST & MR = 4.0

88-0418RP4/TE
OTVM 4



NOTE: OFF DESIGN CODE DOES NOT INCORPORATE PUMP LEAKAGE

w =	FLOW = lb/sec
P =	PRESSURE = psia
T =	TEMPERATURE = deg R

OTV ENGINE
F = 750 lbf
PUMPED IDLE
MR = 5.0
Isp = 477.32 sec

FIGURE 6
OFF-DESIGN ENGINE PERFORMANCE
AT 10% THRUST & MR = 5.0

88-0418RP5/TE
OTVM 5

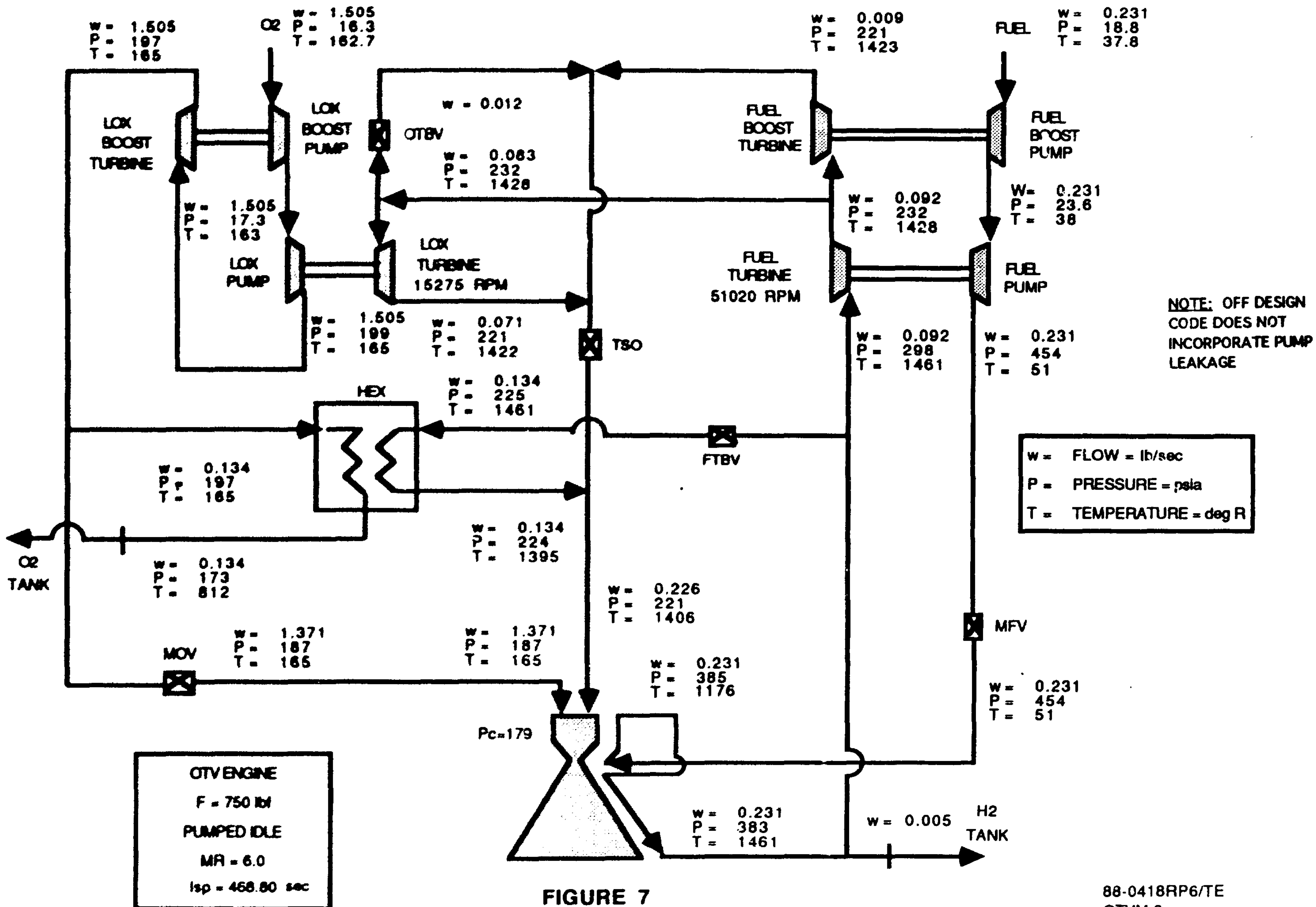


FIGURE 7
OFF-DESIGN ENGINE PERFORMANCE
AT 10% THRUST & MR = 6.0

88-0418RP6/TE
OTVM 6

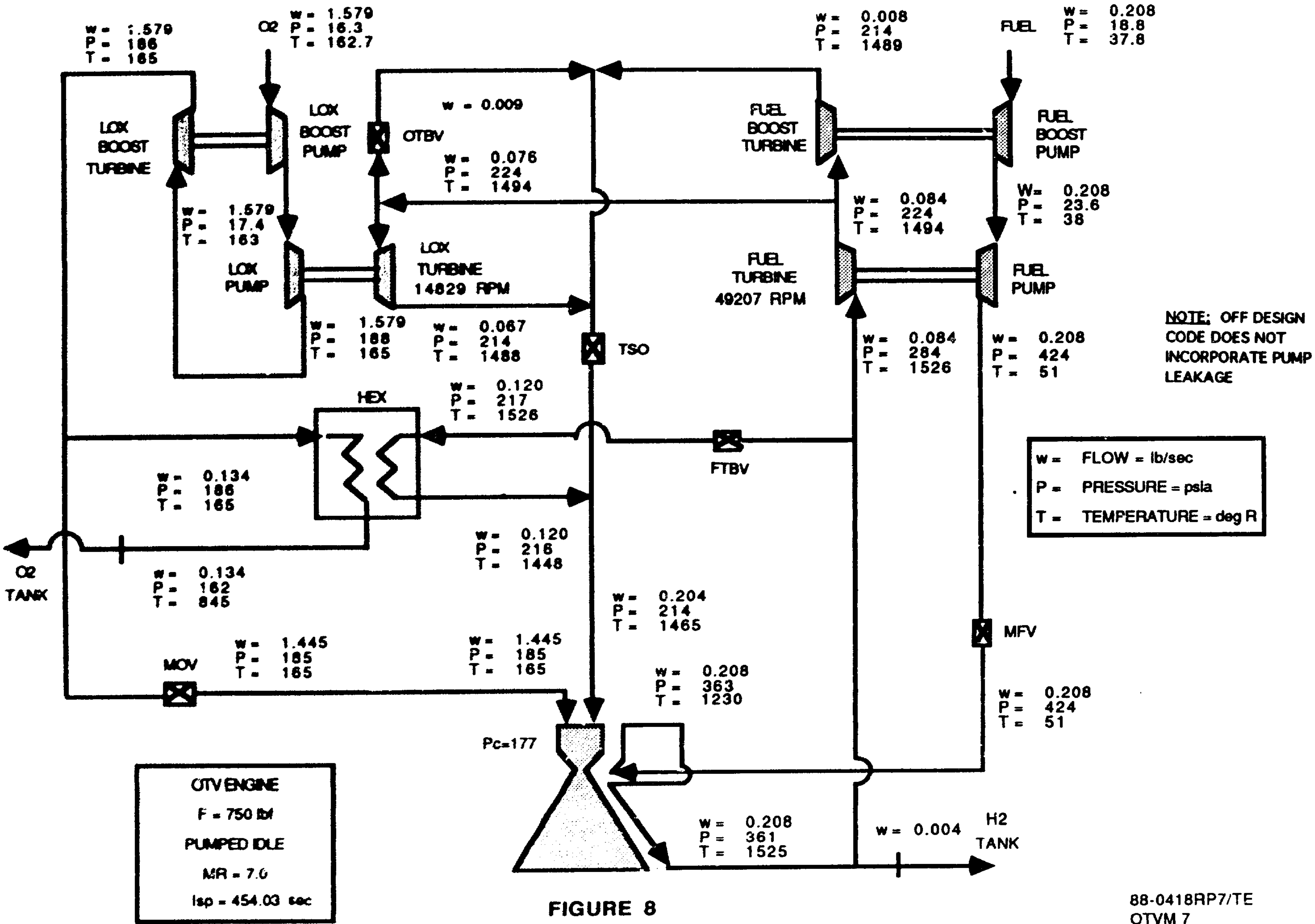


FIGURE 8
OFF-DESIGN ENGINE PERFORMANCE
AT 10% THRUST & MR = 7.0

Detailed listings of the computer output for the on-design and off-design conditions are presented in Appendix A.

The engine balance incorporated updated nozzle and combustor heat transfer rates and coolant system pressure drops and the latest turbomachinery efficiency correlations. The combustor heat transfer rates incorporate an enhancement factor of 42% over that of a smooth wall combustor. This value is projected from experimental data from the Enhanced Heat Transfer Technology, Task C.1 (Reference 3). Turbomachinery technology limits used for on-design (balance value) and off-design (maximum limit) operating conditions are presented in Table 3.

Table 3. OTV Turbomachinery Limits

Parameter	Maximum Limit	Balance Value
Fuel pump impeller tip speed (ft/s)	1900	1865
Fuel turbine pitch line velocity (ft/s)	1500	1480
Oxidizer pump impeller tip speed (ft/s)	900	646
Oxidizer turbine pitch line velocity (ft/s)	1600	1183
Fuel oxidizer bearing DN(E^{-6}) (Diam. in MM)(RPM) (E^{-6})	No limit/2.0	2.6/0.75
Fuel/oxidizer turbine AN^2 (E^{-10}) (Annulus Area)$(RPM)^2$(E^{-10})	10	7.7/0.89

Results of the off-design conditions at the 7.5Klb thrust level indicated that operation at mixture ratio = 5.0 imposes the more stressful conditions upon the fuel turbomachinery than at the nominal mixture ratio of 6.0. Therefore, it was necessary to build margins into the on-design turbomachinery limits in order to accommodate the more severe operating conditions experienced at a mixture ratio = 5.0. Turbomachinery impeller tip speed limits and turbine pitch line velocity limits, 1900 and 1600 ft/s, respectively, were applied to this off-design condition. No fuel turbopump bearing DN limits were assumed since hydrostatic bearings are incorporated.

The pump impeller tip speed limit plays an important role in engine design in that it defines the maximum pump discharge pressure which in turn dictates attainable chamber pressure (Pc). A four-stage pump was chosen in order to maximize the pump exit pressure and Pc at the 7.5Klb thrust level.

With the series flow turbine configuration used in this engine system design, chamber pressure and Isp are relatively insensitive to oxidizer turbopump design. The reason is that the oxidizer turbine horsepower required is only 18% of that of the fuel turbopump. Therefore, with series flow turbines there is an excess of flow available to power the LOX turbine. The optimizer code chooses the lowest allowable turbine pressure ratio (1.16) in order to maximize chamber pressure and bypasses the extra flow around the turbine. Thus oxidizer turbine and pump efficiencies have essentially no effect on Pc or engine performance. No oxidizor turbopump operating limits were encountered in the optimization.

OTV engine pump parametrics, summarizing the on-design and off-design pump characteristics, are presented in Table 4. Figures 9 and 10 present high-pressure fuel and oxidizer pump maps for the engine system. These parametrics data served as the starting point for the detailed turbopump designs.

6.2 Component Analysis

A comprehensive review was conducted on all components to incorporate the latest technology into the preliminary design of the 7.5Klb thrust engine. This component analysis section follows the following order: (1) combustion devices components (injector, igniter, combustor, and nozzle), (2) turbomachinery (high-pressure fuel turbopump, high-pressure oxidizer turbopump, low-pressure fuel turbopump, and low-pressure oxidizer turbopump), (3) valves, and (4) integrated control and health monitoring.

Table 4. OTV Engine Pump Parametrics (Sheet 1 of 2)

		ON-DES	OFF-DES	OFF-DES	OFF-DES
THRUST	(LBF)	7500	7500	7500	750
MIXTURE RATIO (O/F)	(NONE)	6	7	5	4
HIGH-PRESSURE FUEL PUMP					
NO. OF STAGES		4	4	4	4
WHEEL SPEED	(RPM)	192487.5	180209.6	210217.0	57310.0
EFFICIENCY	(%)	60.23	60.04	59.95	43.79
HORSEPOWER		1083.27	861.41	1437.90	22.98
FLOW RATE	(LB/SEC)	2.209	1.95	2.57	0.31
OUTLET PRESSURE	(PSIA)	5639.39	5055.82	6504.79	568.42
DIAMETER	(IN.)	2.22	2.22	2.22	2.22
EFFECTIVE DENSITY	(LB/FT3)	4.94	4.94	4.94	4.94
INDUCER					
INLET FLOW VELOCITY	(FT/SEC)	117.66	104.02	137.12	16.73
TIP SPEED	(FT/SEC)	782.36	732.46	854.42	232.94
FLOW COEFFICIENT		0.15	0.14	0.16	0.07
HEAD COEFFICIENT		0.10	0.09	0.09	0.10
STAGE SPECIFIC SPEED		10070.23	9938.43	10967.61	6670.86
IMPELLER					
INLET FLOW VELOCITY	(FT/SEC)	118.60	104.86	138.22	16.87
TIP SPEED	(FT/SEC)	1864.65	1745.71	2036.39	555.17
FLOW COEFFICIENT		0.11	0.14	0.16	0.07
HEAD COEFFICIENT		0.43	0.38	0.36	0.41
STAGE SPECIFIC SPEED		919.6	919.16	1014.34	616.96
HEAD RISE PER STAGE	(FT)	46261.08	35961.9	46553.37	3928.80
HIGH-PRESSURE OXIDIZER PUMP					
NO. OF STAGES		1	1	1	1
WHEEL SPEED	(RPM)	64074.3	63170.2	62340.4	16700.4
EFFICIENCY	(%)	67.12	66.97	67.12	42.89
HORSEPOWER		201.59	201.39	188.03	2.60
FLOW RATE	(LB/SEC)	13.258	13.68	12.89	1.38
OUTLET PRESSURE	(PSIA)	2969.62	2838.73	2812.78	233.14
DIAMETER	(IN.)	2.31	2.31	2.31	2.31
EFFECTIVE DENSITY	(LB/FT3)	71.14	71.14	71.14	71.14
INDUCER					
INLET FLOW VELOCITY	(FT/SEC)	40.51	41.81	39.39	4.21
TIP SPEED	(FT/SEC)	269.36	265.56	262.07	70.21
FLOW COEFFICIENT		0.15	0.16	0.15	0.06
HEAD COEFFICIENT		0.10	0.10	0.10	0.11
STAGE SPECIFIC SPEED		10070.23	10456.04	10065.1	5931.76
IMPELLER					
INLET FLOW VELOCITY	(FT/SEC)	36.87	38.05	35.85	3.84
TIP SPEED	(FT/SEC)	646.47	637.35	628.98	168.50
FLOW COEFFICIENT		0.11	0.14	0.14	0.05
HEAD COEFFICIENT		0.43	0.43	0.43	0.48
STAGE SPECIFIC SPEED		900.28	934.91	899.96	530.38
HEAD RISE PER STAGE	(FT)	5641.25	5376.74	5341.53	420.79

Table 4. OTV Engine Pump Parametrics (Sheet 2 of 2)

		OFF-DES	OFF-DES	OFF-DES	
THRUST	(LBF)	750	750	750	
MIXTURE RATIO (O/F)	(NONE)	5	6	7	
HIGH-PRESSURE FUEL PUMP					
NO. OF STAGES		4	4	4	
WHEEL SPEED	(RPM)	53649.6	51020.2	49207.4	
EFFICIENCY	(%)	40.60	38.10	36.24	
HORSEPOWER		18.30	15.39	13.61	
FLOW RATE	(LB/SEC)	0.26	0.23	0.21	
OUTLET PRESSURE	(PSIA)	500.62	454.27	423.51	
DIAMETER	(IN.)	2.22	2.22	2.22	
EFFECTIVE DENSITY	(LB/FT3)	4.94	4.94	4.94	
INDUCER					
INLET FLOW VELOCITY	(FT/SEC)	14.08	12.28	11.10	
TIP SPEED	(FT/SEC)	218.06	207.37	200.00	
FLOW COEFFICIENT		0.06	0.06	0.06	
HEAD COEFFICIENT		0.10	0.10	0.10	
STAGE SPECIFIC SPEED		6328.57	6070.92	5883.87	
IMPELLER					
INLET FLOW VELOCITY	(FT/SEC)	14.19	12.38	11.19	
TIP SPEED	(FT/SEC)	519.71	494.24	476.68	
FLOW COEFFICIENT		0.07	0.06	0.06	
HEAD COEFFICIENT		0.41	0.41	0.41	
STAGE SPECIFIC SPEED		585.3	561.47	544.17	
HEAD RISE PER STAGE	(FT)	3439.20	3104.61	2882.63	
HIGH-PRESSURE OXIDIZER PUMP					
NO. OF STAGES		1	1	1	
WHEEL SPEED	(RPM)	15830.8	15274.7	14828.8	
EFFICIENCY	(%)	46.12	48.71	51.31	
HORSEPOWER		2.29	2.11	1.98	
FLOW RATE	(LB/SEC)	1.44	1.51	1.58	
OUTLET PRESSURE	(PSIA)	211.67	198.43	188.05	
DIAMETER	(IN.)	2.31	2.31	2.31	
EFFECTIVE DENSITY	(LB/FT3)	71.14	71.14	71.14	
INDUCER					
INLET FLOW VELOCITY	(FT/SEC)	4.41	4.60	4.83	
TIP SPEED	(FT/SEC)	66.55	64.21	62.34	
FLOW COEFFICIENT		0.07	0.07	0.08	
HEAD COEFFICIENT		0.11	0.11	0.11	
STAGE SPECIFIC SPEED		6222.76	6465.55	6722.38	
IMPELLER					
INLET FLOW VELOCITY	(FT/SEC)	4.01	4.19	4.39	
TIP SPEED	(FT/SEC)	159.72	154.11	149.61	
FLOW COEFFICIENT		0.06	0.07	0.07	
HEAD COEFFICIENT		0.48	0.48	0.48	
STAGE SPECIFIC SPEED		556.40	578.11	601.07	
HEAD RISE PER STAGE	(FT)	378.88	353.01	332.66	

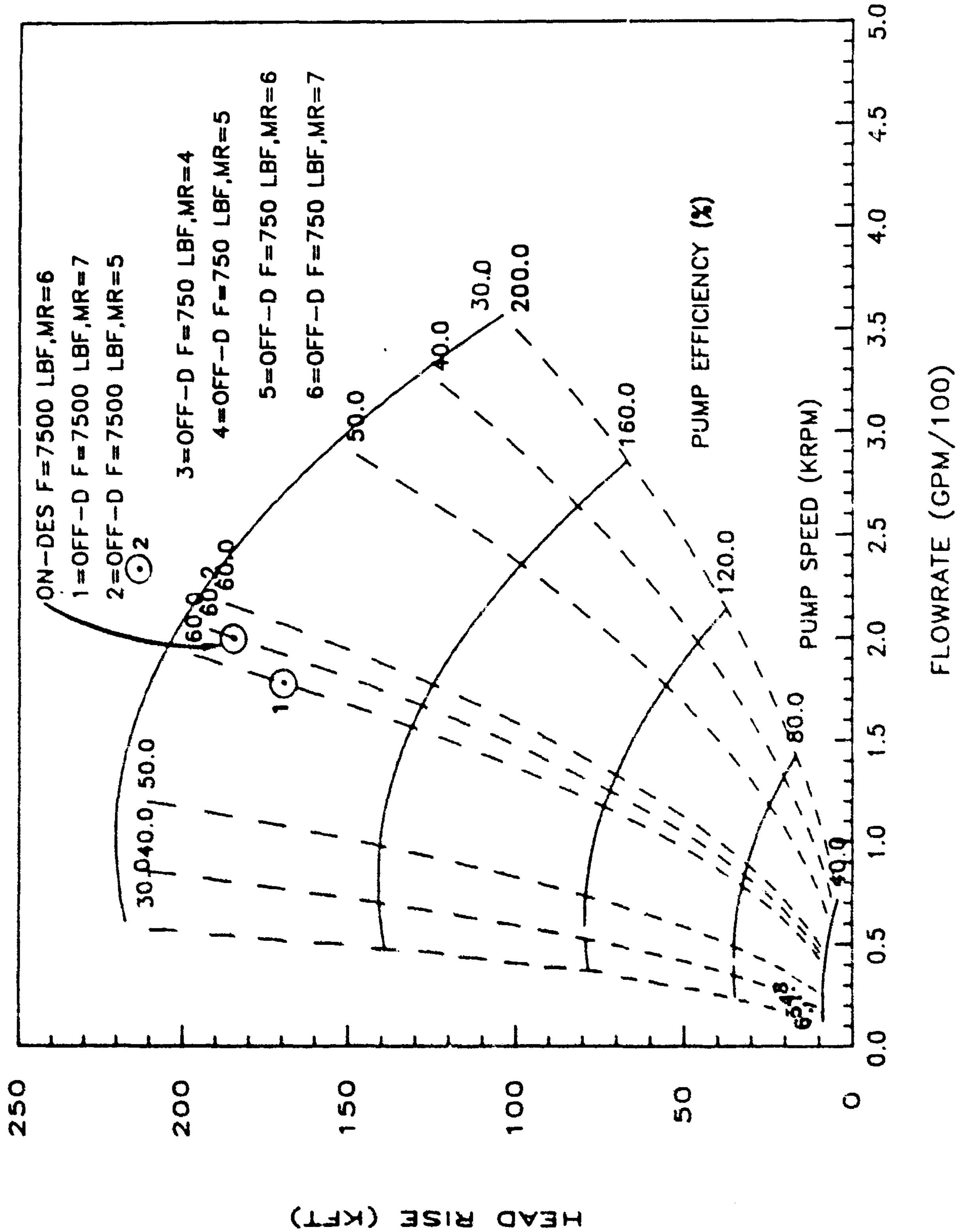


Figure 9. OTV Fuel Pump Map

5471e

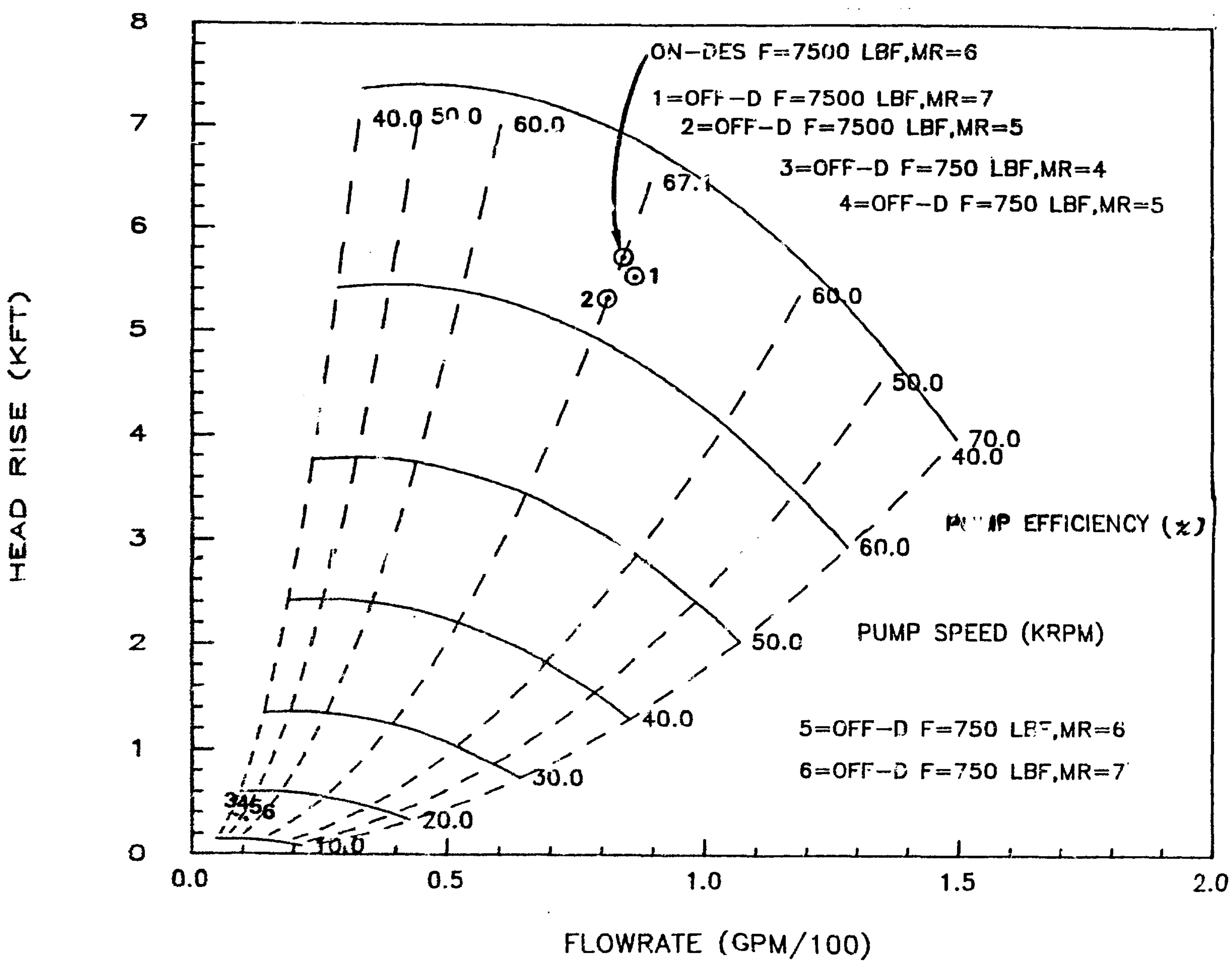


Figure 10. OTV Oxidizer Pump Map

5471e

6.2.1 Injector/Igniter

The element of choice for a gaseous hydrogen injector is the coaxial, or concentric injection element. This selection has strong historical precedent and is the most assured approach to provide high combustion efficiency and combustion stability. Other element concepts, such as an unlike impinging element, were ruled out because of the unknowns from stability and compatibility standpoints. Figure 11 presents a sketch of a single element. The element design incorporates an inner liquid oxygen core surrounded by an outer gaseous hydrogen shroud.

With the coaxial element injector concept defined, details of the pattern were reviewed. The coaxial element was chosen because of higher heat fluxes near the injector and high combustion efficiency. A removable rigimesh faceplate was selected to provide a high margin on face cooling. A faceplate retention system using face nuts was selected to maximize flexibility in injector element geometry, and provide structural support for the faceplate. The 7.5Klb thrust engine could have incorporated an edge supported faceplate, because of the small 3.5-in. diameter, but the added margin, flexibility, and scalability of the face nut system outweighed the potential simplicity of the self support faceplate.

An innovative face nut design allows close element spacing, and the 3.5-in. injector diameter can accommodate four circular rows of elements for a total of 60 elements. The face pattern design is shown in Figure 12. Minimum spacing on these elements is under 3/8 in., which is very close for an adjustable face nut design. The baseline face material is the same stainless steel rigimesh as used for the SSME main injector. High performance and good chamber compatibility are predicted for this design. Heat fluxes should follow reasonable predictions for LOX/hydrogen operation with full combustion being completed very close to the injector face.

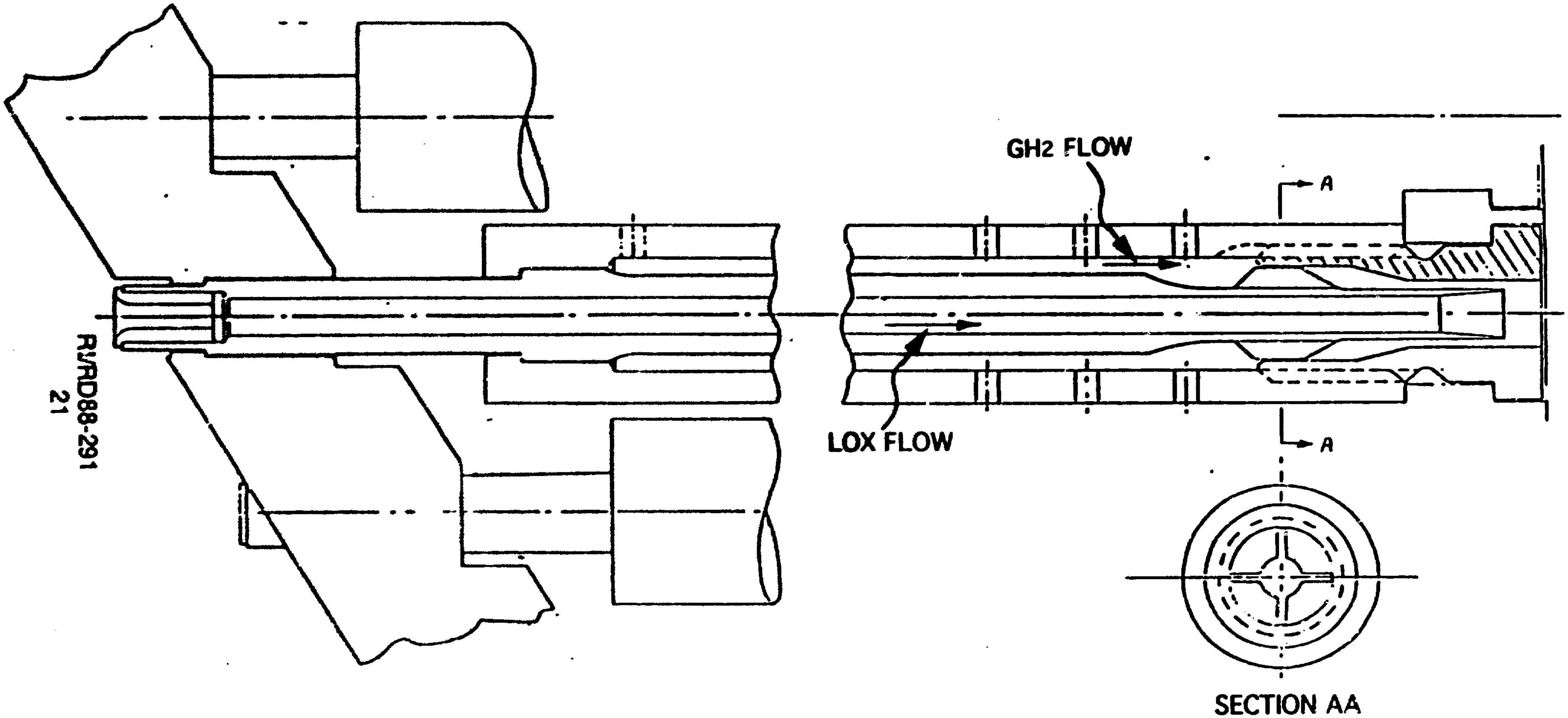


Figure 11. Single-Element Sketch

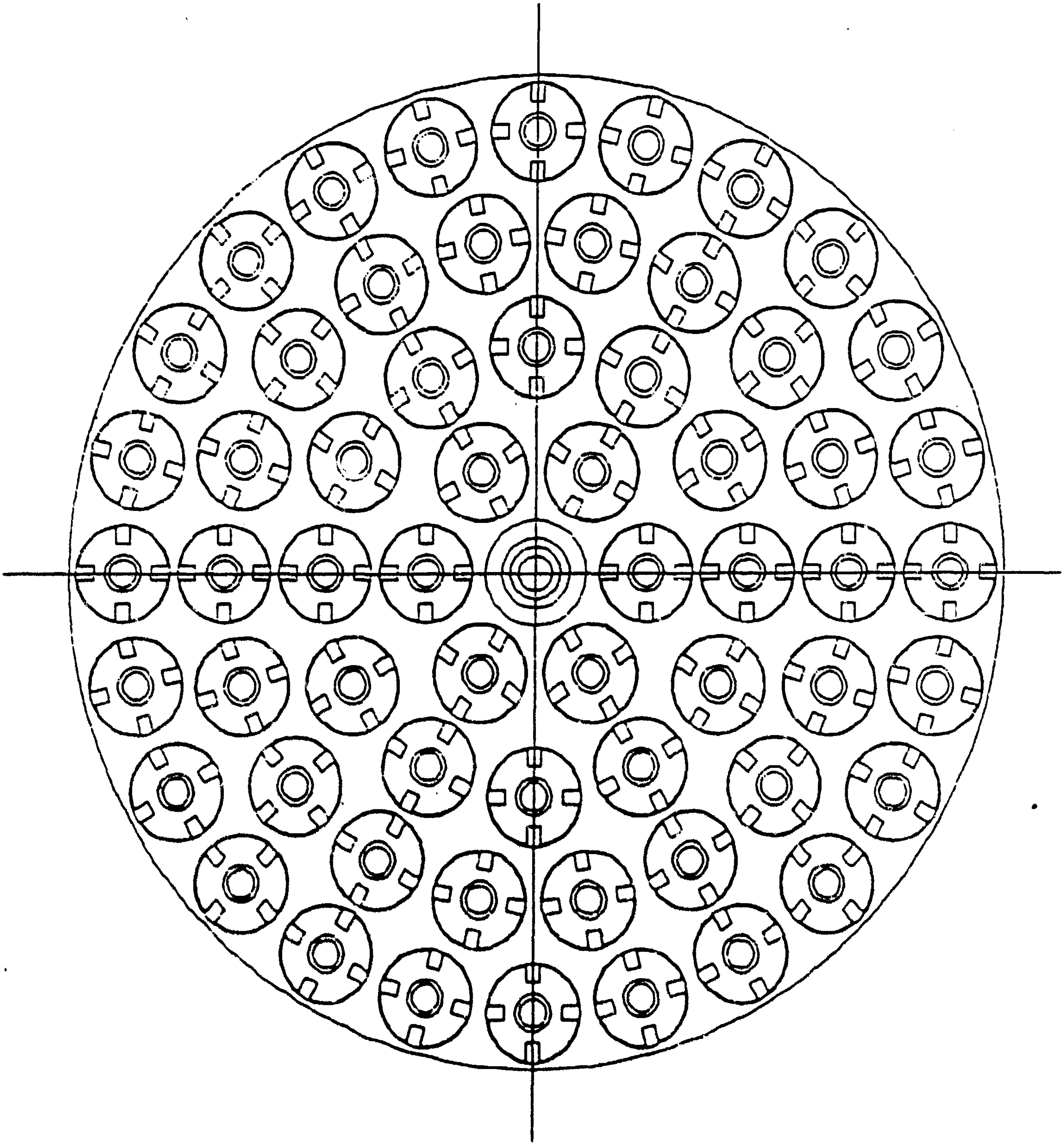


Figure 12. Face Pattern Design

The complete injector /igniter assembly is shown in Figure 13. The design incorporates a centerline igniter and provision for gimbaling. The igniter design is presented in Figure 14. The igniter utilizes a dual spark plug plasma-torch design. Duality provided by two spark plugs ensures ignition. A similar design, utilizing a single spark plug, has proven reliable in 13 starts in the 15Klb thrust ICE engine tests.

Injector stability was determined on the 15Klb thrust injector design and analyzed to be stable for mainstage, 10% thrust, and transients. Hot-fire tests on this injector showed no signs of instability. The 7.5Klb thrust injector design is a similar injector configuration. A review of the design indicated that instability is not expected. A instability analysis of the 7.5Klb thrust injector design was not completed.

6.2.2 Combustor/Nozzle

The combustor and nozzle dimensions and key features are defined in the system model (reference Appendix A). Key combustor characteristics include a 20-in. thrust chamber length and a 4:1 contraction ratio. The thrust chamber incorporates enhanced heat transfer technology with 0.040-in.-high ribs in the combustion side of the chamber and a single, 0.024-in.-high fin in each of the coolant channels. Figure 15 shows a cross section of the thrust chamber showing the rib and fin configuration, and the materials of construction. Proven fabrication technologies (developed for the SSME and the Advanced Space Engine combustion chambers) and materials (Narloy Z and electroformed nickel) were used in the thrust chamber design.

A heat transfer enhancement factor of 42% over that of a smooth wall combustor is predicted for the ribbed combustor. Note the ribs and fins extend only along the straight length of the thrust chamber; i.e., they do not extend into the contraction or throat area. This value is projected from experimental data from the Enhanced Heat Transfer Technology, Task C.1 (Reference 3). The coolant channel fin configuration incorporates a single 0.024 in. fin. This fin height was selected based on 2-d hot-air and cold flow data obtained during the OTV Enhanced Heat Transfer Combustor contract testing. The test results show a single 0.024 in. coolant channel fin decreases the liner temperature by 40 degrees F, reference Figure 15a. A confirming CFD analysis, for a 15Klb thrust combustor, shows the maximum wall temperature decreases 44 degrees F with finned coolant channels when compared to the non finned case, reference Figure 15b. The effect of the decrease in temperature on structural strain is shown in Figure 15c. The finned coolant channel combustor liner strain is less than 1%. Nominal strain for a non-finned liner is in the 2.3 to 2.5% range. Operating at lower combustor liner temperature decreases thermal stress and increases structural life.

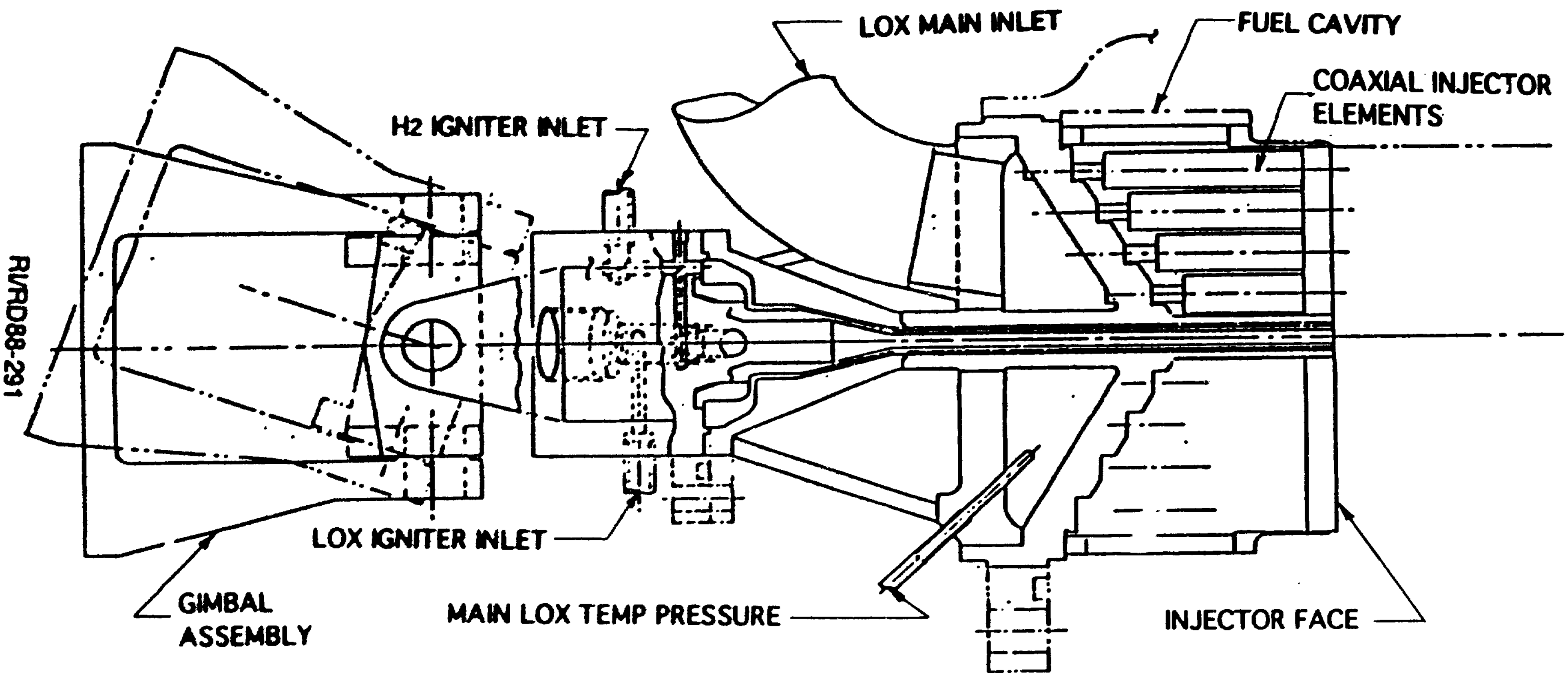


Figure 13 Complete Injector/Igniter Assembly

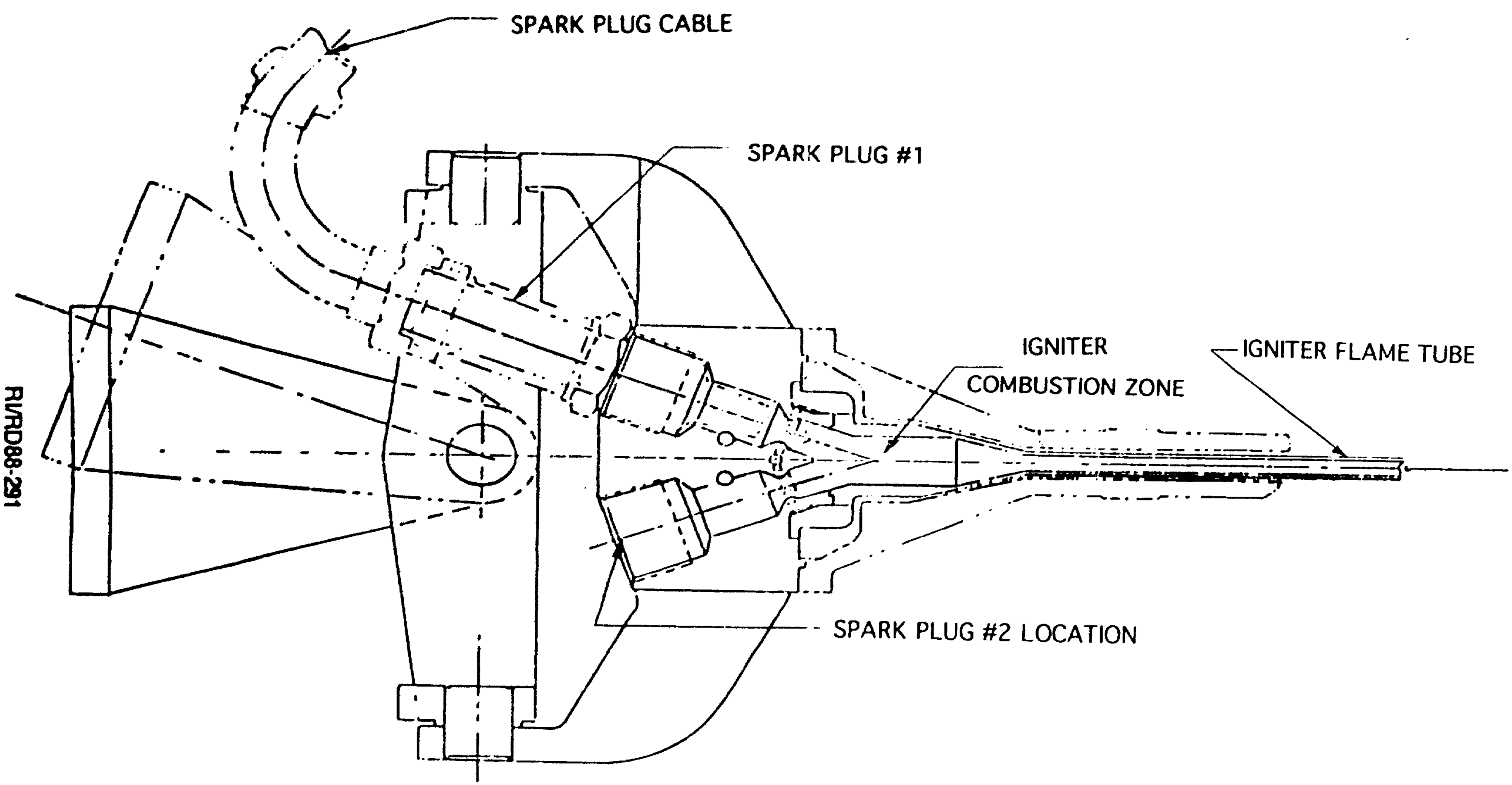


Figure 14. Igniter Design

NOTE: All dimensions are in inches.

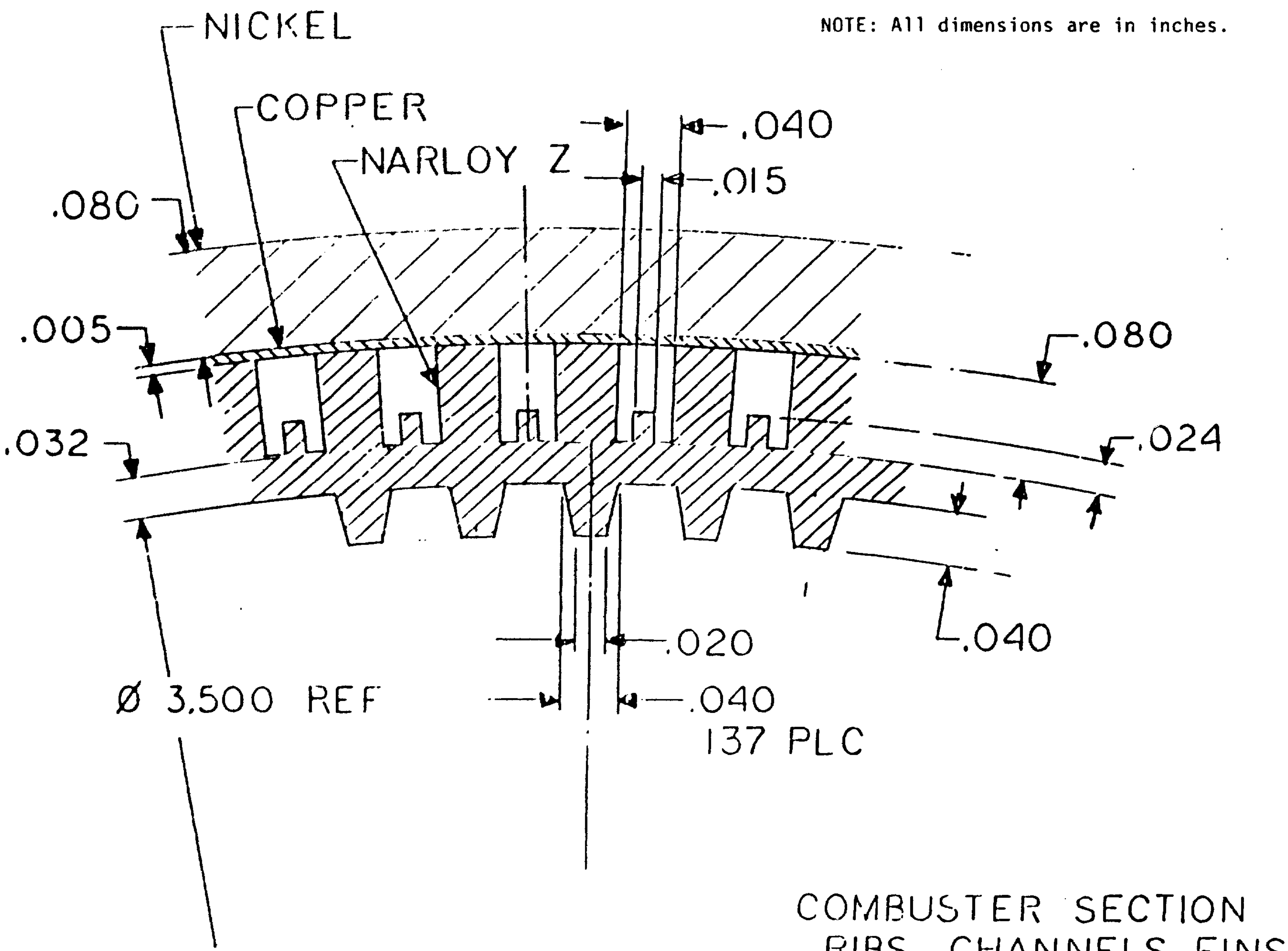


Figure 15. Cross Section of Thrust Chamber

5471e

HOT GAS SIDE WALL TEMPERATURE CHANGE °F

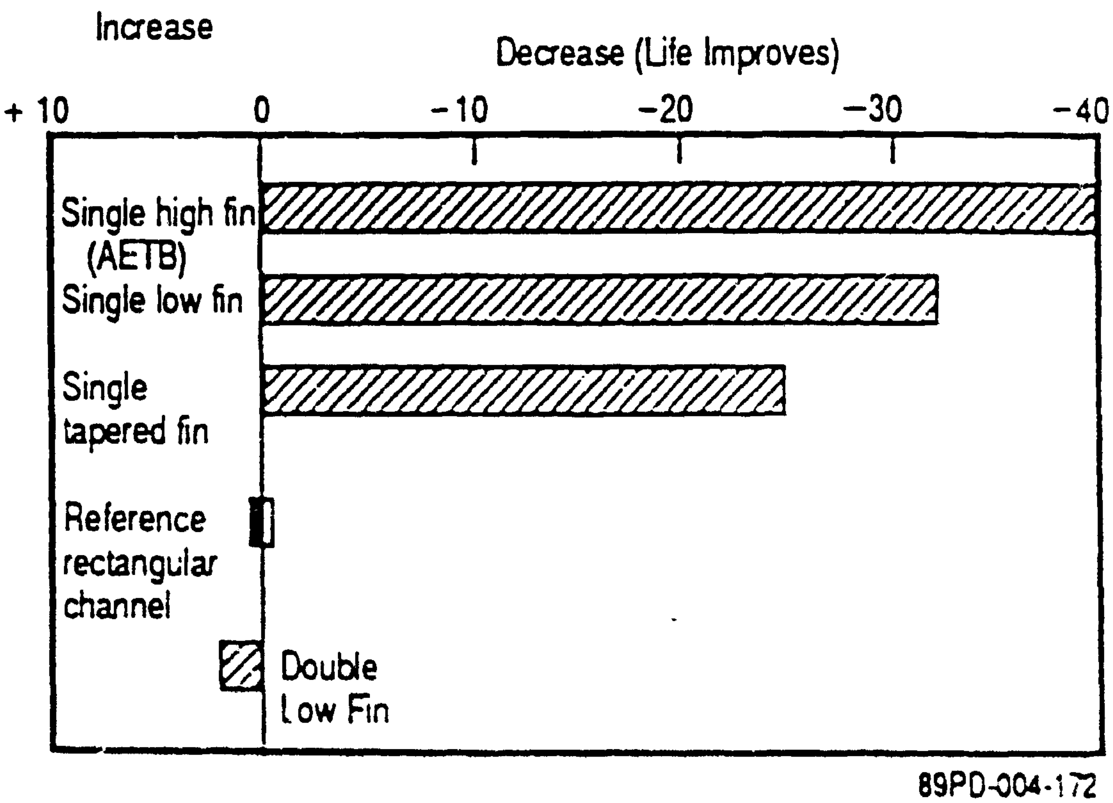


Figure 15a. Liner Temperature Change with Enhanced Channels

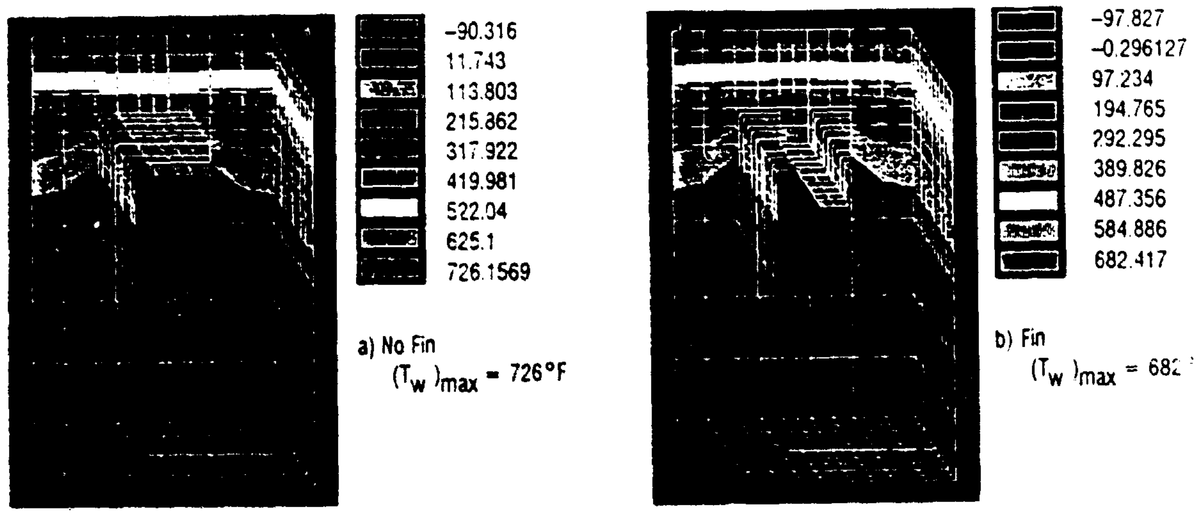
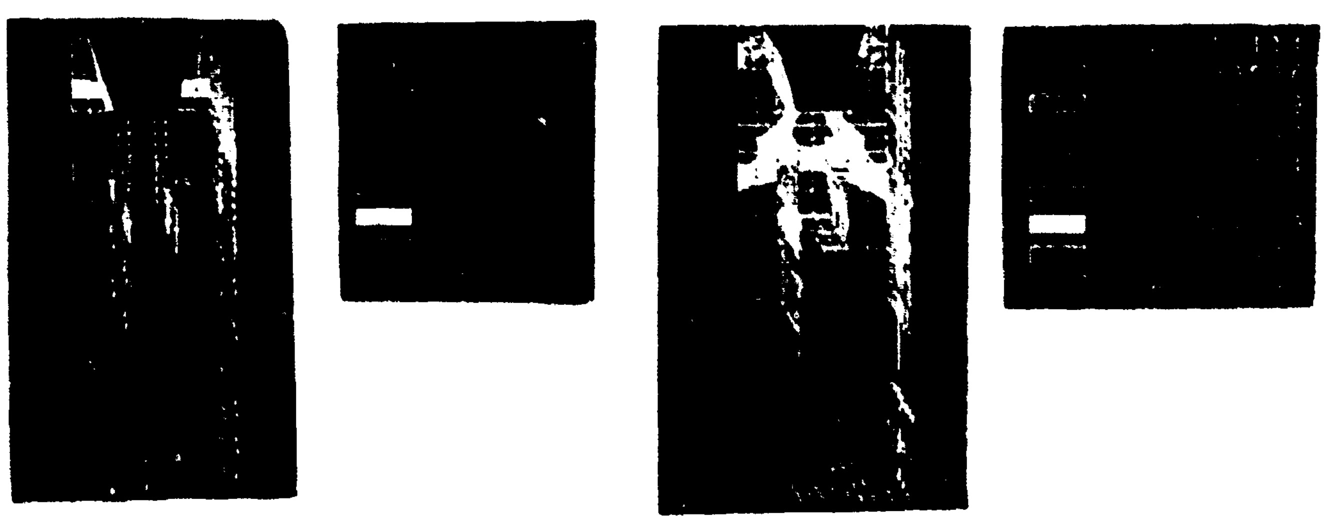


Figure 15b. CFD Thermal Analysis Fin Configuration (15Klb Combustor)



a.) Temperature Profile (°F)

b.) Thermal Strain (in/in)

Figure 15c. CFD Thermal Analysis Rib/Fin Configuration (15Klb Combustor);
a.) Temperature Profile b.) Thermal Strain

The nozzle dimensions are 90 inches in length with an exit diameter of 53 inches. The expansion ratio is 1034:1 and a RAO optimum nozzle contour is utilized. The design utilizes a retractable-extendable nozzle. The fixed part of the nozzle is regeneratively cooled and the extendable nozzle is radiatively cooled. The regeneratively cooled nozzle is 32 inches in length and features a 1-1/2 pass tube or coolant channel design. Nozzle design alternatives are presented later in this section. The regeneratively cooled nozzle extends to an area ratio of 427:1. The radiatively cooled, extendable nozzle is 58 inches in length and can be fabricated from coated carbon/carbon, SEP Carbinox, or Haynes 214. An estimated weight for the coated carbon/carbon nozzle is 30 lb and an estimated weight for the Haynes nozzle is 64 lb.

A significant analytic effort was completed to determine the coolant passage geometry for the thrust chamber nozzle. The design objective was to provide a coolant passage geometry which would provide a minimum operating life of 2000 cycles. Both the combustor and the fixed nozzle require regenerative cooling to survive the harsh thermal combustion process environment. The REGEN computer program (Reference 4) was used to conduct the analyses. The coolant inlet conditions were obtained from the "on-design and off-design" analyses (reference Appendix A). Thrust chamber contour and related heat transfer parameters were obtained from a boundary layer computer analysis. Hydrogen was used as the coolant. Figure 16 presents the thrust chamber combustor profile.

6.2.3 Combustor

A channel design coolant configuration was chosen for the combustor section, extending from the injector face (X = -20 in.) to the nozzle attach point at X = 2.5 in. The combustor throat is the model zero reference point. The nozzle attach point is at an area ratio of 14:1. An up-pass flow orientation (i.e., the flow direction is from the nozzle attach point to the injector face) was selected to provide the lowest temperature coolant in the throat region, the area of maximum heating. Narloy-Z was used for the chamber walls and an electrodeposited (EP) nickel closeout was assumed. A fin-and-rib configuration was used for the barrel section of the combustor from X = -1.975 in. to X = -20.0 inches.

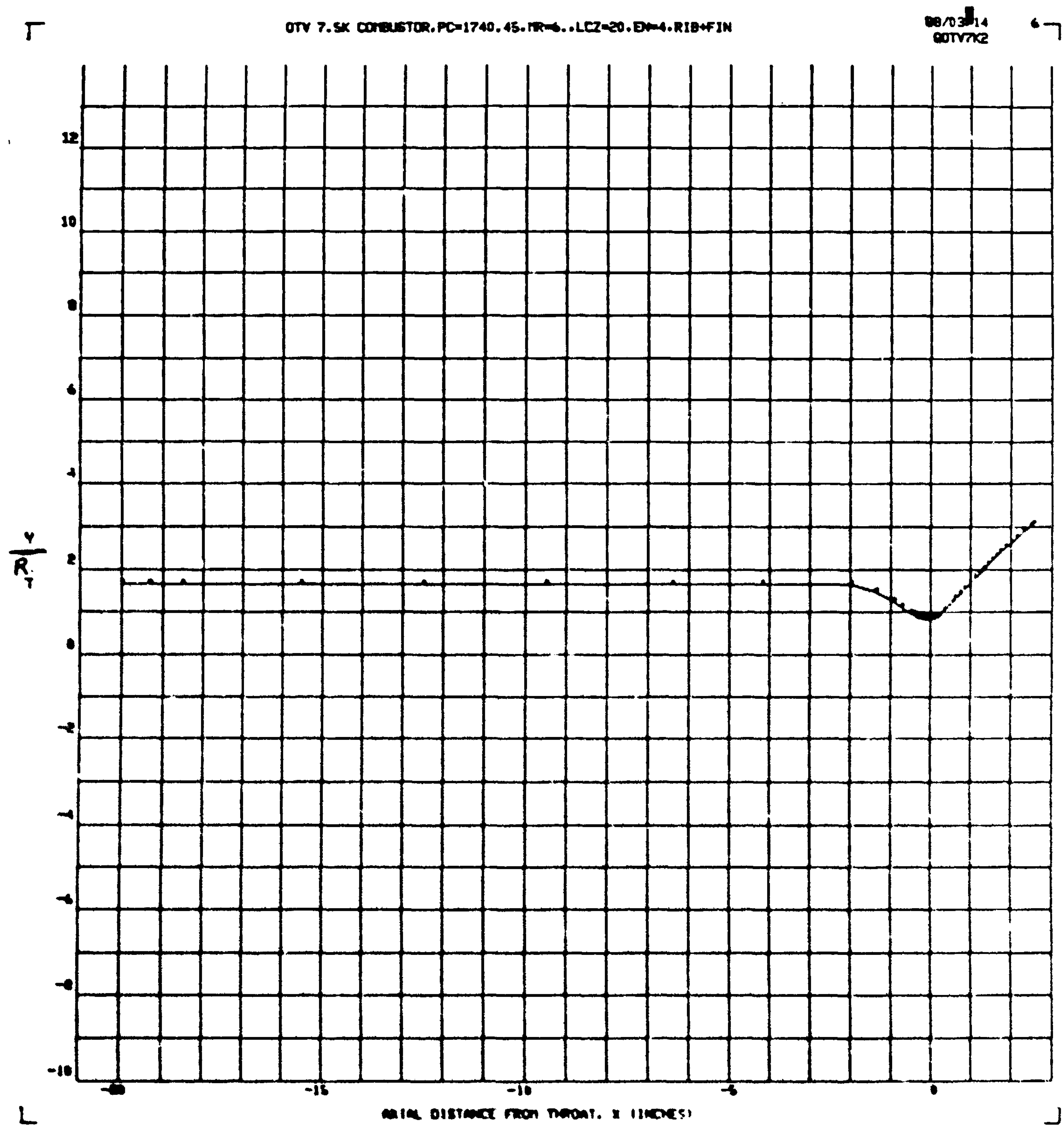


Figure 16. Thrust Chamber Combustor Profile

5471e

The heat transfer enhancement introduced by the ribs was calculated using the correlation from Reference 5.

$$\text{Effective hg} = (1 + \text{Ex}100)^{*}\text{Asmooth}^{*}\text{hgsmooth/Arib}$$

where

$\text{Ex} = 160.12^{*}X^{1/7} - 67.41$

X = distance from injector face (in.)

Asmooth = chamber surface area without rib ($in.^2$)

Arib = chamber surface area with rib (in.2)

hgsmooth = heat transfer coefficient predicted by the boundary layer code ($Btu/s \cdot in.^2 \cdot {}^\circ F$)

Effective hg = heat transfer coefficient with rib ($Btu/s \cdot in.^2 \cdot {}^\circ F$)

The combustor section shown in Figure 15 is the rib and fin configuration used in the analysis. This configuration was based on the test results of Reference 3. The number of channels utilized in the rib/fin combustor section (cylindrical section) was 120 and the number of channels in the remainder of the combustor was 60.

The rib and wall temperatures occurring on the hot gas side of the channels are presented on Figure 17 along with the coolant side wall temperature. The maximum rib temperature of 1157 degrees F occurs at X = -19.318 inches, which is near the injector face. The throat area maximum hot gas wall temperature, 611 degrees F, occurs just upstream of the throat at X = -0.303. Tables 5 and 6 present the temperature plots for these locations, respectively. Figures 18 through 20 provide the coolant static and total pressure, heat flux and gas side film coefficient, respectively. The coolant velocity and bulk temperature are given in Figures 21 and 22. The maximum velocity of 1000 ft/s is not excessive for hydrogen gas coolant (mach number less than 0.2). The combustor coolant channel width and height are provided in Figures 23 and 24. The complicated channel height profile shown by the code output, between -0.7 and -2 in., could be smoothed to a height of 0.08 in. without a significant Δp increase (estimated at around 2 psi).

Table 5. Temperature Distribution Plot in °F for Rib & Fin Geometry

STATION NO. 66 X = -10.318 X/HT - 23.490

NUMBER OF ITERATIONS = 100
DIFFERENCE BETWEEN IN AND HEAT OUT = .01931 PERCENT

HEAT INFLUX = 28.278

Rib

Fin

					1157	1146	1139	1137
					1105	1091	1082	1080
					1038	1021	1011	1008
					958	942	934	931
810	811	815	822	834	852	[illegible]	856	856
760	761	763	767	773	778	784	788	789
699	699	701	705	709	713	719	723	725
626	627	629	642	650	650	658	663	665
596	595	596			591	606	613	616
581	580	573			550	564	571	574
568	565	556			520	531	538	540
556	553	543			496	506	512	514
545	542	532			478	486	492	493
537	534	524			465	472	477	479
					[illegible]	462	467	469
414	416	420	424	432	446	457	462	464
435	435	436	438	440	442	446	448	449
439	439	439	440	441	442	444	445	446

A. RIB HEIGHT = .04000 FIN HEIGHT = .02400
B. RIB TOP WIDTH = .02000 FIN BASE = .01500
1. LAND WIDTH = .04780 FIN TIP WIDTH = .01500
2. CHANNEL WIDTH = .04000 HG FACTOR = 1.00000
3. WALL THICKNESS = .03200
4. CHANNEL DEPTH = .08000
5. CLOSEOUT THICKNESS = .04000
6. TAW = 6335. DEG. F
7. HG = .0032081
8. TC = 381. DEG. F
9. REFERENCE HC = .06478
10. HC FACTOR FOR UPPER WALL = 1.00000
11. HC FACTOR LOWER WALL = 1.00000
12. EXPONENT = .55000
13-14. K OF REGION 1 = .004875 + (-.1870E-06) * T
15-16. K OF REGION 2 = .004875 + (-.1870E-06) * T
17-18. K OF REGION 3 = .001340 + (-.1390E-05) * T
19. CONVERGENCE CRITERION = .0100 DEG. F

Table 6. Temperature Distribution Plot in °F for Throat Geometry

```
TATION NO. 52     X =   -.303    X/RT =   -.360

NUMBER OF ITERATIONS =   88
DIFFERENCE BETWEEN HEAT IN AND HEAT OUT =  .00241 PERCENT

HEAT INFLUX =  58.906
```

[illegible]	609	606	606	607	607
501	498	493	495	496	497
394	388	378	383	387	389
282	280	251	274	284	286
240	224	169			
192	173	106			
149	128	57			
112	89	18			
81	57	-14			
56	32	-41			
38	12	-64			
26	0	-87	-159	-191	-200
-44	-56	-89	-105	-115	-119
-67	-68	-86	-94	-100	-102

```
     1.  LAND WIDTH =  .05532
     2   CHANNEL WIDTH =  .04000
     3.  WALL THICKNESS =  .02700
     4.  CHANNEL DEPTH =  .04000
     5.  CLOSEOUT THICKNESS =  .04000
     6.  TAW = 6299. DEG. F
     7.  HG =  .0103601
     8.  TC = -276. DEG. F
     9.  REFERENCE HC =  .4132408
    10.  HC FACTOR FOR UPPER WALL = 1.0000
    11.  HC FACTOR FOR LOWER WALL = 1.0000
    12.  EXPONENT =   .5500
 13-14.  K OF REGION 1 =  .004875 + ( -.1870E-06 ) * T
 15-16.  K OF REGION 2 =  .004875 + ( -.1870E-06 ) * T
 17-18.  K OF REGION 3 =  .001340 + ( -.1[illegible]0E-05 ) * T
    19.  CONVERGENCE CRITERION =  .0100 DEG. F
    20.  COATING THICKNESS = 0.000000
 21-23.  COATING K = 0.          + ( 0.          ) * T
```


5471e

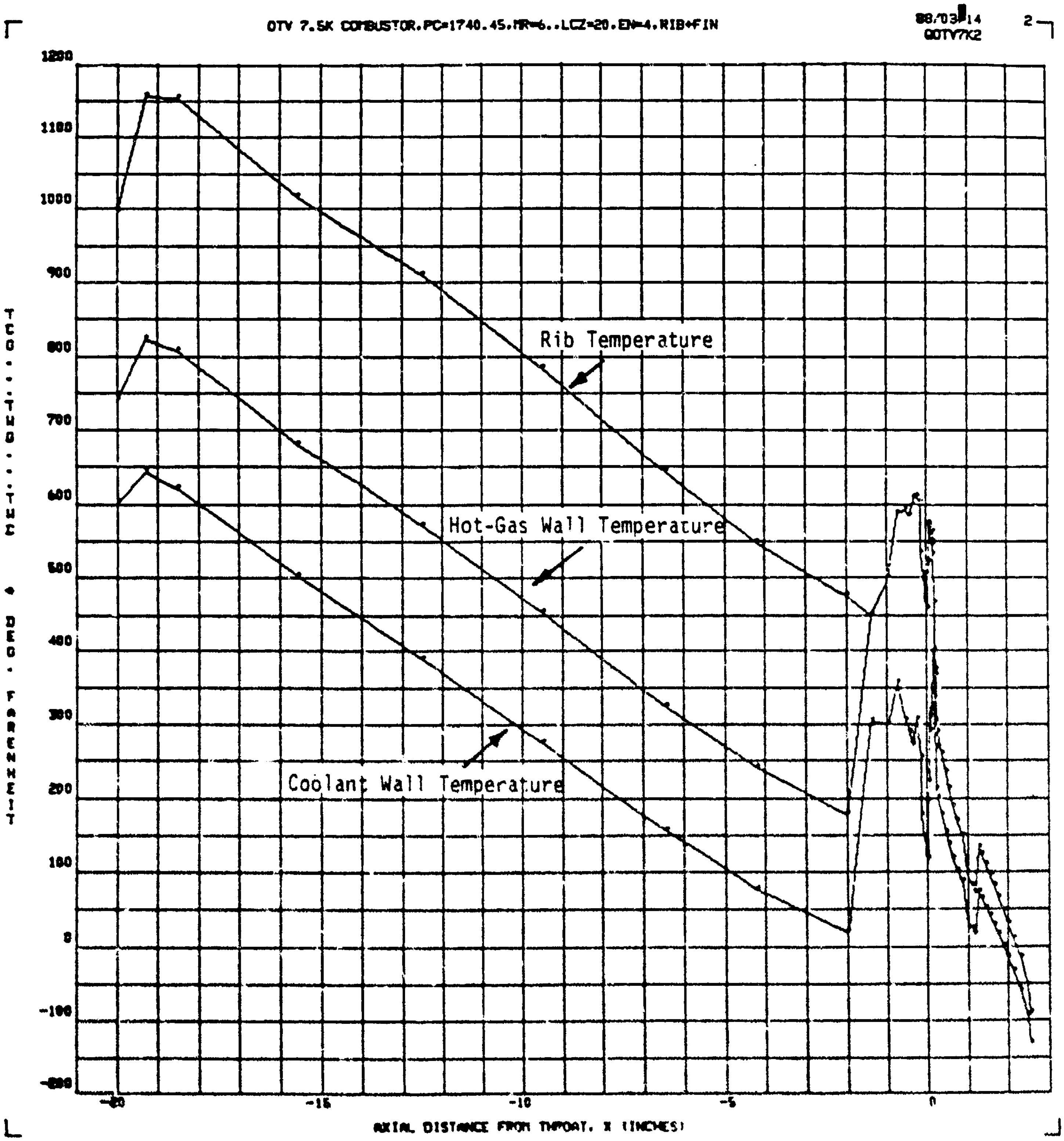


Figure 17. Rib and Wall Temperature Profile

5471e

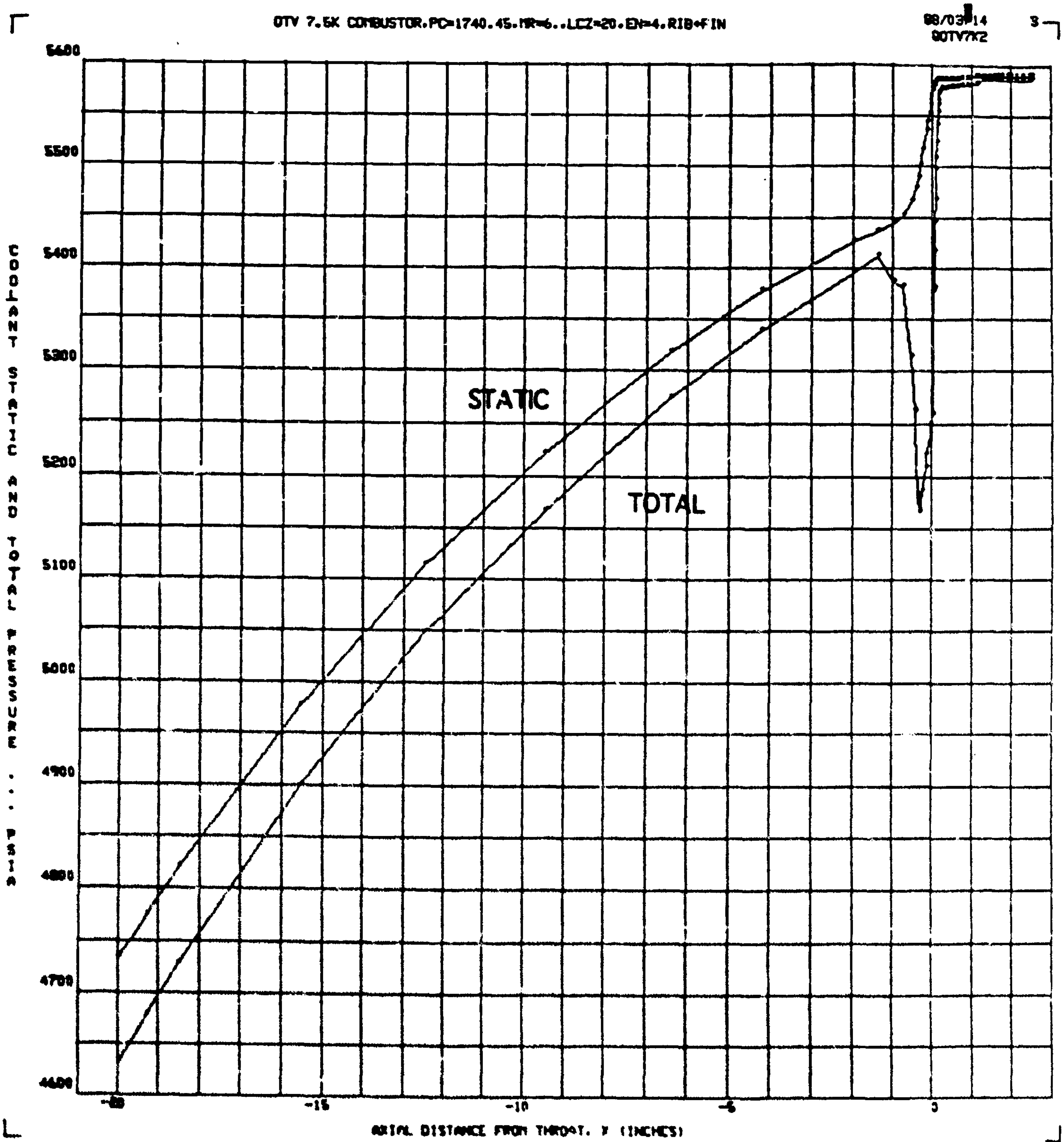


Figure 18. Coolant Pressure (Total and Static) Profile

5471e

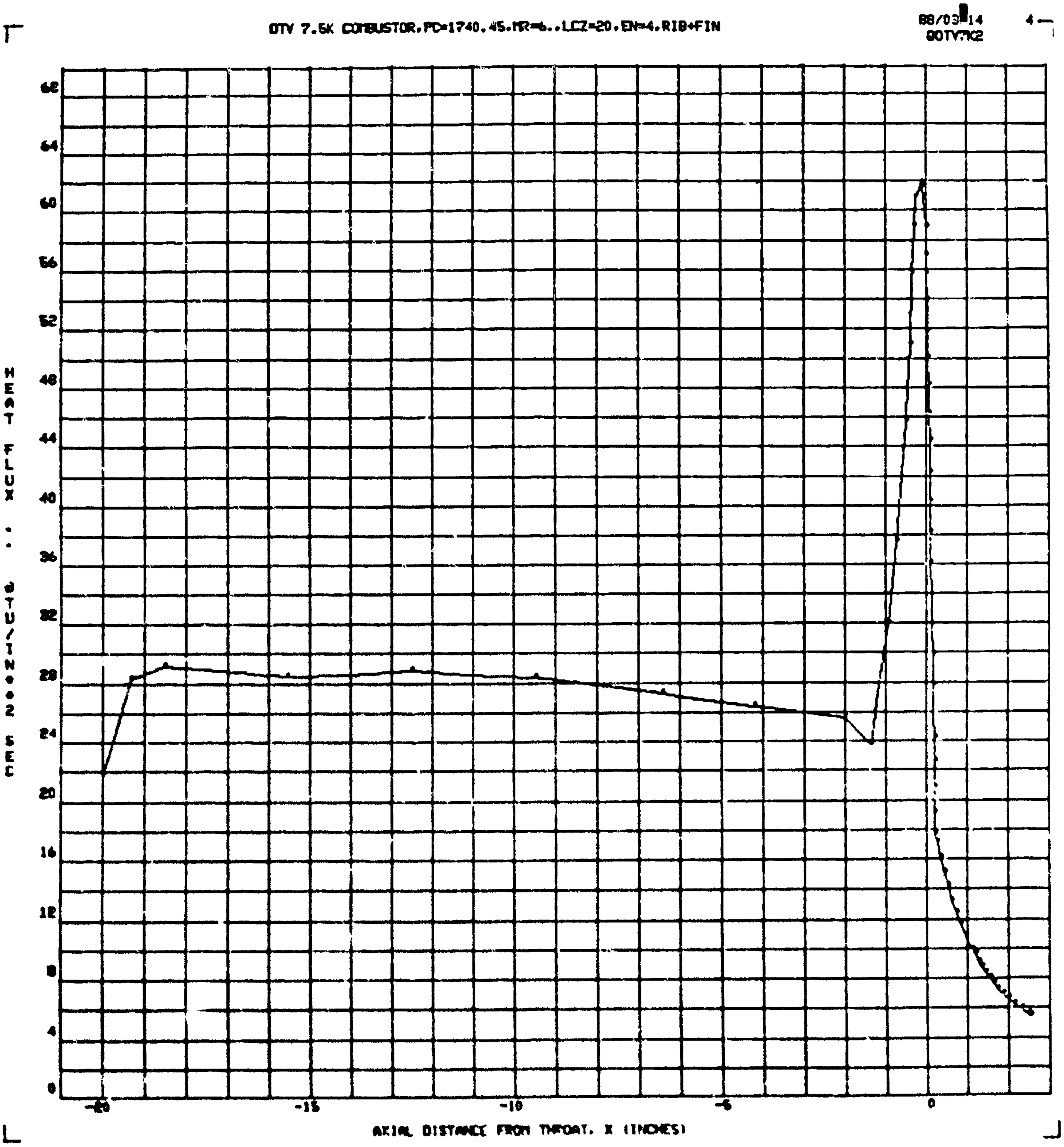


Figure 19. Wall Heat Flux Profile

5471e

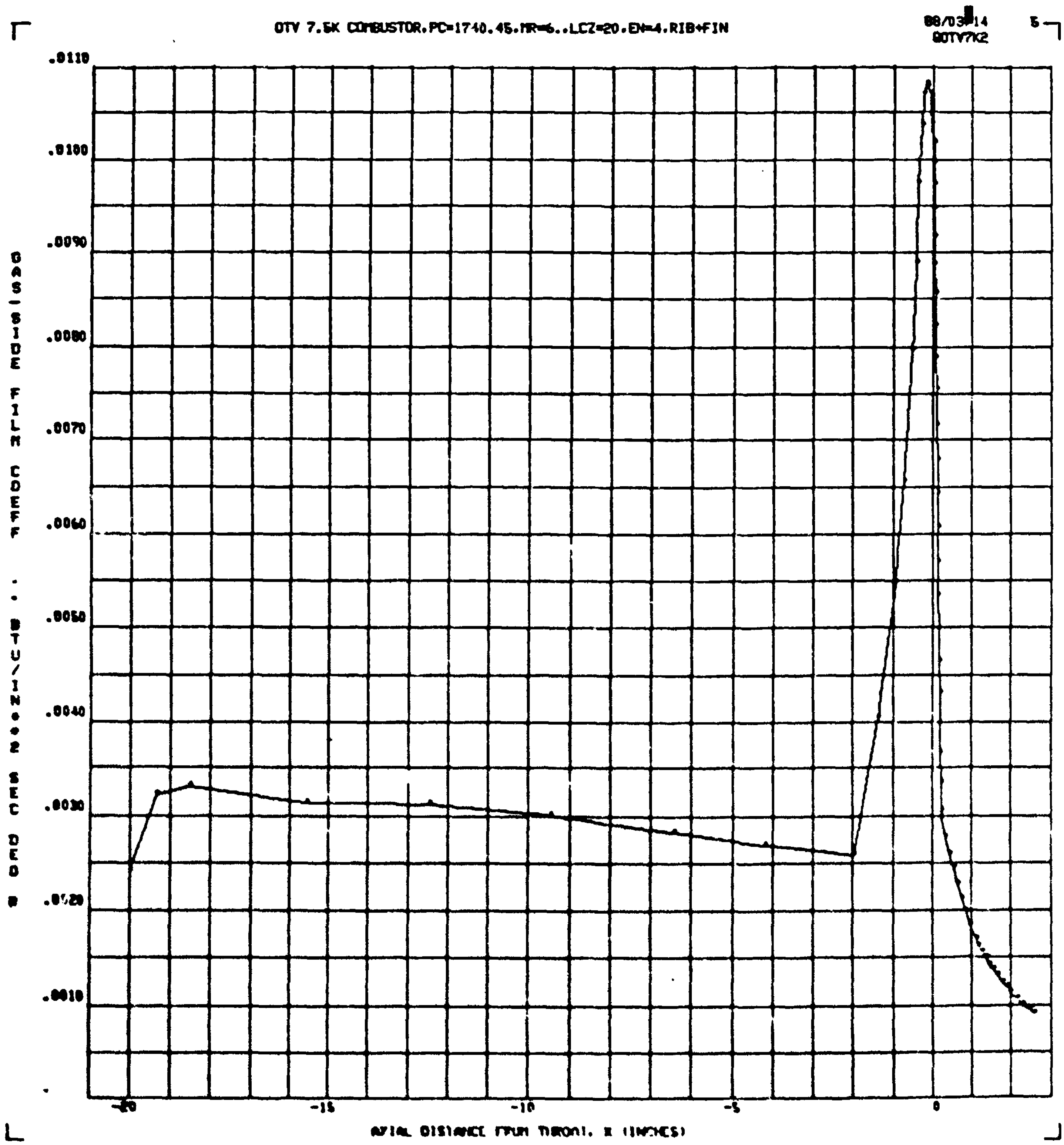


Figure 20. Gas-Side Heat Transfer Film Coefficient Profile

5471e

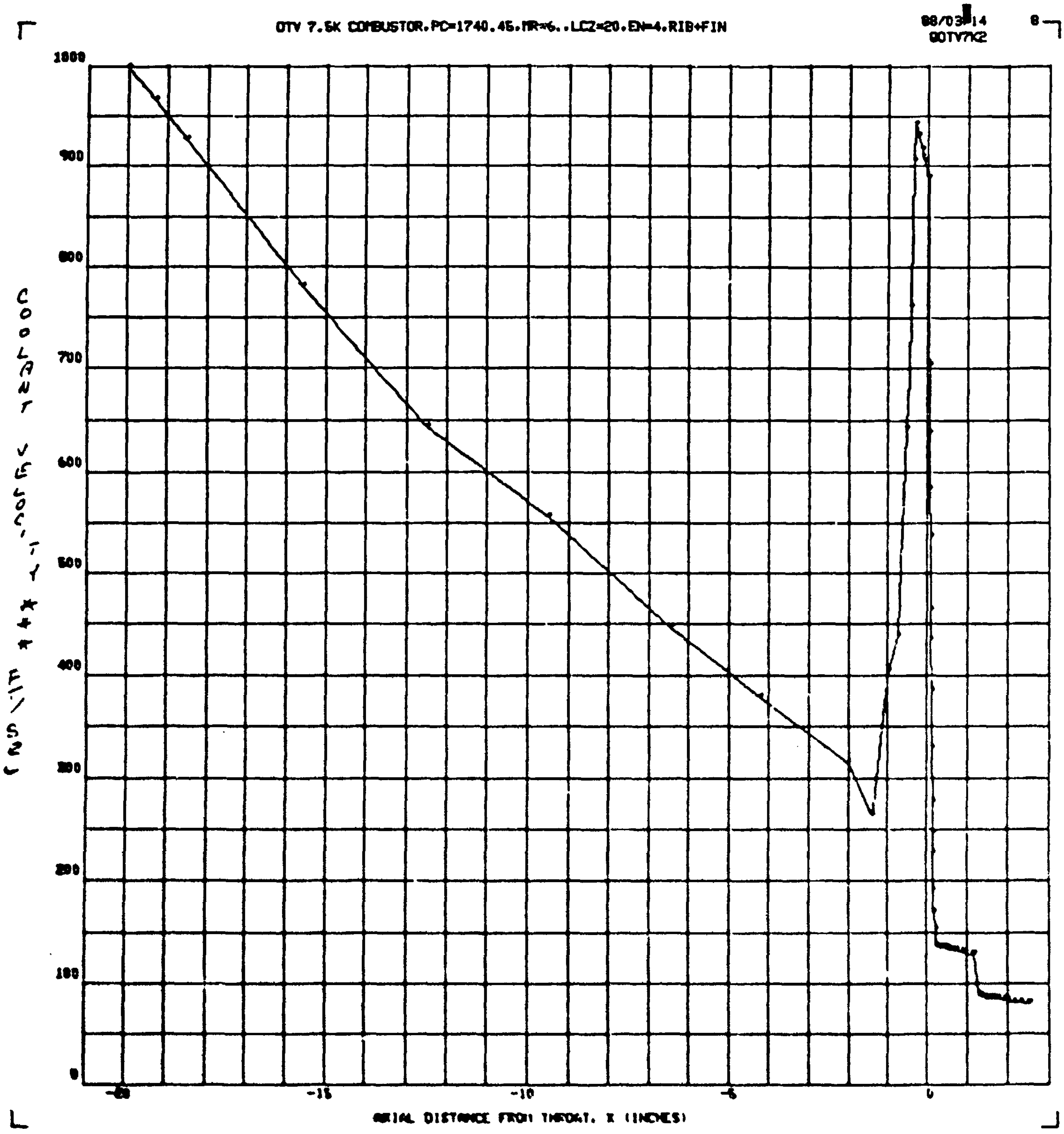


Figure 21. Coolant Velocity Profile

5471e

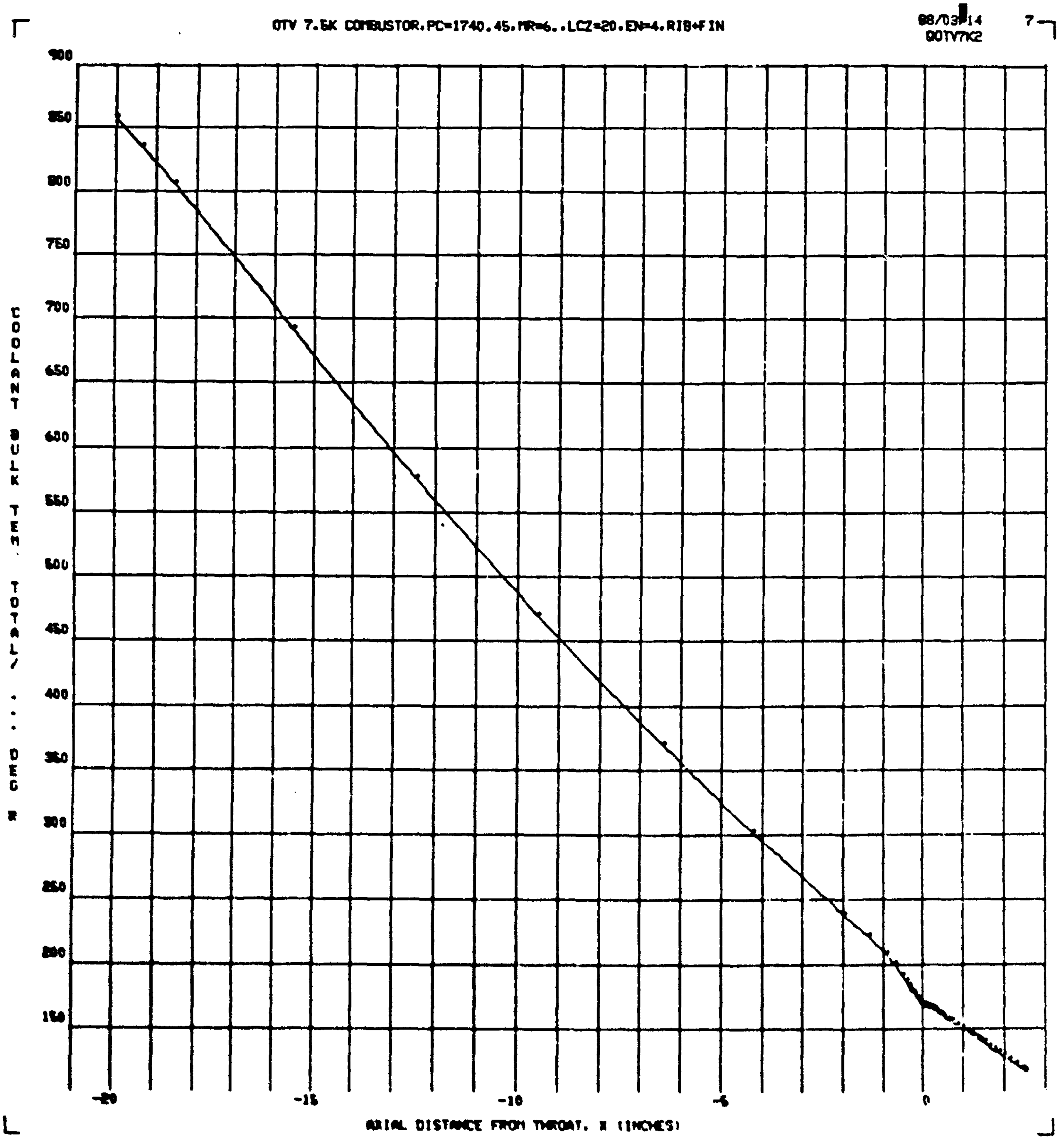


Figure 22. Coolant Bulk Temperature Profile

5471e

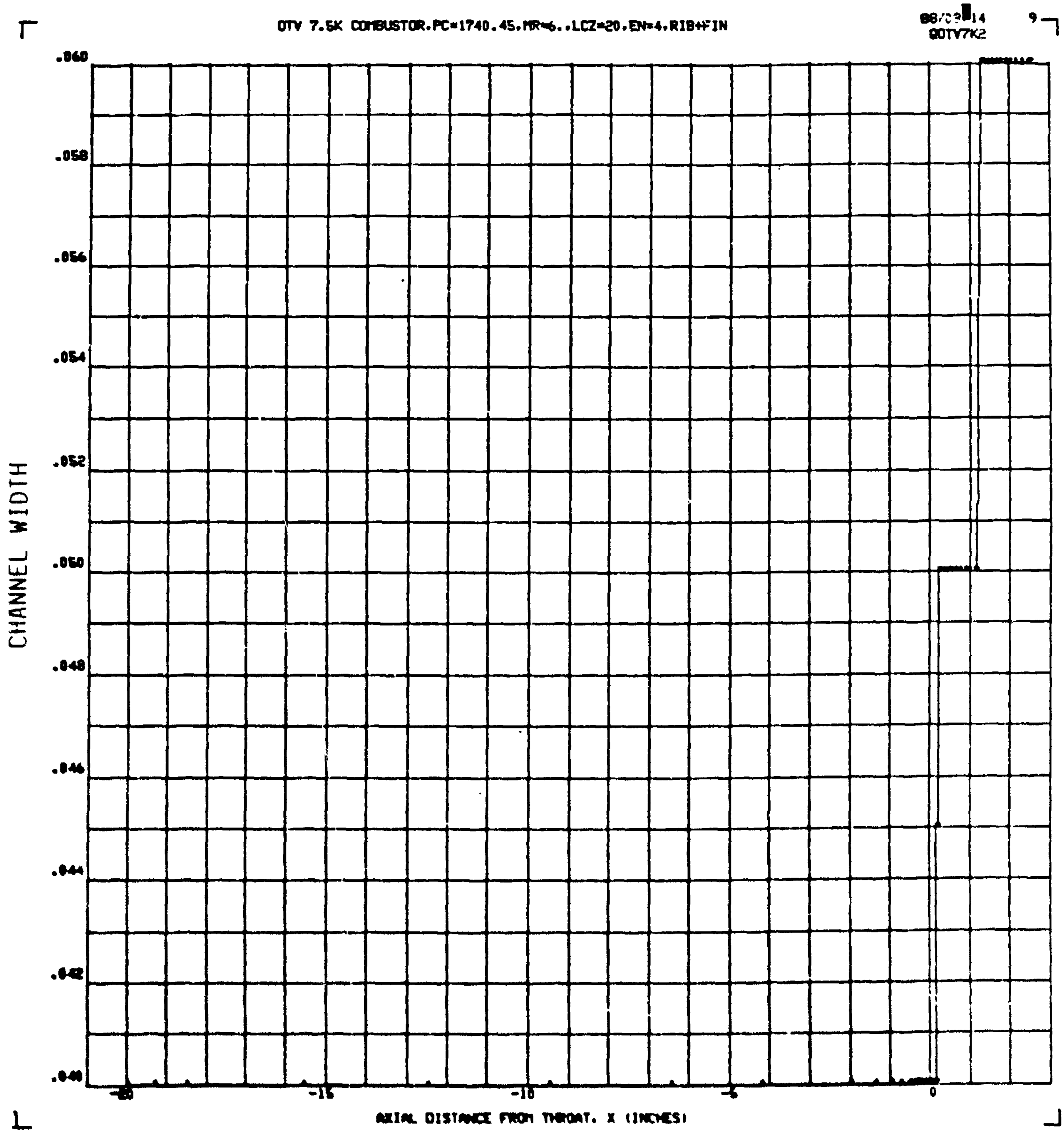


Figure 23. Combustor Channel Width Profile

5471e

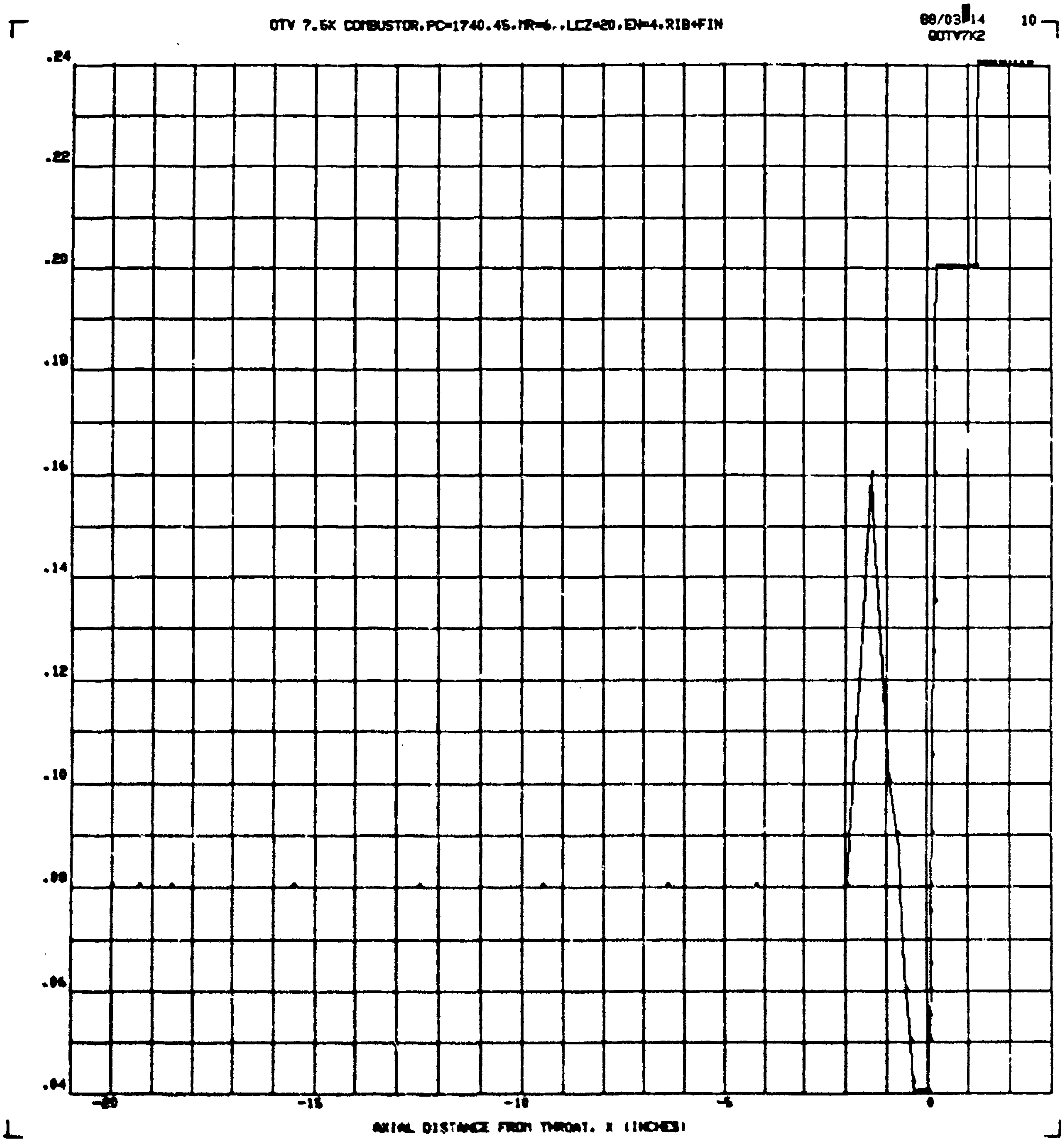


Figure 24. Combustor Channel Height Profile

5471e

An analysis of the combustor minimum life cycle was conducted to determine if the combustor design would meet structural requirements for creep and fatigue strain. This analysis indicates that the worst area occurs at X = -0.170 in., with a total life of 2429 cycles, (607 cycles with a factor of safety of 4.0). All other areas of the combustor were higher than this value. The combustor coolant wall channels were sized based on an iterative analytical process which balanced hot-gas wall cooling requirements with combustor wall thickness, channel aspect ratio and life cycles. The life evaluation was based on minimum material properties, wall thickness and hot-gas wall temperature which used standard structural analysis equations to calculate creep and fatigue life damage. These values were then divided by the predicted number of cycles to failure (in the case of fatigue), or hours to failure in the case of creep stress. This resulted in "damage fractions" for both fatigue and creep stress. The damage fractions were added together and multiplied times a factor of safety, 4.0. This safety factor meant that at a damage fraction of 1.0, or predicted failure of the part, the combustor would have accumulated only 25% total creep stress and fatigue strain. This gave a high degree of confidence that the combustor sized for the 7.5Klb thrust engine would meet the minimum life requirement of 500 cycles.

6.2.4 Nozzle, Tube Design

Two nozzle configurations were evaluated: (1) The tubular nozzle and (2) the channel nozzle. The primary nozzle configuration considered was a tubular design, consisting of 240 tubes. The nozzle tubes would be fabricated from A286 Stainless Steel, the same material as currently used on the SSME flight nozzle. The coolant tubes are brazed together and brazed to a one piece structural jacket. Substantial experience in fabrication techniques has been gained from using this same method during the SSME program and will be directly applicable to the 7.5Klb regeneratively cooled nozzle. This will result in a smoother fabrication cycle and lower costs and lower fabrication time. The regeneratively cooled portion of the nozzle extends from an area ratio (epsilon) of 14, X = 2.539 in., to an epsilon of 427, X = 32.515 in. A 1-1/2 pass design (i.e., single downpass followed by a 1/2 up-pass flow) was selected for the coolant flow configuration (Figure 25). The thrust chamber nozzle profile is provided in Figure 26. The total coolant flow to the nozzle is 2.18 lb/sec., which exits from the combustor at 4730 psia and 864 deg. R.

The tube wall temperature distribution for both the hot gas side and the coolant side are presented in Figure 27. The maximum hot gas side wall temperature of 965 deg. F occurs at X = 15.176 inches. Figures 28 through 30 provide the coolant static and total pressure, heat flux, and gas side film coefficient, respectively, along the nozzle length. The coolant velocity and bulk temperature are given in Figures 31 and 32. Figure 33 shows the cross section of the nozzle tube and defines the inner radius and flat length dimensions. The inner radius and flat length profile of the tube is presented in Figures 34 and 35. The nozzle total heat into the coolant is 1736 Btu/sec. resulting in a coolant bulk outlet temperature of 1094°R. The coolant exits the nozzle at 4726 psia with a net pressure loss of 4 psi. Table 7 presents the metal temperature distribution plot at the maximum hot gas side wall temperature location.

The minimum predicted analytical life of 3317 cycles is located at a position of X = 2.539 in. (829 cycles with a factor of safety of 4.0). The life evaluation was based on minimum material properties, wall thickness and hot-gas wall temperature which used standard structural analysis equations to calculate creep and fatigue life damage. These values were then divided by the predicted number of cycles to failure (in the case of fatigue), or hours to failure (in the case of creep stress). This resulted in "damage fractions" for both fatigue and creep stress. These damage fractions were added together and multiplied times a factor of safety, 4.0. This safety factor meant that at a damage fraction of 1.0 (the predicted failure of the part), the combustor would have accumulated only 25% total creep stress and fatigue strain. This gave a high degree of confidence that the nozzle sized for the 7.5Klb thrust engine would meet the minimum life requirement of 500 cycles.

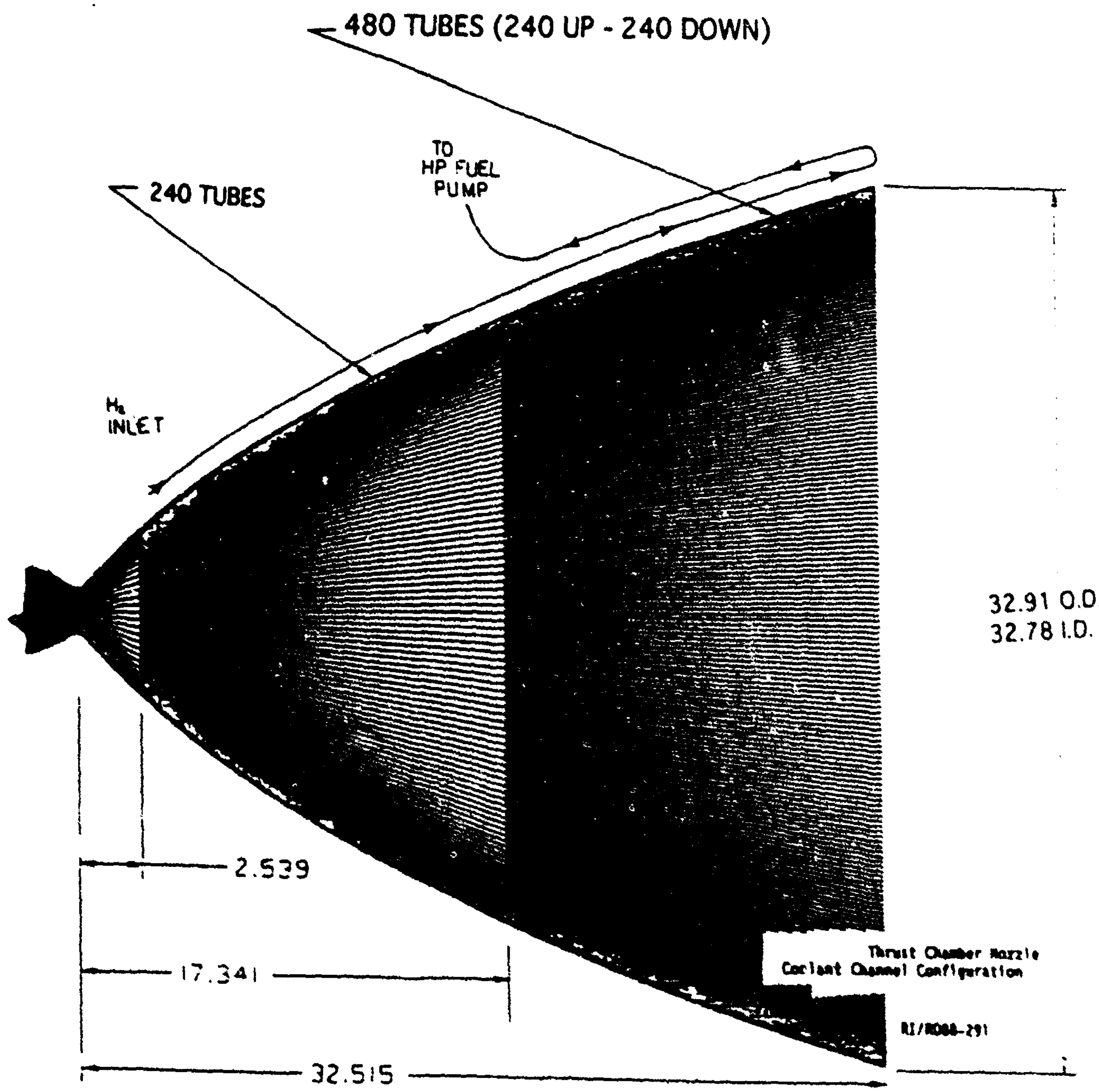


Figure 25. 1-1/2 Pass Nozzle Cooling Design

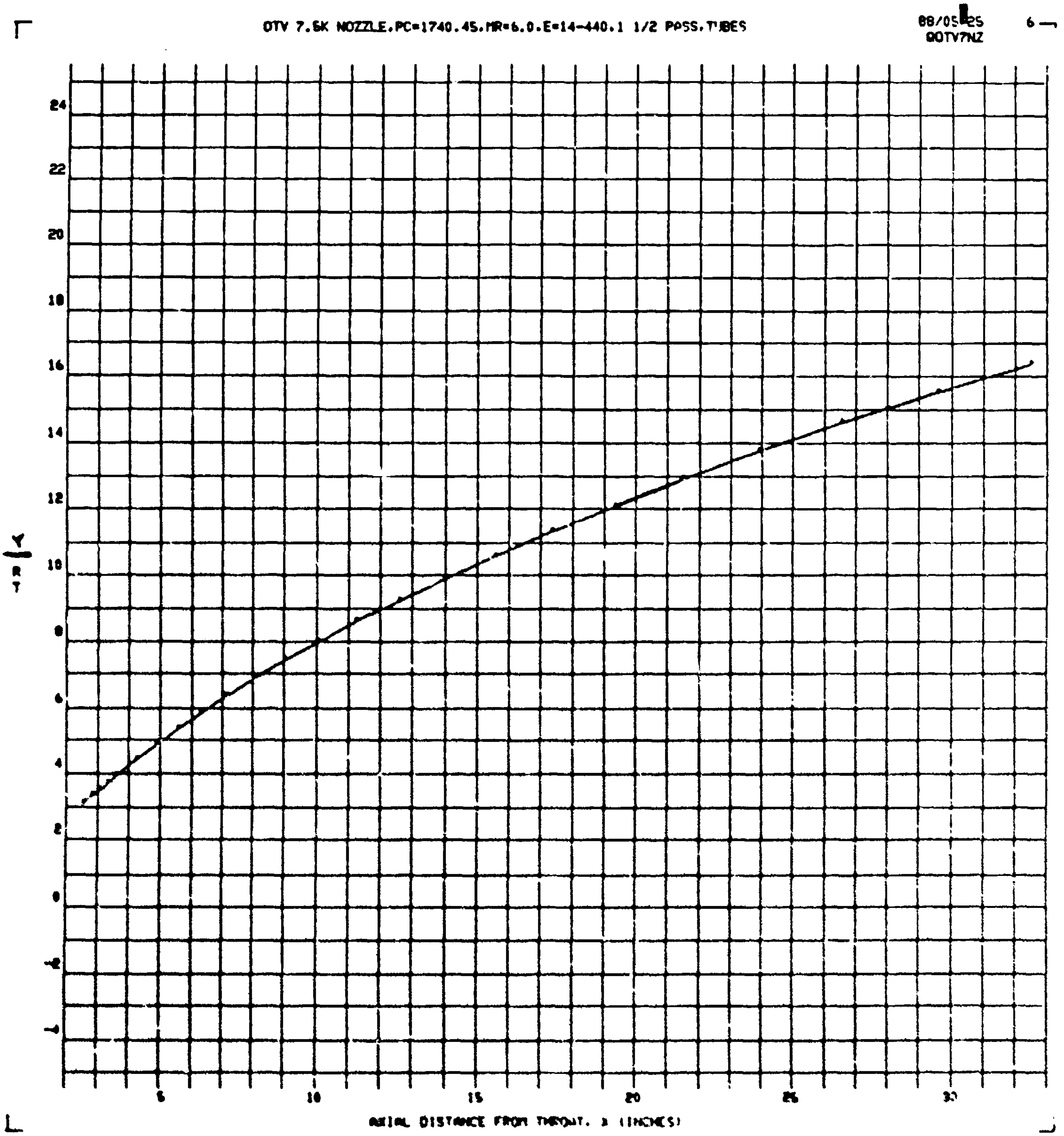


Figure 26. Nozzle Profile

5471e

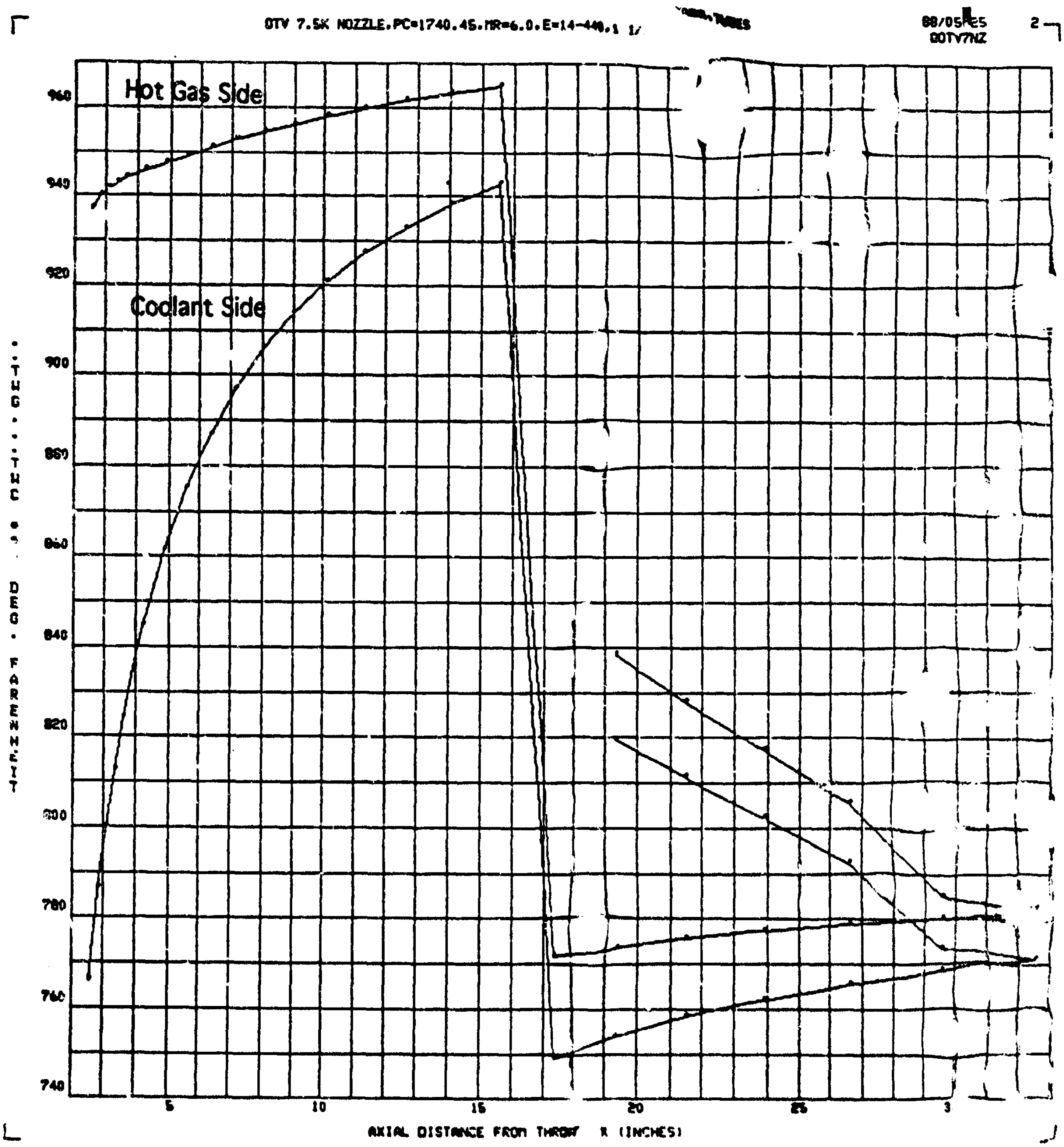


Figure 27. Hot Gas Side and Coolant Side Wall Temperature Profile

5471e

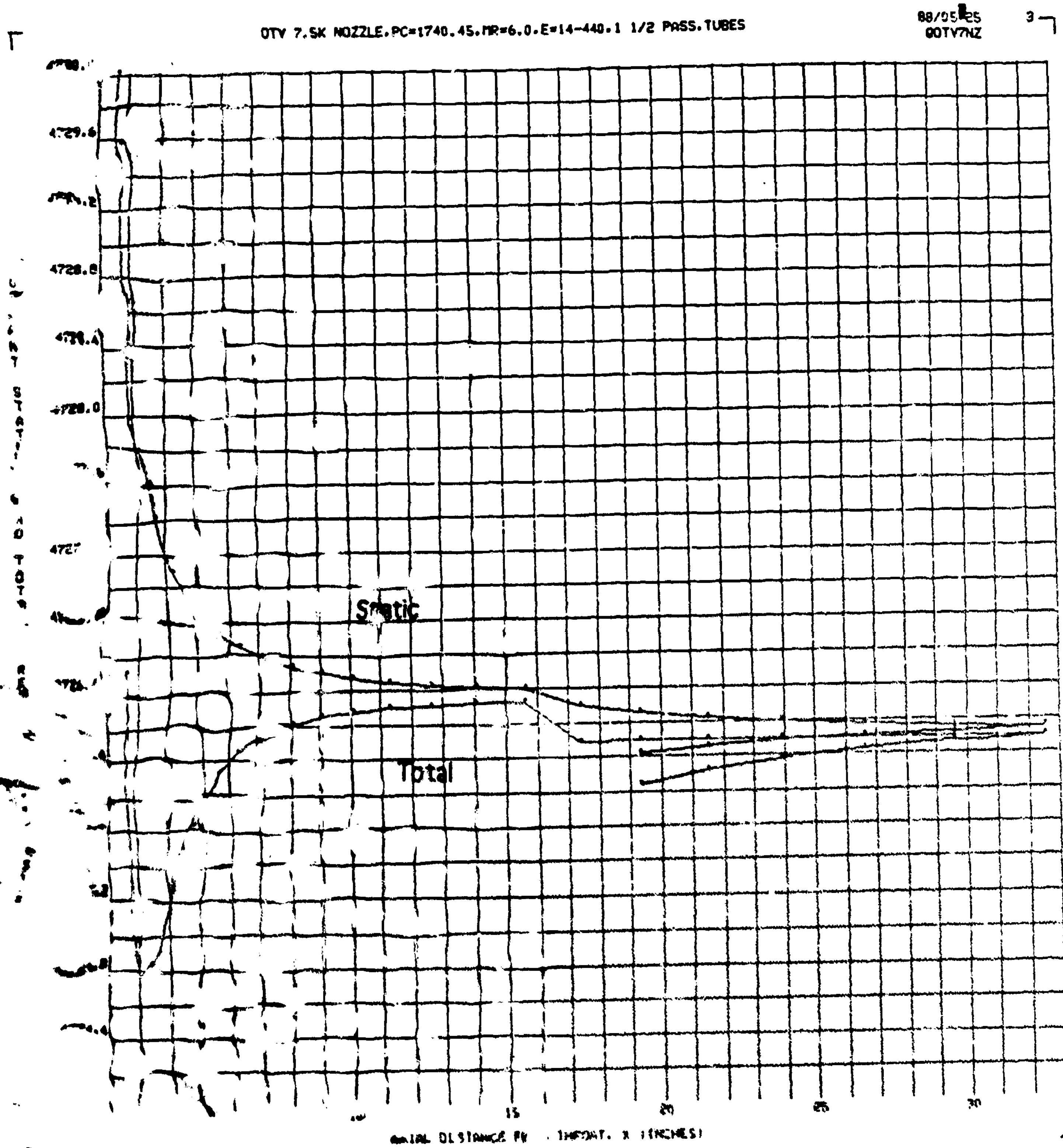


Figure 28 Coolant Static and Total Pressure Profile

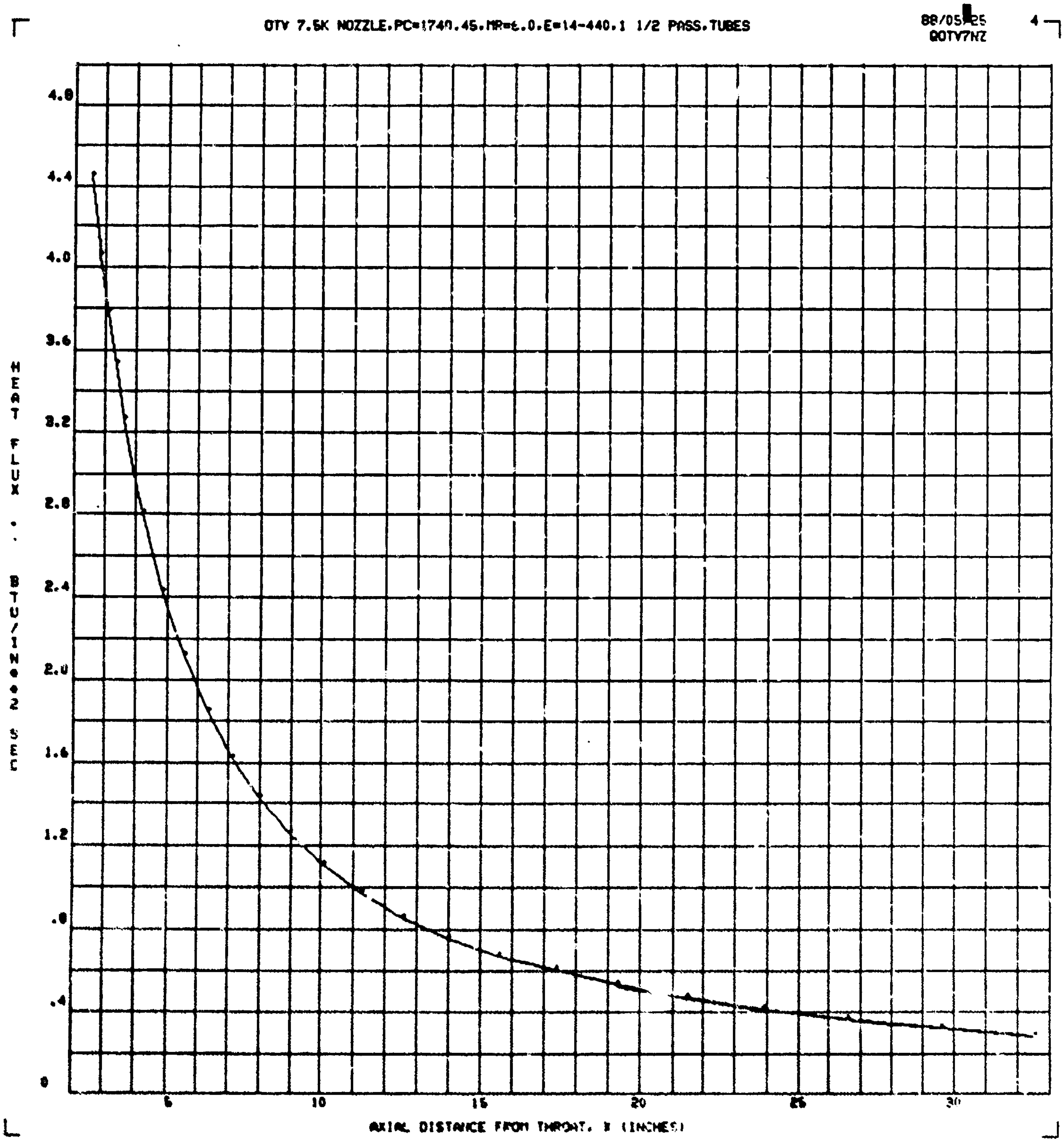


Figure 29. Nozzle Wall Heat Flux Profile

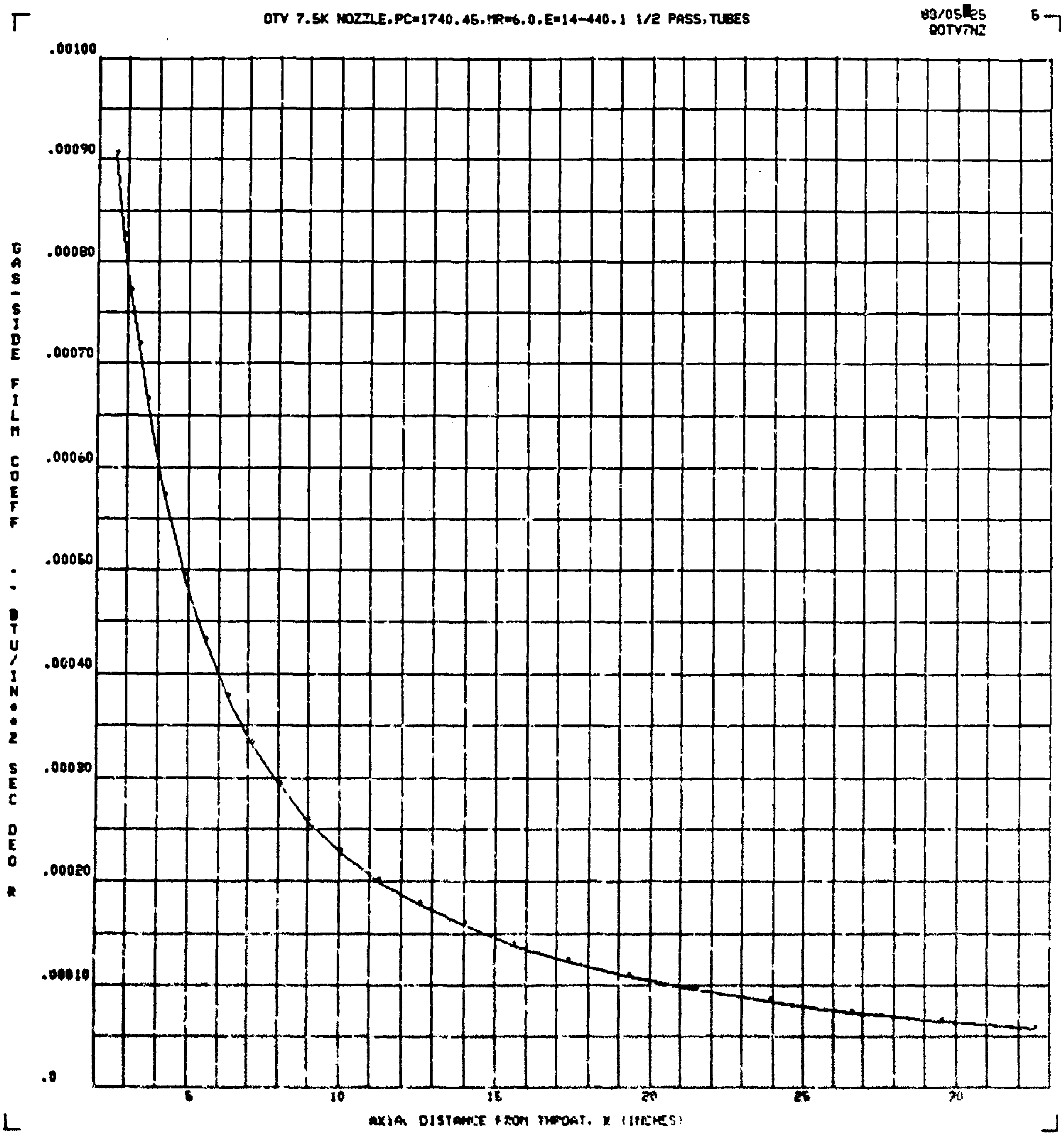


Figure 30. Gas Side Heat Transfer Film Coefficient

5471e

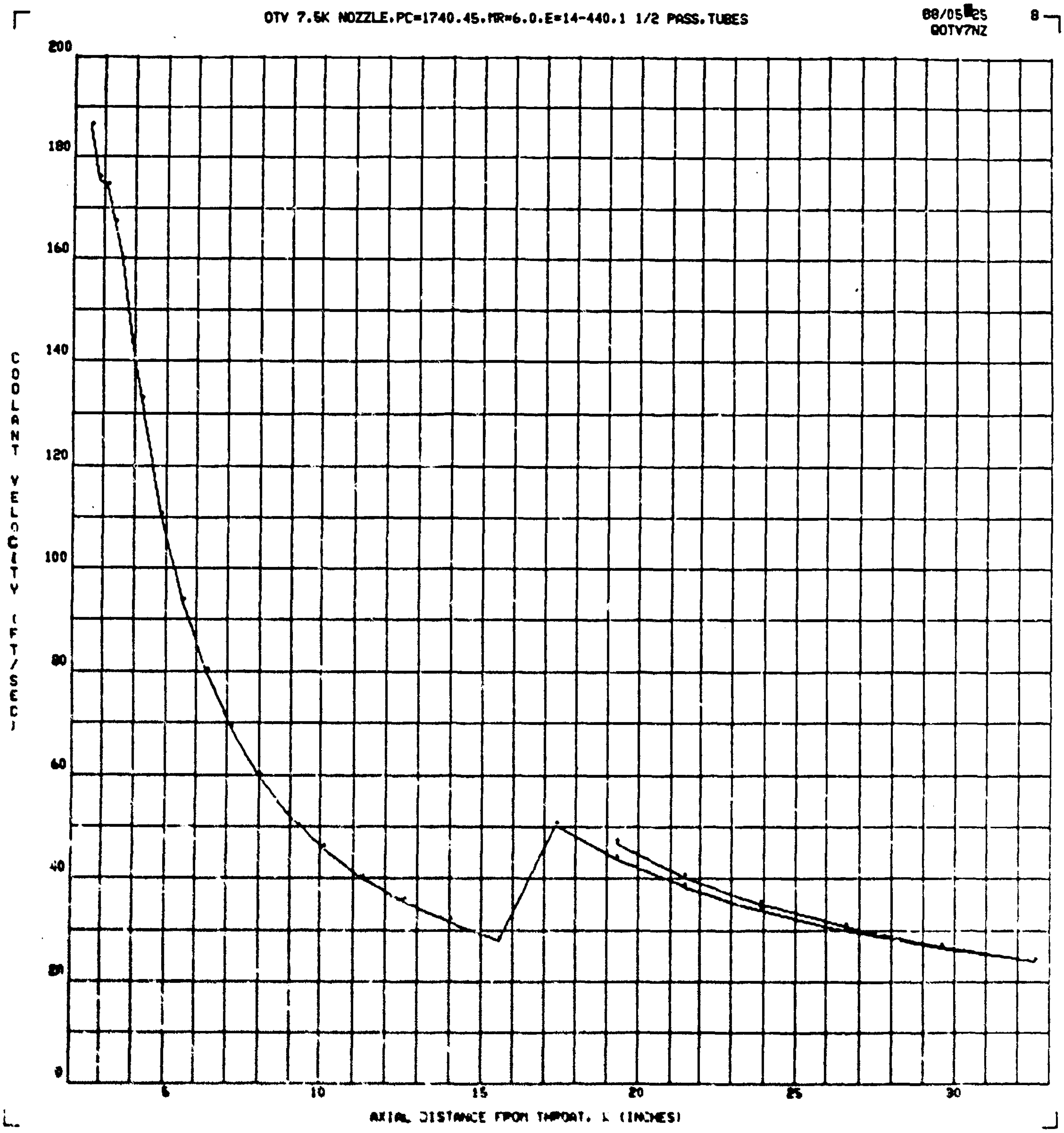


Figure 31. Coolant Velocity Profile

5471e

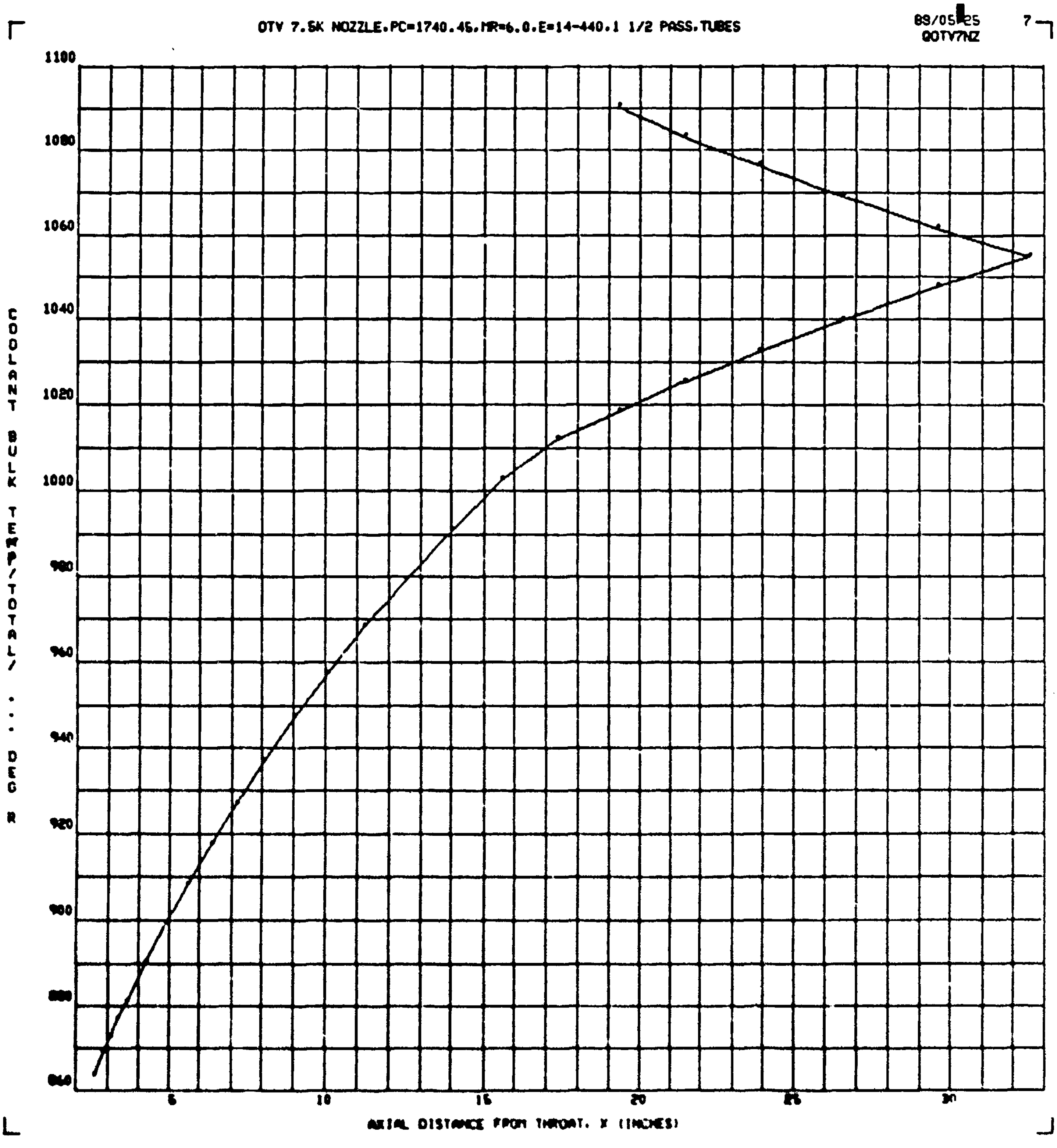


Figure 32. Coolant Bulk Total Temperature Profile

5471e

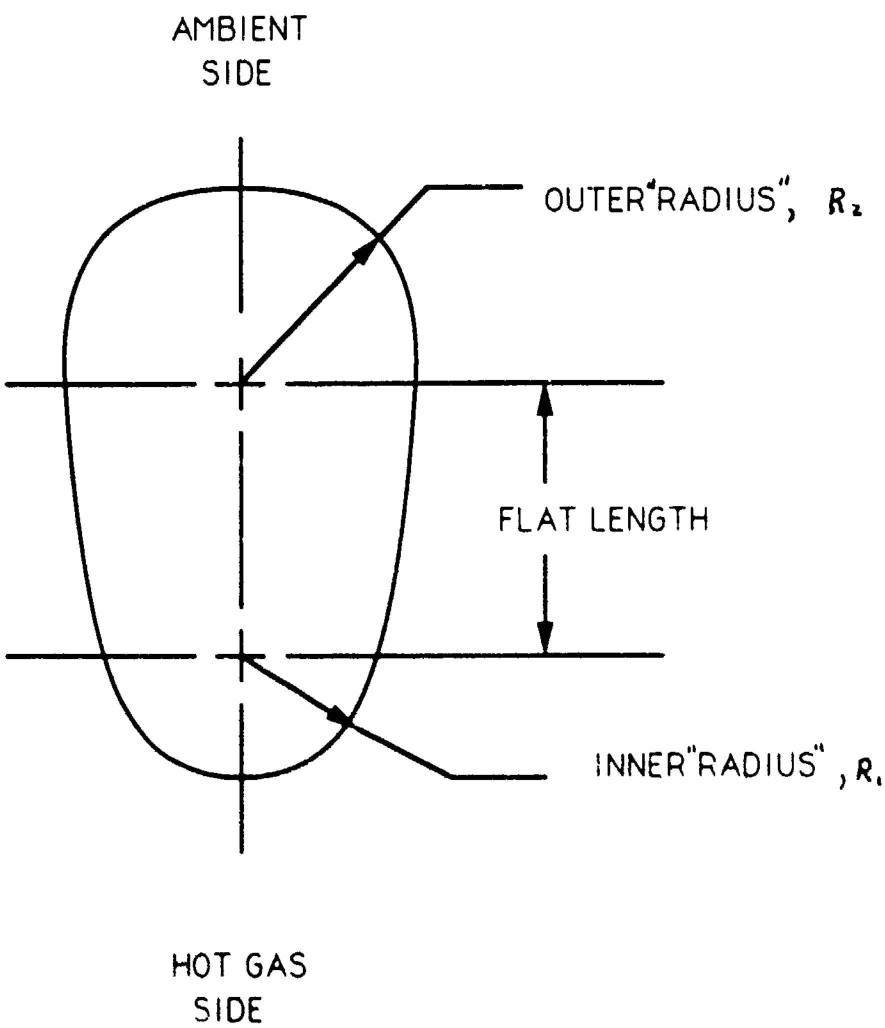


Figure 33. Nozzle Tube Cross Section

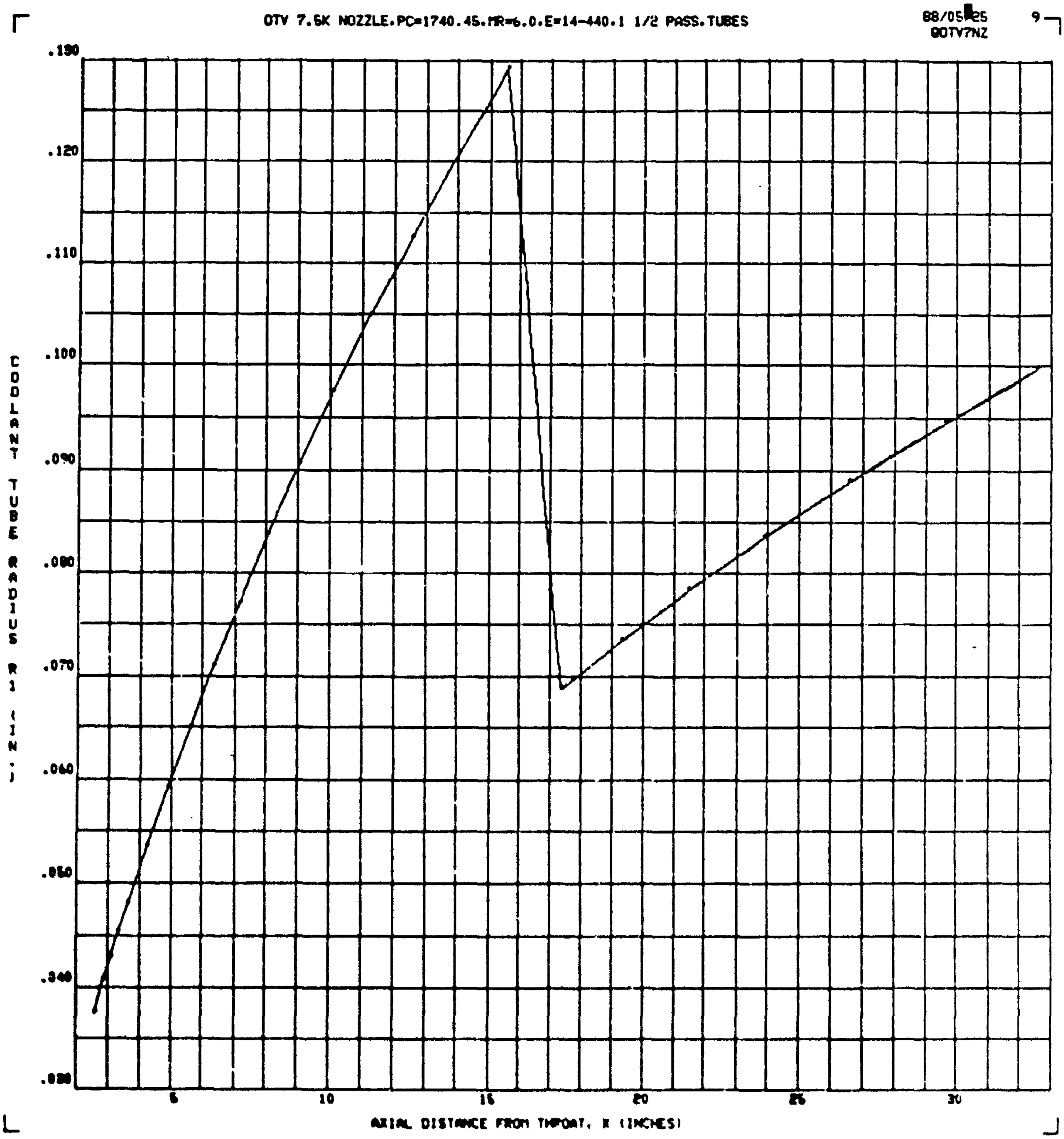


Figure 34. Tube Gas Side Radius Profile

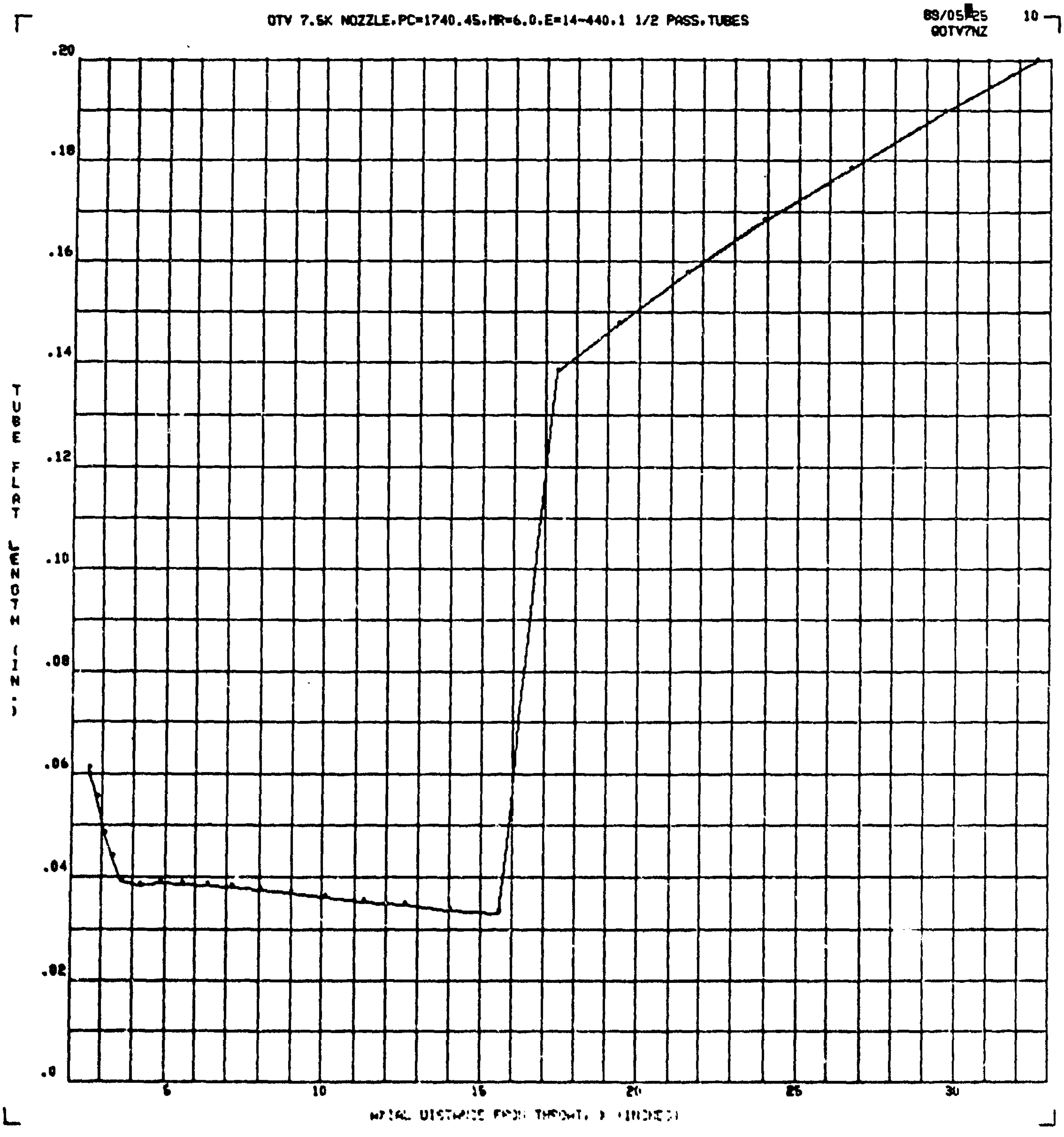


Figure 35. Tube Flat Length

5471e

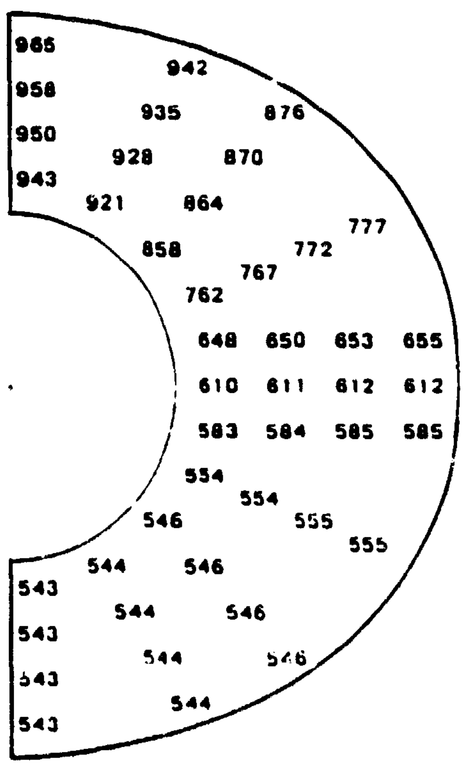
Table 7. Metal Temperature Distribution Plot at Maximum Hot Gas Side Wall Temperature

OTV 7.5K NOZZLE,PC=1740.45,MR=6.0,E=14-440,1 1/2 PASS,TUBES

STATION NO. 16 X = 15.576 X/RT = 18.939

NUMBER OF ITERATIONS = 42
DIFFERENCE BETWEEN HEAT IN AND HEAT OUT = .02421 PERCENT

CROWN HEAT FLUX = .6598



Temperatures in °F

1. OUTSIDE RADIUS = .12912
2. INSIDE RADIUS = .11913
3. COATING THICKNESS = .00000
4. FLAT LENGTH = .03299
5. TAW = 5722. DEG. F
6. HG = .00013872
7-11. HG FACTORS = .9953 .9395 .7807 .5431 .3349
12. RIPPLE FACTOR = 1.5707
13. TC = 543. DEG. F
14. REFERENCE HC = .0310665
15. EXPONENT = .5500
16+17. K OF TUBE = .0001514 + (.1500E-06) * T
18+19. K OF COATING = .0001514 + (.1500E-06) * T
20. CONVERGENCE CRITERION = .0100 DEG. F

5471e

6.2.5 Nozzle, Channel Design

An alternate configuration considered for the regeneratively cooled portion of the nozzle was a channel design, consisting of 248 channels.. As in the tubular design, the total coolant exiting the combustor section is 2.18 lb/s at 4730 psia and 864°R, was used to cool the nozzle. A 1-1/2 pass coolant flow configuration was selected for the channel design as was chosen for the tubular geometry. A single pass was not used as the channel geometry at the exit would have been large. The regeneratively cooled portion of the nozzle was again considered to be from an area ratio of 14 to an area ratio of 427, from X = 2.539 in. to X = 32.515 in. The nozzle coolant channels were designed to be fabricated from nickel-cobalt using an E-D process, and incorporate a Narloy-Z liner.

The nozzle temperature distribution for both the hot gas side and the coolant side is presented in Figure 36. Figures 37 through 39 provide the coolant static and total pressure, heat flux and gas side film coefficient, along the nozzle length. The coolant velocity and bulk temperature are given in Figures 40 and 41. The channel width and height are provided in Figures 42 and 43.

The analytical results for the channel design nozzle indicate that the peak hot gas side wall temperature (650°F) occurs at X = 17.341 in. At X = 29.556 in., the minimum life (2039 cycles) is realized. The total heat into the coolant is 1611 Btu/s, yielding a coolant bulk outlet temperature of 1077°R. The pressure exiting the nozzle is 4691 psia for a pressure drop of 39 psi. Table 8 presents the temperature plot at the maximum hot gas side wall temperature location.

The tubular nozzle has the advantage over the channel nozzle in that the coolant pressure losses are lower, the total heat into the coolant is greater (desirable for an expander cycle engine), and the minimum life is increased. The disadvantage of a tubular nozzle configuration are a higher hot gas side peak operating temperature. Both configurations provide workable designs, however, the tubular design is the priority design choice for the preliminary design.

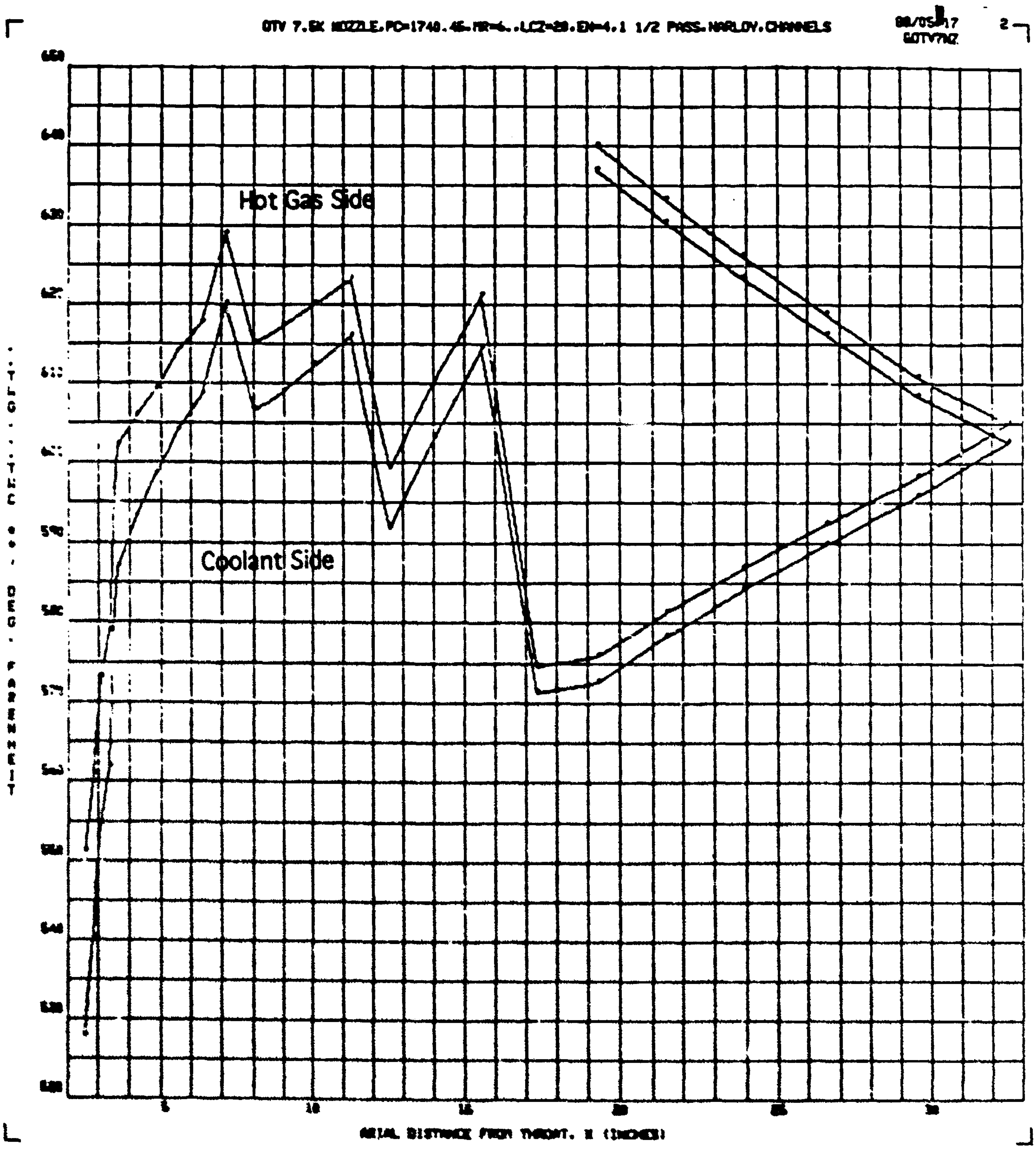


Figure 36. Nozzle Channel Wall Temperature Profile

5471e

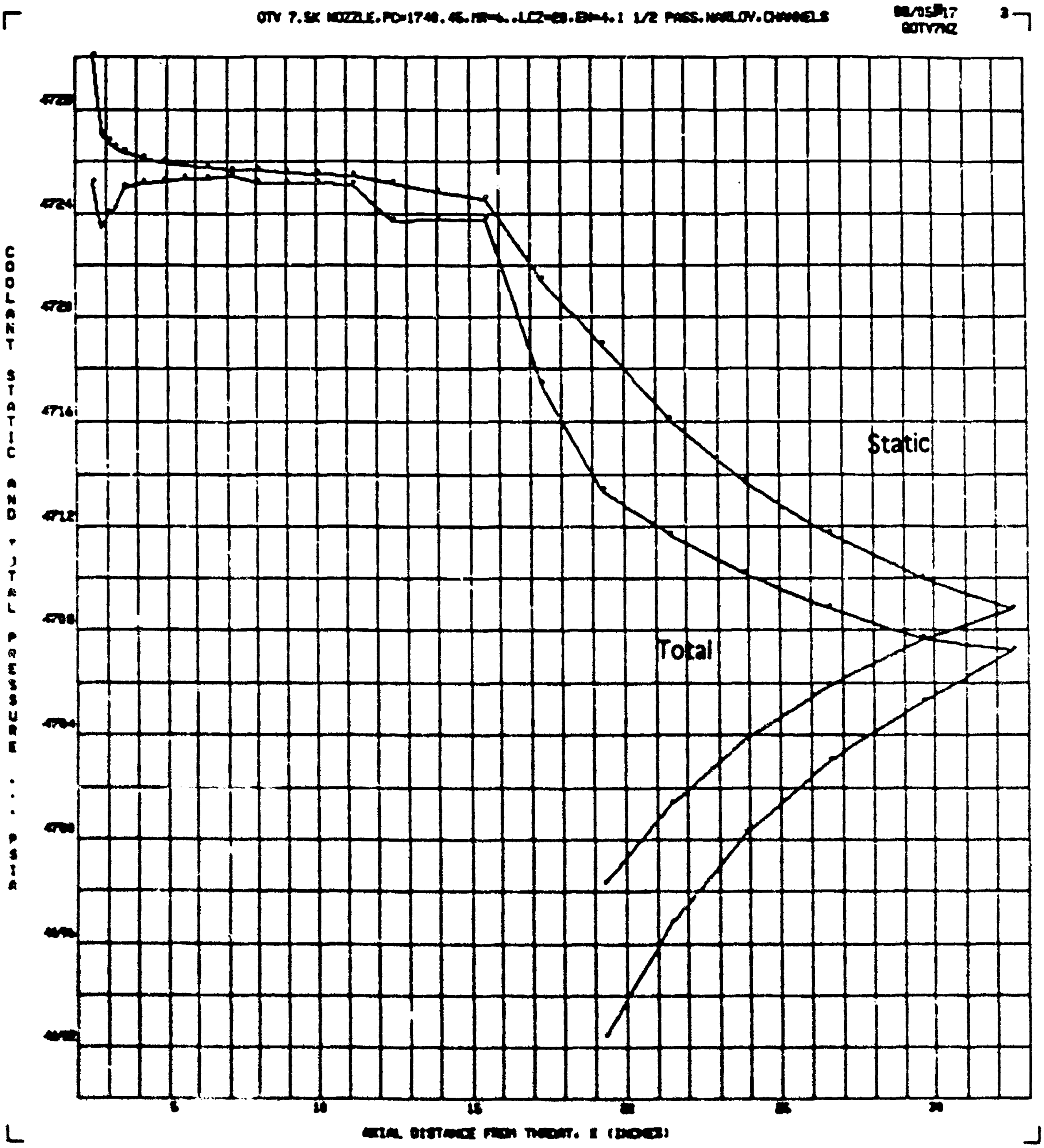


Figure 37. Coolant Static and Total Pressure Profile

5471e

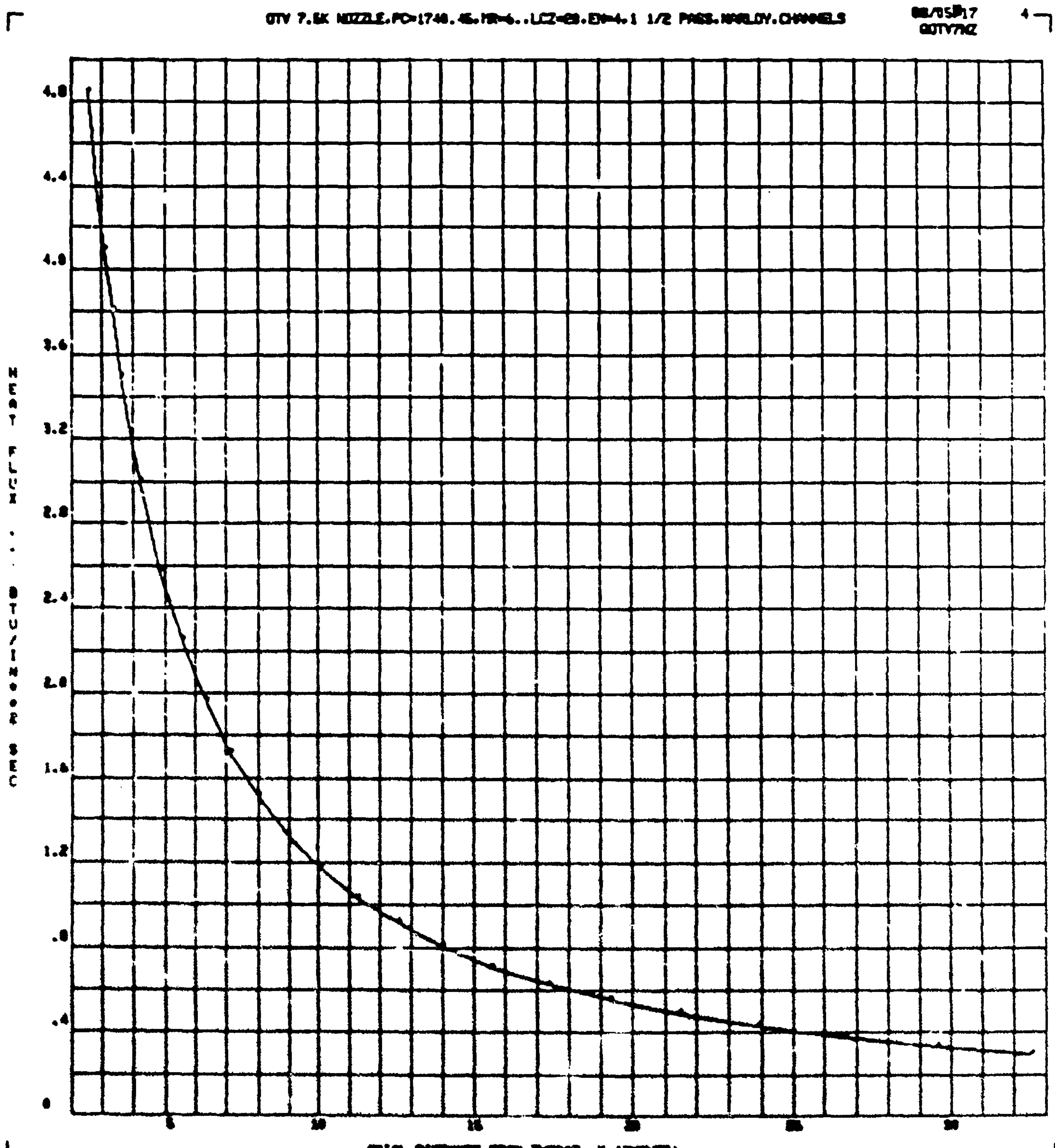


Figure 38. Channel Wall Nozzle Heat Flux Profile

5471e

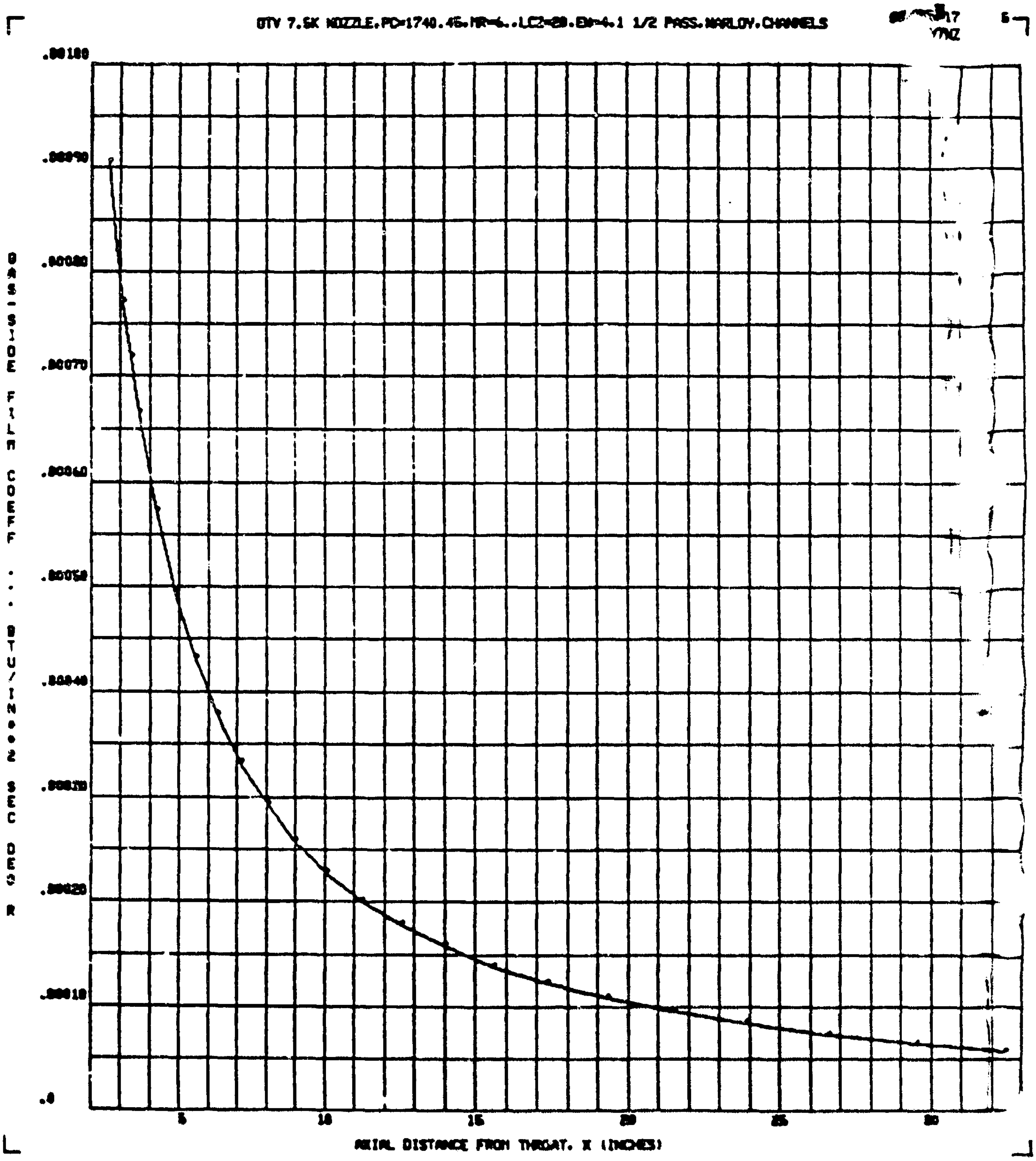


Table 39. Channel Wall Nozzle Gas Side Heat Transfer Coefficient

5471e

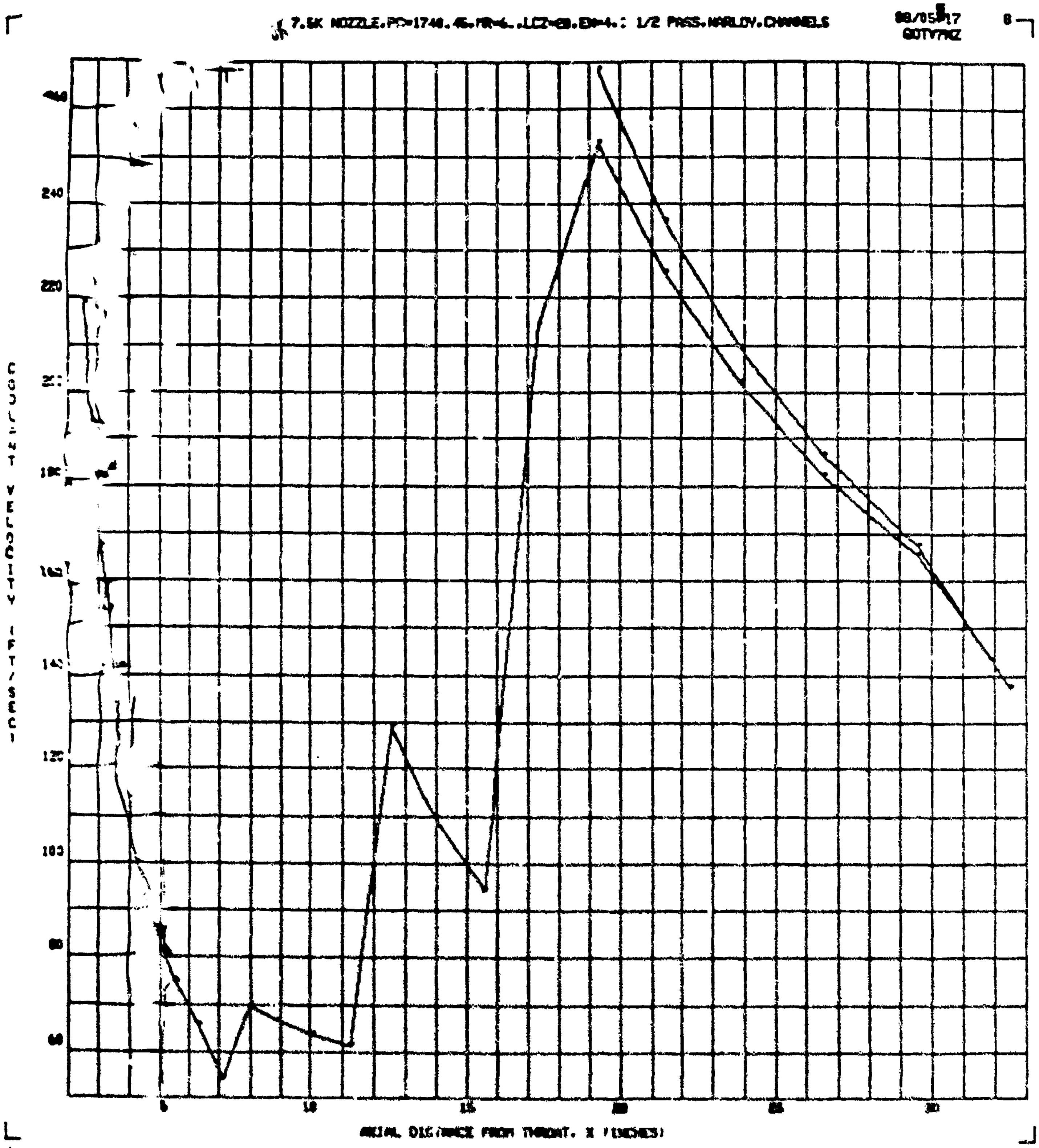


Figure 40. Coolant Velocity Profile for Channel Wall Nozzle

5471e

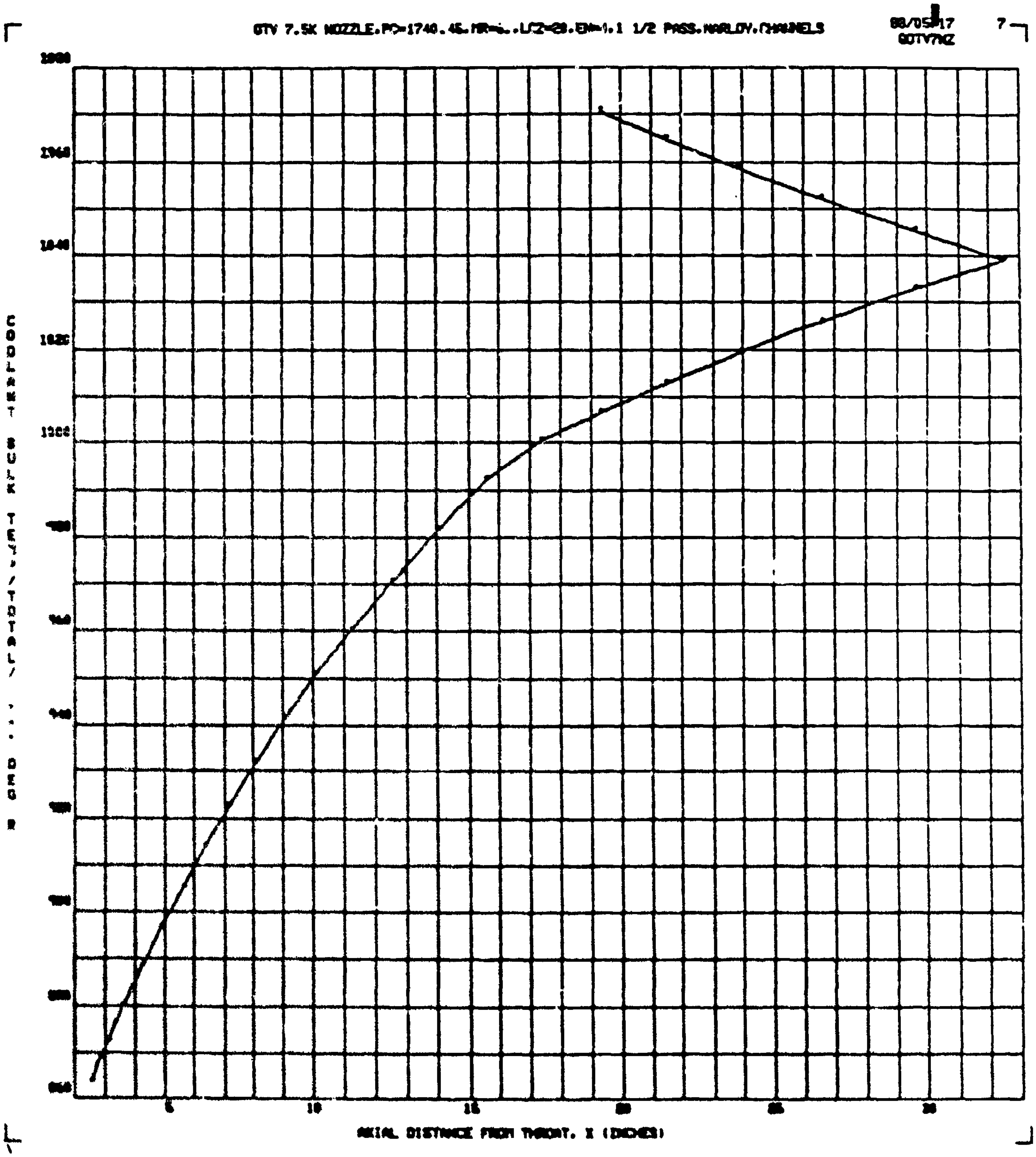


Figure 41. Coolant Bulk Temperature Profile for Channel Wall Nozzle

5471e

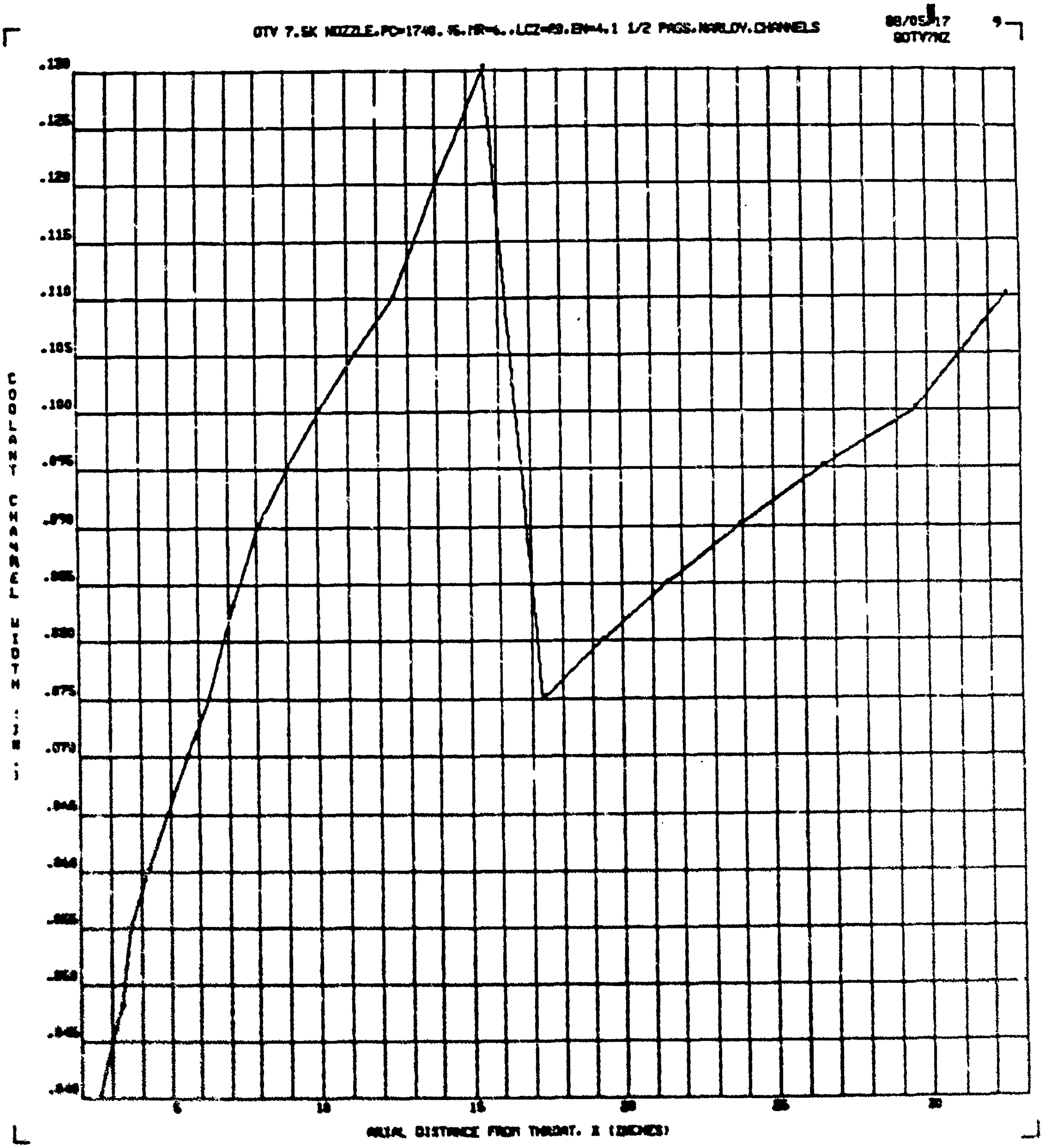


Figure 42. Coolant Channel Width for Nozzle

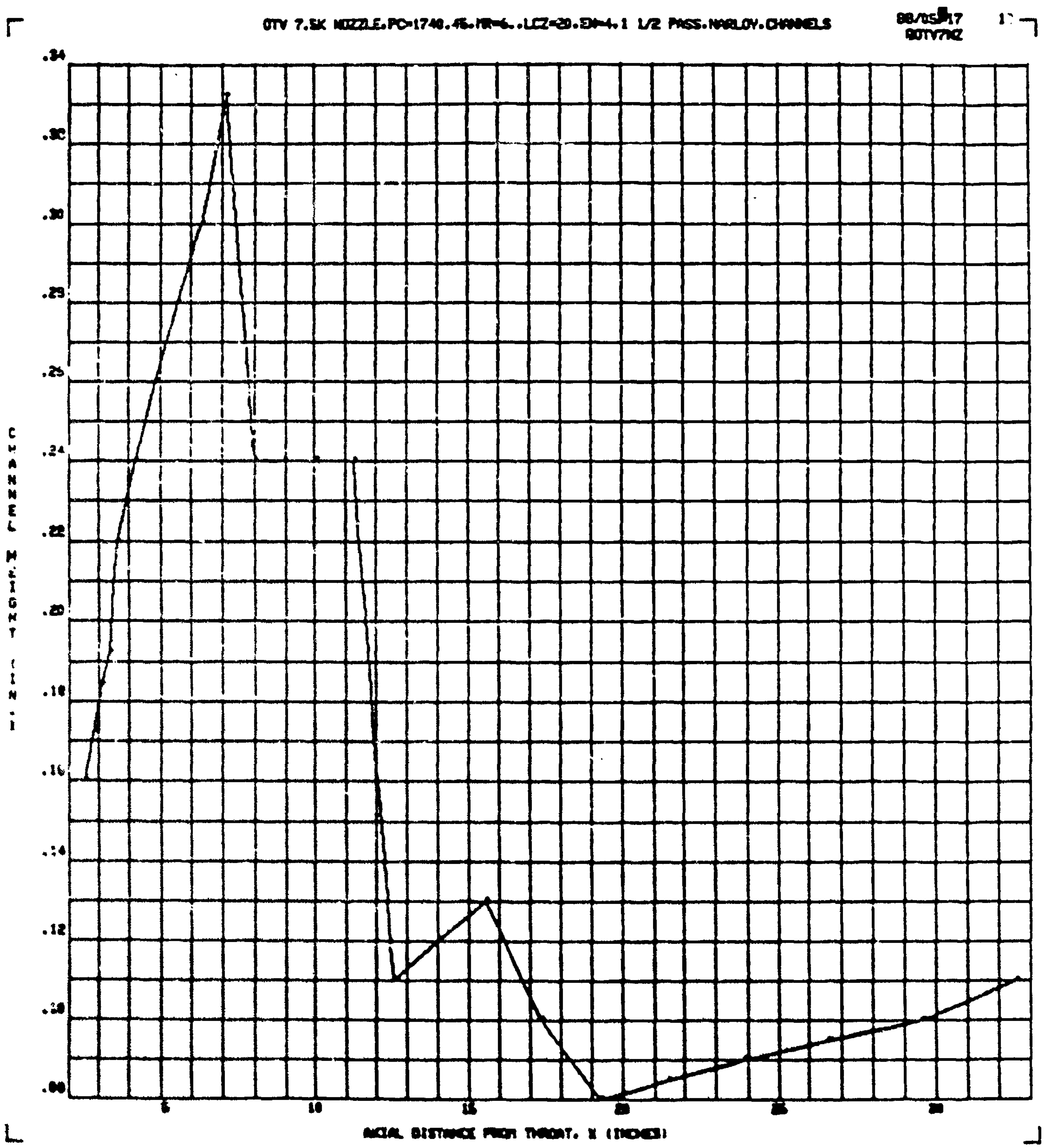


Figure 43. Coolant Channel Height for Nozzle

5471e

Table 8. Temperature Distribution Plot in Nozzle Channel Wall

OTV 7.5K NOZZLE,PC=1740.45,MR-6.,LCZ-20,LN 4,1 1/2 PASS,NARLOY,CHANNELS

STATION NO. 29   X = 17.341   X/HT = 21.086

NUMBER OF ITERATIONS = 60
DIFFERENCE BETWEEN HEAT IN AND HEAT OUT - .31494 PERCENT

HEAT INFLUX = .620
2-D/1-D Q/A = 1.00000

649	649	649	650	650	650
648	648	648	648	649	649
646	646	647	647	648	648
645	645	645	646	647	647
643	643	642			
641	641	640			
639	639	639			
638	638	637			
637	637	636			
636	636	635			
636	635	634			
635	635	634	628	626	625
634	633	632	630	629	628
633	632	631	630	629	629

Temperatures in °F

1. LAND WIDTH = .07335
2. CHANNEL WIDTH = .07500
3. WALL THICKNESS = .03100
4. CHANNEL DEPTH = .10000
5. CLOSEOUT THICKNESS = .04000
6. TAW = 5712. DEG. F
7. HG = .0001225
8. TC = 617. DEG. F
9. REFERENCE HC = .0122287
10. HC FACTOR FOR UPPER WALL = 1.0000
11. HC FACTOR FOR LOWER WALL = 1.0000
12. EXPONENT = .5500
13-14. K OF REGION 1 = .004875 + (-.1870E-06) * T
15-16. K OF REGION 2 = .004875 + (-.1870E-06) * T
17-18. K OF REGION 3 = .001340 + (-.1390E-05) * T
19. CONVERGENCE CRITERION = .0100 DEG. F
20. COATING THICKNESS = .000010
21-22. COATING K = .0000E+00 + (.0000E+00) * T

Remaining issues for the thrust chamber and nozzle are determining the need for acoustic cavity stability aids, evaluating nozzle tubes versus channels (coolant approach between tubes and channels), and determining the minimum radiative nozzle wall thickness.

6.3 Turbomachinery Analysis

The turbomachinery analysis includes the high-pressure fuel turbopump (HPFTP), the high-pressure oxidizer turbopump (HPOTP), the low-pressure fuel turbopump (LPFTP), and the low-pressure oxidizer turbopump (LPOTP). The HPFTP analysis effort was conducted under Task B.7. The HPFTP final report is incorporated into the Task D.5 final report for completeness in describing the OTV Engine Preliminary Design.

The depth of analysis has been sufficient to identify the design and off-design performance of the HPFTP. Design and analysis of the boost pumps (LPFTP and LPOTP) and HPOTP have been conducted to assure the validity of the turbomachinery relationship to the engine system.

The technology requirements of the high-speed fuel turbopump are key to the success of the Orbit Transfer Vehicle Engine(OTVE)program. The high-speed fuel turbopump capability dictates the engine performance and configuration to a great degree and the basic operating parameters must be correct to optimize the OTVE design. A high-speed design has been selected maximizing specific speed (Ns) for high efficiency and minimizing size for low weight. Three major issues have been identified and were addressed in the preliminary design studies. These are:

1. The high-speed requirement of the turbopump is well beyond the range of operation of conventional ball bearings.
2. This high speed also exceeds the range of current rotordynamic analysis experience on conventional turbopumps.
3. At this small turbopump size, the performance of the turbomachinery is impacted by the clearances and leakage losses inherent across seals and bearings.

6.3.1 High-Pressure Fuel Turbopump

The objectives were to complete a preliminary design of a liquid hydrogen turbopump for operation over the wide range of conditions corresponding to the established engine operating parameters (Table 9). Selected turbopump components were initially to be utilized in a rotordynamic simulator to characterize the turbopump dynamic behavior at high speed. Scope changes have eliminated the rotordynamic simulator objective and restricted the effort to the sizing and analysis currently accomplished.

6.3.1.1 Turbomachinery Design Requirements - The engine requirements and goals, presented in Table 9, impose definite requirements for the turbomachinery. The selection of the expander engine cycle dictates that the pump turbines be in series with the combustion chamber, thus limiting the available turbine pressure ratio. Also, in this cycle, turbine temperature is limited by the energy available in the engine coolant, hydrogen, which is used to drive the turbines.

On the pump side, the required fuel pump discharge pressure is established by the combustion chamber injection pressure plus the turbine pressure ratio and any line and valve pressure drops. The fuel pump must be designed to meet all of the pressure drops with an appropriate discharge pressure. Similarly, the required oxidizer pump discharge pressure is established by the combustion chamber injection pressure and line and valve pressure drops. These requirements result in relatively high discharge pressures. Propellant flow requirements are dictated by the engine thrust level, throttling requirements, and mixture ratio.

The final design of a turbopump is the result of a series of compromises between conflicting design objectives. These design objectives, approaches to solutions, and compromises are discussed in their respective technical sections.

Table 9. Orbit Transfer Propulsion Requirements and Goals

Requirements	
Propellants—fuel, oxidizer	Hydrogen, oxygen
Vacuum thrust	Design point engine thrust level is to be based on an orbit transfer vehicle total vacuum thrust level of 15,000 lbf with a minimum of two engines
Engine mixture ratio	Design point engine mixture ratio (O/F) will be 6.0 with capability for operation in the O/F range from 5.0 to 7.0
Propellant inlet conditions	Design point hydrogen and oxygen inlet temperatures will be 37.8°R and 162.7°R, respectively. Design point net positive suction head (NPSH) at full thrust will be 15 ft-lbf/lbm at the hydrogen pump inlet and 2 ft-lbf/lbm at the oxygen pump inlet
Design criteria	The engine is to be man-rated The engine must be compatible with aero-assist return of the vehicle to low earth orbit The engine must be capable of being space based
Gimbal	Engine gimbal requirements are +20 deg in the pitch and yaw planes
Start cycle	Engine start to full thrust is to be accomplished using tank-head-idle and pumped-idle operating modes as shown below: • Tank-head-idle: Propellants are supplied from the vehicle tanks at saturated conditions. This mode of operation is intended to settle propellants and thermally condition the engine. • Pumped-idle: Propellants are supplied initially at saturated conditions. Pumps operate at a power level sufficient to provide autogeneous pressurization of the vehicle propellant tanks to pump inlet design point NPSH levels. • Autogeneous pressurization continues during acceleration to and at full thrust.

Goals	
Vacuum-specific impulse	490 s
Vacuum thrust throttling ratio	10:1
Weight	360 lbm (maximum total weight of main propulsion system engines)
Length (stowed)	TBD
Service life between overhauls	500 starts/20-h operation
Service free life	100 starts/4-h operation

6.3.1.2 Preliminary HPFTP Design and Sizing Analysis - A liquid hydrogen pump was sized to deliver 2.209 lb/s, raising the pressure from an inlet pressure of 63.82 psia to an outlet pressure of 5639.4 psia. The turbopump configuration, shown in Figure 44, is a four-stage centrifugal pump which rotates at 208,200 rpm and has an inducer with a kicker blade row in front of the first-stage impeller and a balance piston behind the fourth-stage impeller to balance axial thrust during steady-state operation. The materials selected for the HPFTP are shown in Figure 44A.

The rotor is supported by two hydrostatic bearings which are externally fed with pressurized LH_2 from the second-stage impeller discharge for the pump end bearing and from the discharge volute for the turbine end bearing. A ball bearing which has a loose fit on the shaft reacts transient axial thrust. The four impellers are identical to reduce manufacturing costs.. The kicker blade row is shrouded and acts as a bearing journal for the hydrostatic bearing. A bearing outboard of the first-stage impeller was necessary to ensure rotordynamic stability, and bearing stiffness is maximized by using the larger diameter of a shroud on an axial blade row for the journal rather than the shaft. The inducer was not used for the bearing journal, as the hydrodynamic design of the blades would be severely compromised to provide sufficient back-up stiffness for the bearing, and this together with the bearing flow being returned to the inducer inlet would have resulted in an unacceptable reduction in suction performance. For these reasons, a shrouded kicker blade row was placed between the inducer and first impeller to act as the bearing journal. The kicker blade row is very lightly loaded hydrodynamically, meaning little turning of the blades, so that the radial stiffness can be maximized without degrading pump performance.

6.3.1.3 Selection of Number of Stages and Impeller Diameter - In general, the rotational speed of a turbopump is increased within the constraints of being able to achieve the required inducer suction performance. This allows the specific speed to be increased, along with efficiency, and the envelope and weight of the turbopump to be decreased. In this case, however,

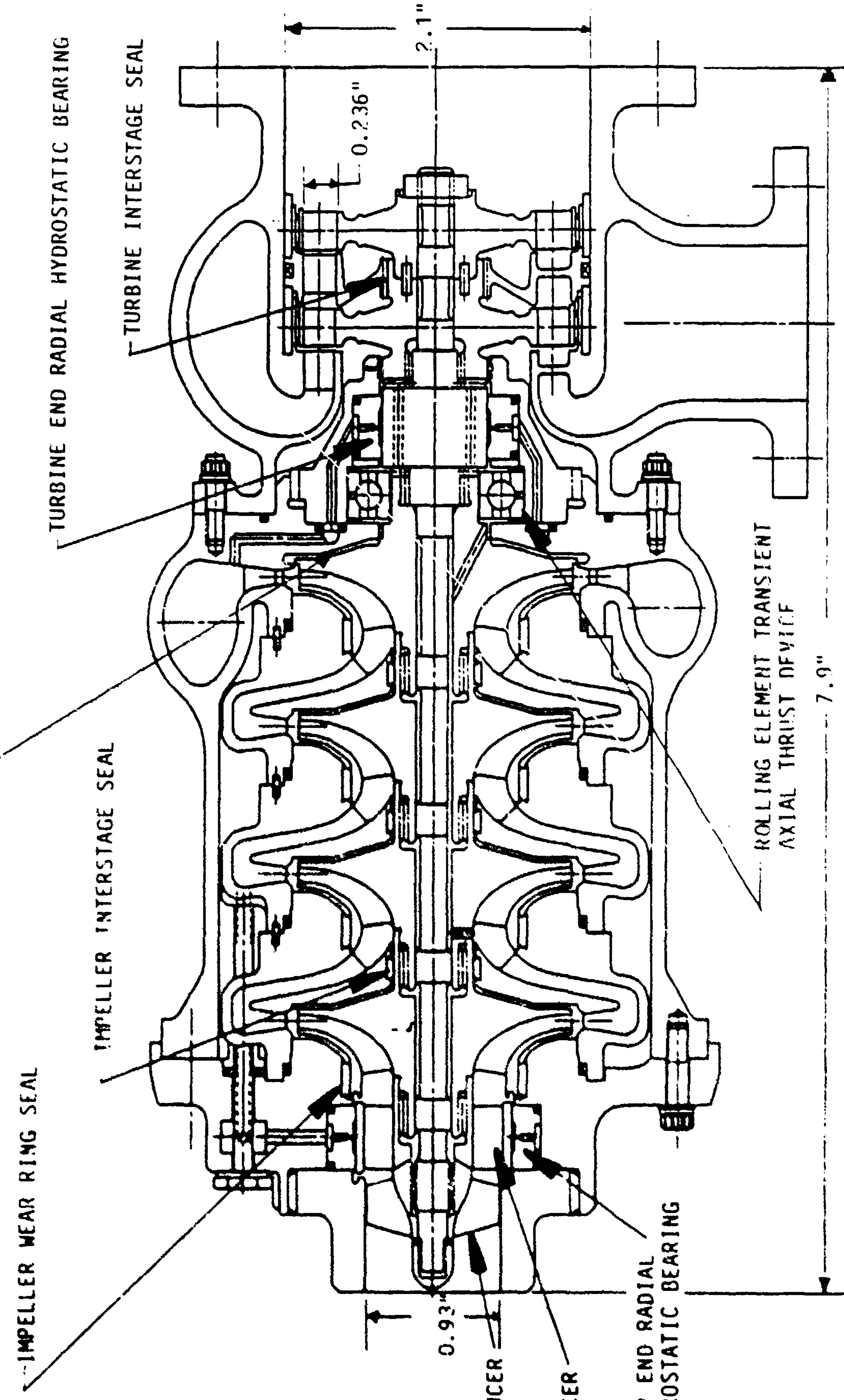


Figure 44. OTVE High-Pressure Fuel Turbopump (HPFTP)

5471e

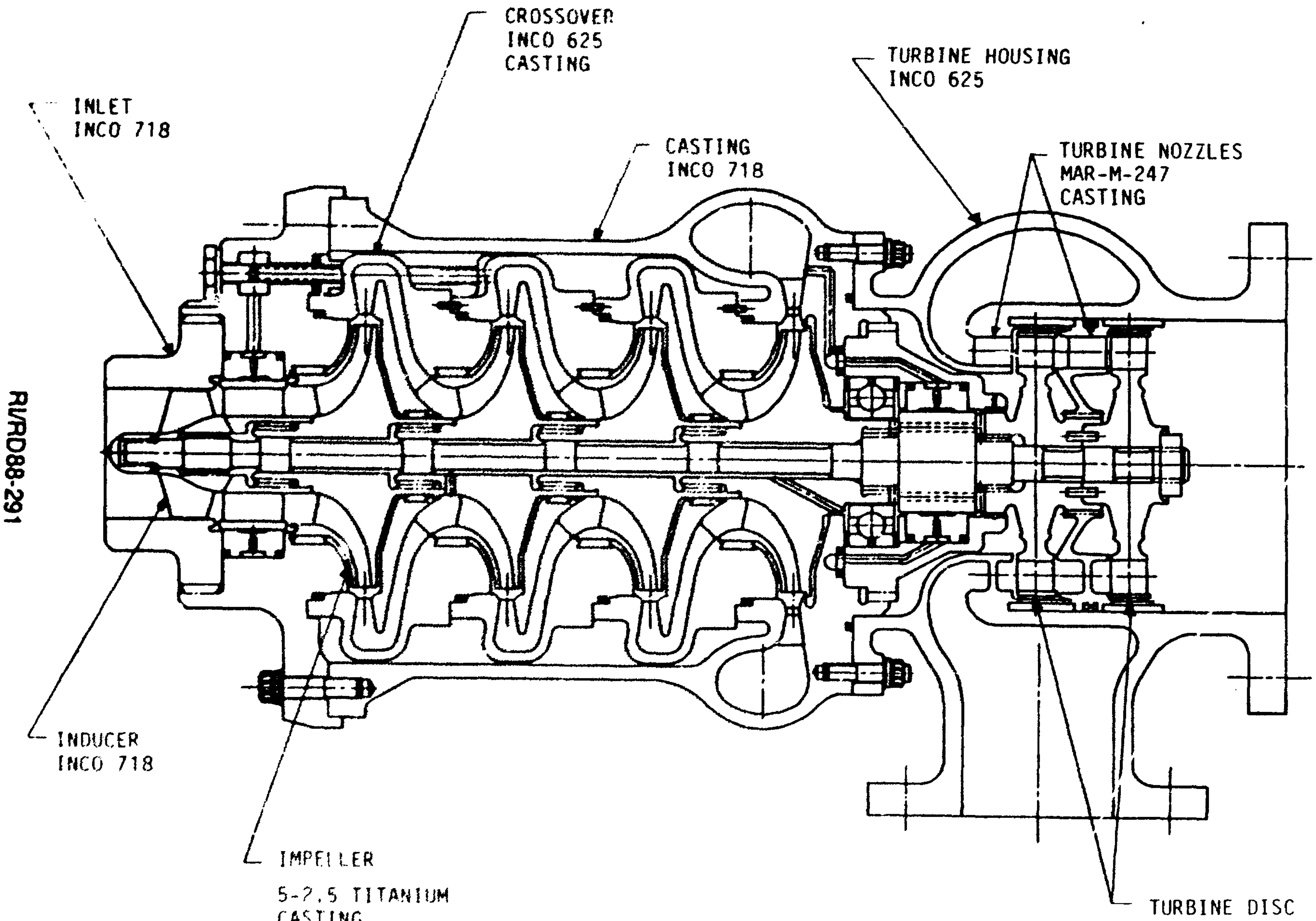


Figure 44A. OTVE High-Pressure Fuel Turbopump Materials the inlet pressure provided by the boost pump provides adequate NPSH margin, as will be shown later, and the design point rotational speed is 208,200 rpm as set by the turbine disk stress limits at the off-design speed of 227,560 rpm. At this rotational speed, the number of stages required and the impeller diameter were selected to provide adequate margin for structural integrity and performance.

Structural analysis of impellers of similar size and design (three-stage Mark 49 OTVE HPFTP) indicated that the impeller tip speed should be less than 1,870 fps to provide margin on burst speed for a cast titanium impeller. This pump is required to operate at a 9.3% overspeed condition point 2 (Figure 9) for propellant usage at mixture ratio 5. The impeller tip speed was set at 1870 ft/s at the off-design point 2, resulting in a tip speed of 1710 ft/s at the design point. To reduce development risk, the stage head coefficient was kept below 0.55 based on Rocketdyne's experience for successful hydrogen impeller designs. Figure 45 shows that a four-stage pump is required to satisfy these criteria. Figure 46 shows that the resulting tip diameter is 1.88 in. and Figure 47 shows that the stage specific speed is 1095, which is well within current design experience.

Since the pump is small, the impeller discharge tip width (the axial length of the flow passage at the impeller discharge) was checked to ensure manufacturing feasibility. The tip width was calculated assuming a 0.1 discharge flow coefficient and accounting for blade and boundary layer blockage. Figure 48 shows how the impeller tip width varies with impeller tip diameter. The tip width is 0.088 in. for a diameter of 1.88 in., which is within current casting capabilities.

6.3.1.4 Performance Calculations - Performance predictions for multistage pumps are performed in two steps. First the stage performance is predicted using empirical loss isolation techniques. This involves calculating the magnitudes of the various loss mechanisms (e.g., skin friction, diffusion, tip clearance) using empirical correlations and summing these to determine stage efficiency. This provides performance characteristics of the stage in terms of

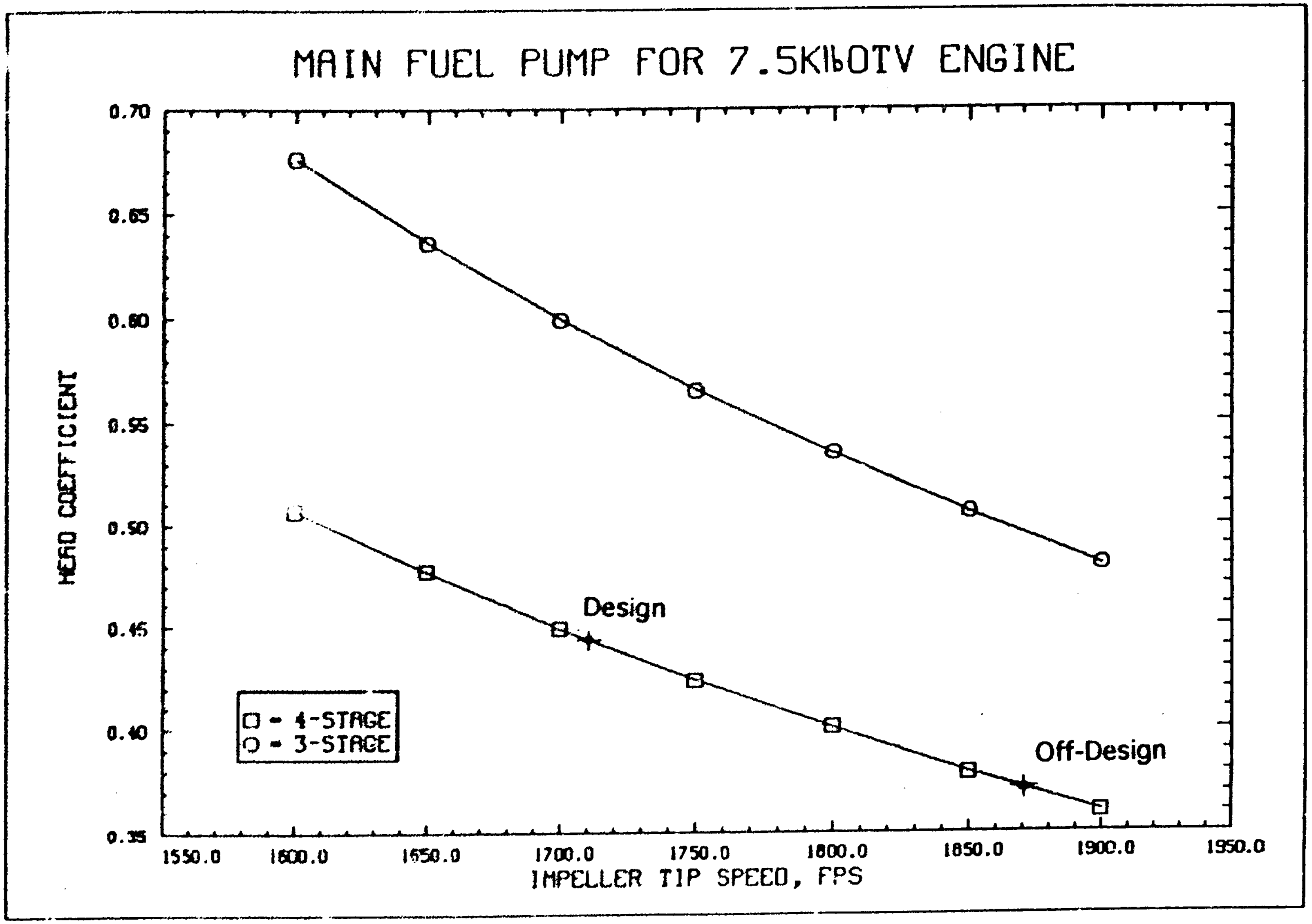


Figure 45. Head Coefficient versus Impeller Tip Speed

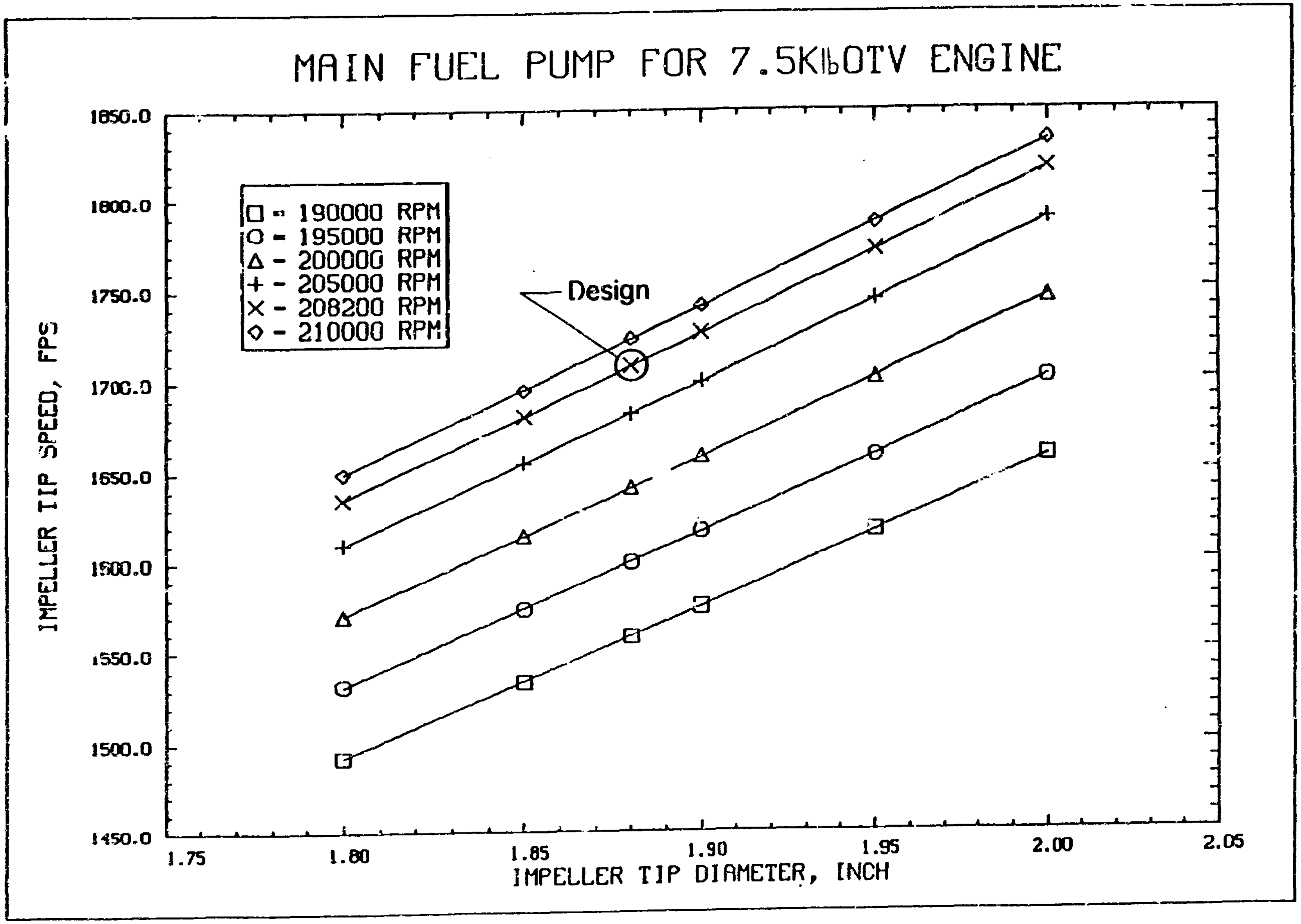


Figure 46. Impeller Tip Speed versus Impeller Tip Diameter

5471e

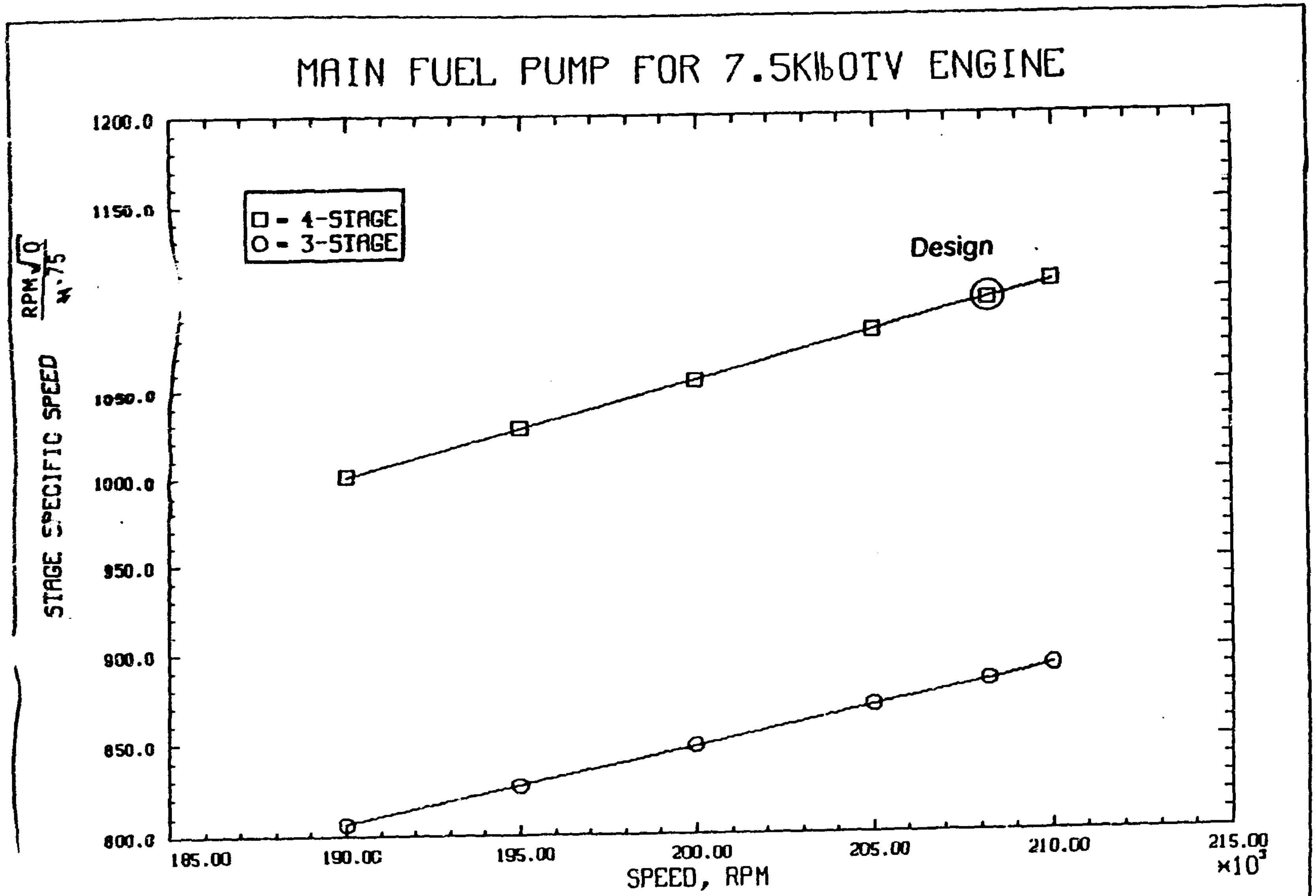


Figure 47. Stage-Specific Speed versus Shaft Speed

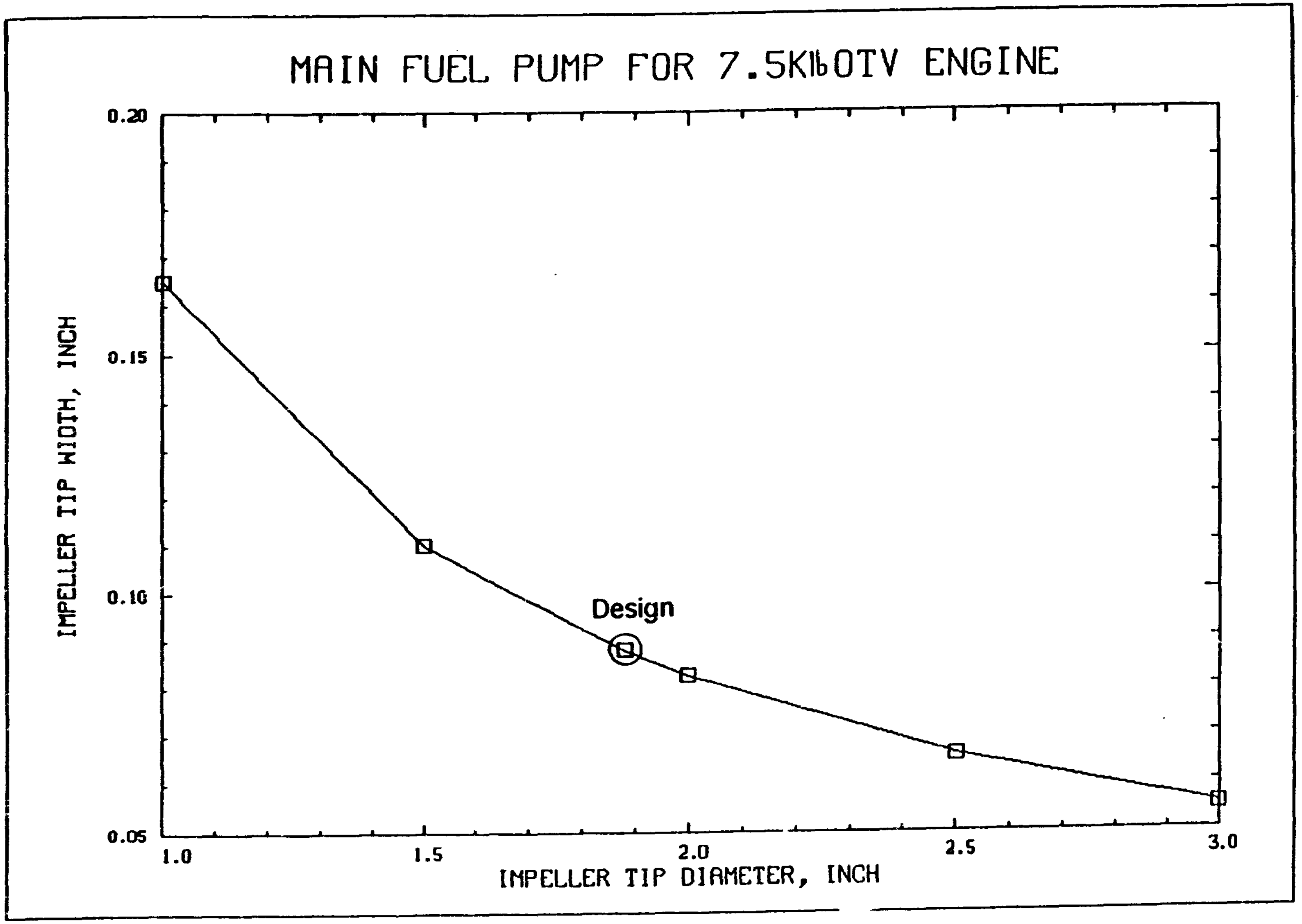


Figure 48. Impeller Tip Width versus Imp er Tip Diameter

5471e

head coefficient versus flow coefficient and efficiency versus flow coefficient. This information is then used in a thermodynamic model of the complete pump. This model calculates the magnitude of the secondary flows, bearing flows, etc. (Figure 49) and the thermodynamic states at all points in the pump. It calculates the overall pump efficiency, which is lower than the stage efficiency, including the stage-to-stage variations of the recirculation flows and the thermodynamic effects caused by the compressibility of hydrogen.

The required flow rate, and inlet and discharge pressures for the design point were taken from the engine balance and are listed in Table 10. Pump speed, and inducer and impeller geometries are also listed in Table 10. The performance calculations are based on soft seal technology which would keep the radial clearances of the interstage seals and the impeller wear ring seals ≤0.001 in. The performance prediction also includes hydrostatic bearing flow rates calculated by Rocketdyne's bearing design program, assuming an operating radial clearance of 0.00125 in.

The stage performance characteristics are shown in Figures 50 and 51. The stage efficiency for this OTV fuel pump is 65% and was anchored using the three-stage MK-49 fuel pump test data corrected to the present OTV pump size and specific speed. The Centrifugal Pump Loss Program includes a stall model which predicts the operating point at which stall occurs and the resulting performance degradation. Figures 50 and 51 show the predicted performance with and without this calculation. The pump performance map used in the preliminary system analysis is shown in Figure 9. Optimization of the impeller designs resulted in a diffusion ratio of 3.5 in the crossovers which is well within

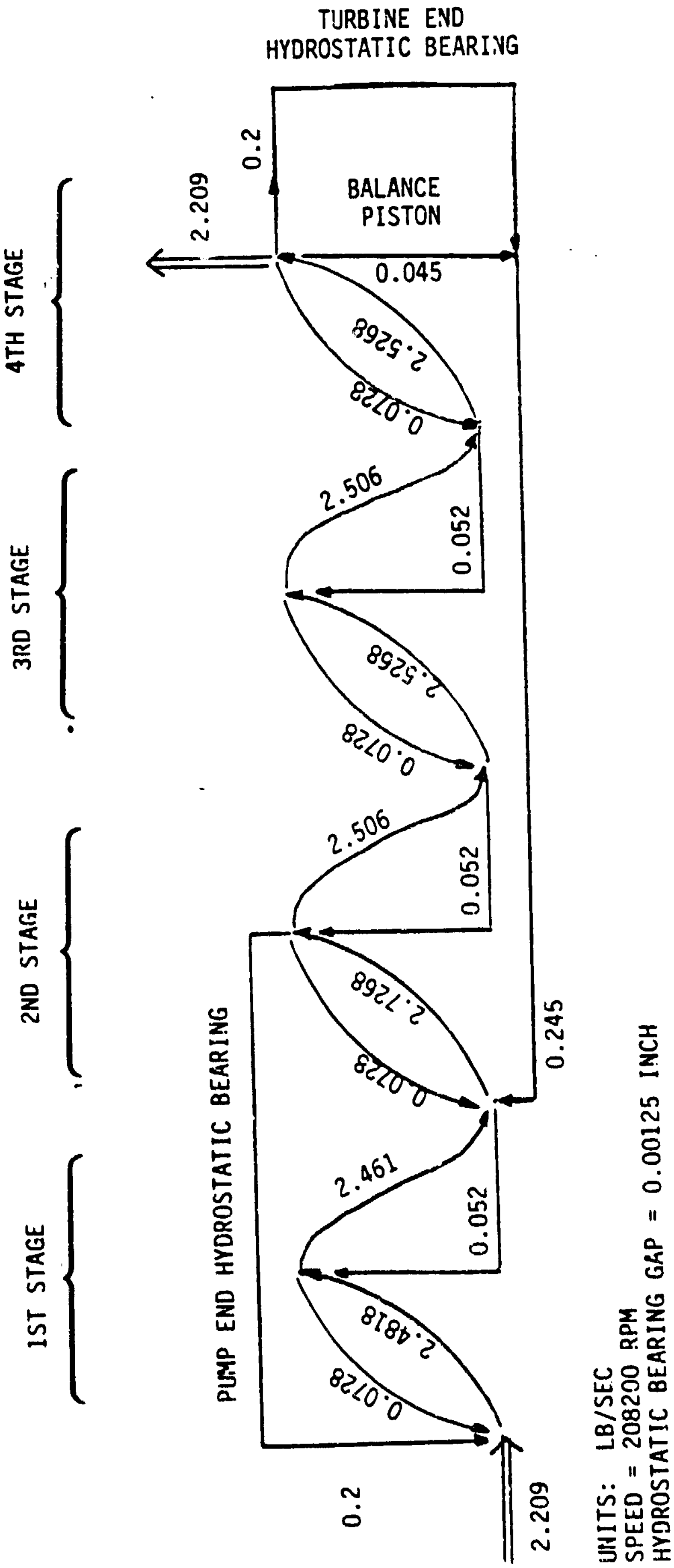


Figure 49. HPFTP Flow Schematic at Design Speed

5471e

Table 10. HPFTP Operating Characteristics

Parameter	Units	Value
Shaft Speed	RPM	208,200
Power	hp	1083
Bearing Dn	10^6 mm-rpm	--
Flowrate	lbm/S	2.209
Inlet Temperature	°R	37.8
Pressure In	psia	63.82
Outlet Temperature	°R	115
Pressure Out	psia	5639.4
Headrise (Total)	ft.	161,575
Number of Stages		4
Stage Specific Speed, Ns		1,095
Stage Efficiency	%	65
Overall Efficiency	%	60
Inducer		
Blade Number		4
Tip Diameter	in.	0.93
Inlet Hub Diameter	in.	0.28
Discharge Hub Diameter	in.	0.55
Inlet Flow Coefficient		0.143
Head Coefficient		0.19
Operating Suction Specific Speed		11,500
Impeller		
Blade Number (Full & Partial)		4+4
Eye Diameter	in.	1.0
Inlet Hub Diameter	in.	0.55
Tip Diameter	in.	1.88
Tip Width	in.	0.088
Tip Speed	fps.	1710

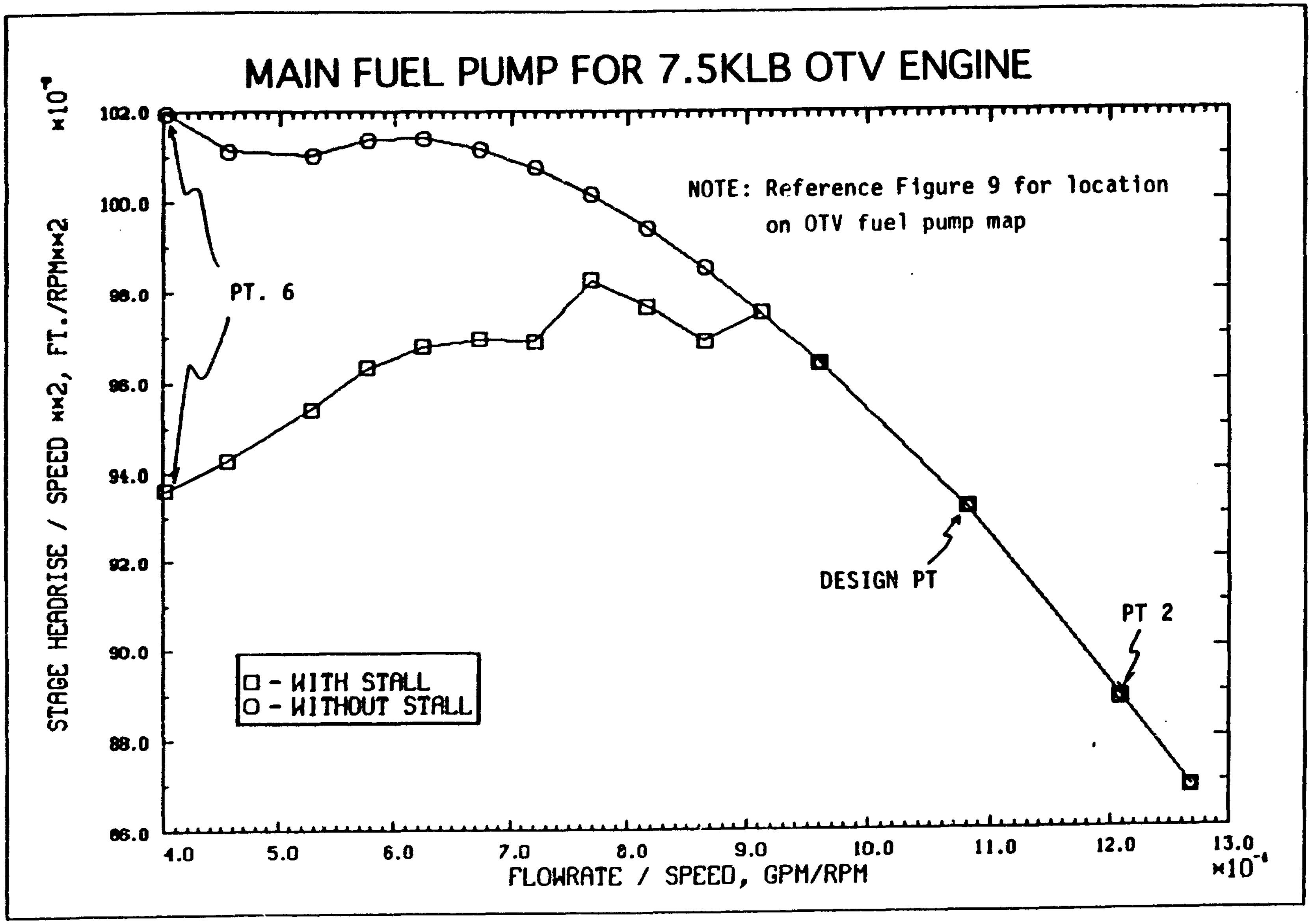


Figure 50. Stage Headrise Versus Flow Rate

5471e

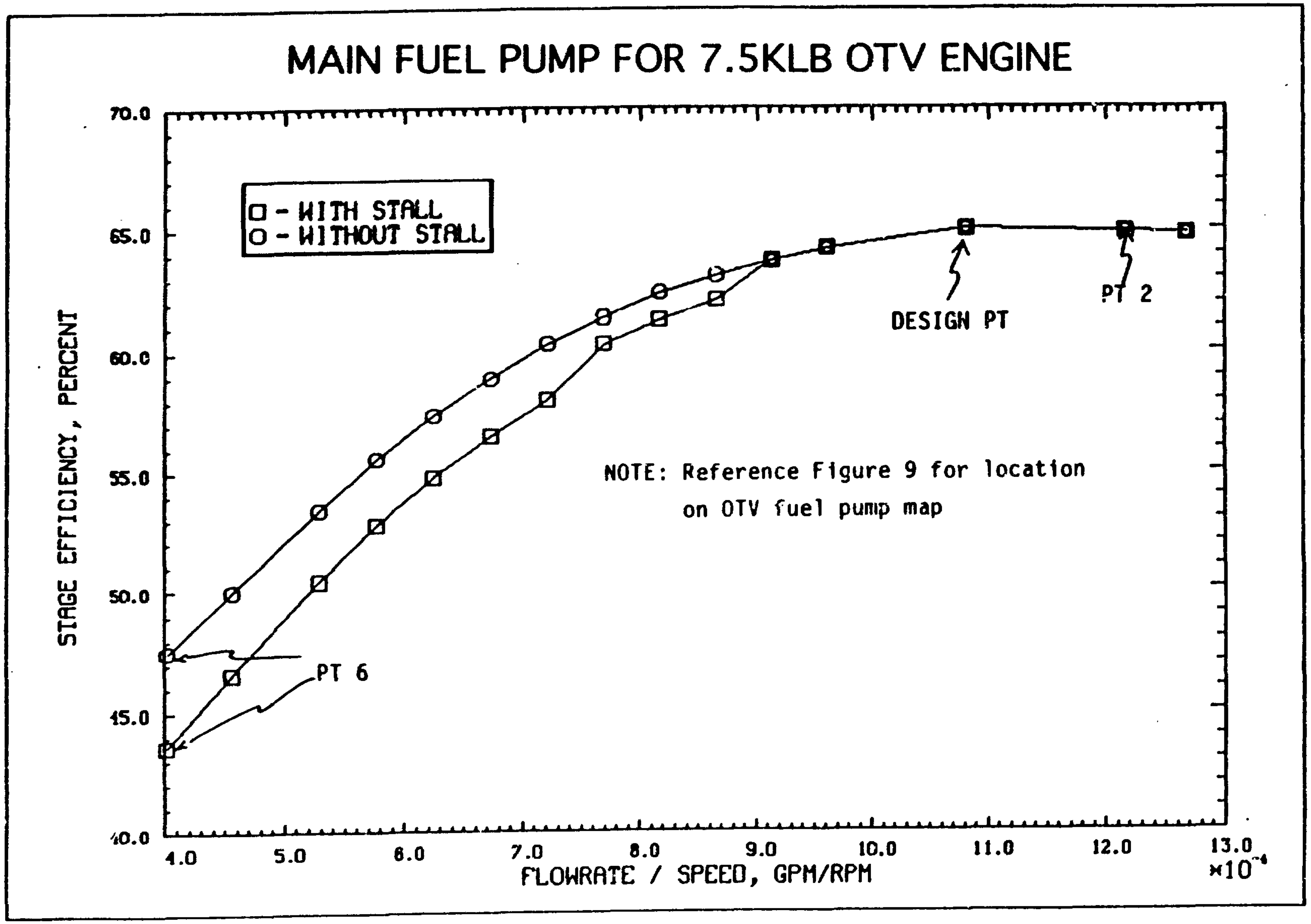


Figure 51. Stage Efficiency Versus Flow Rate

current design experience. The results of the thermodynamic model at the design point are shown in Figure 49. The overall isentropic efficiency for the four-stage OTV fuel pump was calculated to be 60% using this model. It was not possible, within the scope of this program, to run the thermodynamic model at the off design points and generate an overall pump performance map. Overall pump performance can be predicted to first order accuracy, however, by using the stage maps presented in Figure 50 and 51 anchored to the overall pump head and efficiency at the design point from Figure 9.

6.3.1.5 Suction Performance - At the design point, the inducer inlet flow coefficient is 0.1445. The NPSH capability at the design speed of 208,200 rpm and design flow rate of 225 gpm in hydrogen is calculated to be 270 ft. The available design point NPSH is 1500 ft based on the 63.82-psia inlet pressure given in the engine balance. The NPSH margin at the design point is therefore 456%.

6.3.1.6 Off-Design Operating Points - According to the pump performance map (Figure 9), the pump is required to operate at some off-design points (points 1, 2, 3, 4, 5, 6). The two extreme points (point 2 and point 6) represent the highest and lowest Q/N (where Q is flowrate in GPM and N is rotating speed in RPM) points and will be discussed in more detail. The H-Q (H is pump head in feet) and η-Q (η is stage efficiency in %) curves as shown in Figures 50 and 51 represent the nondimensional head and stage efficiency over a wide range of nondimensional flows. The extreme off-design points are marked on these curves. The actual efficiencies will be slightly lower for point 2 and higher for point 6 due to compressibility effects in liquid hydrogen. For most of the off-design points, the nondimensional flow (Q/N) is less than 50% of the current design value. As shown in the nondimensional H-Q curves (Figure 50) these points will all potentially operate with some elements of the pump stalled. There are several ways to delay or reduce the severity of these stall characteristics such as (1) increasing the design point Q/N to delay stall; (2) designing a blunt blade leading edge to reduce the sensitivity to stall; and (3) increasing the recirculation flow which increases the component Q/N and delays stall. Addressing these stall characteristics requires more analysis than was possible under the scope of the current study.

A major concern when operating at off-design points, where the pump efficiency is low, is hydrogen boil-off in the pumping process. Figure 52 is a hydrogen T-S diagram showing the two-phase flow boundary. The OTV fuel main pump inlet condition, the first-stage discharge and overall pump discharge for both design and off-design operating point 6 are shown on the diagram. As can be seen, at off-design operating point 6 the thermodynamic state comes closest to the two-phase dome but there is still sufficient margin for boil-off not to be a concern.

In a multistage machine, the majority of the radial load on the impellers is generated at the final stage where the potential of a nonuniform discharge pressure distribution exists because of the volute discharge configuration. The nondimensional radial load at off-design points is much higher than at the design point due to the mismatched area distribution of the volute. The radial load at point 6 (Figure 9) was calculated and, despite having a nondimensional value about four times that of design, was found to be only about 25% of the design point radial load because of the much lower operating speed. However, at point 2 the flow rate is 16% higher than design flow. The nondimensional radial load at point 2 is about 4 times higher than at the design point; the actual radial load is almost 5 times higher than at the design point because point 2 is operating at 9.3% higher speed. The radial load at off-design point 2 can be reduced if the volute is sized for a higher flow (for example, 10% higher than design flow). Another way to reduce the radial load is to use a "double-tongue" volute to improve the uniformity of circumferential pressure distribution.

At off-design conditions, the suction performance capability is also reduced. The point of most concern is the off-design point 2 where the flow is above the design flow and is about 1.065 times the design Q/N. Based on Rocketdyne data for similar inducers, the suction specific speed capability will be reduced by 6.5%. This means that the NPSH capability in hydrogen will be 411 ft. The available point 2 NPSH is calculated to be 1183 ft, thus providing an adequate NPSH margin of 188%.

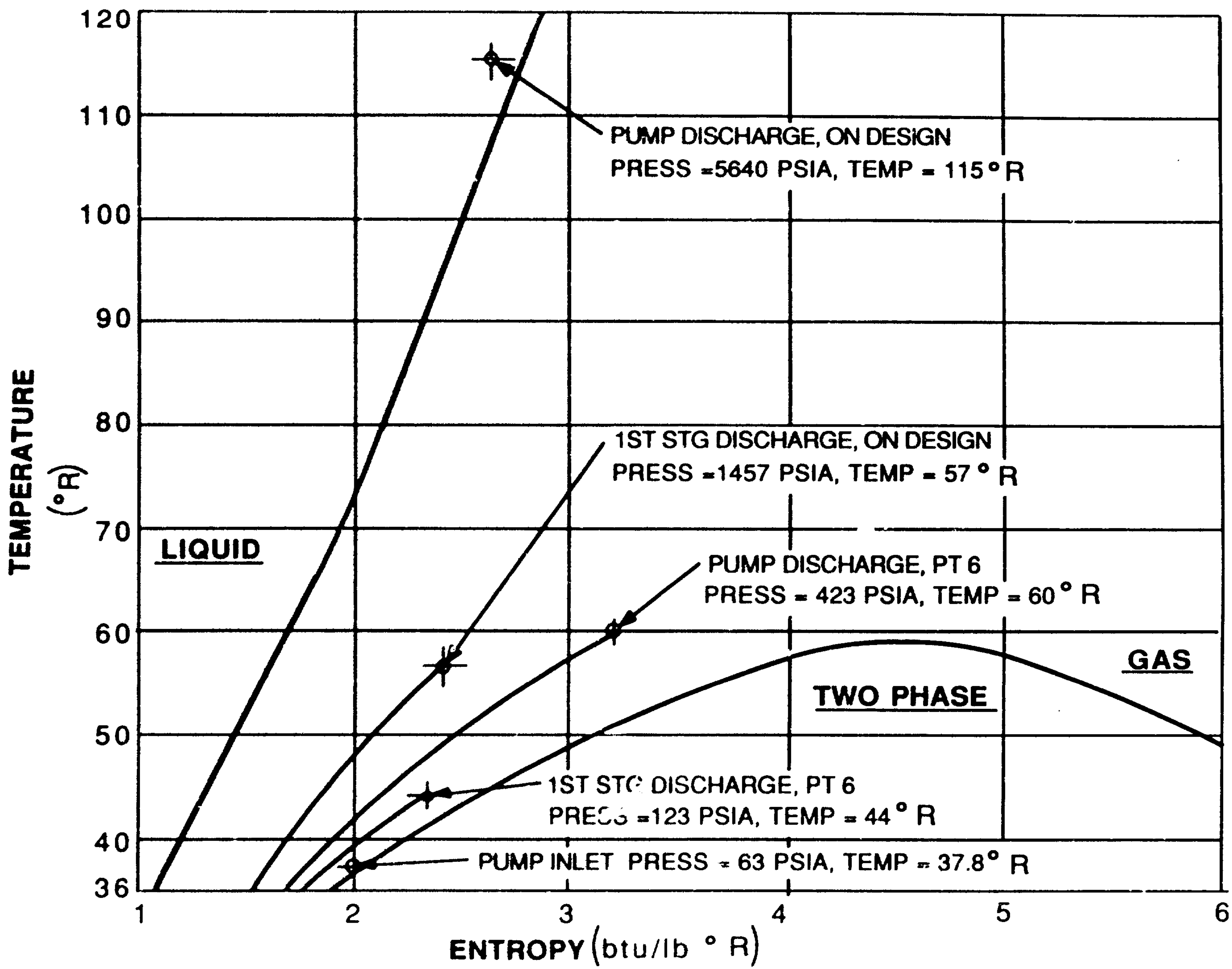


Figure 52. Hydrogen Temperature--Entropy Diagram

Another concern when operating far from the design point, especially when there is the potential for stall, is the increased level of dynamic loads which can cause rotordynamic instabilities and reduce component life due to fatigue. The operating speeds at the low Q/N off-design point, however, are much lower than at the design point and this, coupled with the low density of hydrogen significantly reduces the magnitude and potential damage of the dynamic loads. This combined with the positive results from the boil-off, radial load and suction performance analyses, indicates that operation at the off-design points is feasible providing the head and efficiency of the pump is adequate for the overall engine system.

6.3.1.7 Axial Thrust - The axial thrust calculation was based on the four-stage turbopump configuration shown in Figure 44. The calculation was performed to assess the balancing thrust required from the balance piston.

Static pressure levels at the impeller discharges were taken from the thermodynamic model. The pumping factor "K" defines the strength of the forced vortices in the impeller shroud cavities as a ratio of the fluid rotational velocity to the pump rotational speed. It is used to calculate the pressure distributions, and thus axial thrusts, on the impeller shrouds. These "K" factors were estimated to be 0.62 for the impeller front shrouds and 0.4 for the rear shrouds based on experimental data on rotating disks and CFD analysis performed to support the MK-49F three-stage OTVE fuel turbopump. Based on the above K-factors and including the fluid momentum forces, the pump axial thrust (without balance piston and without turbine) was calculated at different speeds and is shown in Figure 53. It has been estimated that the turbine axial thrust toward the pump is about 1,000 lb at design speed, and therefore the required balance piston thrust is about 8,000 lb. It was also calculated that the maximum balance piston capability, with the high-pressure orifice fully open, is about 11,000 lb and the minimum balance piston capability, with the high-pressure orifice fully closed, is about 6,800 lb. This preliminary analysis shows that the design point axial thrust is within the balance piston capability,

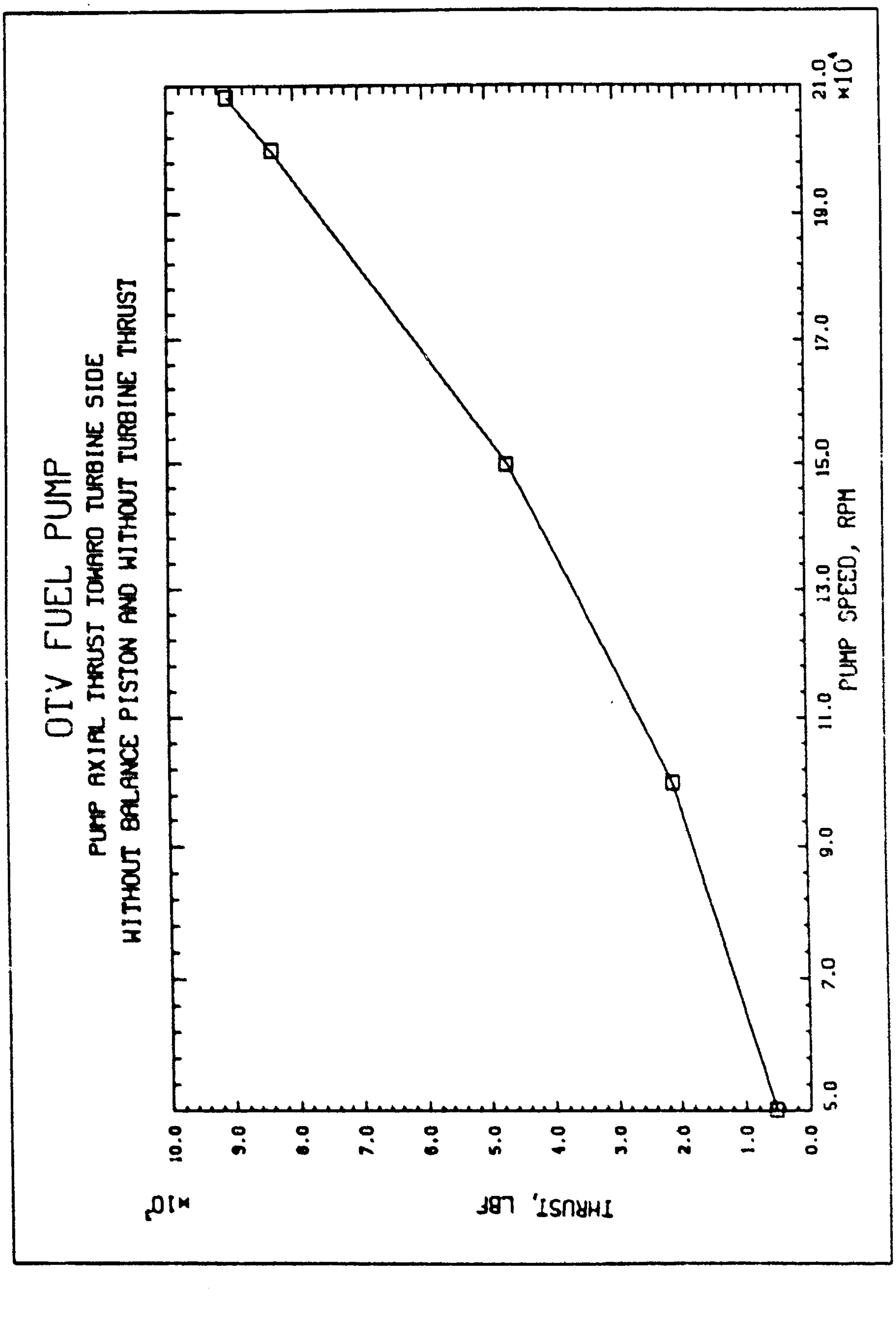


Figure 53. Pump Axial Thrust versus Shaft Speed

5471e

however, this capability is sensitive to the assumed pumping factors and the transient axial thrust balance must still be addressed. More detailed analysis should be performed if the design is continued any further.

6.3.1.8 OTVE HPFTP Turbine Analysis - The preliminary turbine analysis and sizing was conducted as described below. The status of this analysis is such that additional effort will be required to confirm assumptions made and fine tune selections made for final detail design.

6.3.1.9 HPFTP Turbine - The successful experience with the Mark 49F turbine, which operated under similar conditions, guided the selection of this turbopump turbine design. The Mark 49F turbine was a two-stage partial-admission design and achieved an operating efficiency 5 points higher than the design prediction during laboratory tests. Two stages were also chosen for this turbine to optimize efficiency. A single-stage design would have been simpler and of somewhat less weight but would have been over 5 points less in efficiency with resultant penalties to the engine performance. A high loading coefficient of over 2.4 directs the selection of a pressure-compounded impulse-type turbine. The maximum operating speed occurs at off-design (point 2) and a speed limit of 1,600 fps for the pitchline velocity was set for this point to maintain acceptable stress limits in the disk. The resulting operating pitch line velocity at the design point is 1,466 fps. Using this velocity, a trade-off design study was made to evaluate the optimum rotational speed and diameter. Two speeds were examined: 240K and 208.2K rpm. For this turbopump, the higher rpm would actually be more efficient for the pump but less efficient for the turbine. The speed of 208.2K rpm was selected because it gave a 2-point efficiency advantage even though it results in a partial rather than a full admission turbine. At speeds lower than 208.2K, both the pump and the turbine efficiency will degrade; therefore, lower rpm was not considered. With a speed of 208.2K rpm, the required pitchline diameter is 1.614 in. At higher speeds, this diameter must be smaller and all key dimensions of the rotor blades must be smaller. The lower efficiency at the higher speed is partially due to the inability to scale some of the design parameters with the small diameter. Two of the driving parameters are:

1. This turbine size will require very thin blades. The estimated trailing edge thickness necessary is about 0.008 in., which is judged to be the minimum for manufacturing and durability purposes. This thickness corresponds to a channel blockage of about 12%, which is considered to be the limit for most turbine designs because higher blockages will significantly degrade efficiency.

2. The throat between two blades is close to 0.050 in., which is not the manufacturing limit; however, if a typical 0.002-in. tolerance on either side of the blade profile is assumed, the throat area could change by 8%. This error in the throat is considered to be the limiting value due to its effect on performance.

Unshrouded blades were chosen for ease of manufacturing; however, to achieve good efficiency, a maximum running tip clearance of 0.005 in. was assumed. The characteristic parameters of the turbine are listed in Table 11. Figure 54 shows the velocity diagram for the two stages at the design point. The exit absolute velocity from each stage is essentially axial which optimizes the efficiency. The blading will be designed to achieve impulse conditions (zero rotor Δp) at the hub to minimize axial thrust of the turbine. This also is favorable for efficiency. Figures 55, 56, and 57 present the key performance curves for the turbine. Figure 55 shows the efficiency as a function of pressure ratio for various speed parameters. Figure 56 shows the corrected mass flow for the same independent parameters. Figure 57 shows the efficiency as a function of the velocity ratio (U/Co) for various pressure ratios. From these curves, both the design point and off-design performance can be assessed. As noted in Figure 57, the efficiency is near the peak.

Table 11. HPFTP Turbine Parameters

Power, hp	1086.
Speed, rpm	208,200
Turbine type	2RPC
Mean diameter, in.	1.614
Pressure ratio	1.73
Inlet temperature, °R	1146.
Inlet pressure, psia	4105.
Admission, %	47./53.
Flow, lbm/s	2.013
Blade speed (based on mean diameter), ft/s	1466.
Efficiency T-S (Total Inlet to Static Outlet)	0.617
Velocity ratio	0.269
First nozzle/rotating blade height, in.	0.205/0.213
Second nozzle/rotating blade height, in.	0.226/0.236
First nozzle/rotating blade width, in.	0.250/0.240
Second nozzle/rotating blade width, in.	0.250/0.240
Axial gap between nozzle and rotor, in.	Max. 0.030
Axial gap between first and second stage, in.	0.200
Running tip clearance, in.	Max. 0.005
Blade TE thickness, in.	Max. 0.008

6.3.1.10 Bearing Selection - Bearings for small, high-speed turbopumps have been reviewed in a parallel program--the OTVE High-Speed Turbopump Bearing task. This effort is summarized here.

The speed of the small OTVE HPFTP (208,200 rpm) exceeds the capabilities of propellant cooled rolling element bearings for long service life. The predicted life of these rolling element bearings (5 hr) falls short of the engine life requirements (20 hr). The ever increasing turbopump shaft speeds coupled with objectives of increased component life continue to amplify the need for

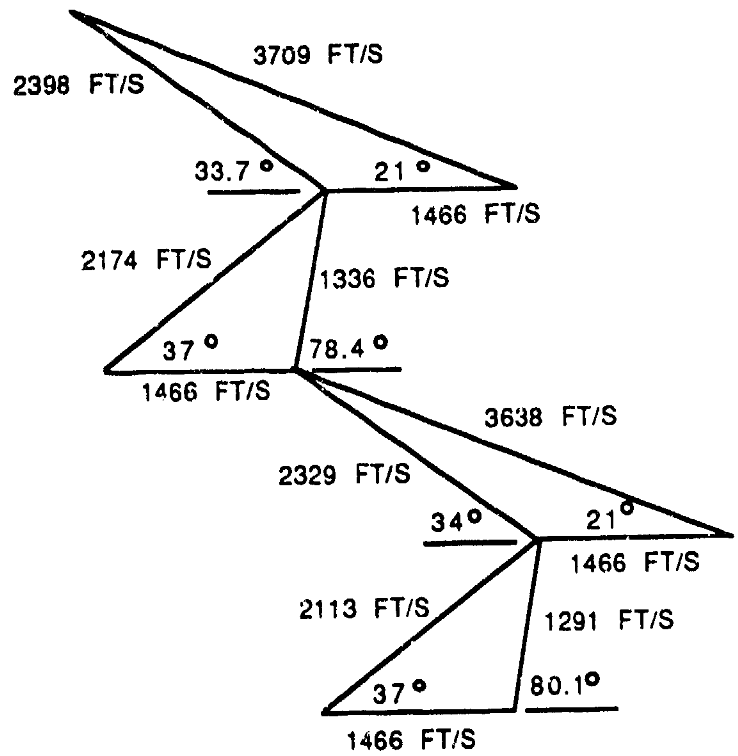


Figure 54. OTVE HPFTP Turbine Velocity Diagram

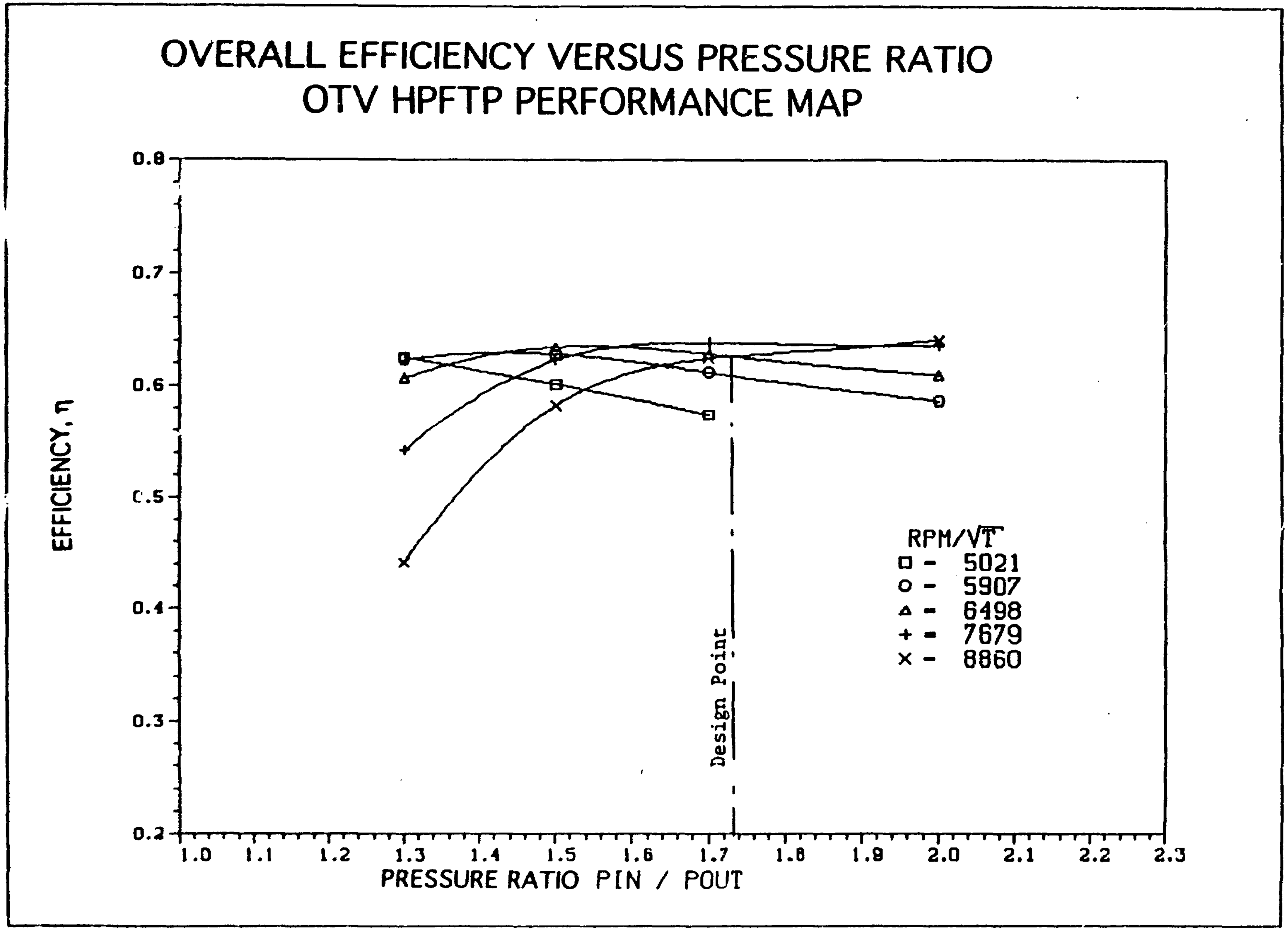


Figure 55. Overall Efficiency Versus Pressure Ratio

5471e

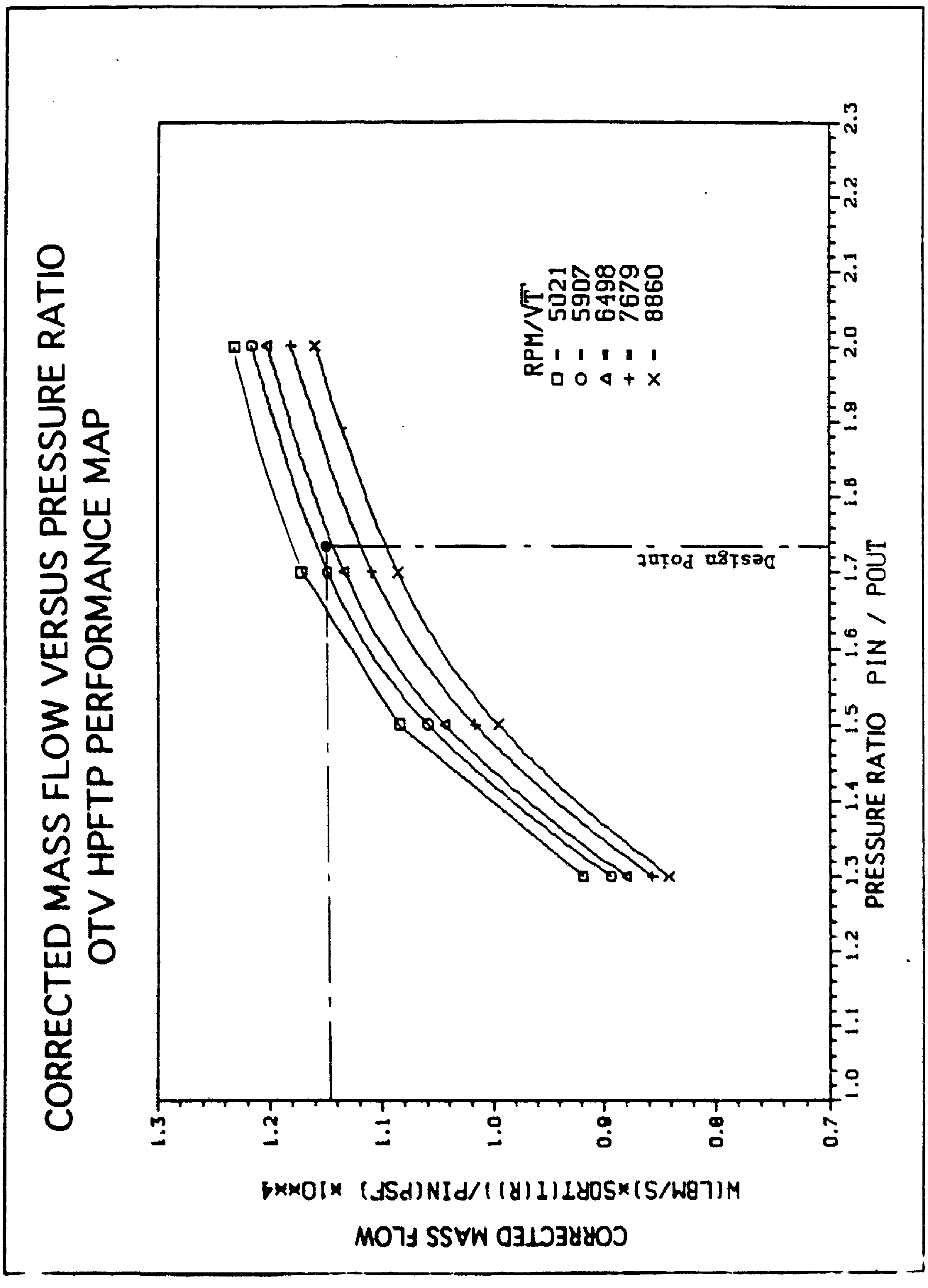


Figure 56. Corrected Mass Flow Versus Pressure Ratio

5471e

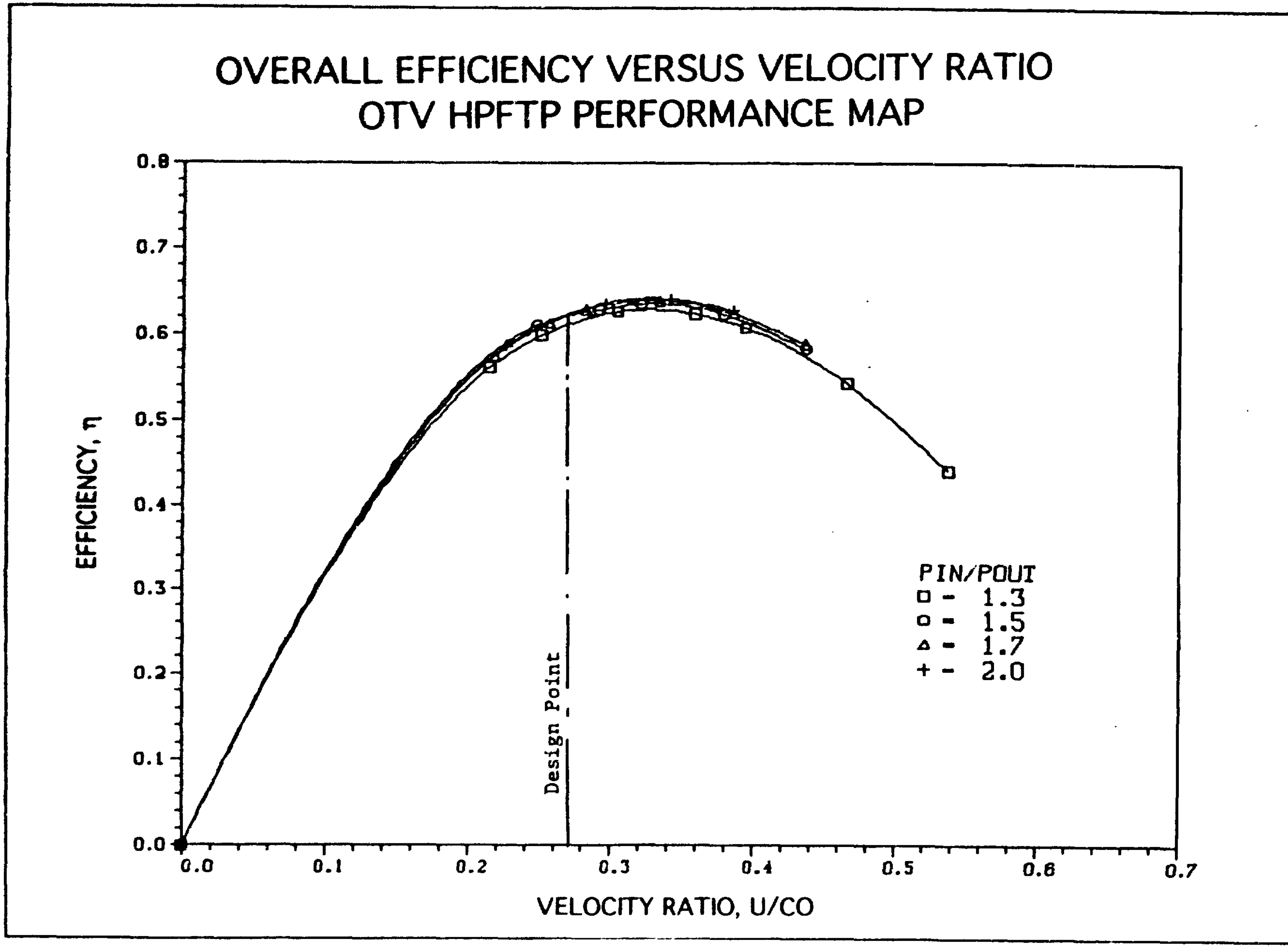


Figure 57. Overall Efficiency Versus Velocity Ratio

5471e

control of the shaft rotordynamics and improved methods of supporting the shaft during operation including start-up and shutdown. Hybrid hydrostatic/ball bearing applications have been studied extensively for larger turbopump designs over the past several years with the objective of developing a bearing design that would accomplish these objectives. Although bearings of this type have been used in other applications, their use in high-speed turbopumps with their severe and hazardous environments is relatively new. Major accomplishments have been achieved in this field since the late 1970s in both analytical procedures and empirical demonstration of various hybrid and hydrostatic components. The effort has resulted in an understanding of the potential design configurations available for various applications. This, coupled with dynamic analysis application studies, has established the limits and applicability of the many configuration options available with hybrid hydrostatic/ball bearings.

Hybrid bearing configurations offer improved life, up to 50 hours; however, the hybrid configurations have larger turbopump cross sectional requirements in both the radial and axial directions. This space requirement makes them less suitable for use in the small diameter OTVE high-speed fuel turbopump. Additionally, the rolling element bearing in the combination will continue to rotate and generate parasitic losses.

The use of a hydrostatic bearing alone is the next potential design configuration. Hydrostatic bearings have very high-speed capability, but may wear during start/stop transients. Additionally, the hydrostatic bearing flow penalties will affect the efficiency of the turbopump. The parallel OTVE Hydrostatic Bearing Tester program explores the feasibility of using a hydrostatic bearing and identifying the means of obtaining adequate wear life by use of wear-resistant hydrostatic bearing materials.

Progress on the OTVE Hydrostatic Bearing Tester has demonstrated the need for the careful selection of hydrostatic bearing materials that are compatible with the housing material. The difference in thermal expansions of the various candidate bearing materials and the associated housing material must be considered when designing a mounting system for the hydrostatic bearings. The stresses caused by the interference fits with differences in thermal expansion rates coupled with the stresses caused by the hydrostatic interdiametral fluid supply pressure eliminates many bearing materials from consideration. Efforts continue in this area to arrive at a material/design configuration that can be successfully mounted in a small turbopump.

Early on in the OTVE High-Speed Turbopump Bearing task, a review was made of foil bearings. This review resulted in the listing of all of the foil bearing types, their characteristics, and the applications that were currently available.

The foil bearing alternative has not been pursued for incorporation into the HPFTP because of the lack of information about their properties in OTVE propellants. Turbopump rotordynamic analysis requires a complete understanding of the stiffness and damping characteristics of the shaft supporting bearings and their load-carrying capability.

These stiffness and damping characteristics are not available for foil bearings in cryogenics.

6.3.1.11 Transient Axial Thrust Control - During steady-state operation of the HPFTP, shaft axial thrust is reacted and controlled by the built-in balance piston located on the back face of the fourth-stage impeller. This device requires adequate pump discharge pressure to be able to function. Consequently, during start and shutdown transients, axial thrust must be reacted by another device. Before start-up, the rotating assembly is positioned radially and axially in a gravity free environment with little contact being made with physical restraints. At start-up and tank-head idle, liquid hydrogen, at available tank pressure, will be introduced into the turbomachinery. This will cause the pumps to rotate and impose an axial load on the shaft. In addition, the pumped idle mode and shutdown conditions of operation will impose transient axial loads.

The magnitude and direction of these axial loads are difficult to predict, however, some assumptions can be made and devices that are capable of reacting these loads can be put in place.

Some concepts to address this need include hybrid bearings, impeller axial hydrostatic bearings, combined axial and radial hydrostatic bearings, an additional pressurized balance piston, rolling element bearings, rub rings, Rayleigh and/or spiral groove bearings, magnetic bearings, and foil bearings. Of the concepts listed, the rolling element bearing was chosen to react transient axial load and provide long life. The bearing inner ring does not touch the shaft either radially or axially during normal operating conditions as shown in Figure 44. This bearing would only be engaged at shaft maximum axial excursions in either direction until the balance piston assumes shaft axial control or the shaft reaches zero speed and load. The bearing outer ring is split axially and both halves are loaded by springs to provide bearing pre-load, thus minimizing and compensating for bearing wear.

6.3.1.12 Seal Selection - Seal selection for the HPFTP is driven by the need for reduced seal radial clearance to minimize flow losses. This is critical in small pumps in that seal clearances do not scale down and the flow losses due to these seal clearances become a larger percentage of total flow. Soft seals have been selected for the internal pump seals which are the impeller front shroud and impeller interstage seals which can be seen in Figure 44. Soft seals are intended to tolerate the rubbing that is expected between the impeller surfaces and the seal surfaces due to the small radial clearances. The soft seals may be made of polymeric materials such as teflon, Kel-f, or VPS 211. These seals are also utilized as rotordynamic aids in that they have inherent damping qualities and the seal length is tailored by rotordynamic requirements. These seals are being evaluated by OTVE Soft Seal Technology Program Task B-5.

The purged labyrinth seal between the turbine end hydrostatic bearing and turbine section is designed to provide a barrier to seal off turbine gases from the pump section.

The turbine interstage seal is a typical honeycomb seal that limits leakage around the second-stage nozzle and also provides rotordynamic damping.

6.3.1.13 OTVE High-Pressure Fuel Turbopump Rotordynamic Analysis - The original finite element model is presented in Appendix B along with all design iterations. The analyses consist of linear damped critical speed and stability calculations. Preliminary analyses have been performed on the evolving cross sections as described in Appendix B. Rotordynamic solutions have been achieved by making modifications to these cross sections; however, more detailed analyses are required on the finalized design to confirm all required margins. Additionally, as the detail design progresses to define housing stiffness, response calculations can be made to specify bearing loads, rotor displacements, and housing accelerations.

Several design iterations of the 7,500 lbf OTV engine HPFTP have been analyzed for critical speeds and rotordynamic stability. In all, five different rotor cross sections were analyzed in combination with numerous different seal and bearing configurations. The end results of each analysis are maps of mode natural frequency versus running speed and modal damping (log dec) versus running speed. The natural frequency maps show what the frequency of each mode is at any given shaft speed. A critical speed is indicated where precession mode crosses the linear shaft speed line.

In virtually all cases studied, the rotor has one critical speed below the quoted operating range of 50,000 to 210,000 rpm, and one critical speed in the operating range in the vicinity of 60,000 to 80,000 rpm. In general for the configurations analyzed, the mode which is in the operating range is too lightly damped to permit continuous operation at that speed. The stability of these two modes is also cause for some concern. The lower frequency first mode is predicted to be stable, but its frequency at max power level is well below our current design limit of 50% of shaft speed. Experience dictates that violating this criteria increases the likelihood that the mode may be unstable in spite of model predictions. Also, the higher frequency second mode, in certain configurations, is predicted to be only very marginally stable. None of the configurations analyzed to date are 100% acceptable from a rotordynamic standpoint. To achieve an acceptable design with our current design criteria will require more shaft and/or seal stiffness to raise the frequency of the first mode, and more damping to permit having the second critical speed in the operating range.

6.3.1.14 HPFTP Remaining Issues - Remaining issues and concerns for the HPFTP are listed below:

1. Additional hydrodynamic and aerodynamic effort is recommended to verify assumptions and further define off-design operating conditions. Analysis/design iterations should continue until a final detail design layout is complete.

2. Additional rotordynamic effort and analysis is recommended and includes a further reduction in the turbine overhang and the introduction of damping, possibly by foil bearing, at the turbine interstage seal.

3. One of the priority criteria for the selection of the hydrostatic bearing material used in the turbopump is the ability to mount the bearing in the turbopump. Bearing materials such as P5N carbon possess thermal expansion coefficients that are far different from the coefficients of typical housing materials. This difference gives rise to concerns about diametral fits at ambient and cryogenic conditions and developed stresses either at ambient or cryogenic conditions. Compatible material combinations need to be carefully scrutinized.

4. The axial thrust control device shown in the turbopump cross section has yet to be demonstrated. While this seems the best configuration at this time, other candidate designs, such as combined axial and radial hydrostatic bearings, may also prove successful.

5. Isolation of the turbine bearing package from the turbine thermal source could be improved.

6. A final detail design layout will require additional structures and materials, analysis, and design.

6.3.2 High-Pressure Oxidizer Turbopump

The high-pressure oxidizer turbopump (HPOTP) employs a single stage centrifugal impeller preceded by an inducer. The turbine is a partial admission single stage impulse type. Turbopump speed for the expander cycle operation has been calculated at approximately 75,000 rpm. Figures 58 and 59 present the turbopump layouts showing (1) principal dimensions and (2) hardware and materials identification. Tables 12 and 13 list the pertinent parameters for the pump and turbine.

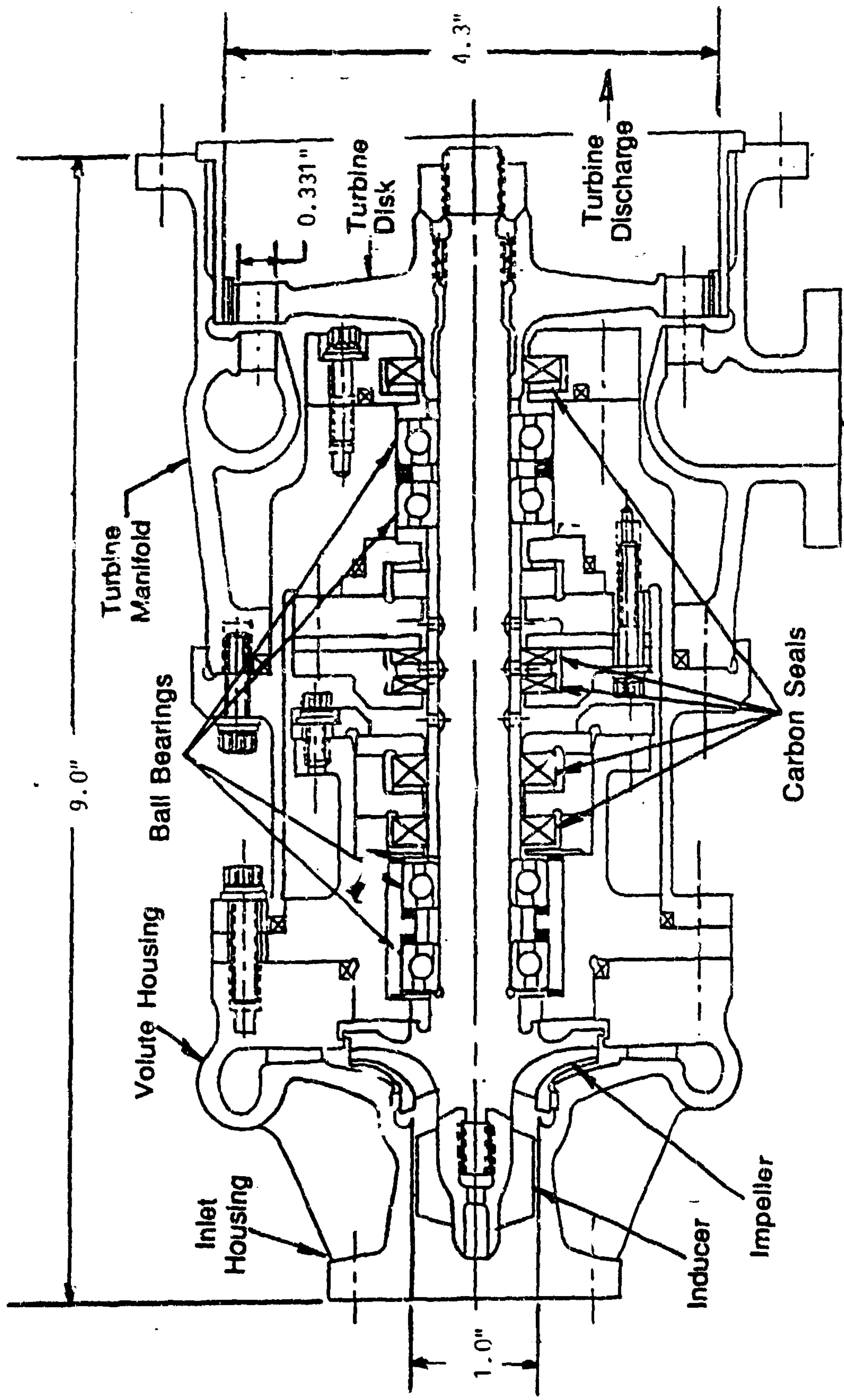


Figure 58. OTVE High-Pressure LO2 Turbopump (HPOTP)

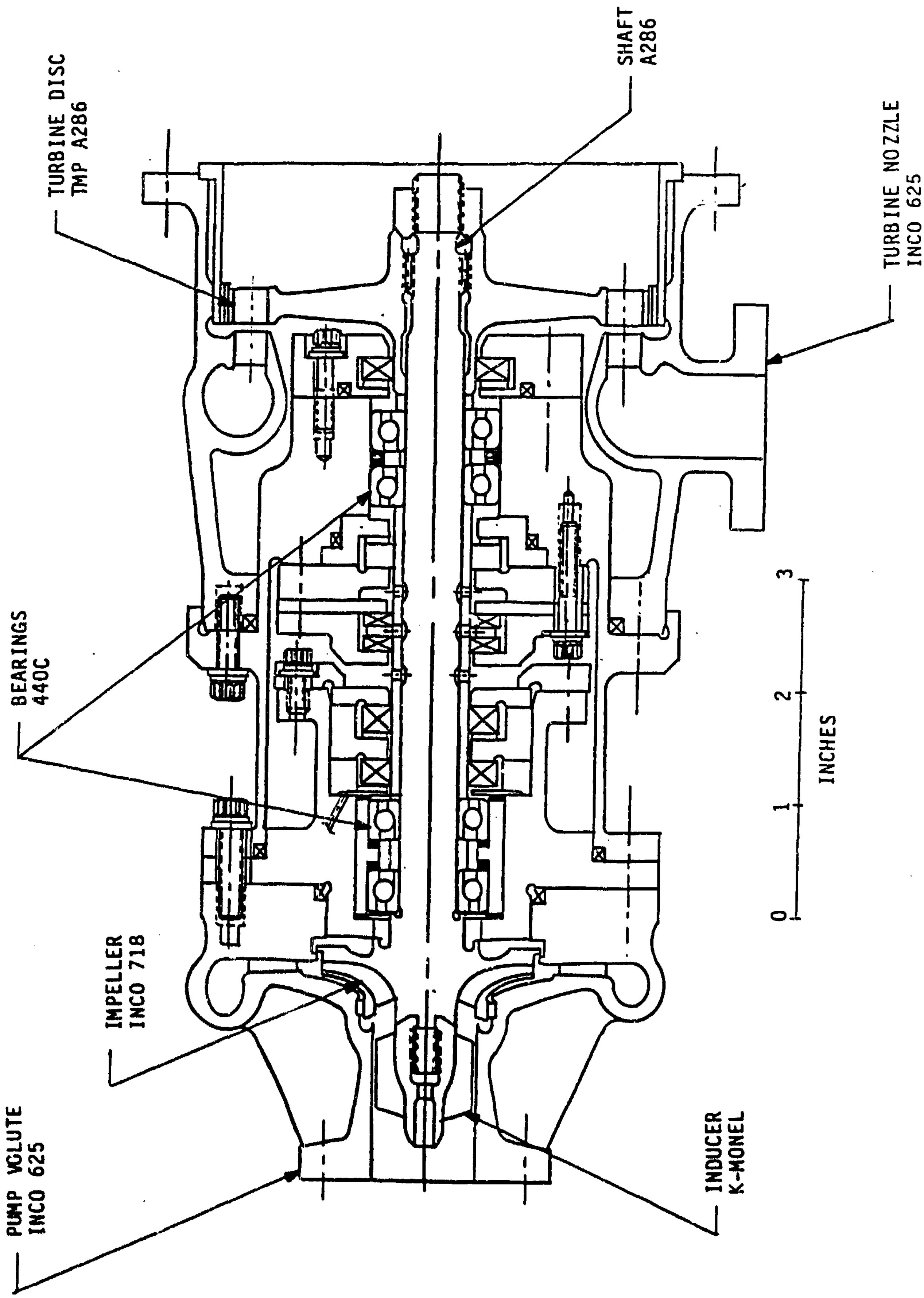


Figure 59. OTVE High-Pressure LO_2 Turbopump Candidate Materials

5472e

Table 12. HPOTP Operating Characteristics

Parameter	Units	Value
Shaft speed	RPM	75,084
Power	hp	254
Bearing DN	10^6 mm-rpm	1.1
Flowrate	lbm/s	13.26
Inlet Temperature	°R	163
Pressure in	psia	71
Outlet temperature	°R	179
Pressure out	psia	3,094
Headrise (total)	ft	6,120
Number of stages		1
Stage-specific speed, Ns		992
Stage Efficiency	%	-
Overall Efficiency	%	58
Inducer		
Blade Number		4
Tip Diameter	in.	1.0
Inlet Hub Diameter	in.	0.28
Discharge Hub Diameter	in.	0.55
Inlet Flow Coefficient		0.143
Hero Coefficient		0.19
Operating Suction Specific Speed		11,500
Impeller		
Blade # (full & partial)		4+4
Eye diameter	in.	1.0
Inlet Hub Diameter	in.	0.55
Tip Diameter	in.	1.88
Tip Width	in.	0.088
Tip Speed	fps	1710

Pump end bearing coolant and balance piston flow passages have been integrated into the volute housing. Liquid oxygen flows from the LOX volute to the turbine side of the pump bearings, through the bearings and into the balance piston cavity for recycling into the pump main stream. The turbine bearing coolant is liquid hydrogen which is supplied from the high pressure fuel turbopump to the port on the turbine housing. Bearing flow proceeds through the bearing, through a controlled gap shaft riding seal and into the turbine cavity. Front and rear bearings are 15 millimeter angular contact duplex sets running at a DN value of approximately 1.1 x 10^6mm-rpm.

Table 13. HPOTP Turbine Parameters

Power, hp	258.
Speed, rpm	75,084
turbine type	1RI
Mean diameter, in.	3.700
Pressure ratio	1.16
Inlet temperature, °R	1044.
Inlet pressure, psia	2355.
Admission, %	45.
Flow, lbm/s	2.096
Blade speed (based on mean diameter), ft/s	1212.
Efficiency T-S (total inlet to static outlet)	0.55
Velocity ratio	0.431
Nozzle/rotating blade height, in.	0.297/0.331
Nozzle/rotating blade width. in.	0.280/0.300
Axial gap between nozzle and rotor, in.	Max. 0.030
Running tip clearance, in.	Max. 0.010
Blade TE thickness, in.	Max. 0.008

6.3.2.1 HPOTP Pump Performance - The high-pressure oxidizer pump is required to operate with a design flow of 13.26 lbm/s and a discharge pressure of at least 3,094 psia. The inlet flow to the pump is provided by the discharge flow from the low-pressure oxidizer pump. Sufficient NPSH is provided that cavitation problems are not expected on the inducer in the high-pressure pump. An inducer is incorporated to prevent cavitation on the impeller.

Pump efficiency is maximized and geometric dimensions of the pump are kept as small as possible to conserve weight. Because of the high head rise and relatively low flow, yielding a specific speed (N_S) of 992, a centrifugal impeller was selected as the pumping element.

6.3.2.2 HPOTP Turbine - The design of this turbine is not limited by pitch line velocity because the LOX pump speed is relatively low. Maximizing the pitch line velocity by increasing the diameter is always beneficial for performance. However, the relative size between the impeller and turbine was also taken into consideration so that both can fit compactly into the same envelope. Given a pump impeller diameter of 2.019 in., it was judged that a 3.7-in. turbine wheel diameter would be a good selection. An impulse turbine was chosen because of a low-velocity ratio and partial admission. Unshrouded blading was also recommended for this design for the same reason as that for the HPFTP turbine. The main turbine parameters are presented in Table 13.

6.3.3 Low-Pressure Fuel Boost Pump

The low-pressure fuel boost pump consists of an axial flow single-stage inducer driven by a partial admission gaseous hydrogen impulse turbine. Figures 60 and 61 present the turbopump layouts showing (1) principal dimensions and (2) hardware and materials identification.

The pump design consists of an inducer, a vaneless diffuser and a volute. The rotor is supported by two 20-mm-diameter ball bearings operating at a DN value of approximately 0.87×10^6 mm-rpm. Bearing coolant is provided by high pressure liquid hydrogen supplied from the high pressure pump. Bearing flow control is maintained by a floating ring controlled gap seal at each bearing location. Coolant flow is introduced into a cavity between the pump and turbine and bearings. Pump end bearing coolant flow is routed into the discharge of the inducer while turbine end bearing coolant flow is directed into the turbine wheel cavity which is downstream of the partial admission turbine nozzle but upstream of the wheel.

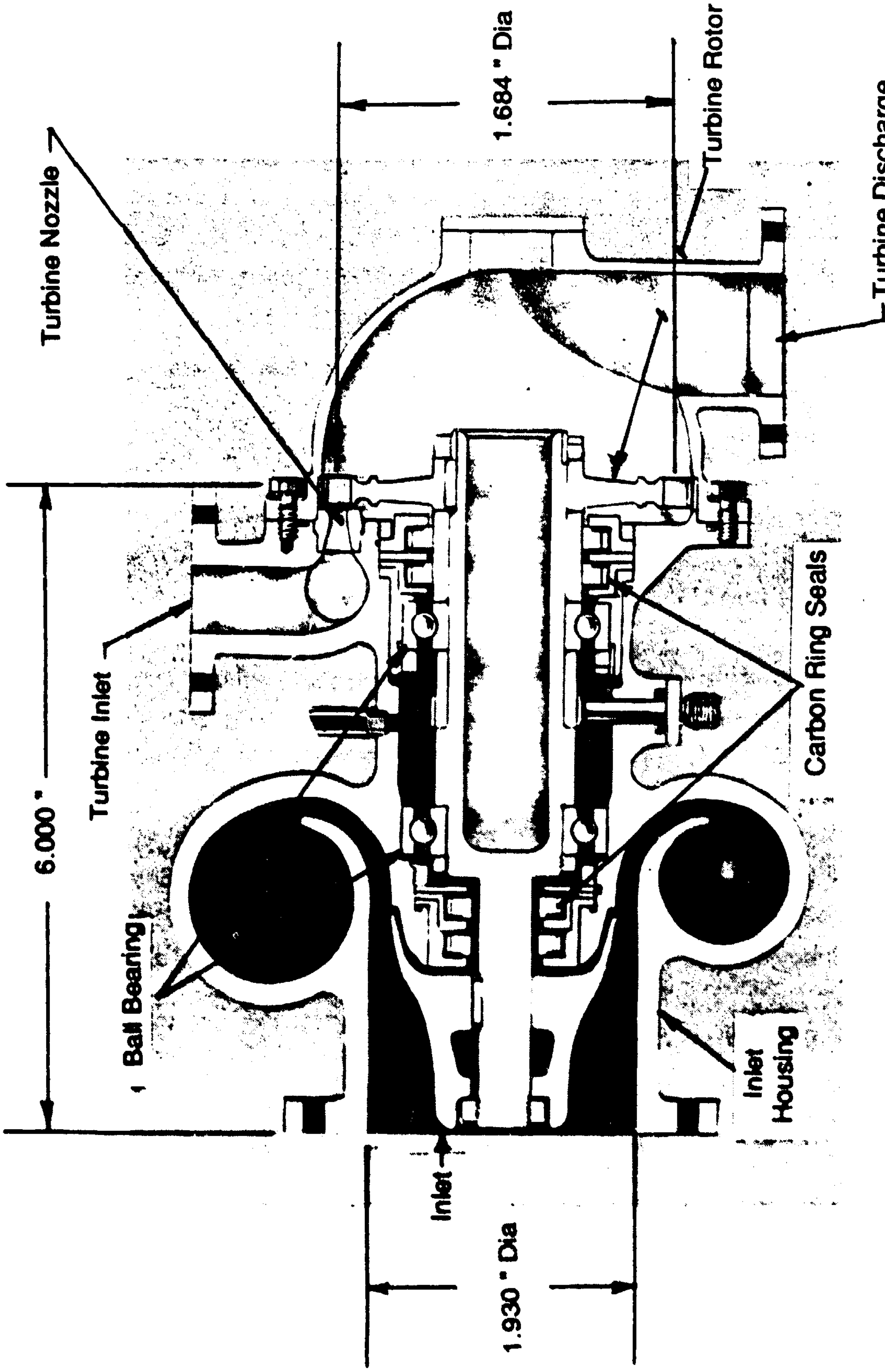


Figure 60. Low Pressure Fuel Pump (7.5Klb)

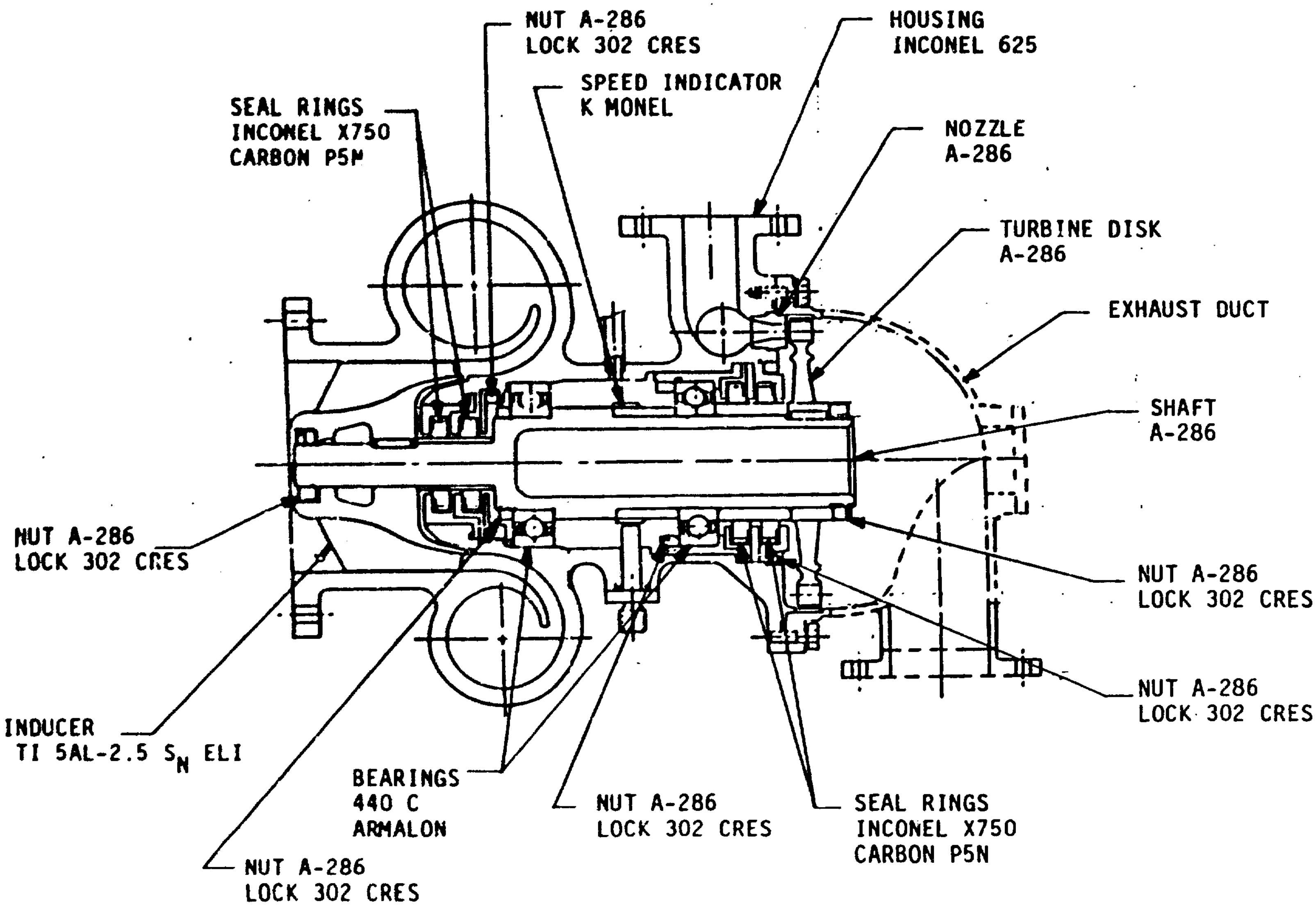


Figure 61. OTVE Low-Pressure Fuel Turbopump Candidate Materials

5472e

6.3.3.1 LPFTP Pump Performance - The low-pressure fuel boost pump is required to operate with a minimum supplied NPSH of 15 feet of liquid hydrogen at a design flow of 2.21 lbm/s. The pressure rise through the pump must be sufficient to insure that there will be no head loss resulting from cavitation on the high pressure fuel pump inducer. On the other hand, it is desirable to keep the boost pump design head coefficient as low as possible to minimize the blade loading. Ideally, the blade loading can be kept low enough that a single-blade row inducer can be used. The blade tip speed, however, should not be allowed to become so large that the design inlet flow coefficient becomes too small. Low inlet flow coefficients result in manufacturing difficulties and inducer friction losses large enough to seriously degrade the boost pump efficiency. The overall pump size should be kept as small as possible.

The selected low-pressure fuel turbopump delivers 74 psia at 40,000 rpm utilizing a single-stage, partial admission 10-hp gaseous hydrogen turbine.

6.3.4 Low-Pressure Oxidizer Boost Pump

The low-pressure oxidizer boost pump consists of an axial flow single-stage inducer driven by a Francis-type radial inflow hydraulic turbine. Turbine drive media is the entire LOX discharge flow from the main oxidizer turbopump. Figures 62 and 63 present the turbopump layouts showing (1) principal dimensions and (2) hardware and materials identification.

The shaft bearings for the boost pump must be selected to carry the maximum expected axial load with sufficient load margin, and to meet the expander cycle life requirement of 20 hr. Bearing coolant (LOX) is directed through the turbine runner tip into the duplex bearings then toward the pump end bearing. A labyrinth seal package just downstream of the pump end bearing lowers the coolant pressure before being directed into the rear shroud of the inducer and then into the boost pump discharge.

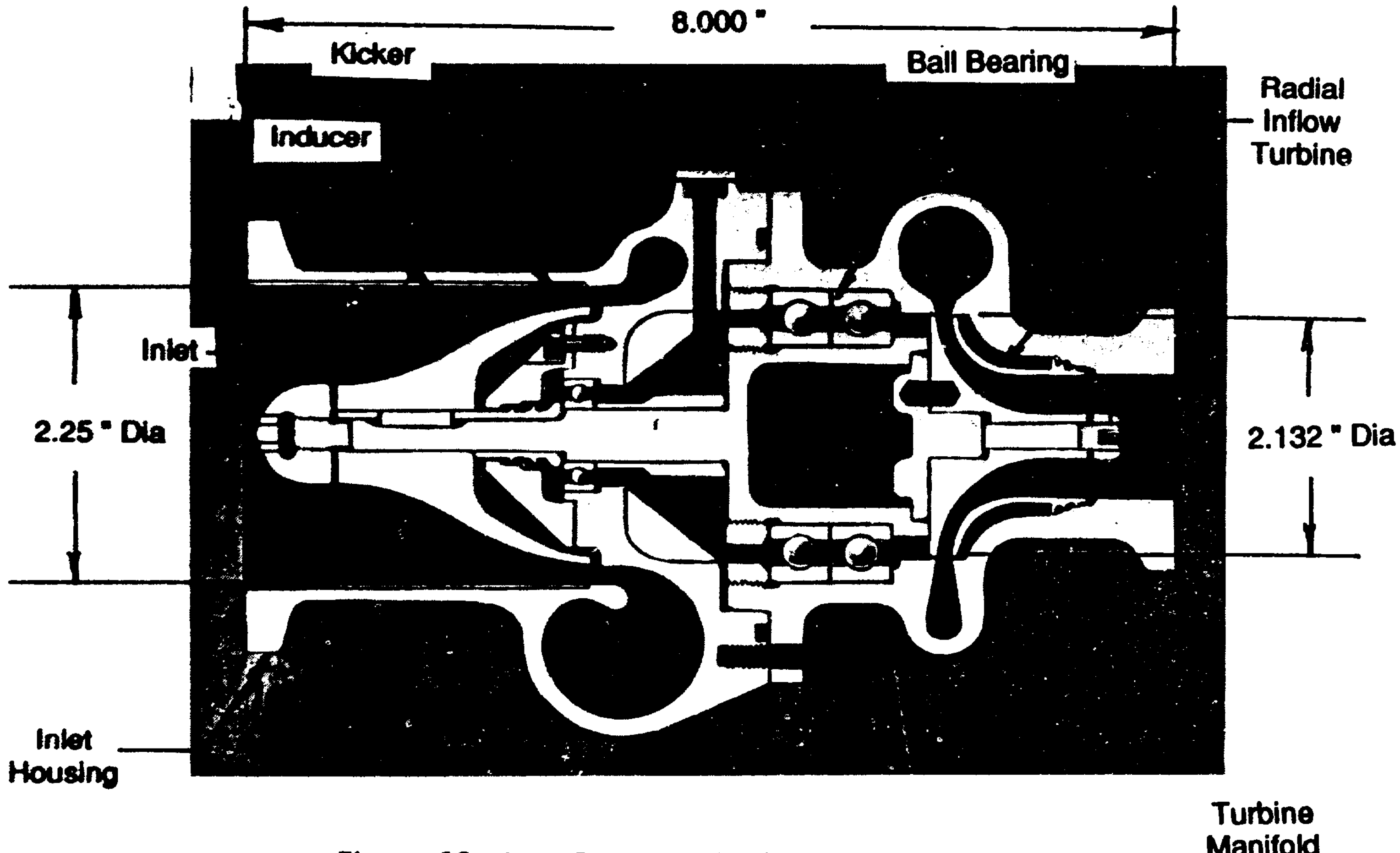


Figure 62. Low-Pressure Oxidizer Pump (7.5Klb)

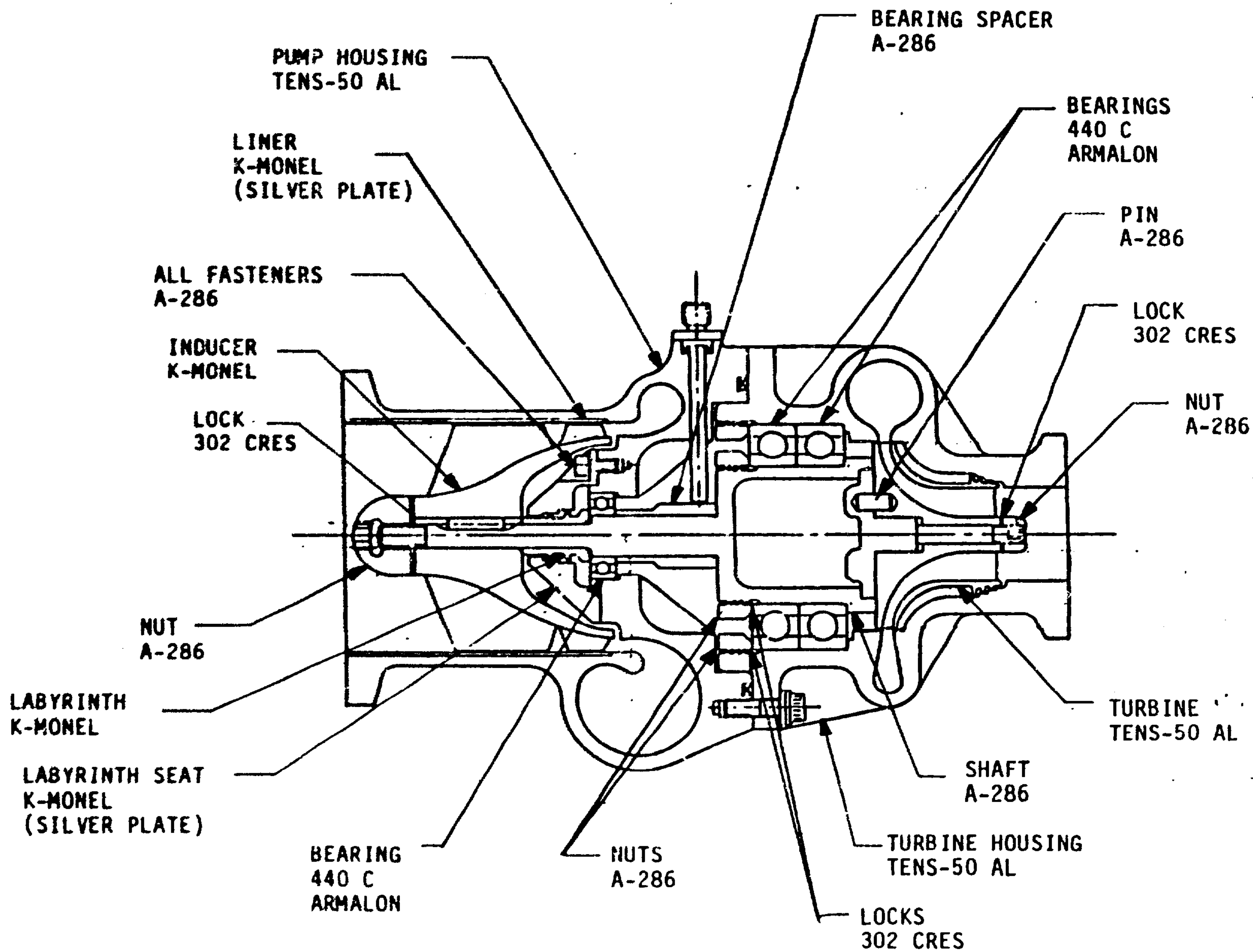


Figure 63. OTVE Low-Pressure Oxidizer Turbopump Candidate Materials

6.3.4.1 LPOTP Pump Performance - The low-pressure oxidizer boost pump is required to operate with a minimum supplied NPSH of 2 ft of liquid oxygen at a design flow of 13.26 lbm/s. The low-pressure oxidizer turbopump delivers 86 psia at 10,000 rpm utilizing a Francis-type radial inflow 5-hp turbine.

6.3.5 Valve Analysis

The engine system incorporates five valves. They are the main oxidizer valve (MOV), the fuel turbine bypass valve (FTBV), the oxidizer turbine bypass valve (OTBV), the main fuel valve (MFV), and the turbine shutoff valve (TSO). Figure 64 shows these valves on the engine schematic and Table 14 lists the engine control valve functions. The MFV and the TSO valves are on/off valves. The MOV, FTBV, and the OTBV are modulating valves used to control the engine.

A major output of the Off-Design Code (reference Systems Analysis) is valve resistance response to off-design engine operation. The code enables one or more general iteration loops to converge main valve resistances to a desired value by changing the resistance of a bypass valve, engine mixture ratio, thrust, or some combination of these or other system variables. Tables 15 through 18 present MFV, MOV, FTBV, and OTBV operating resistance calculations for on- and off-design engine conditions. The TSO resistance calculations are not shown, since it is an on/off valve with suitable capacity for all conditions.

A summary of valve resistance range for on-design and for the off-design conditions is presented in Table 19. The resistance ratio is defined as the valve resistance at a given operating condition divided by the resistance of that valve at on-design operating condition. The resistance range is the maximum resistance divided by the minimum resistance. The acceptable range for reasonable control is 100 or less. As can be seen from Table 19, the fuel turbine bypass valve resistance range greatly exceeds 100. The reason is that at the 10% thrust level, a very low resistance is required for the FTBV to allow bypass of most of the drive gas around the turbines. At full thrust, and the

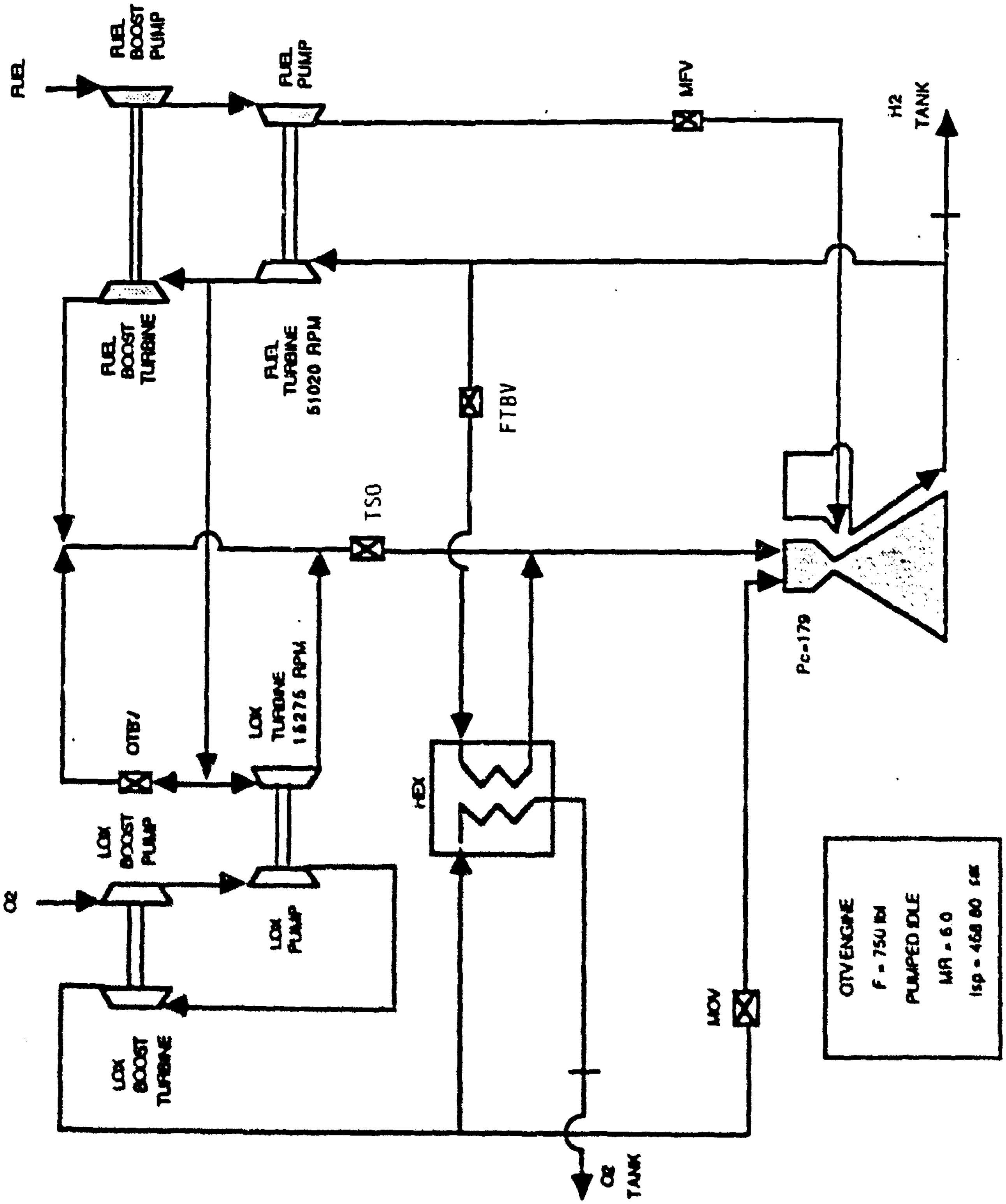


Figure 64. Control Valve Locations

Table 14. 7.5Klb Engine Control Valves

Valve	Control Function
Main oxidizer (MOV)	Shutoff, mixture
Main fuel (MFV)	Shutoff
Turbine shutoff (TSO)	Tank head idle shutoff
Turbine bypass (FTBV)	Throttling
Ox, turbine bypass (OTBV)	Mixture ratio

Table 15. Off-Design Valve Summary

MFV - H_2						
Thrust F (lb_f)	Mixture Ratio MR (none)	Flowrate $\dot{M}$ (lb/sec)	Pressure Drop ΔP (psid)	Resistance $\frac{lbf\ sec^2}{lbm\ ft^3\ in^2}$	$\frac{R_{Off\ Design}}{R_{On\ Design}}$	Chamber Pressure P_c (psia)
7500 On Design	6	2.182	25	2.373E01	1.00	1740
7500	5	2.575	33	2.381E01	1.0036	1800
7500	7	1.950	19	2.380E01	1.0032	1695
750 (Pumped Idle)	4	0.314	0.54	2.380E01	0.9968	189
750 (Pumped Idle)	5	0.264	0.39	2.382E01	1.0038	184
750 (Pumped Idle)	6	0.231	0.30	2.365E01	0.9968	179
750 (Pumped Idle)	7	0.208	0.24	2.381E01	1.0037	177

Table 16. Off-Design Valve Summary

MOV - O_2						
Thrust F (lb_f)	Mixture Ratio MR (none)	Flowrate $\dot{M}$ (lb/sec)	Pressure Drop ΔP (psid)	Resistance $\frac{lbf\ sec^2}{lbm\ ft^3\ in^2}$	$\frac{R_{Off\ Design}}{R_{On\ Design}}$	Chamber Pressure P_c (psia)
7500 On Design	6	13.106	426	1.760E02	1.00	1740
7500	5	12.756	255	1.116E02	0.634	1800
7500	7	13.546	288	1.117E02	0.6345	1695
750 (Pumped Idle)	4	1.245	36	1.670E03	1.8974	189
750 (Pumped Idle)	5	1.309	19	8.049E02	0.9146	184
750 (Pumped Idle)	6	1.371	10	3.874E02	0.4402	179
750 (Pumped Idle)	7	1.445	0.71	2.404E01	0.0273	177

5.0 mixture ratio, a relatively high resistance is required in the same valve. The remaining valve resistance ranges were acceptable.

The fuel turbine bypass valve design was evaluated to eliminate the resistance ratio problem. Two possible solutions were developed, a parallel valve and a sector valve concept The parallel valve concept is shown in Figure 65. Two valves operating in parallel will reduce the resistance range to acceptable values at both low- and high-thrust engine operation. The sector valve concept (reference Figure 66) also shows promise for solving the problem. The sector valve incorporates a variable cross sectional area which increases control in

Table 17. Off-Design Valve Summary

FTBV - H_2						
Thrust F (lb_f)	Mixture Ratio MR (none)	Flowrate $\dot{M}$ (lb/sec)	Pressure Drop ΔP (psid)	Resistance $\frac{lbf\ sec^2}{lbm\ ft^3\ in^2}$	$\frac{R_{Off\ Design}}{R_{On\ Design}}$	Chamber Pressure P_c (psia)
7500 On Design	6	0.236	2082	0.17[illegible]E05	1.00	1740
7500	5	0.152	25[illegible]8	0.604E05	3.49	1800
7500	7	0.280	1784	0.934E04	0.54	1695
750 (Pumped Idle)	4	0.181	96	0.133E03	0.00769	189
750 (Pumped Idle)	5	0.153	82	0.134E03	0.00775	184
750 (Pumped Idle)	6	0.134	73	0.137 03	0.00792	179
750 (Pumped Idle)	7	0.120	67	0.144E03	0.00832	177

the deep throttling mode while maintaining control at full-thrust operation. The result is valve resistance tailored to the operating regime of the engine. The sector valve has the added advantage that only one valve is needed for control. Additional analysis will be required to validate utilizing the sector valve or the parallel valve concept for the fuel turbine bypass valve design.

An advanced electric actuated valve has been designed and fabricated for the OTV engine application. Figure 67 shows a cross section of the valve. This prototype valve was designed for liquid oxygen application. The valve features are listed in Table 20. Defined electric valve issues and solution options are presented in Table 21.

Table 18. Off-Design Valve Summary

OTBV - O_2						
Thrust F (lb_f)	Mixture Ratio MR (none)	Flowrate $\dot{M}$ (lb/sec)	Pressure Drop ΔP (psid)	Resistance $\frac{lbf\ sec^2}{lbm\ ft^3\ in^2}$	$\frac{R_{Off\ Design}}{R_{On\ Design}}$	Chamber Pressure P_c (psia)
7500 On Design	6	0.221	325	2.488E03	1.00	1740
7500	5	0.535	323	0.484E03	0.195	1800
7500	7	0.052	318	0.394E05	15.84	1695
750 (Pumped Idle)	4	0.026	12	0.687E03	0.276	189
750 (Pumped Idle)	5	0.018	11	0.111E04	0.446	184
750 (Pumped Idle)	6	0.012	10	0.195E04	0.784	179
750 (Pumped Idle)	7	0.009	10	0.336E04	1.350	177

6.3.6 ICHM Analysis

The control system for the baseline engine provides for elements of sensing and monitoring engine performance, the electronic controller (one of whose functions is to generate electronic commands to modulate and sequence the valves), the final control elements (valves) to execute those commands, the ignition system, and the electrical harness to interconnect the engine control system. The three primary modes of operation for the engine are the tank head idle, pumped idle, and mainstage. In addition to the control of the engine and its operating modes during start, mainstage and shutdown, other major

Table 19. Control Valve Requirements

Thrust (Klbf)	O/F	Resistance Ratio = R/R_{des}			
		MOV	MFV	OTBV	FTBV
7.5	6.0	1.00	1.00	1.00	1.00
7.5	5.0	0.63	1.00	0.20	3.49
7.5	7.0	0.63	1.00	1.58	0.54
.75	4.0	1.90	1.00	0.28	0.0077
.75	5.0	0.91	1.00	0.45	0.0078
.75	6.0	0.44	1.00	0.78	0.0079
.75	7.0	0.027	1.00	1.35	0.0083
Maximum Resistance Ratio $\frac{R_{max}}{R_{min}}$;		69	1.00	81	454*

*Exceeds Allowable Maximum of 100

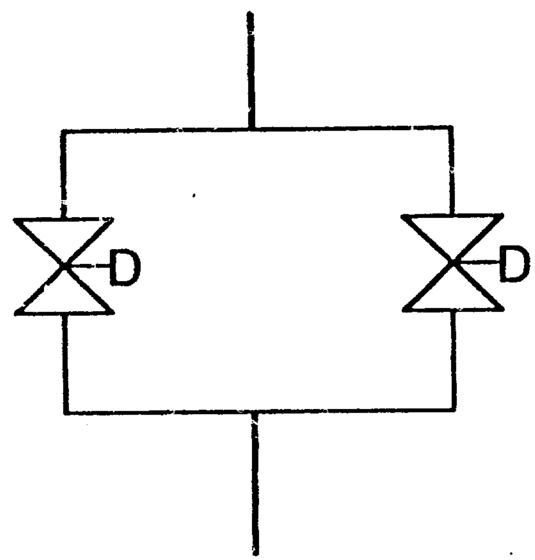
functions include checkout and status monitoring, input/output data processing, and protection of the engine to enhance man-rated capability. The control system concepts have been covered in Task D.1/D.3, Advanced Engine Study (Reference 1). Additional work in this area was not completed under Task D.5.

Health monitoring plays a key role in achieving space-based maintainability. Advanced monitoring techniques such as spectroscopic analysis of exhaust plume, eddy current and EMAT combustor wall thickness measurement, isotope bearing wear detection, fiberoptic deflectometer for turbopump shaft speed, shaft radial displacement, and shaft axial displacement, will enable maintenance on an efficient as-need basis through accurate assessment of the engine health. Activity in the above health monitoring areas have been completed under OTV Rocketdyne Engine Technology Tasks E.5 through E.8. These health monitoring task results are covered in separate task reports.

PROBLEM: THROTTLED OPERATION REQUIRES EXCESSIVE RANGE IN FTBV RESISTANCE (R_{MAX}/R_{MIN} = 454 >> ALLOWABLE = 100)

POSSIBLE SOLUTION: TWO VALVES OPERATING IN PARALLEL REDUCED RESISTANCE RANGE TO ACCEPTABLE VALVES (R_{MAX}/R_{MIN} = 21.3 << 100)

LOW
RESISTANCE RANGE
$0.00769 \le R_1 \le 0.164$
$\left(\frac{lb_f\ sec^2}{lb_m\ ft^3\ in^2}\right)$
LOW
THRUST OPERATION



HIGH
RESISTANCE RANGE
$0.164 \le R_2 \le 3.49$
HIGH
THRUST OPERATION

Figure 65. OTV 7.5 Klb Fuel Turbine Bypass Valve (FTBV)

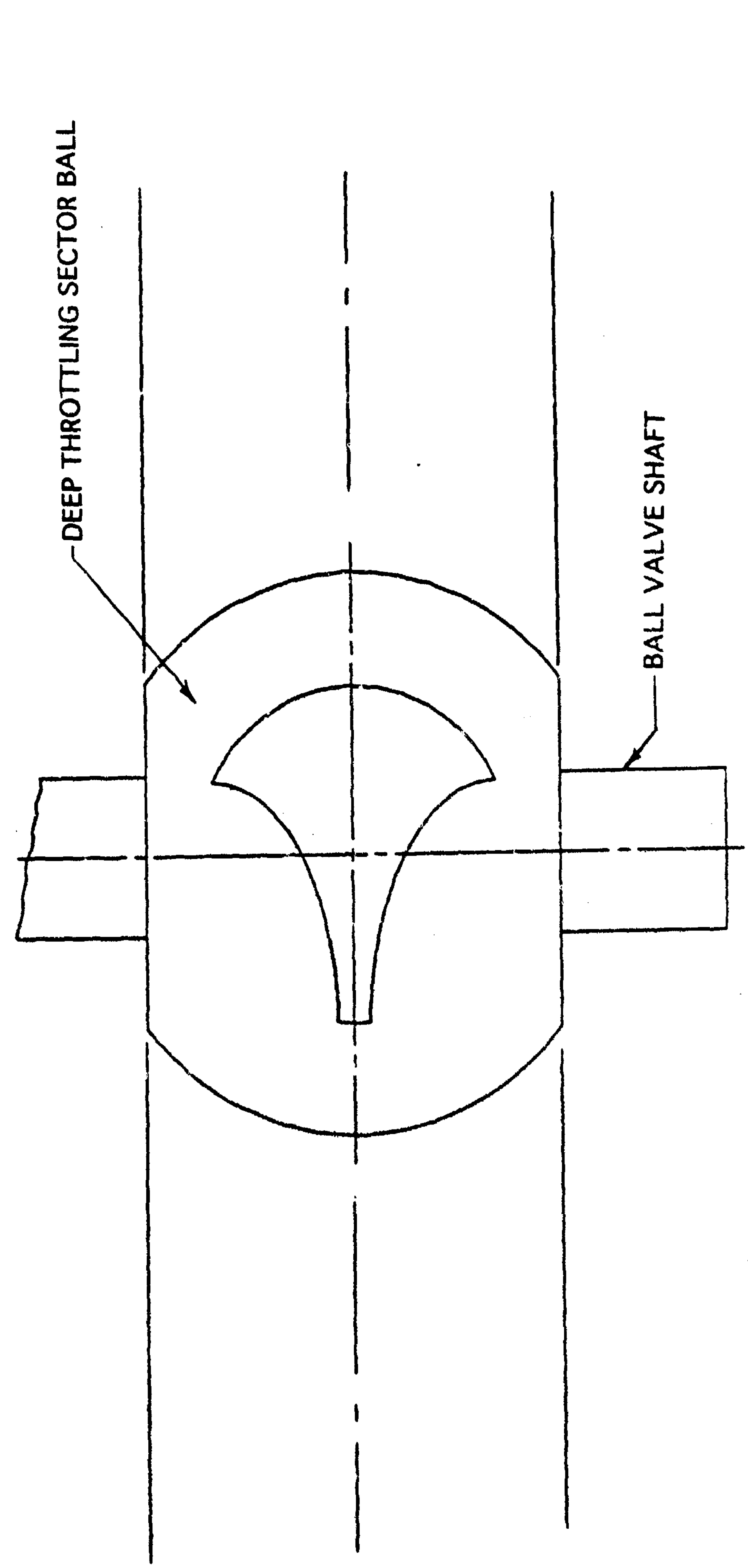


Figure 66. OTV FTBV Deep Throttling Sector Concept

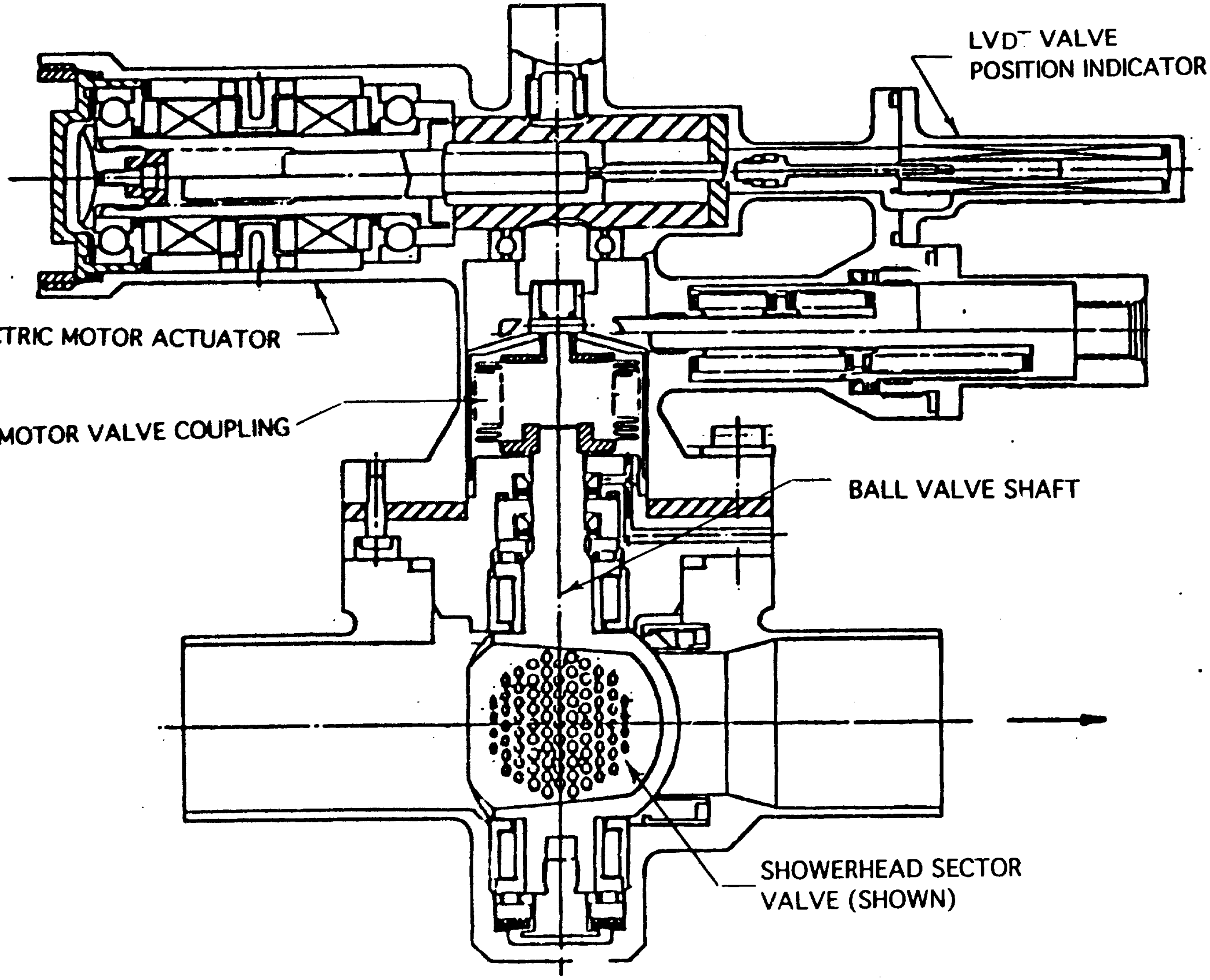


Figure 67. Advanced Electric Actuated Valve -- for FTBV

Table 20. Advanced Electric Actuated Valve

- Type - deep throttling, light weight, quiet flow, sector ball valve with line replaceable elements
- Line size - 1-1/4 in. ID
- Pressure - 2800 psig
- Flow - 0.3 to 28 lb/sec
- Pressure drop - 580 psi max
- Internal leakage - 100 scim He max
- Actuator - dual rare-earth electric motors with ball screw/ lever/link
- Control - modulating at 100%/s with 0.1 deg precision
- Weight - 6.0 pounds

Table 21. OTV Valves Issues

Issues	Options
Control System Redundancy	Fail lock in position
	Dual electric motors/controls (fail operable)
	Pneumatic override (fail safe)
	Dual feedback optical encoder
Thermal Conditioning	Heated actuator
	Cryogenic actuator
Turbine Bypass Valve Deep Throttling	Ball with deep throttle flow section Two valves in parallel
Smart Control	Built-in electric motor controller

6.4 Technology Level

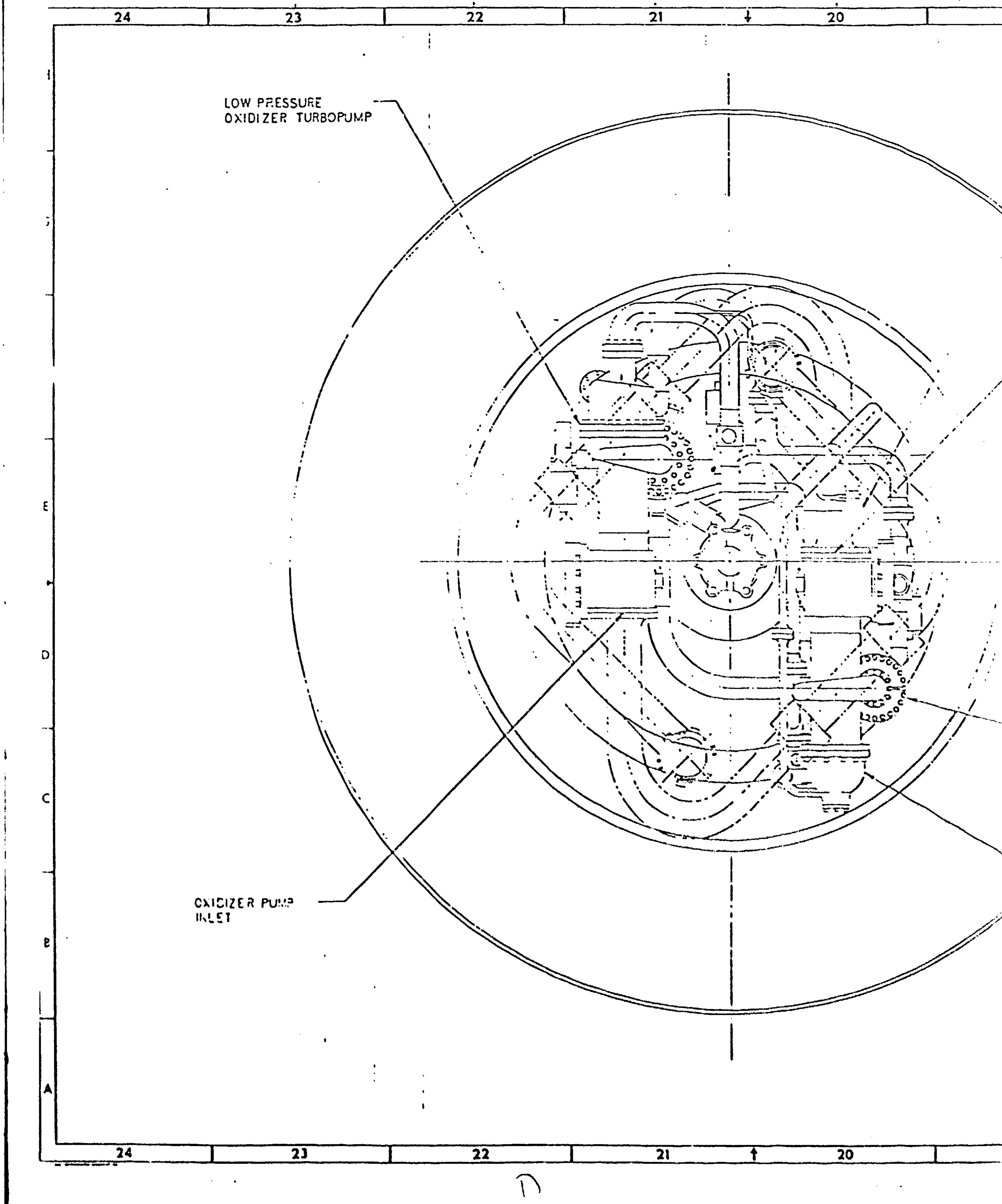
Advanced technology ground rules are assumed for the thrust chamber (rib and fin heat transfer), several turbopump components, electric valves, and integrated control and health monitoring. The turbopump advanced technologies include two-stage, partial admission turbines, hydrostatic bearings, and soft-wear ring seals. Demonstration tasks are ongoing, reference Table 1, or have been completed to validate many of these advanced technology ground rules assumptions. Areas where the 7.5Klb thrust engine technology levels can be enhanced are: deep throttling valves, advanced sensors, selected CFD analysis on heat transfer enhancements, long-life combustor technology, turbopump shaft axial thrust control, plasma-sprayed turbine tip shroud development, and quantifying hydrostatic bearing stiffness and damping coefficients,.

6.5 Engine Layout

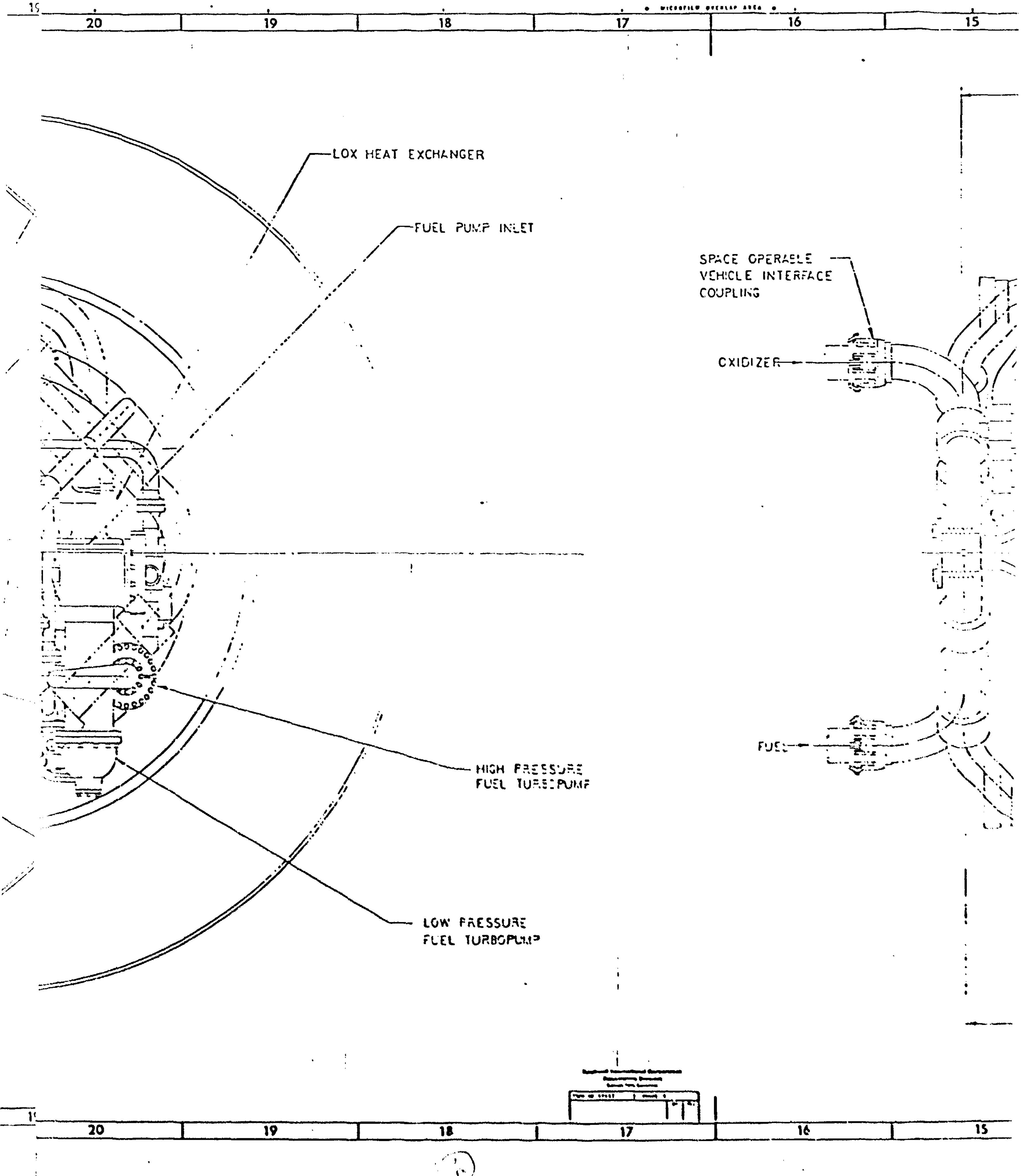
The engine arrangement layout, Figure 68, shows the location of major components and the general ducting configuration. The turbopump ducting and valve arrangement are similar to those developed in the Task D.4 Advanced Engine Study (Reference 2). The uncooled nozzle extension is shown in both the retracted and extended positions. Engine length with the nozzle retracted and extended is 60 in. and 117 in., respectively. The maximum engine diameter, at the nozzle exit, is approximately 53 in. Table 22 presents a tabulation of engine weights. The engine weights are similar to those presented in Reference 1 except for updating the nozzle extension weight calculations.

6.6 Component Layouts

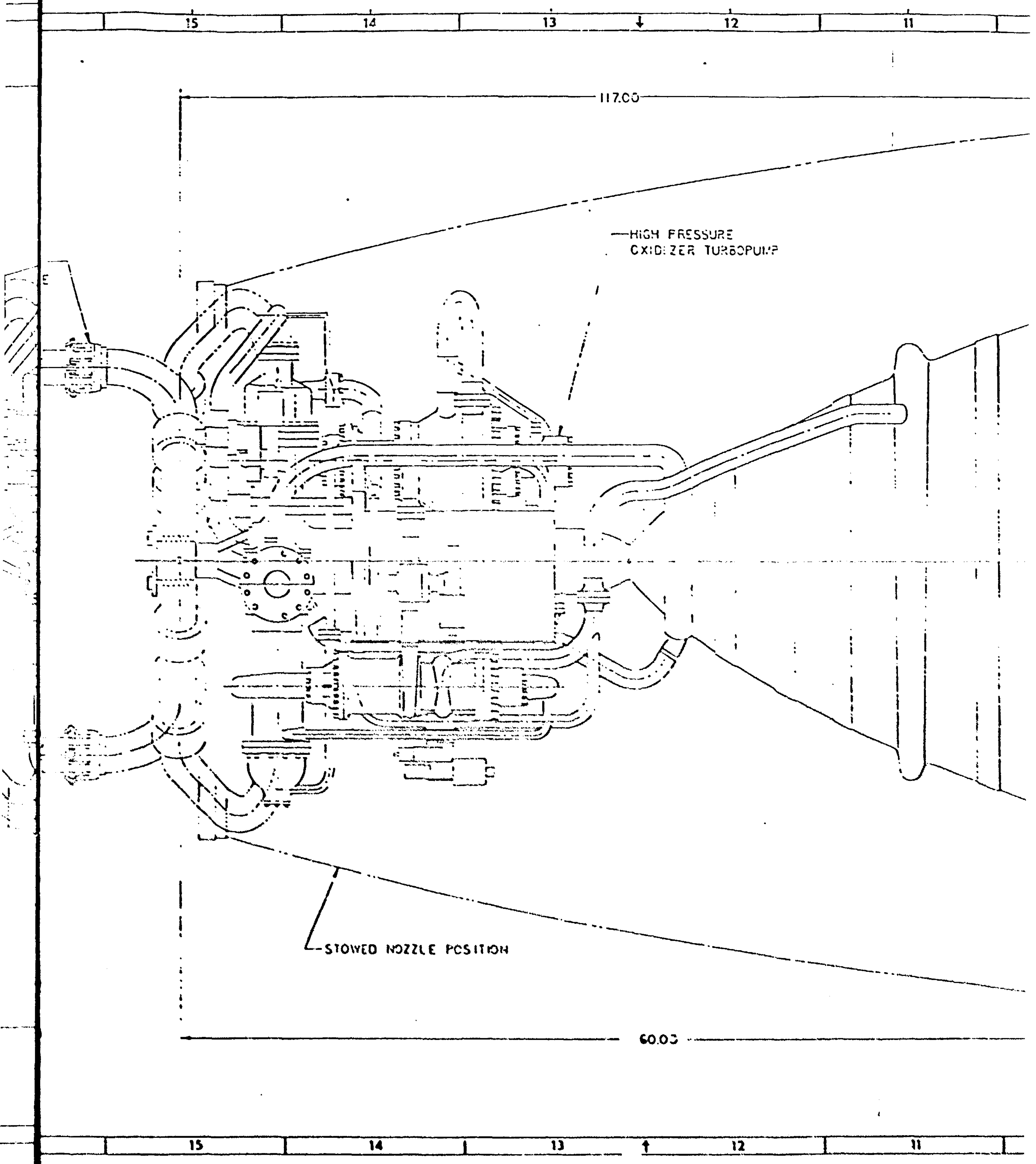
The 7,500-lb thrust engine preliminary component design layout drawings include an injector/igniter assembly drawing, Figure 69, a nozzle/combustion chamber drawing, Figure 70(a and b), and a thrust chamber nozzle coolant channel configuration layout drawing, Figure 71, and an uncooled nozzle extension, Figure 72.



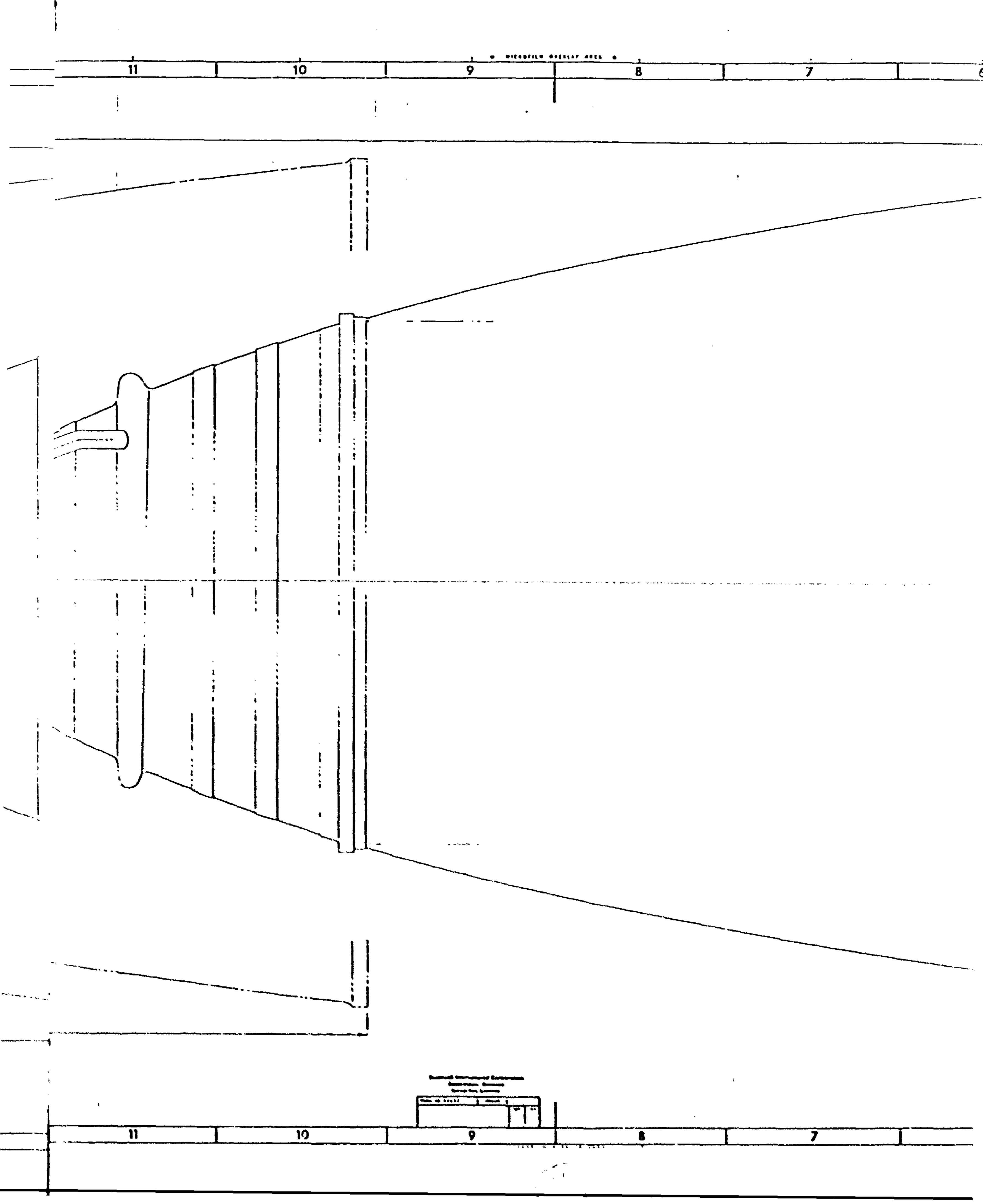
LOW PRESSURE OXIDIZER TURBOPUMP
OXIDIZER PUMP INLET



20
19
18
17
16
15
LOX HEAT EXCHANGER
FUEL PUMP INLET
SPACE OPERABLE
VEHICLE INTERFACE
COUPLING
OXIDIZER
FUEL
HIGH PRESSURE
FUEL TURBOPUMP
LOW PRESSURE
FUEL TURBOPUMP



15
14
13
12
11
117.00
HIGH PRESSURE
OXIDIZER TURBOPUMP
STOWED NOZZLE POSITION
60.00


11
10
9
8
7
11
10
9
8
7

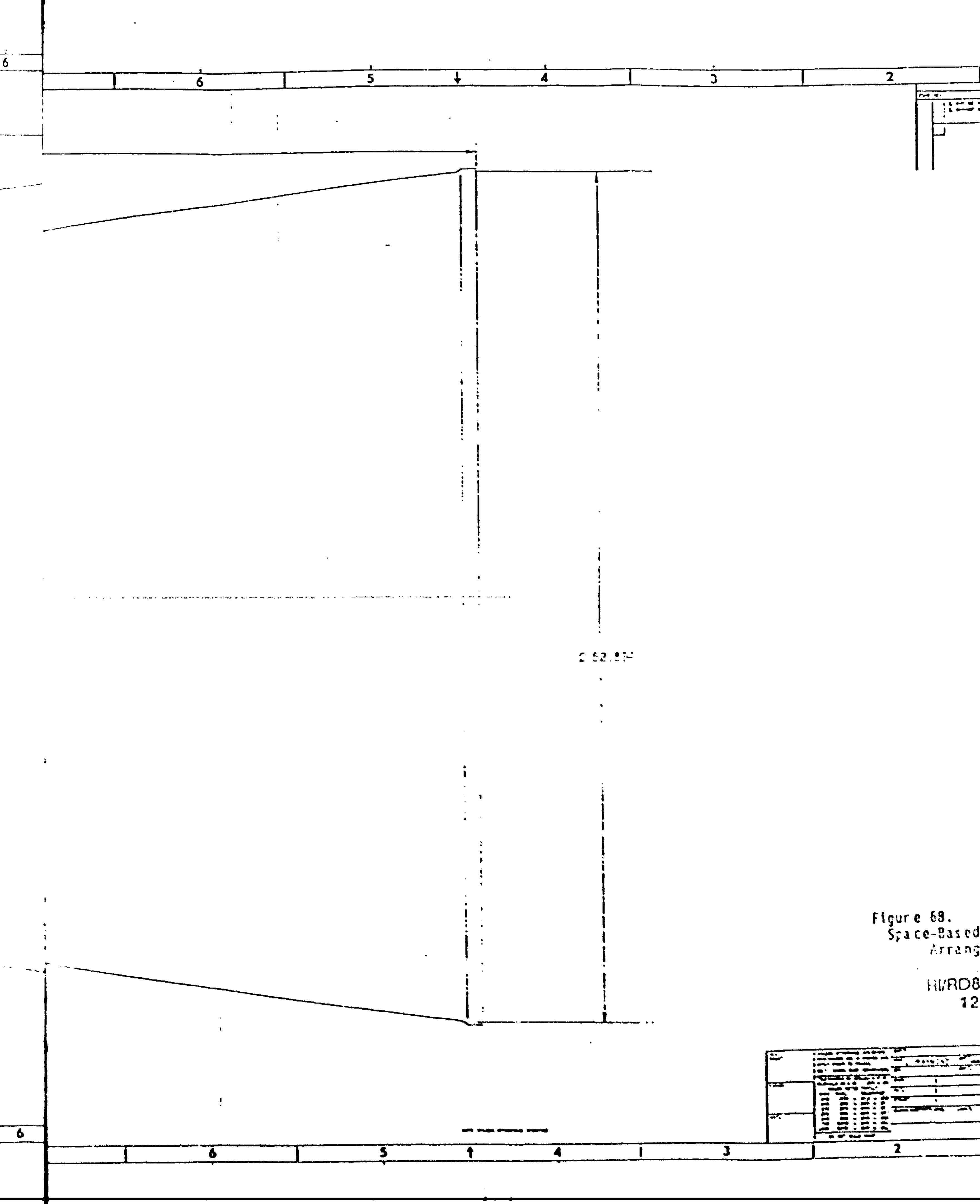
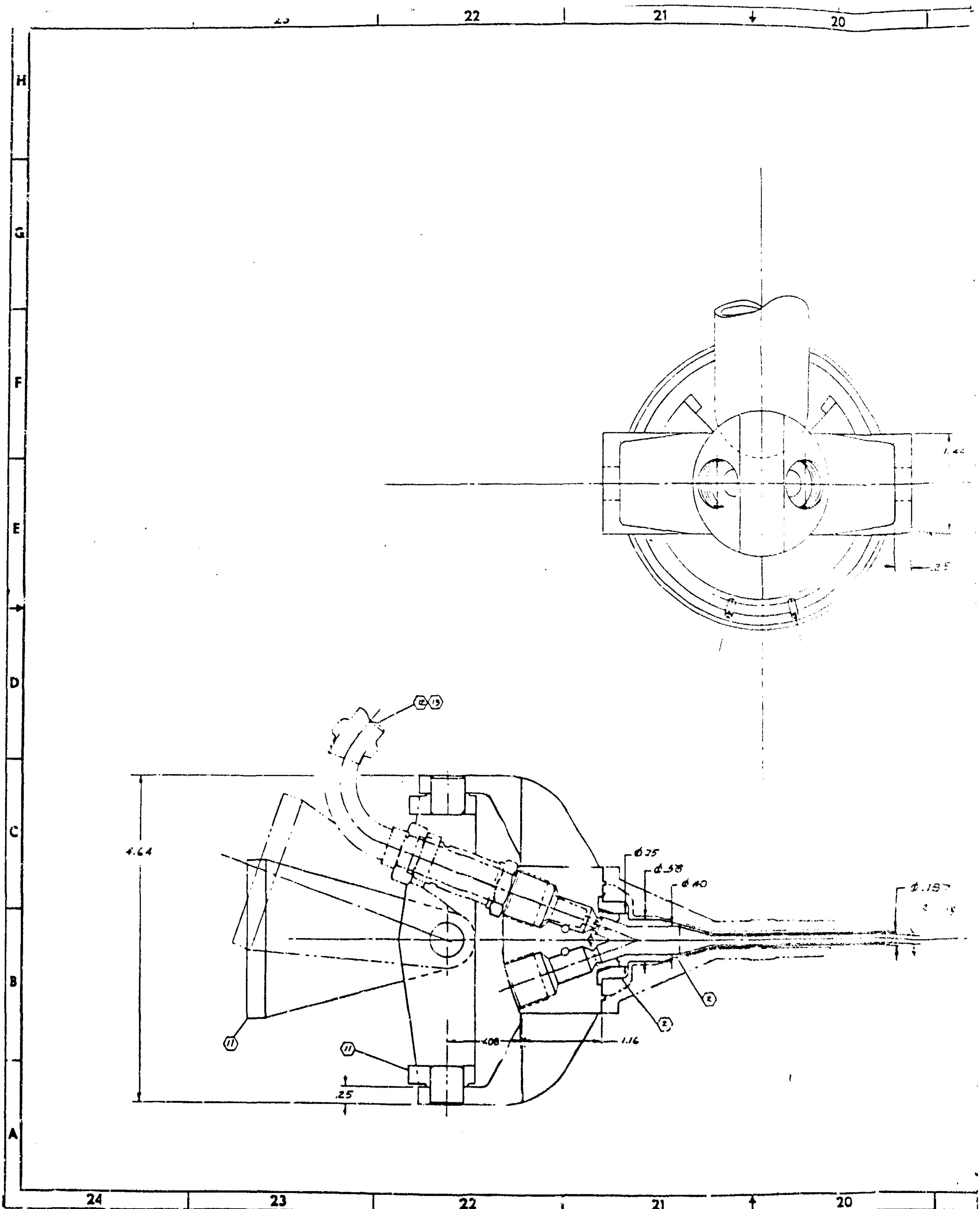


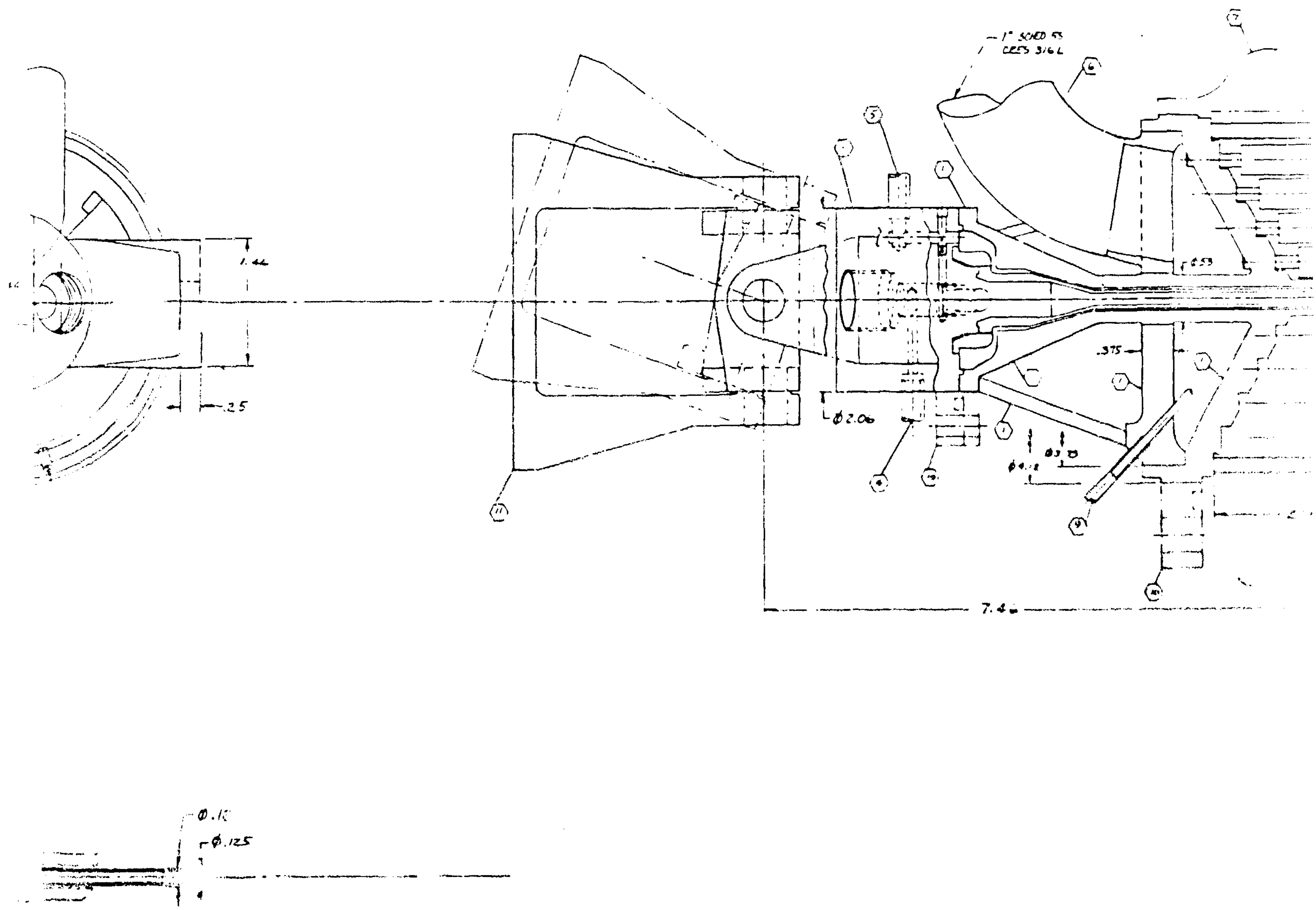
Figure 68.
Space-Based
Arrang

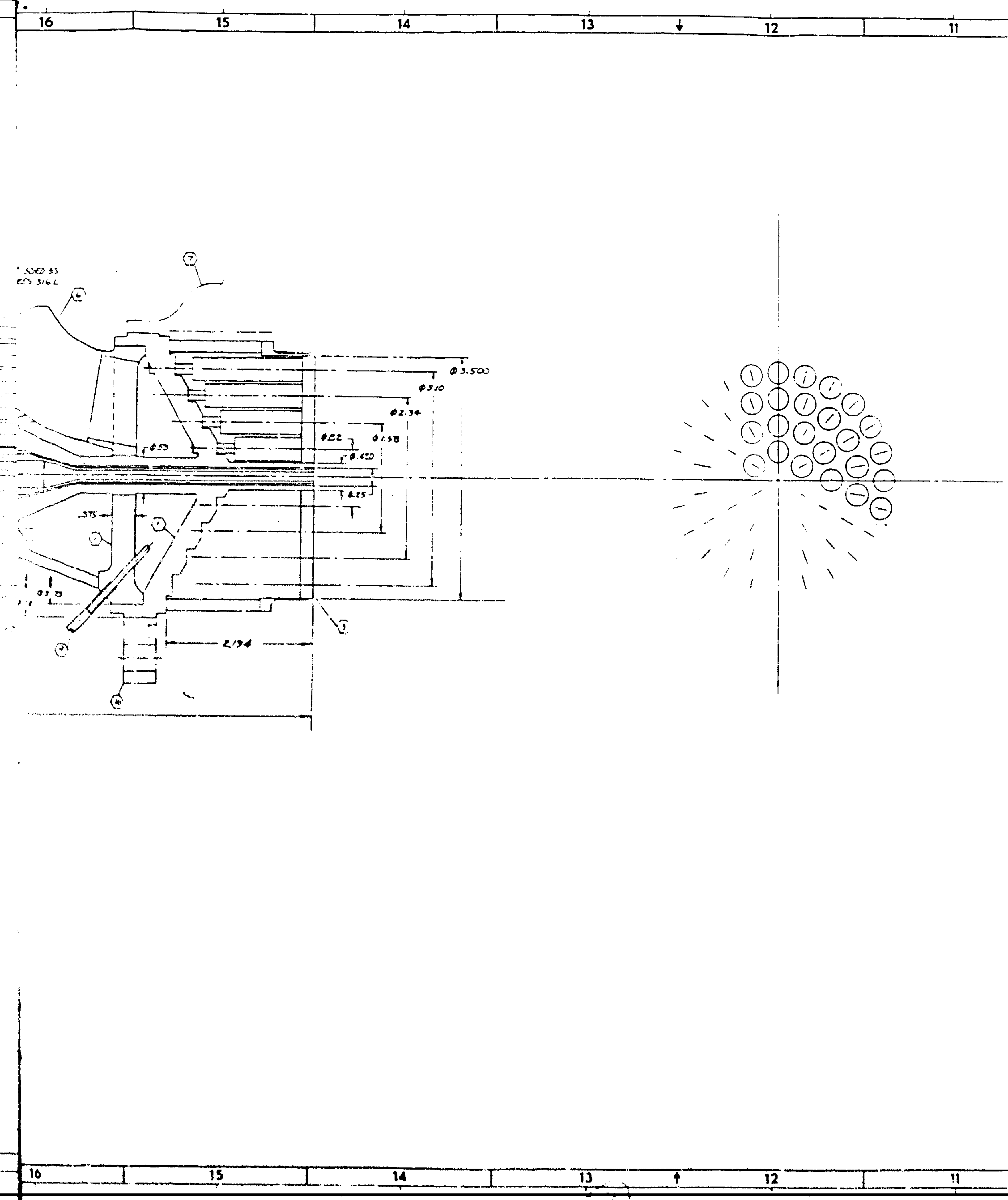
RI/RD8
12

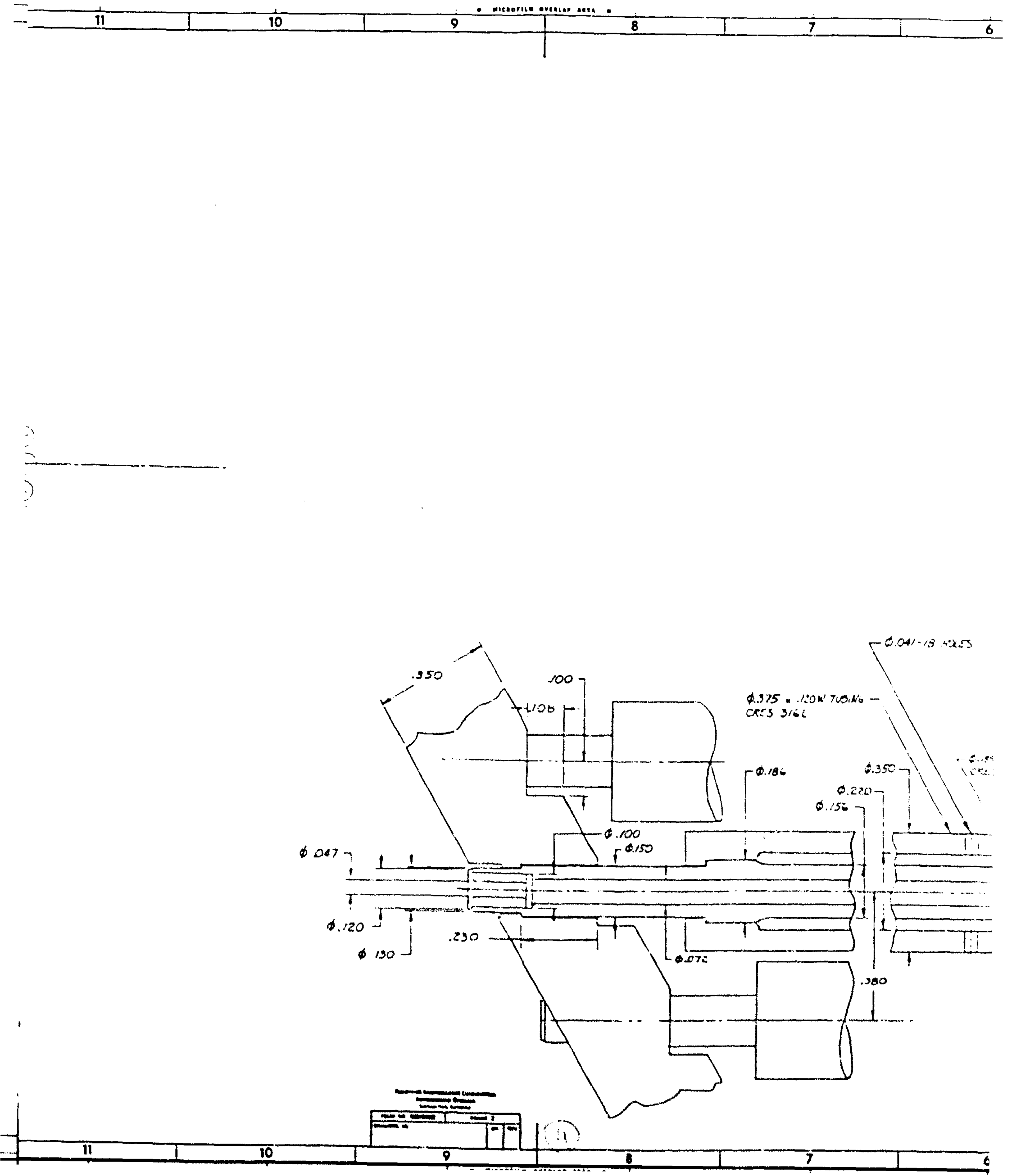
Figure 68. 7.5KlbAdvanced Space-Based OTV Engine Arrangement



4.64
.25
.408
1.16
ϕ.75
ϕ.58
ϕ.40


1" SCHED 5S
CRES 316L
1.44
.25
ø2.06
.375
7.4
ø.125


16
15
14
13
12
11
Ø 3.500
Ø 3.10
Ø 2.34
Ø 1.58
Ø .82
Ø .420
Ø .59
.25
.375
2.194
ESS 316 L


MICROFILM OVERLAP AREA
11
10
9
8
7
6
.350
.100
.106
Ø.375 × .120W TUBING
CRES 316L
Ø.041 - 18 HOLES
Ø.186
Ø.350
Ø.220
Ø.156
Ø.100
Ø.150
Ø.047
Ø.120
Ø.130
.230
Ø.072
.380

REVISION

1. MATERIAL : INCONEL 625
2. MATERIAL : NICKEL 200
3. MATERIAL : RIGIMESH
4. LOX IGNITION INLET
5. FUEL IGNITION INLET
6. LOX MAIN INLET
7. FUEL MAIN (PART OF THRUST
8. MACHINE PER RA0103-036 — EDM
9. MAIN LOX TEMP/ PRESSURE
10. GROUND TEST (REMOVABLE)
11. GFE (GOVERNMENT FURNI
12. SPARK PLUG CABLE (WARD AL
13. 707-SR SPARK PLUG (BG A

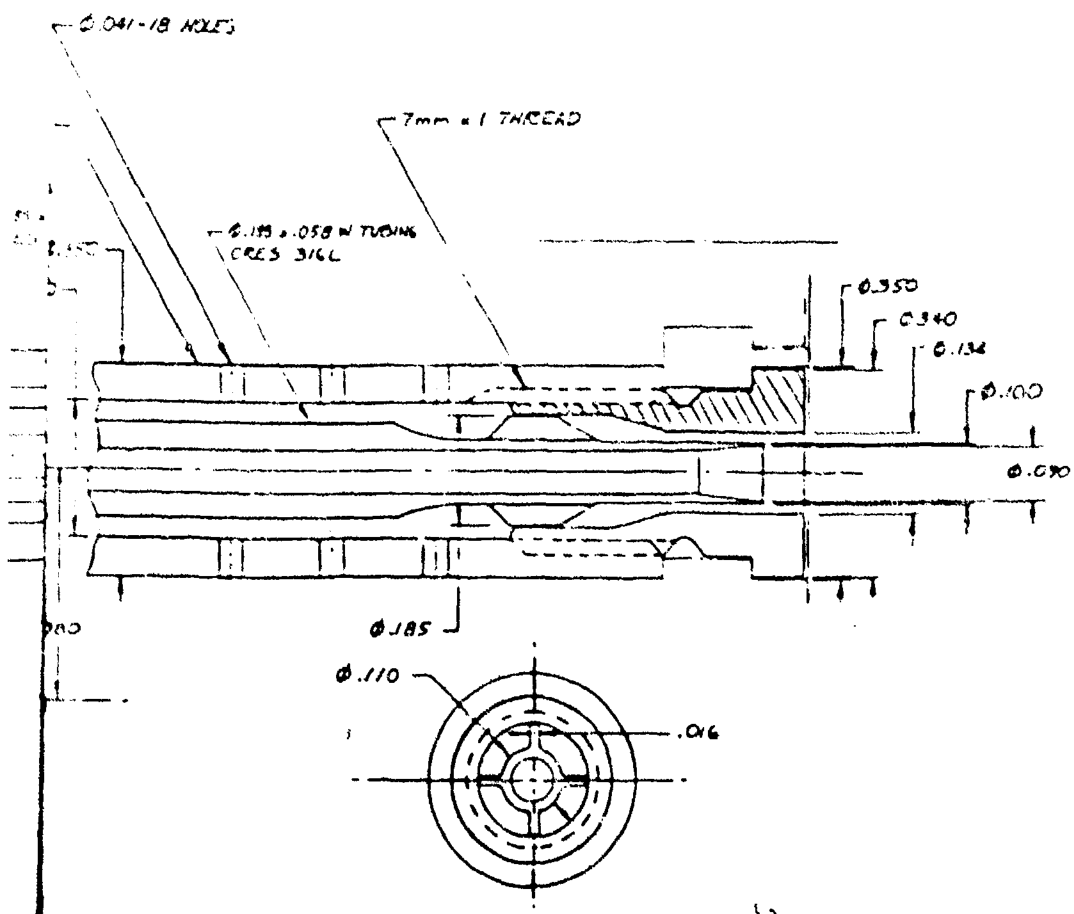


Figure 69. Injecto
Assembly Draw

INJECT
7.5 Klb

1

H

ST

) PL

T CHAMBER)

PERMISSIBLE

) FLANGE

ISHED EQUIPMENT

ED OR EQ)

AIRCRAFT OR EQ)

G

F

E

D

C

tor

awi

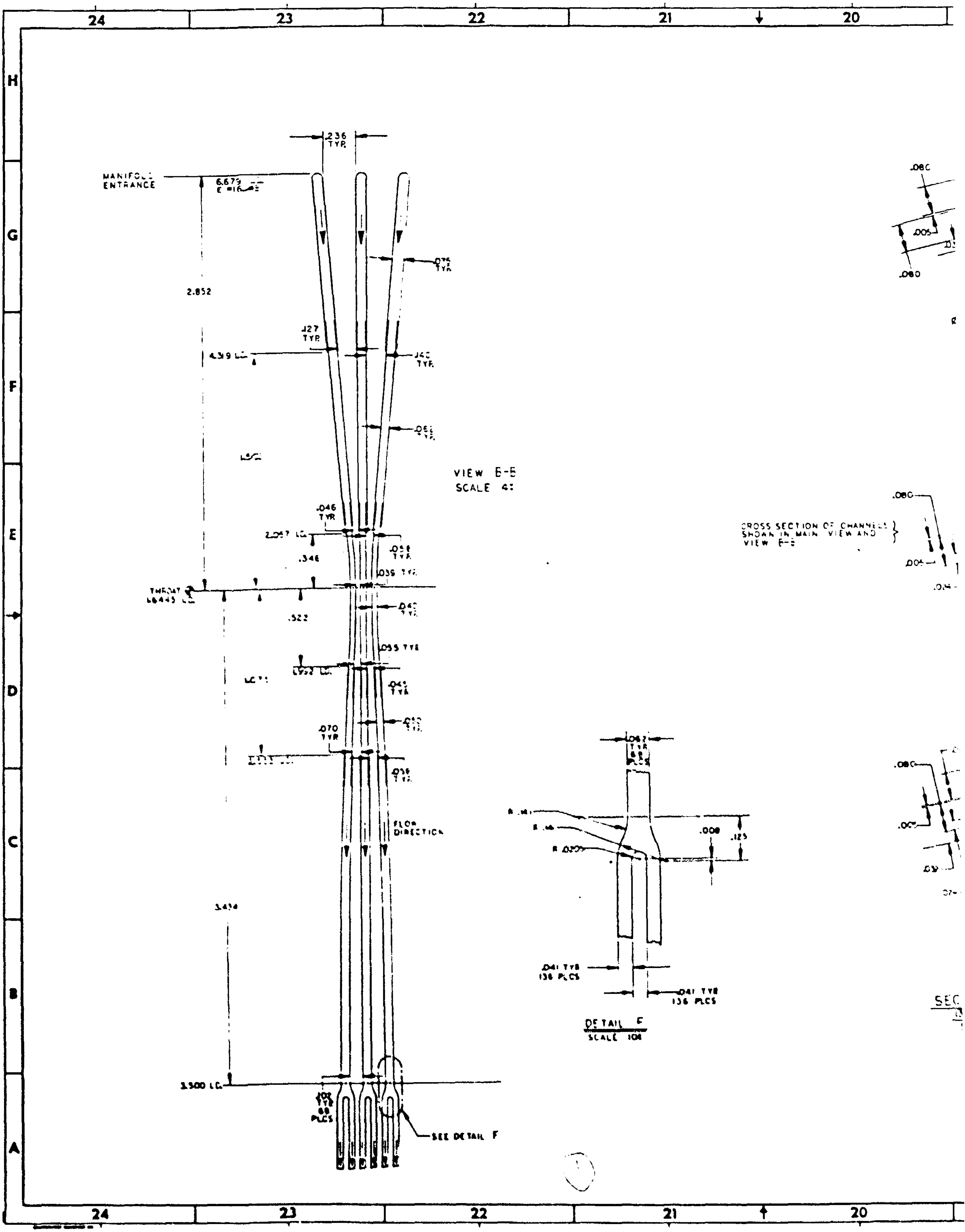
r/Igniter

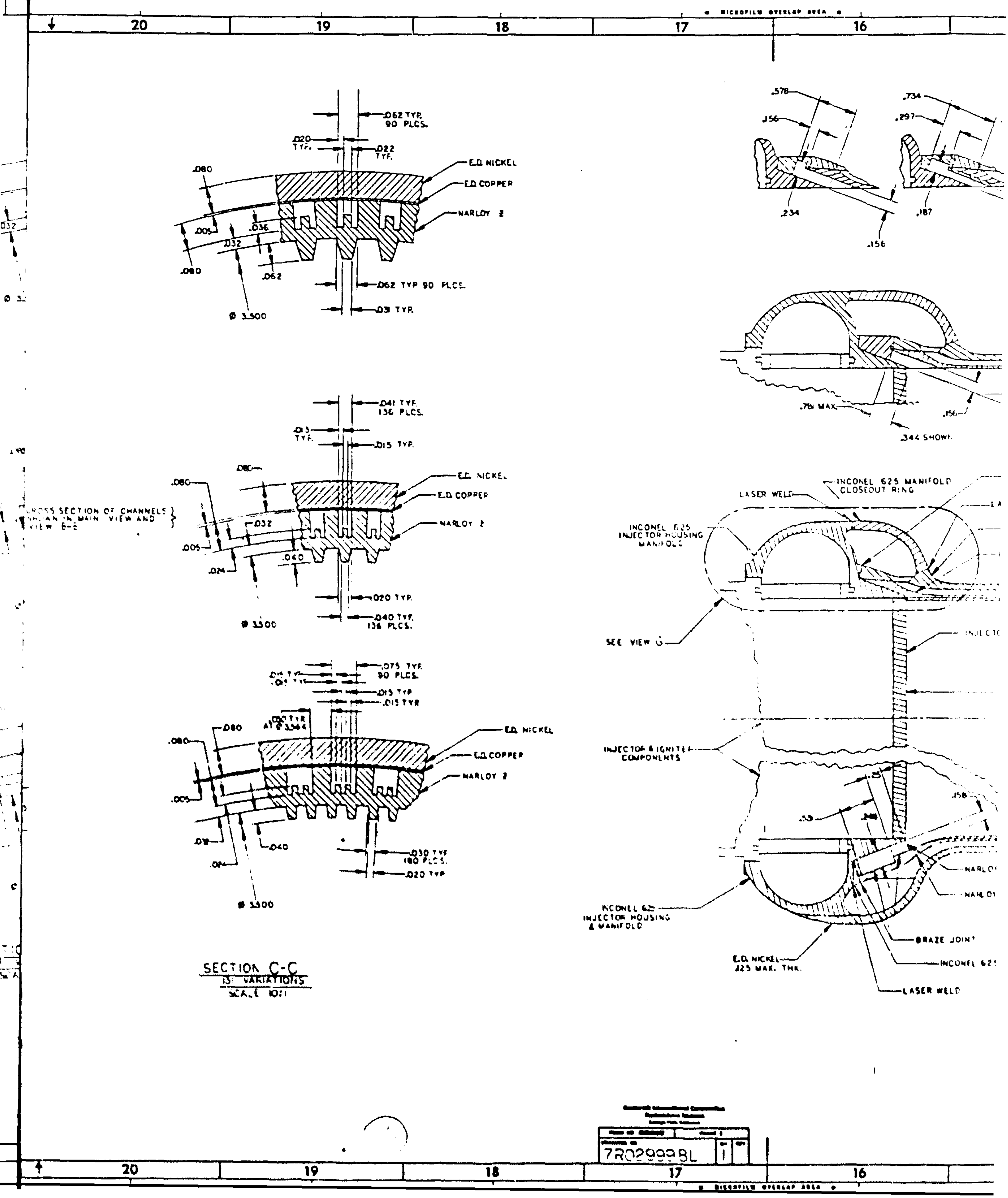
ving

R/ IGNITOR ASSY

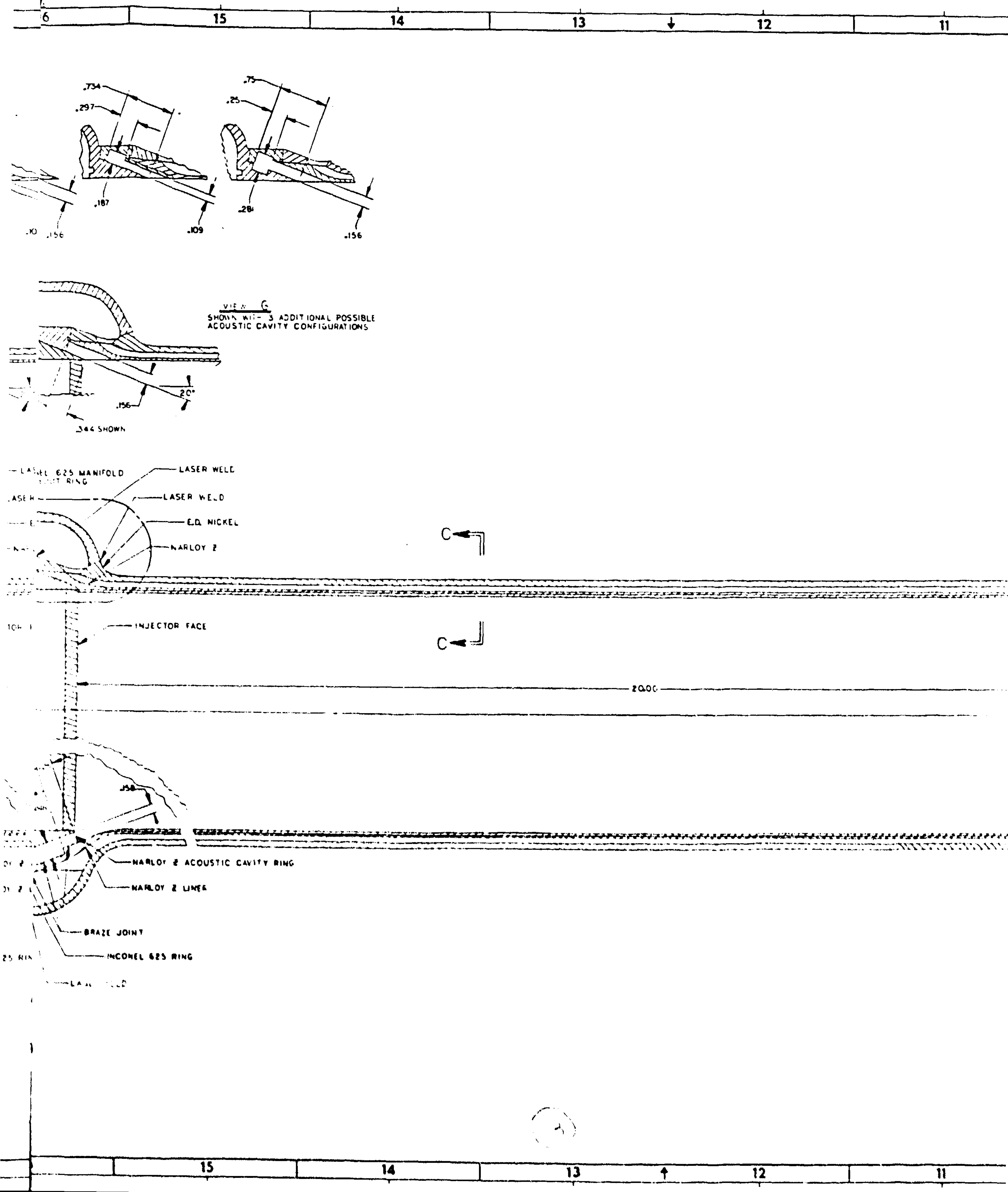
OTV ENGINE

A

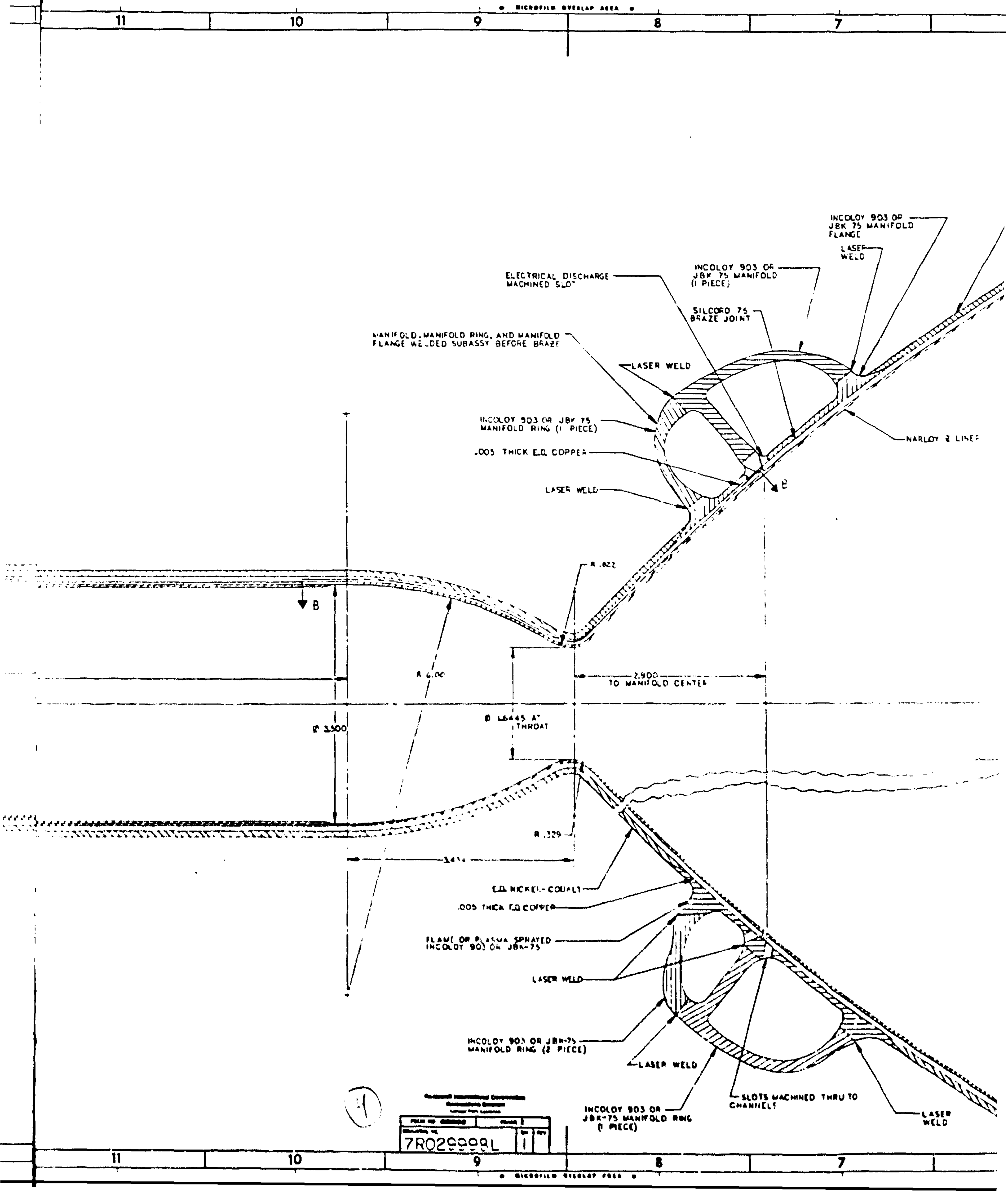

24
23
22
21
20
H
G
F
E
D
C
B
A
MANIFOLD ENTRANCE
.236 TYP
2.852
.127 TYP
.075 TYP
.046 TYP
.346
THROAT
.522
.035 TYP
.055 TYP
.070 TYP
FLOW DIRECTION
3.434
3.500 LG.
SEE DETAIL F
VIEW B-B
.125
.041 TYP 136 PLCS
DETAIL F
.080
.005
CROSS SECTION OF CHANNELS SHOWN IN MAIN VIEW AND VIEW B-B



20
19
18
17
16
.062 TYP. 90 PLCS.
.020 TYP.
.022 TYP.
.080
E.D. NICKEL
E.D. COPPER
NARLOY Z
.005
.036
.032
.080
.062
.062 TYP 90 PLCS.
.031 TYP.
Ø 3.500
.041 TYP. 136 PLCS.
.013 TYP.
.015 TYP.
.080
CROSS SECTION OF CHANNELS SHOWN IN MAIN VIEW AND VIEW E-E
.005
.024
.040
.020 TYP.
.040 TYP. 136 PLCS.
.075 TYP. 90 PLCS.
.015 TYP
.015 TYP
.030 TYP. 180 PLCS.
.020 TYP
SECTION C-C
13 VARIATIONS
SCALE 10/1
.578
.156
.734
.297
.234
.187
.156
.781 MAX.
.344 SHOWN
INCONEL 625 MANIFOLD CLOSEOUT RING
LASER WELD
INCONEL 625 INJECTOR HOUSING MANIFOLD
SEE VIEW G
INJECTOR & IGNITER COMPONENTS
INCONEL 625 INJECTOR HOUSING & MANIFOLD
E.D. NICKEL .025 MAX. THK.
BRAZE JOINT
INCONEL 625
LASER WELD
MICROFILM OVERLAP AREA
7R029998L



16
15
14
13
12
11
.734
.297
.187
.109
.156
.75
.25
.281
.156
VIEW G
SHOWN WITH 3 ADDITIONAL POSSIBLE ACOUSTIC CAVITY CONFIGURATIONS
.156
20°
.344 SHOWN
LASER WELD
LASER WELD
E.D. NICKEL
NARLOY Z
C
C
INJECTOR FACE
20.00
.158
NARLOY Z ACOUSTIC CAVITY RING
NARLOY Z LINER
BRAZE JOINT
INCONEL 625 RING
15
14
13
12
11


MICROFILM OVERLAP AREA
11
10
9
8
7
INCOLOY 903 OR
JBK 75 MANIFOLD
FLANGE
LASER
WELD
INCOLOY 903 OR
JBK 75 MANIFOLD
(1 PIECE)
ELECTRICAL DISCHARGE
MACHINED SLOT
SILCORO 75
BRAZE JOINT
MANIFOLD, MANIFOLD RING, AND MANIFOLD
FLANGE WELDED SUBASSY BEFORE BRAZE
LASER WELD
INCOLOY 903 OR JBK 75
MANIFOLD RING (1 PIECE)
NARLOY Z LINER
.005 THICK E.D. COPPER
LASER WELD
B
R .822
B
R 6.00
2.900
TO MANIFOLD CENTER
Ø 3.500
Ø 1.6445 AT
THROAT
R .329
3.414
E.D. NICKEL-COBALT
.005 THICK E.D. COPPER
FLAME OR PLASMA SPRAYED
INCOLOY 903 OR JBK-75
LASER WELD
INCOLOY 903 OR JBK-75
MANIFOLD RING (2 PIECE)
LASER WELD
SLOTS MACHINED THRU TO
CHANNELS
INCOLOY 903 OR
JBK-75 MANIFOLD RING
(1 PIECE)
LASER
WELD
7R029998L
1
11
10
9
8
7
MICROFILM OVERLAP AREA

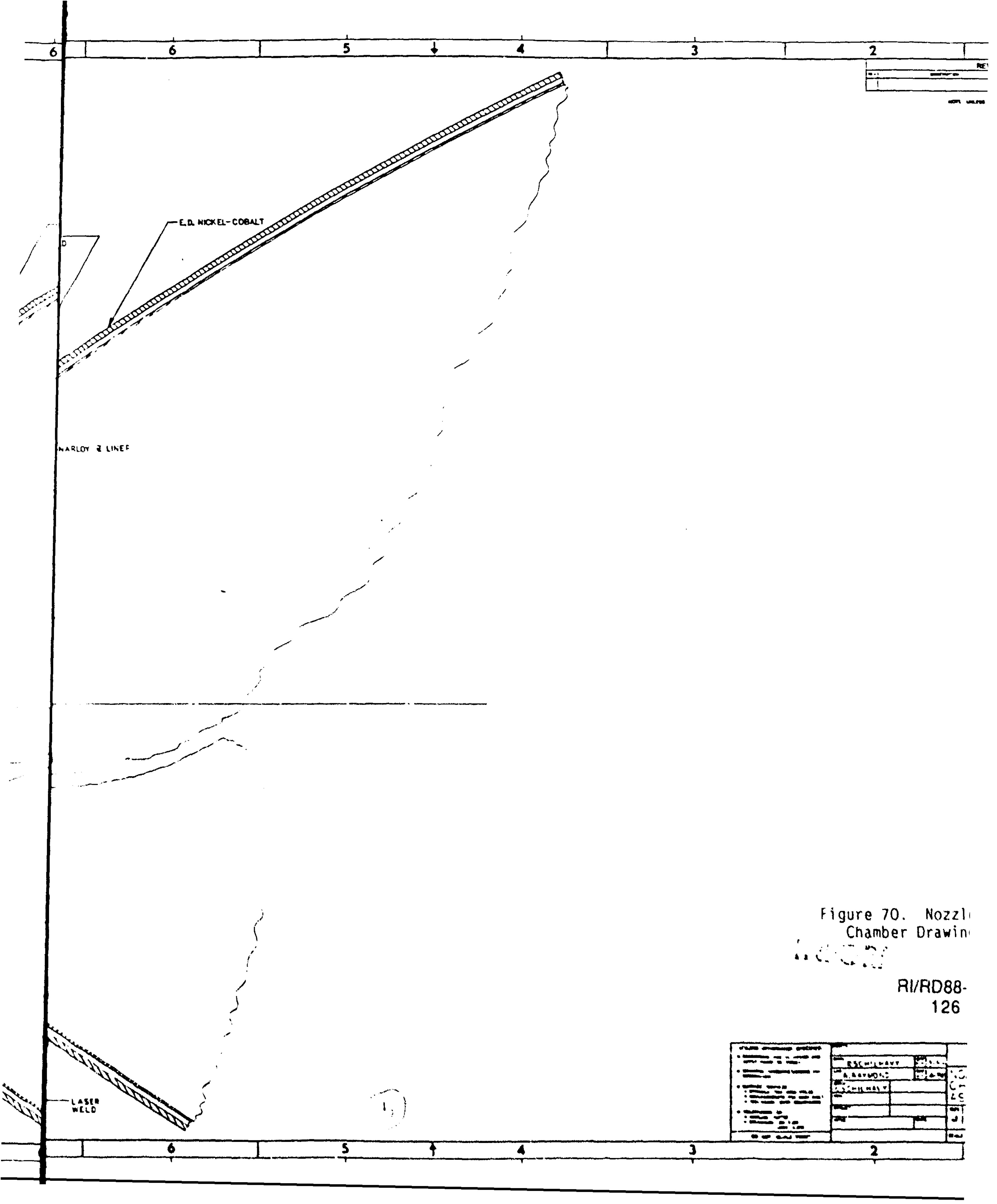


Figure 70. Nozzl
Chamber Drawin

Figure 70. Nozzle/Combustion Chamber Drawing (Part A)

NOZZLE / COMBUSTION CHAMBER, 7.5K NOTV ENGINE, ASSY OF

7R029998L

24 23 22 21 20

H

G

F

E

D

C

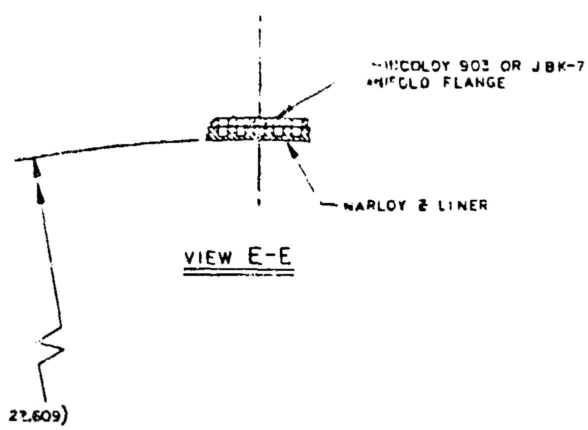
B

A

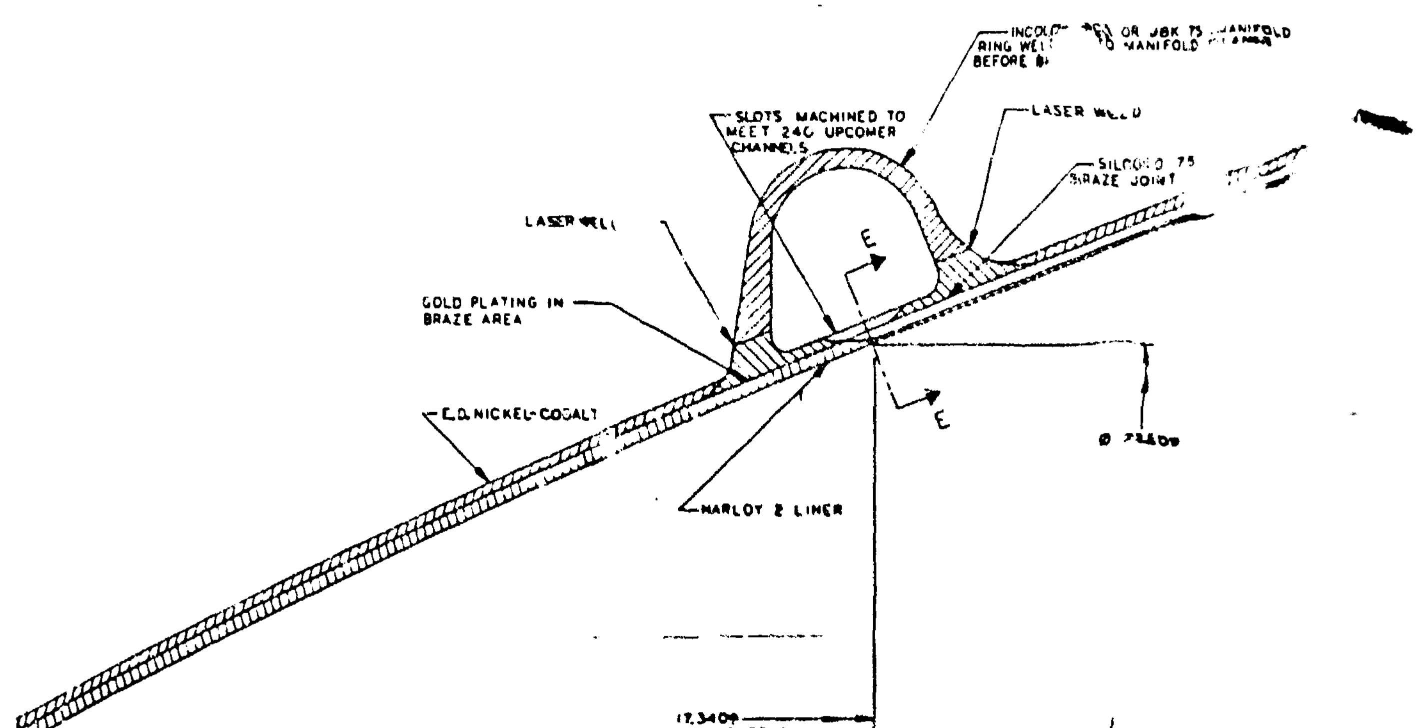
20	19	18	17	16

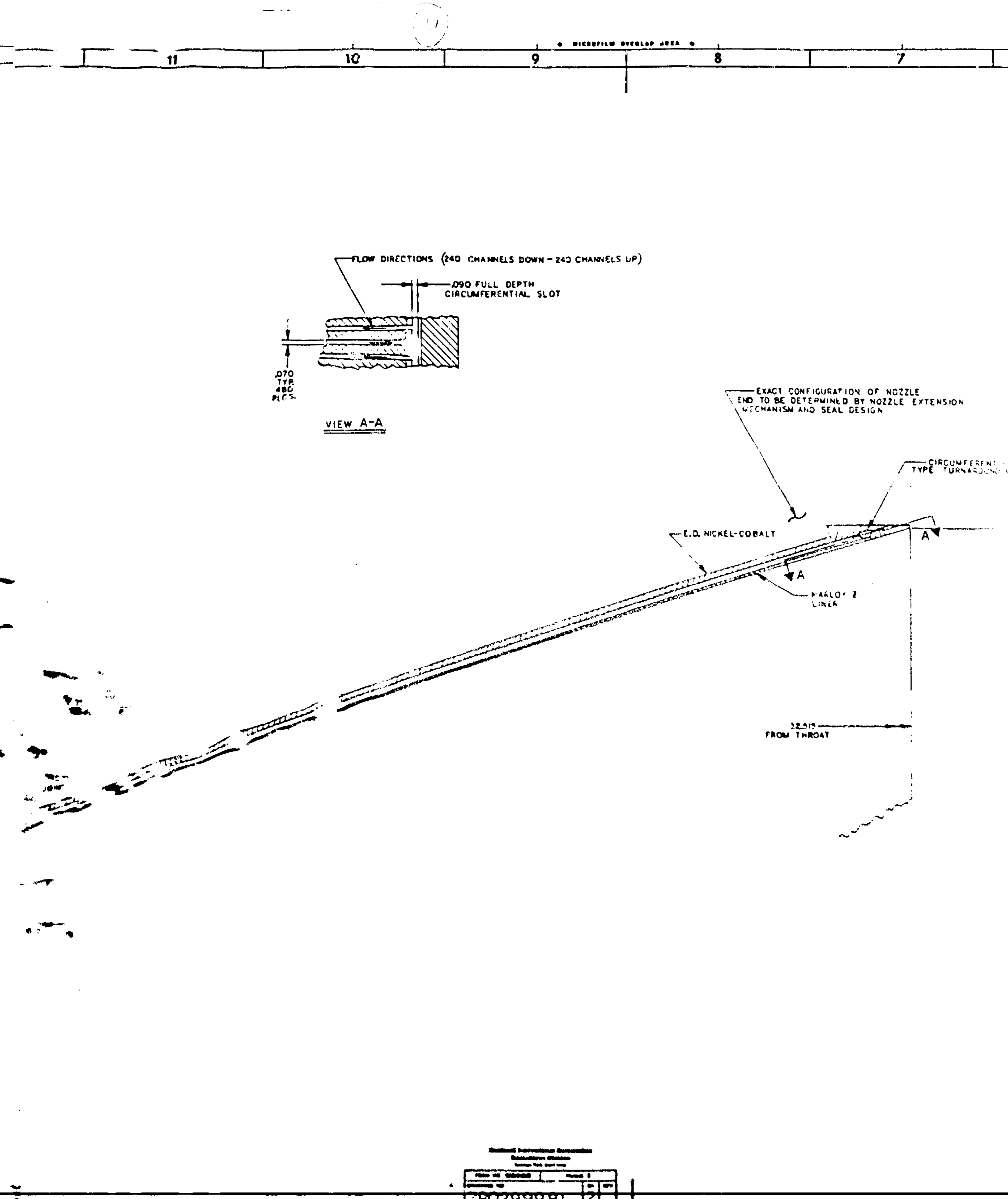
MICROFILM OVERLAP AREA

16 15 14 13 12 11

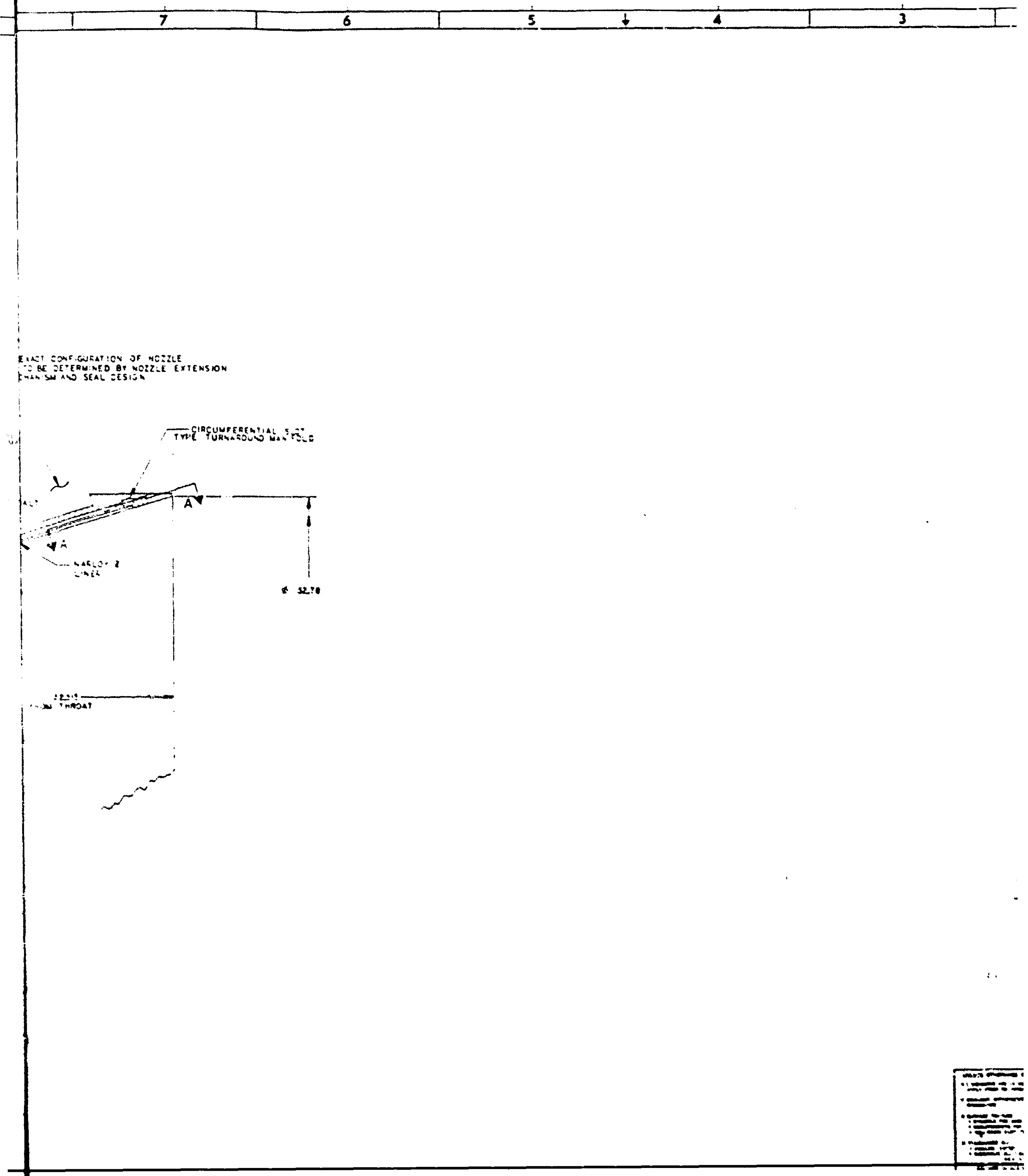


VIEW E-E





MICROFILM OVERLAP AREA
11
10
9
8
7
FLOW DIRECTIONS (240 CHANNELS DOWN - 240 CHANNELS UP)
.090 FULL DEPTH
CIRCUMFERENTIAL SLOT
.070
TYP.
480
PLCS.
VIEW A-A
EXACT CONFIGURATION OF NOZZLE
END TO BE DETERMINED BY NOZZLE EXTENSION
MECHANISM AND SEAL DESIGN
E.D. NICKEL-COBALT
A
A
NARLOY Z
LINER
FROM THROAT



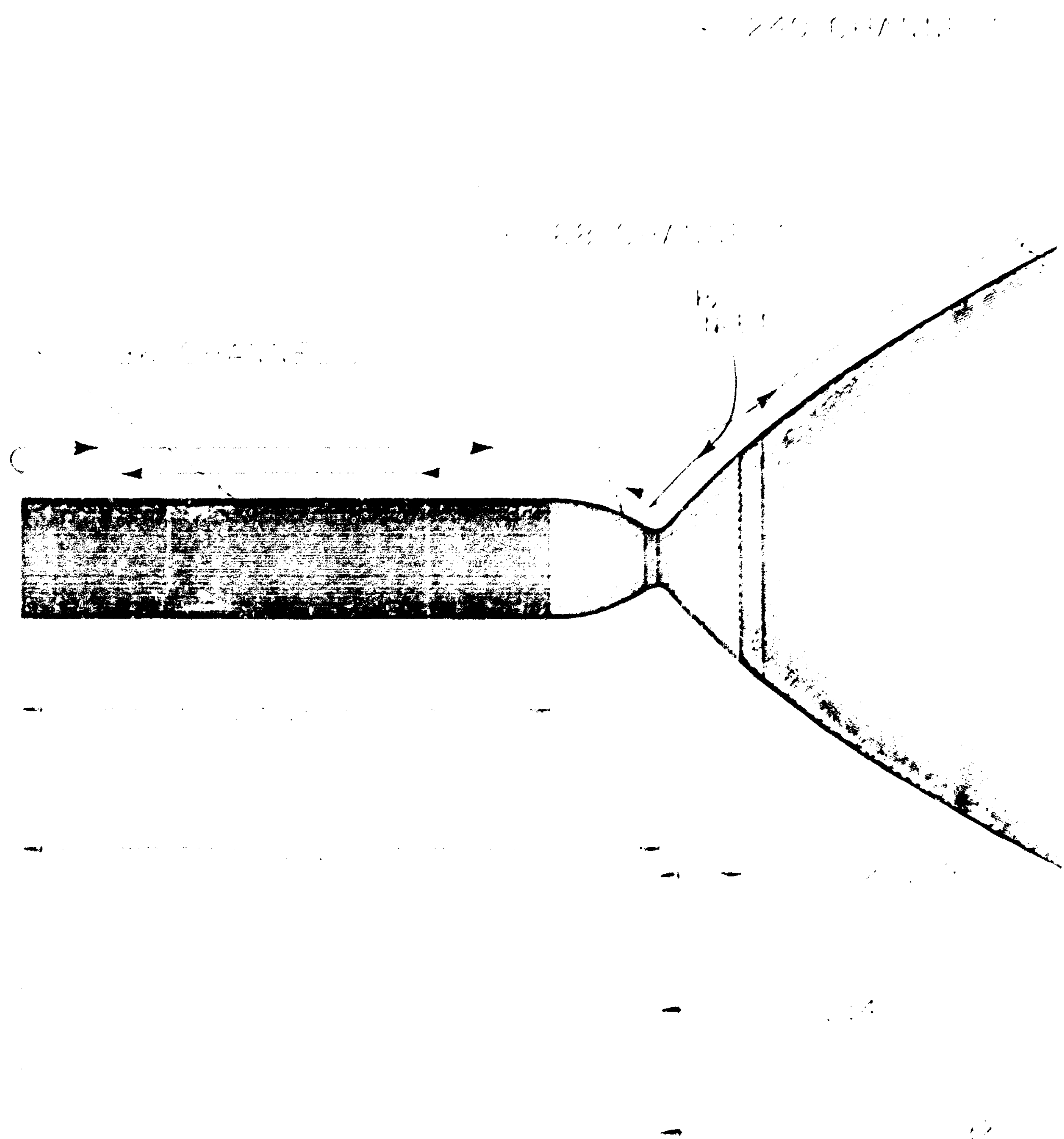
7
6
5
4
3
EXACT CONFIGURATION OF NOZZLE
TO BE DETERMINED BY NOZZLE EXTENSION
AND SEAL DESIGN
CIRCUMFERENTIAL SLOT
TYPE TURNAROUND MANIFOLD
A
NARLOY Z
LINER
52.78
THROAT

Figure 70. Nozzle Combustion Chamber Drawing (Part B)

NOZZLE / COMBUSTION CHAMBER, 7.5 KNOTV ENGINE, ASSY OF

7PO2999BL

ONLY CENTERLINES OF CHANNELS SHOWN



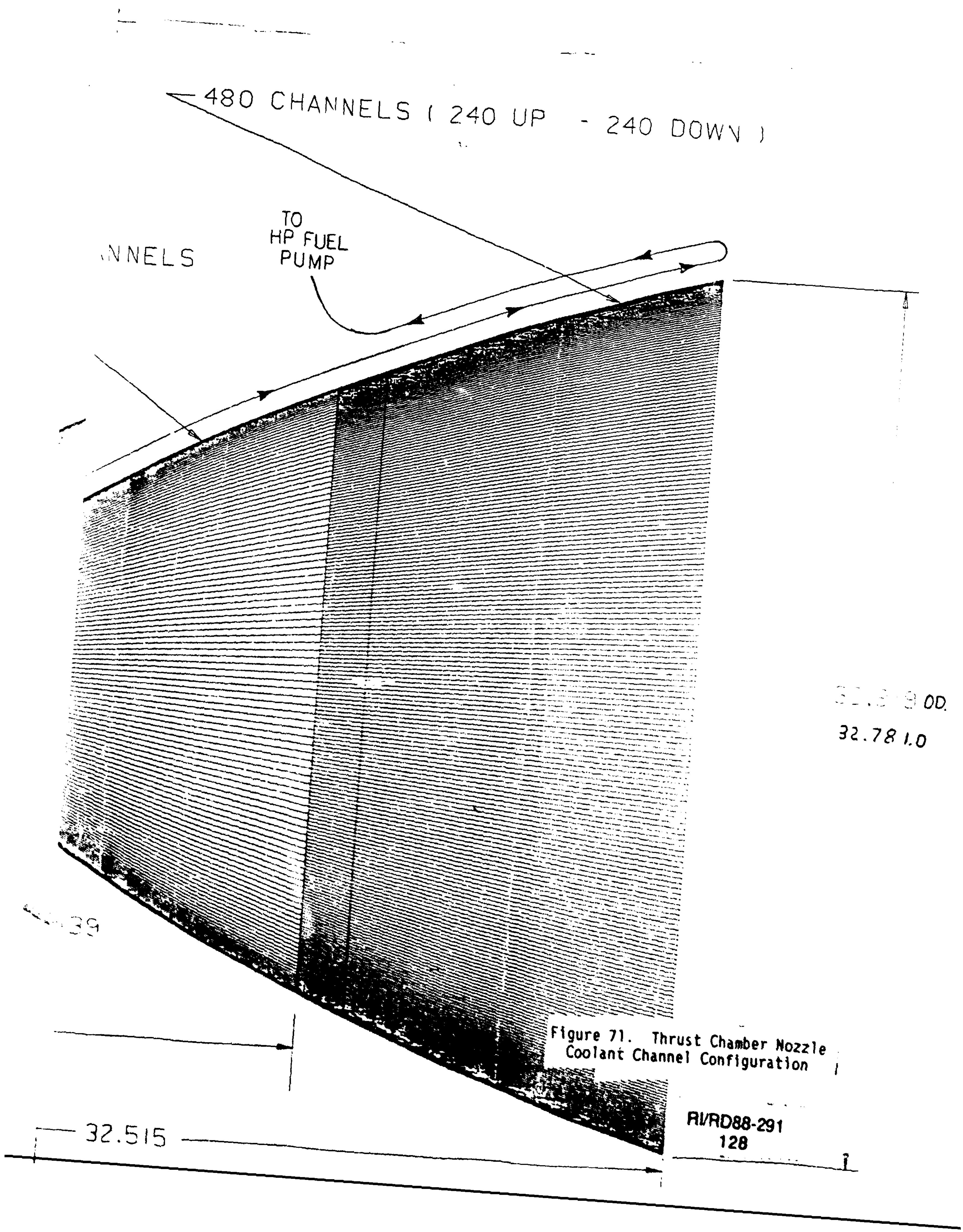
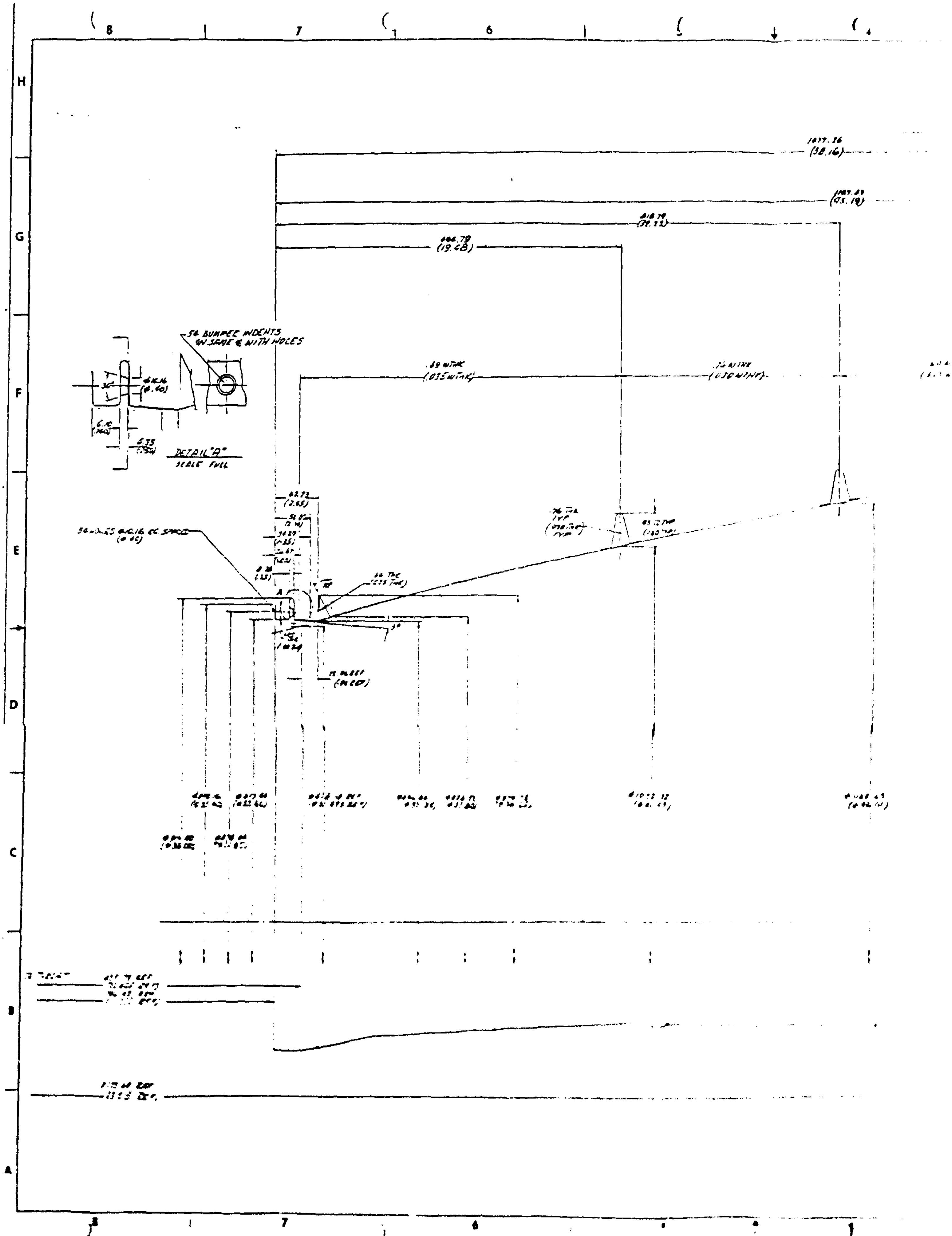


Figure 71. Thrust Chamber Nozzle Coolant Channel Configuration



54 BUMPER INDENTS ON SAME ℄ WITH HOLES
DETAIL "A"
SCALE FULL
1077.86
(38.16)
464.79
(19.68)

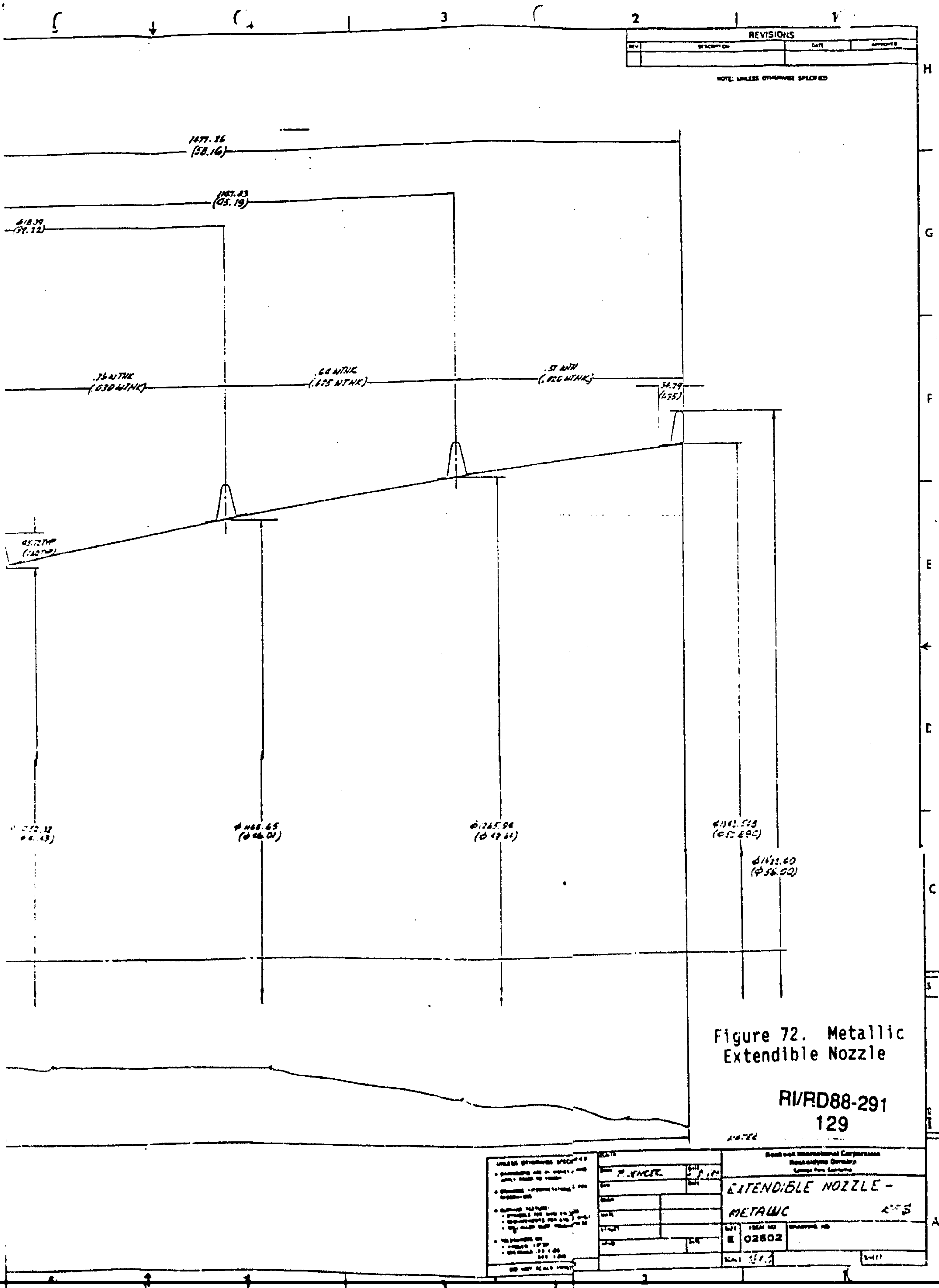


Figure 72. Metallic Extendible Nozzle

6.7 Injector/Igniter Assembly Layout

The injector/igniter assembly layout, Figure 69, includes 60 coaxial elements in four rows on a 3.5-in. diameter injector face. The assembly incorporates a dual spark plug plasma-torch igniter. The design has a strong historical base and is optimized for maximum heat transfer to the thrust chamber.

6.8 Nozzle/Combustion Chamber Assembly Layout

The nozzle-thrust chamber assembly layout drawings, Figure 70 (a and b), incorporate a combined thrust chamber/nozzle coolant manifold, and have a 1-1/2-pass cooled nozzle configuration. Figure 71 shows the coolant channel configuration and validates the fabricability of the design. The cold hydrogen enters the combustor coolant inlet manifold 2.9 inches downstream of the throat and flows up the coolant channels to the outlet manifold at the injector face. The coolant is then routed to the nozzle coolant inlet manifold just downstream of the combustor inlet. From there the hydrogen flows down 240 channels to the end of the cooled nozzle, 32.515 inches from the throat. At this point the coolant passes through a turnaround manifold and returns up the nozzle to the exit manifold 17.341 inches from the throat through 240 more channels interspersed between those carrying the downpass flow. The uncooled, metallic nozzle extension is shown in Figure 72.

6.9 Fuel and Oxidizer Turbopump Assembly Layouts

The high-pressure fuel turbopump, the low-pressure fuel turbopump, and high-pressure oxidizer turbopump, and the low-pressure oxidizer turbopump layout drawings are presented in the turbopump section of this report.

REFERENCES

1. Martinez, A., "Orbit Transfer Rocket Engine Technology Program--Interim Report, Advanced Engine Study," NASA CR175084, January 1986

2. Erickson, C., "Orbit Transfer Rocket Engine Technology Program--Interim Report, Advanced Engine Study, Phase II," NASA CR179602, February 1987

3. Baily, R. D., "Enhanced Heat Transfer Combustor Technology Interim Report--Subtasks I and II, Task C.I," NASA CR179541, 16 December 1986

4. Gerstley, J. G., "Regenerative Cooling Design/Analysis Computer Program," ASR-73-170, July 1973

5. Morinishi, R., "Input to the Enhanced Transfer Combustor Final Report," AATU-86-6017, 6 March 1986

APPENDIX A

ON-DESIGN AND OFF-DESIGN ENGINE SYSTEM ANALYSIS CODE OUTPUT

Table D.5-1. Optimizer/Design Code Output
(Sheet 1 of 8)

OTV POINT-DESIGN MODEL
VERSION 3.0

ENGINE DESCRIPTION

	(UNITS)		
CYCLE TYPE		EXPANDER CYCLE	
TURBINE ARRANGEMENT		SERIES	
OXYGEN PROPERTIES COMPUTED			
CHAMBER IS NOT TAPERED			
CHAMBER IS RIBBED			
THRUST	(LBF)	7500.00 (ENG)	7500.00 (T/C)
MIXTURE RATIO	(NONE)	6.00 (ENG)	6.10 (T/C)
DELIVERED SPECIFIC IMPULSE	(LB-SEC/LBM)	490.20 (ENG)	491.68 (T/C)
MAIN TURBINES BYPASS	(PERCENT)	10.984	
MAIN OX TURBINE BYPASS	(PERCENT)	10.276	
		OXIDIZER	FUEL
INLET PROPELLANT TEMPERATURE	(DEG R)	162.70	37.80
INLET NPSH	(FT)	2.00	15.00
PROPELLANT FLOW RATE	(LBS/SEC)	13.11	2.15 (T/C)
PROPELLANT FLOW RATE	(LBS/SEC)	13.12	2.18 (ENG)
PRESSURIZATION FLOWRATE	(LBS/SEC)	.13	.03
OVERBOARD LEAKAGE FLOWS	(LBS/SEC)	.018	.027

COMBUSTOR AND NOZZLE DESCRIPTION

	(UNITS)		
CHAMBER PRESSURE	(PSIA)	1740.45	
CHAMBER TEMPERATURE	(DEG R)	6797.55	
AREA RATIO	(AE/AT)	1034.40	
BREAKPOINT EPSILON	(NONE)	427.93	
NUMBER OF ENGINE SEGMENTS	(NONE)	2	
INPUT LIFE	(CYCLES)	2000.00	
RIB HEIGHT	(INCHES)	.0400	
NOZZLE PERCENT LENGTH	(PERCENT)	93.61	
FUEL INLET HEAT OF FORMATION	(KCAL/MOLE)	1.826	
DUMP COOLING FLOW RATE	(LBS/SEC)	0.00	
NOZZLE LENGTH	(INCHES)	89.54	
COMBUSTOR LENGTH	(INCHES)	20.00	
ENGINE LENGTH (EXT)	(INCHES)	117.00	
ENGINE LENGTH (RET)	(INCHES)	60.00	
CONTRACTION RATIO	(NONE)	4.00	
C SUB F	(NONE)	2.027	
THROAT AREA	(IN**2)	2.125	
HEAT LOSS BEFORE BL ATTACH	(BTU/SEC)	594.67	
HEAT LOSS DUE TO LEAKS AND PRESS.	(BTU/SEC)	0.00	
		COMBUSTOR	NOZZLE
COOLANT FLOW RATE	(LBS/SEC)	2.18	2.18
COOLANT DELTA P	(PSID)	997.31	7.04
HEAT INPUT	(BTU/SEC)	6534.52	1692.80
OUTLET PRESSURE	(PSIA)	4592.01	4576.37
INLET TEMPERATURE	(DEG R)	115.71	921.47
OUTLET TEMPERATURE	(DEG R)	921.40	1142.88
EXIT WALL TEMPERATURE	(DEG F)	920.71	
DELTA-T EXIT TO MAX	(DEG F)	101.06	
MAX WALL TEMPERATURE	(DEG F)	1021.77	
INLET ENTHALPY	(BTU/LBS)	243.62	3238.28
OUTLET ENTHALPY	(BTU/LBS)	3238.28	4014.06
COOLANT DENSITY	(LBS/FT**3)	2.665	.753

Table D.5-1. Optimizer/Design Code Output (Sheet 2 of 8)

OTV POINT-DESIGN MODEL
VERSION 3.0

PUMP DESCRIPTION	(UNITS)	MAIN PUMP OXIDIZER	MAIN PUMP FUEL	BOOST PUMP OXIDIZER	BOOST PUMP FUEL	AUXILIARY FUEL PUMP
PUMP						
WHEEL SPEED	(RPM)	84074.3	192487.5	9707.3	40514.0	0.0
EFFICIENCY	(FRACTION)	.8712	.6023	.7049	.7081	0.000
HORSEPOWER	(HP)	201.58	1083.27	4.89	10.29	0.00
INLET PRESSURE	(PSIA)	71.34	63.82	16.34	18.82	0.00
OUTLET PRESSURE	(PSIA)	2960.62	5639.39	86.34	73.82	0.00
FLOW RATE	(LBS/SEC)	13.258	2.209	13.258	2.210	0.000
DIAMETER	(IN)	2.31	2.22	2.25	1.93	0.00
EFFECTIVE DENSITY	(LB/FT**3)	71.14	4.94			0.00
INDUCER						
INLET FLOW VELOCITY	(FT/SEC)	40.51	117.66	7.48	27.36	
TIP SPEED	(FT/SEC)	269.36	782.36	95.48	341.61	
FLOW COEFFICIENT	(NONE)	.15	.15	.08	.08	
HEAD COEFFICIENT	(NONE)	.10	.10	.50	.50	
DELTA ?	(PSID)	111.43	57.70	70.00	55.00	
EFFICIENCY	(FRACTION)	.752	.752	.705	.708	
DELIVERED NPSH	(FT)	58.49	276.57	2.00	15.00	
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	10070.23	10070.23			
IMPELLER						
INLET FLOW VELOCITY	(FT/SEC)	36.87	118.60			0.00
TIP SPEED	(FT/SEC)	646.47	1864.65			0.00
FLOW COEFFICIENT	(NONE)	.11	.11			0.00
HEAD COEFFICIENT	(NONE)	.43	.43			0.00
HEAD RISE PER STAGE	(FT)	5641.25	46261.08			0.00
EFFICIENCY	(FRACTION)	.67	.58			0.00
DELIVERED NPSH	(FT)	35.98	200.64			0.00
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	900.28	919.60			0.00
TIP WIDTH	(IN)	.095	.092			0.000

Table D.5-1. Optimizer/Design Code Output (Sheet 3 of 8)

OTV POINT-DESIGN MODEL
VERSION 3.0

TURBINE DESCRIPTION		MAIN TURBINE OXIDIZER	MAIN TURBINE FUEL	BOOST TURBINE OXIDIZER FF HYD	BOOST TURBINE FUEL COOLANT	AUXILIARY HPFI
TYPE						
PITCH DIAMETER	(IN)	4.229	1.761	2.132	1.684	0.000
FLOW RATE	(LBS/SEC)	1.506	1.912	13.258	.185	0.000
ADMISSION	(FRACTION)	.513	.421	.900	.080	0.000
BEARING DN*E-6	(MM*RPM)	.751	2.608	.039	.131	0.000
ANNULUS AREA SPEED SQUARED*E-10	((RPM-IN)SQ)	.890	7.666	.034	.217	0.000
PITCH LINE VELOCITY	(FT/SEC)	1183.15	1480.27	90.36	342.24	0.00
FIRST STG BLADE HEIGHT	(INCHES)	.141	.254	.031	.250	0.000
SECOND STG BLADE HEIGHT	(INCHES)	.163	.374	0.000	0.000	0.000
VELOCITY RATIO	(NONE)	.421	.265	.470	.109	0.000
INLET PRESSURE	(PSIA)	2355.22	4104.87	2969.62	2355.22	0.00
OUTLET PRESSURE	(PSIA)	2030.36	2369.02	2844.26	2030.36	0.00
EFFICIENCY	(FRACTION)	.600	.644	.800	.249	0.000
PRESSURE RATIO	(NONE)	1.16	1.73	1.04	1.16	0.00
MAIN TURBINE INLET TEMP	(DEG R)	1043.98	1146.40	0.00	1043.98	0.00
MAIN TURBINE EXIT TEMP	(DEG R)	1016.97	1043.89	0.00	1034.83	0.00
HORSE POWER	(HP)	201.59	1083.27	4.89	10.29	0.00
GAS SPECIFIC HEAT	(BTU/LB-DEG R)	3.658	3.747	0.000	3.658	0.000
GAS PROCESS GAMMA	(NONE)	1.397	1.398	0.000	1.397	0.000
INLET ENTHALPY	(BTU/LBS)	3613.52	4014.06	0.00	3613.52	0.00
OUTLET ENTHALPY	(BTU/LBS)	3518.91	3613.52	0.00	3574.20	0.00
INLET ENTROPY	(BTU/LBS-DEG R)	12.79	12.57	0.00	0.00	0.00
GAS MOLECULAR WEIGHT	(NONE)	2.02	2.02	0.00	2.02	0.00

GASEOUS OXIDIZER HEAT EXCHANGER DESCRIPTION		FUEL	OXIDIZER
HEAT RATE	BTU/SEC	24.28	24.28
FLOW RATE	LBM/SEC	.24	.13
PRESSURE LOSS	PSIA	1.14	1.00
INLET PRESSURE	PSIA	2022.57	2844.26
INLET TEMPERATURE	DEG R	1161.03	178.72
OUTLET TEMPERATURE	DEG R	1131.53	669.14
SPECIFIC HEAT	BTU/LB-R	3.49	.37

Table D.5-1. Optimizer/Design Code Output
(Sheet 4 of 8)

OTV POINT-DESIGN MODEL
VERSION 3.0

PERFORMANCE

THRUST	(LBF)	7500.00
CHAMBER PRESSURE	(PSIA)	1740.45
ENGINE MIXUTRE RATIO	(BY WEIGHT)	6.00
AREA RATIO	(AE/AT)	1034.40
ODE SPECIFIC IMPULSE	(LBF-SEC/LBM)	514.24
ODE CHARACTERISTIC VELOCITY	(FT/SEC)	7810.52
SPECIFIC IMPULSE ENERGY RELEASE EFFICIENCY	(PERCENT)	99.900
SPECIFIC IMPULSE REACTION KINETIC EFFICIENCY	(PERCENT)	99.535
SPECIFIC IMPULSE DIVERGENCE EFFICIENCY	(PERCENT)	99.574
SPECIFIC IMPULSE HEAT LOSS EFFICIENCY	(PERCENT)	99.687
SPECIFIC IMPULSE BOUNDARY LAYER EFFICIENCY	(PERCENT)	96.601
EFFECTIVE TDK SPECIFIC IMPULSE	(LBF-SEC/LBM)	509.16
BOUNDARY LAYER IS LOSS	(LBF-SEC/LBM)	17.48
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	491.68 (T/C)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	534.64 (DUMP)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	490.20 (ENGINE)

SYSTEM PRESSURES

	(UNITS)	PROPELLANT OXIDIZER	PROPELLANT FUEL	GAS OXIDIZER	GAS FUEL
ENGINE INLET PRESSURE	(PSIA)	16.	19.		
BOOST PUMP DISCHARGE PRESSURE	(PSIA)	86.	74.		
MAIN PUMP INLET PRESSURE		7:.	64.		
MAIN PUMP DISCHARGE PRESSURE	(PSIA)	2844.	5639.		
COOLING JACKET INLET PRESSURE	(PSIA)		5589.		
COMBUSTOR DISCHARGE PRESSURE	(PSIA)				4592.
NOZZLE DISCHARGE PRESSURE	(PSIA)				4576.
BOOST TURBINE INLET PRESSURE	(PSIA)			2970.	2355.
BOOST TURBINE DISCHARGE PRESSURE	(PSIA)			2844.	2030.
MAIN TURBINE INLET PRESSURE	(PSIA)			2355.	4105.
MAIN TURBINE DISCHARGE PRESSURE	(PSIA)			2030.	2369.
CHAMBER INJECTION PRESSURE	(PSIA)	2401.			2021.
CHAMBER COMBUSTION PRESSURE	(PSIA)				1740.

Table D.5-1. Optimizer/Design Code Output
(Sheet 5 of 8)

HEAT EXCHANGER DESIGN

OTV POINT-DES MODEL VER 1.0

	(UNITS)		
HEAT RATE	(BTU/SEC)	1.00	
DELTA-T	(DEG-R)	908.07	
DELTA-T (AVERAGE)	(DEG-R)	908.07	
THERMAL EFFICIENCY	(FRACTION)	.000	
LENGTH	(INCH)	.00	
FRONTAL AREA	(IN**2)	16.00	
MATERIAL FLAG	(NONE)	0.00	
CHANNEL DIAMETER	(INCH)	.100	
WALL THICKNESS	(INCH)	.025	
CHANNEL SPACING	(INCH)	.050	
WEIGHT	(LBM)	.005	
		COLD SIDE	HOT SIDE
CHANNEL HEIGHT	(INCH)	.100	.100
LOSS FACTOR	(NONE)	.500	.500
FRICTION FACTOR	(NONE)	.020	.020
FLOW RATE	(LBM/SEC)	2.182	1.912
HEAT TRANSFER COEF	(BTU/SQIN-R-SEC)	.008	.009
FLOW AREA	(IN**2)	4.267	4.267
DELTAP	(PSID)	.06	.63
OUTLET PRESSURE	(PSIA)	5603.42	2025.43
INLET TEMPERATURE	(DEG R)	115.43	1023.66
OUTLET TEMPERATURE	(DEG R)	115.60	1023.52
INLET ENTHALPY	(BTU/LBM)	243.16	3535.18
OUTLET ENTHALPY	(BTU/LBM)	243.62	3534.66
INLET ENTROPY	(BTU/LBM-R)	3.67	12.87
OUTLET ENTROPY	(BTU/LBM-R)	3.68	12.87
AVERAGE DENSITY	(LBM/FT**3)	4.509	.353
AVERAGE SPECIFIC HEAT	(BTU/LBM-R)	2.852	3.587

Table D.5-1. Optimizer/Design Code Output (Sheet 6 of 8)

PROPELLANT PROPERTIES SUMMARY	LOCATION	PRESSURE (PSIA)	TEMPERATURE (DEG R)	NBS ENTHALPY (BTU/LB)	DELTA-H (BTU/LB)	ENERGY (BTU/SEC)	ENTROPY (BTU/LB-R)	DENSITY (LB/FT3)	FLOWRATE (LB/SEC)
ENGINE OXIDIZER INLET	(O1)	16.3	162.70	-57.47	-174.57	(-2314.45)	.70	71.149	(13.258)
BOOST OXIDIZER PUMP OUTLET	O2	86.3	163.16	-57.44	-174.54	-2314.04	.70	71.138	13.258
MAIN OXIDIZER PUMP LEAKAGE	(O3)	2844.3	178.72	-46.69	-163.79	(3.02)	.72	71.173	(-.018)
MAIN OXIDIZER PUMP OUTLET	O4	2844.3	178.72	-46.69	-163.79	-2146.60	.72	71.173	13.106
OXIDIZER TANK PRESSURIZATION	(O5)	2843.3	669.14	134.32	17.42	(-2.33)	1.24	12.486	(-.134)
MAIN OXIDIZER VALVE OUTLET	O6	2417.6	180.37	-46.69	-163.79	-2146.60	.73	70.542	13.106
MAIN OXIDIZER INJECTOR INLET	(O7)	2400.6	182.91	-46.69	-163.79	(2146.60)	.74	70.136	(-13.106)
ENGINE FUEL INLET	(F1)	16.8	37.80	-106.67	-1919.65	(-4241.80)	2.30	4.367	(2.210)
BOOST FUEL PUMP OUTLET	F2	73.8	38.55	-103.39	-1916.36	-4234.53	2.02	4.370	2.210
MAIN FUEL PUMP OUTLET	F3	5639.4	115.13	243.16	-1569.82	-3425.44	3.66	4.524	2.182
MAIN FUEL PUMP LEAKAGE	(F4)	5639.4	115.13	243.16	-1569.82	(42.15)	3.66	4.524	(-.027)
MAIN FUEL VALVE OUTLET	F5	5614.4	115.34	243.16	-1569.82	-3425.44	3.67	4.514	2.182
HEAT EXCH OUTLET (COLD)	(F6)	5603.4	115.60	243.62	-1569.36	(3424.44)	3.68	4.508	(-2.182)
COMBUSTOR OUTLET	F7	4592.0	921.40	3238.28	1425.30	3110.08	11.70	.828	2.182
NOZZLE OUTLET	(F8)	4576.4	1142.88	4014.06	2201.08	(4802.88)	12.45	.679	(2.182)
MAIN FUEL TURBINE INLET	F9	4104.9	1146.40	4014.06	2201.08	4728.04	12.57	.614	2.148
FUEL TANK PRESSURIZATION	(F10)	4104.9	1146.40	4014.06	2201.08	(-74.94)	12.57	.614	(-.034)
MAIN FUEL TURBINE OUTLET	F11	2359.0	1043.89	3613.52	1800.54	3442.86	12.79	.402	1.912
MAIN OXIDIZER TURBINE INLET	F12	2355.2	1043.98	3613.52	1800.54	3442.86	12.79	.400	1.912
MAIN OXIDIZER TURBINE OUTLET	F13	2030.4	1018.97	3518.91	1705.93	2569.81	12.85	.355	1.506
BOOST FUEL TURBINE OUTLET	F14	2030.4	1034.83	3574.20	1761.22	325.82	12.91	.350	.185
OXIDIZER HEAT EXCHANGER INLET	F15	2021.4	1131.53	3911.14	2096.16	495.03	13.22	.320	.236
HEAT EXCH OUTLET (HOT)	F16	2025.4	1023.52	3534.66	1721.68	3292.06	12.87	.353	1.912
MAIN FUEL INJECTOR INLET	(F17)	2021.4	1037.21	3576.01	1763.03	(-3787.09)	13.07	.348	(-2.148)
SUMMATION (W,E) AT CONTROL SURFACE (SHOWN IN () AND FLOW OUT IS NEG)						-1.43			.00
ENERGY AND MASS BALANCE ACCURACY AT CONTROL SURFACE (PERCENT)						99.98			100.00

Table D.5-1. Optimizer/Design Code Output (Sheet 7 of 8)

CONTROL SURFACE SUMMARY	LOCATION	PRESSURE (PSIA)	TEMPERATURE (DEG R)	NBS ENTHALPY (BTU/LB)	DELTA-H (BTU/LB)	ENERGY (BTU/SEC)	FLOWRATE (LB/SEC)	HEAT OF FORMATION (CAL/MOLE)
ENGINE OXIDIZER INLET	(O1)	16.3	162.70	-57.47	-174.57	(-2314.45)	(13.258)	-3103.5
MAIN OXIDIZER PUMP LEAKAGE	(O3)	2844.3	178.72	-46.69	-163.79	(3.02)	(-.018)	-2911.9
OXIDIZER TANK PRESSURIZATION	(O5)	2843.3	659.14	134.52	17.42	(-2.33)	(-.134)	309.8
MAIN OXIDIZER INJECTOR INLET	O7	2400.6	162.91	-46.69	-163.79	2146.60	-13.106	-2911.9
MAIN OXIDIZER INJECTOR	(O8)	2400.6	153.32	-57.47	-174.57	(2287.84)	(-13.106)	-3103.5
T/C OXIDIZER - B.L. ATTACHMENT	O9	1740.5	156.22	-57.47	-174.57	-2287.94	13.106	-3102.0 (NBP)
ENGINE FUEL INLET	(F1)	18.8	37.80	-106.67	-1919.65	(-4241.80)	(2.210)	-2150.0
MAIN FUEL PUMP LEAKAGE	(F4)	5639.4	115.13	243.16	-1569.82	(42.15)	(-.027)	-1758.2
HEAT EXCH OUTLET (COLD)	(F5)	5603.4	115.60	243.62	-1569.38	(3424.44)	(-2.192)	-1757.7
NOZZLE OUTLET	(F8)	4576.4	1142.88	4014.06	2201.08	(4802.86)	(2.182)	2465.2
FUEL TANK PRESSURIZATION	(F10)	4104.8	1146.40	4014.06	2201.08	(-74.84)	(-.034)	2465.2
MAIN FUEL INJECTOR INLET	F17	2021.4	1037.21	3576.01	1763.03	-3787.09	-2.148	1974.6
MAIN FUEL INJECTOR	(F18)	2021.4	1054.27	3641.77	1828.79	(-3928.33)	(-2.148)	2048.2
T/C FUEL - B.L. ATTACHMENT	F19	1740.5	976.83	3354.92	1551.94	3333.66	2.148	1738.2

SUMMATION (W,E) AT CONTROL SURFACE (SHOWN IN () AND FLOW OUT IS NEG) -1.43 .00

ENERGY AND MASS BALANCE ACCURACY AT CONTROL SURFACE (PERCENT) 99.98 100.00

Table D.5-1. Optimizer/Design Code Output
(Sheet 8 of 8)

NOZZLE SEGMENTATION SUMMARY

OTV POINT-DESIGN MODEL
VERSION 3.0

		SEGMENT 1	SEGMENT 2	SEGMENT
SEGMENT TYPE		REGEN	RADIATION	
BREAKPOINT EPSILON	NONE	427.9	1034.4	
SEGMENT LENGTH	INCHES	32.54	89.54	
RADIATION SEGMENT AREA	IN**2	2310.39	7890.12	
DELTA-H ODE	BTU/LBM	5466.50	5466.50	
B/L Q	BTU/SEC	4893.189	704.102	
TOTAL Q	BTU/SEC	7632.643	704.102	
PER-SEGMENT DELTA ADIAB	NONE	.01733	.02321	
K2 FACTOR	NONE	.97966	.98248	
DELTA-ETA-QBL	NONE	.03054	.00435	
DELTA-DELTA PER SEG	NONE	.01733	.00588	

NOZZLE CONTOUR DEFINITION

THETA MAX	DEGREES	45.104
THETA EXIT	DEGREES	5.219
RCIRC/RT	NONE	0.000
M-SUB-X	INCHES	.36353
M-SUB-Y	INCHES	1.05026
P	NONE	-.24477
Q	INCHES	-17.40113
S	INCHES	43.44774
T	IN**2	302.7992

PARABOLIC CONTOUR EQUATION IS:
R = MY + P*(X-MX) + Q + SQRT(S*(X-MX) + T)

ENGINE DESCRIPTION

	(UNITS)		
THRUST	(LBF)	7500.00 (ENG)	7500.00 (T/C)
MIXTURE RATIO	(NONE)	5.0000 (ENG)	5.0568 (T/C)
DELIVERED SPECIFIC IMPULSE	(LB-SEC/LBM)	489.9595 (ENG)	491.5684 (T/C)
MAIN TURBINES BYPASS	(PERCENT)	6.028	
MAIN OX TURBINE BYPASS	(PERCENT)	21.227	
		OXIDIZER	FUEL
INLET PROPELLANT TEMPERATURE	(DEG R)	162.70	37.80
INLET NPSH	(FT)	2.00	15.00
PROPELLANT FLOW RATE	(LBS/SEC)	12.73824	2.51905 (T/C)
PROPELLANT FLOW RATE	(LBS/SEC)	12.75616	2.55123 (ENG)
OVERBOARD LEAKAGE FLOW RATE	(LBS/SEC)	.01771	.03149
PRESSURANT FLOW RATE	(LBS/SEC)	.13400	.02359

COMBUSTOR AND NOZZLE DESCRIPTION

CHAMBER PRESSURE	(PSIA)	1800.02	
CHAMBER TEMPERATURE	(DEG R)	6418.14	
AREA RATIO	(AE/AT)	1034.40	
BREAKPOINT EPSILON	(NONE)	427.93	
NOZZLE PERCENT LENGTH	(PERCENT)	93.61	
FUEL INLET HEAT OF FORMATION	(KCAL/MOLE)	1.39	
DUMP COOLING FLOW RATE	(LBS/SEC)	.00	
NOZZLE LENGTH	(INCHES)	89.54	
COMBUSTOR LENGTH	(INCHES)	20.00	
ENGINE LENGTH (EXT)	(INCHES)	117.00	
ENGINE LENGTH (RET)	(INCHES)	60.00	
CONTRACTION RATIO	(NONE)	4.00	
C SUB F	(NONE)	1.960	
THROAT AREA	(IN**2)	2.125	
HEAT LOSS BEFORE BL ATTACH	(BTU/SEC)	626.92	
		COMBUSTOR	NOZZLE
COOLANT FLOW RATE	(LBS/SEC)	2.543	2.543
COOLANT DELTA P	(PSID)	1233.84	7.74
HEAT INPUT	(BTU/SEC)	6881.21	1792.23
OUTLET PRESSURE	(PSIA)	5205.74	5188.50
INLET TEMPERATURE	(DEG R)	126.64	849.28
OUTLET TEMPERATURE	(DEG R)	849.21	1049.75
INLET ENTHALPY	(BTU/LBS)	292.84	2999.17
OUTLET ENTHALPY	(BTU/LBS)	2999.17	3704.04
COOLANT DENSITY	(LBS/FT**3)	2.765	.906

OTV OFF-DESIGN MODEL
VERSION 6.0

$\dot{F} = 7500$

MR = 5

PUMP DESCRIPTION	(UNITS)	MAIN PUMP OXIDIZER	MAIN PUMP FUEL	BOOST PUMP OXIDIZER	BOOST PUMP FUEL	AUXILIARY FUEL PUMP
PUMP						
WHEEL SPEED	(RPM)	62340.4	210217.0	9446.6	38050.5	.0
EFFICIENCY	(FRACTION)	.6712	.5995	.7049	.6671	.000
HORSEPOWER	(HP)	188.03	1437.90	4.47	9.25	.00
INLET PRESSURE	(PSIA)	68.49	45.26	16.34	18.82	.00
OUTLET PRESSURE	(PSIA)	2812.78	6504.79	82.66	58.84	.00
FLOW RATE	(LBS/SEC)	12.89	2.57	12.89	2.57	.00
DIAMETER	(IN)	2.31	2.22	2.25	1.93	.00
EFFECTIVE DENSITY	(LB/FT**3.	71.14	4.94			.00
INDUCER						
INLET FLOW VELOCITY	(FT/SEC)	39.39	137.12	7.27	31.88	
TIP SPEED	(FT/SEC)	262.07	854.42	92.92	320.84	
FLOW COEFFICIENT	(NONE)	.15	.16	.08	.10	
HEAD COEFFICIENT	(NONE)	.10	.09	.00	.41	
DELTA P	(PSID)	105.51	66.84	66.33	40.03	
EFFICIENCY	(FRACTION)	.752	.752	.705	.667	
DELIVERED NPSH	(FT)	55.34	344.46	2.00	15.00	
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	10065.10	10967.61			
IMPELLER						
INLET FLOW VELOCITY	(FT/SEC)	35.85	138.22			.00
TIP SPEED	(FT/SEC)	628.98	2036.39			.00
FLOW COEFFICIENT	(NONE)	.14	.16			.00
HEAD COEFFICIENT	(NONE)	.43	.36			.00
HEAD RISE PER STAGE	(FT)	5341.53	46553.37			.00
EFFICIENCY	(FRACTION)	.67	.58			.00
DELIVERED NPSH	(FT)	34.04	249.90			.00
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	899.96	1014.34			.00

TURBINE DESCRIPTION

		MAIN TURBINE OXIDIZER	MAIN TURBINE FUEL	BOOST TURBINE OXIDIZER FF HYD	BOOST TURBINE FUEL COOLANT	AUXILIARY HPFT
TYPE						
DIAMETER	(IN)	4.229	1.761	2.132	1.684	.000
FLOW RATE	(LBS/SEC)	1.632	2.367	12.890	.200	.000
ADMISSION	(FRACTION)	.513	.421	.900	.080	.000
TIP SPEED	(FT/SEC)	1151.14	1616.61	87.93	279.89	.00
FIRST STG BLADE HEIGHT	(INCHES)	.141	.254	.031	.250	.000
SECOND STG BLADE HEIGHT	(INCHES)	.163	.374	.000	.000	.000
VELOCITY RATIO	(NONE)	.282	.442	.709	.125	.000
INLET PRESSURE	(PSIA)	2461.65	4665.67	2926.96	2461.65	.00
OUTLET PRESSURE	(PSIA)	2139.06	2479.60	2708.75	2139.06	.00
EFFICIENCY	(FRACTION)	.601	.654	.800	.280	.000
PRESSURE RATIO	(NONE)	1.15	1.88	1.04	1.15	.00
MAIN TURBINE INLET TEMP	(DEG R)	946.18	1053.67	.00	946.18	.00
MAIN TURBINE EXIT TEMP	(DEG R)	924.91	946.07	.00	937.37	.00
HORSE POWER	(HP)	188.02	1437.85	4.48	9.24	.00
GAS SPECIFIC HEAT	(BTU/LB-DEG R)	3.685	3.803	.000	3.685	.000
GAS PROCESS GAMMA	(NONE)	1.393	1.395	.000	1.393	.000
INLET ENTHALPY	(BTU/LBS)	3274.72	3704.03	.00	3274.72	.00
OUTLET ENTHALPY	(BTU/LBS)	3153.29	3274.72	.00	3236.78	.00
INLET ENTROPY	(BTU/LBS-DEG R)	12.41	12.15	.00	.00	.00
NOZZLE AREA	(IN**2)	.23	.15			.00
FLOW PARAMETER	(NONE)	.00	.00			.00

GASEOUS OXIDIZER HEAT EXCHANGER DESCRIPTION

		OXIDIZER	FUEL
HEAT RATE	(BTU/SEC)	21.89	21.89
FLOW RATE	(LB/SEC)	.134	.152
PRESSURE LOSS	(PSID)	24.28	1.14
INLET PRESSURE	(PSIA)	68.50	2127.91
INLET TEMPERATURE	(DEG R)	178.72	1071.43
OUTLET TEMPERATURE	(DEG R)	620.73	1030.10

Note: OTV Off Design model output for the heat exchanger is inaccurate predicting pressure loss and temperatures & values are estimated on schematics

PERFORMANCE

THRUST	(LBF)	7500.00	
CHAMBER PRESSURE	(PSIA)	1800.02	
ENGINE MIXUTRE RATIO	(BY WEIGHT)	5.00	
AREA RATIO	(AE/AT)	1034.40	
ODE SPECIFIC IMPULSE	(LBF-SEC/LBM)	513.35	
ODE CHARACTERISTIC VELOCITY	(FT/SEC)	8070.45	
SPECIFIC IMPULSE ENERGY RELEASE EFFICIENCY	(PERCENT)	99.967	
SPECIFIC IMPULSE REACTION KINETIC EFFICIENCY	(PERCENT)	99.795	
SPECIFIC IMPULSE DIVERGENCE EFFICIENCY	(PERCENT)	99.574	
SPECIFIC IMPULSE HEAT LOSS EFFICIENCY	(PERCENT)	99.656	
SPECIFIC IMPULSE BOUNDARY LAYER EFFICIENCY	(PERCENT)	96.419	
EFFECTIVE TDK SPECIFIC IMPULSE	(LBF-SEC/LBM)	508.20	
BOUNDARY LAYER IS LOSS	(LBF-SEC/LBM)	18.38	
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	491.57	(T/C)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	534.64	(DUMP)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	489.96	(ENGINE)

SYSTEM PRESSURES

	(UNITS)	PROPELLANT		GAS	
		OXIDIZER	FUEL	OXIDIZER	FUEL
ENGINE INLET PRESSURE	(PSIA)	16.	19.		
BOOST PUMP DISCHARGE PRESSURE	(PSIA)	83.	59.		
MAIN PUMP INLET PRESSURE		68.	45.		
MAIN PUMP DISCHARGE PRESSURE	(PSIA)	2813.	6505.		
COOLING JACKET INLET PRESSURE	(PSIA)		6440.		
COMBUSTOR DISCHARGE PRESSURE	(PSIA)				5206.
NOZZLE DISCHARGE PRESSURE	(PSIA)				5189.
BOOST TURBINE INLET PRESSURE	(PSIA)			2827.	2462.
BOOST TURBINE DISCHARGE PRESSURE	(PSIA)			2709.	2139.
MAIN TURBINE INLET PRESSURE	(PSIA)			2462.	4666.
MAIN TURBINE DISCHARGE PRESSURE	(PSIA)			2139.	2480.
CHAMBER INJECTION PRESSURE	(PSIA)	2423.			2128.
CHAMBER COMBUSTION PRESSURE	(PSIA)				1800.

OZZLE SEGMENTATION SUMMARY

		REGEN. COOLED	RADIATION COOLED
BREAKPOINT EPSILON	(NONE)	427.93	1034.40
SEGMENT LENGTH	(INCHES)	32.54	89.54
B/L Q	(BTU/SEC)	5318.47	.00
TOTAL Q	(BTU/SEC)	8046.52	.00
ADIABATIC LOSS	(NONE)	.01729	.00590
NET HEAT LOSS	(NONE)	.03330	.00473

HEAT EXCHANGER DESIGN

	(UNITS)	
HEAT RATE	(BTU/SEC)	1.02
DELTA-T	(DEG-R)	776.47
DELTA-T (AVERAGE)	(DEG-R)	776.48
THERMAL EFFICIENCY	(FRACTION)	.000
LENGTH	(INCH)	.00
FRONTAL AREA	(IN**2)	16.00
MATERIAL FLAG	(NONE)	.00
CHANNEL DIAMETER	(INCH)	.100
WALL THICKNESS	(INCH)	.025
CHANNEL SPACING	(INCH)	.050
WEIGHT	(LBM)	.005

		COLD SIDE	HOT SIDE
CHANNEL HEIGHT	(INCH)	.100	.100
LOSS FACTOR	(NONE)	.500	.500
FRICTION FACTOR	(NONE)	.020	.020
FLOW RATE	(LBM/SEC)	2.543	2.367
HEAT TRANSFER COEF	(BTU/SQIN-R-SEC)	.009	.010
FLOW AREA	(IN**2)	4.267	4.267
DELTAP	(PSID)	.09	.82
OUTLET PRESSURE	(PSIA)	6457.41	2132.69
INLET TEMPERATURE	(DEG R)	126.36	931.27
OUTLET TEMPERATURE	(DEG R)	126.50	931.15
INLET ENTHALPY	(BTU/LBM)	292.44	3215.37
OUTLET ENTHALPY	(BTU/LBM)	292.84	3214.93

PROPELLANT PROPERTIES SUMMARY

BEFORE DENS CALL: 18.8160 37.8000 -106.6670 1.9983

PROPELLANT PROPERTIES SUMMARY	PRESSURE (PSIA)	TEMPERATURE (DEG R)	ENTHALPY (BTU/LB)	ENTROPY (BTU/LB-R)	DENSITY (LB/FT3)
ENGINE FUEL INLET	18.8	37.80	-106.67	2.00	4.37
ENGINE OXID INLET	16.3	162.70	-57.47	.70	71.15
BOOST PUMP OUTLET	58.8	38.41	-104.13	2.02	4.37
BOOST OXIDIZER PUMP OUTLET	82.7	163.16	-57.44	.70	71.13
MAIN PUMP OUTLET	6504.8	125.35	290.67	3.66	4.57
MAIN OXIDIZER PUMP OUTLET	2694.6	177.67	-47.16	.72	71.20
MAIN VALVE OUTLET	6471.7	125.63	290.67	3.67	4.56
MAIN OXIDIZER VALVE OUTLET	2439.5	179.13	-47.16	.73	70.75
HEAT EXCH OUTLET (COLD)	6457.4	126.50	292.84	3.68	4.54
COMBUSTOR OUTLET	5205.7	849.21	2999.17	11.70	.99
NOZZLE OUTLET	5188.5	1049.75	3704.04	12.45	.82
FUEL PRESSURIZATION TAP-OFF	5188.5	1049.75	3704.04	12.45	.82
MAIN FUEL TURBINE INLET	4665.7	1053.67	3704.04	12.57	.74
MAIN FUEL TURBINE OUTLET	2479.6	946.07	3274.72	12.79	.46
MAIN OXID TURBINE INLET	2461.6	946.18	3274.72	12.79	.46
MAIN OXID TURBINE OUTLET	2139.1	924.91	3193.29	12.85	.41
BOOST FUEL TURBINE OUTLET	2139.1	937.37	3236.78	12.91	.40
GASEOUS OXYGEN HEAT EXCHANGER	2127.5	1030.10	3559.90	13.22	.37
HEAT EXCH OUTLET (HOT)	2132.7	931.15	3214.93	12.97	.41
MAIN FUEL INJECTOR INLET	2127.5	939.19	3235.73	13.07	.40
MAIN OXIDIZER INJECTOR INLET	2423.1	182.67	-46.70	.74	70.19

FUEL PUMP OVERALL EFFICIENCY (PERCENT) = 59.954
FUEL PUMP IDEAL EFFICIENCY (PERCENT) = 58.442

ERROR SUMMARY

ERROR	TIMES
0115	3138

ENGINE DESCRIPTION

	(UNITS)		
THRUST	(LBF)	7500.00 (ENG)	7500.00 (T/C)
MIXTURE RATIO	(NONE)	7.0000 (ENG)	7.0795 (T/C)
DELIVERED SPECIFIC IMPULSE	(LB-SEC/LBM)	484.3866 (ENG)	485.7492 (T/C)
MAIN TURBINES BYPASS	(PERCENT)	14.667	
MAIN OX TURBINE BYPASS	(PERCENT)	2.738	
		OXIDIZER	FUEL
INLET PROPELLANT TEMPERATURE	(DEG R)	162.70	37.80
INLET NPSH	(FT)	2.00	15.00
PROPELLANT FLOW RATE	(LBS/SEC)	13.52904	1.91102 (T/C)
PROPELLANT FLOW RATE	(LBS/SEC)	13.54806	1.93544 (ENG)
OVERBOARD LEAKAGE FLOW RATE	(LBS/SEC)	.01881	.02389
PRESSURANT FLOW RATE	(LBS/SEC)	.13400	.01790

COMBUSTOR AND NOZZLE DESCRIPTION

CHAMBER PRESSURE	(PSIA)	1695.15	
CHAMBER TEMPERATURE	(DEG R)	6928.15	
AREA RATIO	(AE/AT)	1034.40	
BREAKPOINT EPSILON	(NONE)	427.93	
NOZZLE PERCENT LENGTH	(PERCENT)	93.61	
FUEL INLET HEAT OF FORMATION	(KCAL/MOLE)	2.01	
DUMP COOLING FLOW RATE	(LBS/SEC)	.00	
NOZZLE LENGTH	(INCHES)	89.54	
COMBUSTOR LENGTH	(INCHES)	20.00	
ENGINE LENGTH (EXT)	(INCHES)	117.00	
ENGINE LENGTH (RET)	(INCHES)	60.00	
CONTRACTION RATIO	(NONE)	4.00	
C SUB F	(NONE)	2.082	
THROAT AREA	(IN**2)	2.125	
HEAT LOSS BEFORE BL ATTACH	(BTU/SEC)	558.99	
		COMBUSTOR	NOZZLE
COOLANT FLOW RATE	(LBS/SEC)	1.929	1.929
COOLANT DELTA P	(PSID)	838.34	6.38
HEAT INPUT	(BTU/SEC)	6149.03	1584.59
OUTLET PRESSURE	(PSIA)	4177.46	4163.29
INLET TEMPERATURE	(DEG R)	108.84	968.95
OUTLET TEMPERATURE	(DEG R)	968.89	1203.72
INLET ENTHALPY	(BTU/LBS)	206.83	3394.64
OUTLET ENTHALPY	(BTU/LBS)	3394.64	4216.14
COOLANT DENSITY	(LBS/FT**3)	2.599	.660

OTV OFF-DESIGN MODEL
VERSION 6.0

F = 7500

MR = 7

PUMP DESCRIPTION	(UNITS)	MAIN PUMP OXIDIZER	MAIN PUMP FUEL	BOOST PUMP OXIDIZER	BOOST PUMP FUEL	AUXILIARY FUEL PUMP
PUMP						
WHEEL SPEED	(RPM)	63170.2	180209.6	10091.0	39420.0	.0
EFFICIENCY	(FRACTION)	.6697	.6004	.7049	.7022	.000
HORSEPOWER	(HP)	201.39	861.41	5.44	9.28	.00
INLET PRESSURE	(PSIA)	78.35	65.92	16.34	18.82	.00
OUTLET PRESSURE	(PSIA)	2838.73	5055.82	92.32	73.73	.00
FLOW RATE	(LBS/SEC)	13.68	1.95	13.68	1.95	.00
DIAMETER	(IN)	2.31	2.22	2.25	1.93	.00
EFFECTIVE DENSITY	(LB/FT**3.	71.14	4.94			.00
INDUCER						
INLET FLOW VELOCITY	(FT/SEC)	41.81	104.02	7.72	24.19	
TIP SPEED	(FT/SEC)	265.56	732.46	99.25	332.39	
FLOW COEFFICIENT	(NONE)	.16	.14	.08	.07	
HEAD COEFFICIENT	(NONE)	.10	.09	.00	.52	
DELTA P	(PSID)	106.20	51.64	75.99	54.92	
EFFICIENCY	(FRACTION)	.752	.752	.705	.702	
DELIVERED NPSH	(FT)	58.61	233.33	2.00	15.00	
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	10456.04	9938.42			
IMPELLER						
INLET FLOW VELOCITY	(FT/SEC)	38.05	104.86			.00
TIP SPEED	(FT/SEC)	637.35	1745.71			.00
FLOW COEFFICIENT	(NONE)	.14	.14			.00
HEAD COEFFICIENT	(NONE)	.43	.38			.00
HEAD RISE PER STAGE	(FT)	5376.74	35961.90			.00
EFFICIENCY	(FRACTION)	.67	.58			.00
DELIVERED NPSH	(FT)	36.05	169.28			.00
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	934.91	919.16			.00

TURBINE DESCRIPTION

		MAIN TURBINE OXIDIZER	MAIN TURBINE FUEL	BOOST TURBINE OXIDIZER FF HYD	BOOST TURBINE FUEL COOLANT	AUXILIARY HPFT
TYPE						
DIAMETER	(IN)	4.229	1.761	2.132	1.684	.000
FLOW RATE	(LBS/SEC)	1.406	1.631	13.682	.173	.000
ADMISSION	(FRACTION)	.513	.421	.900	.080	.000
TIP SPEED	(FT/SEC)	1166.46	1385.85	93.93	289.96	.00
FIRST STG BLADE HEIGHT	(INCHES)	.141	.254	.031	.250	.000
SECOND STG BLADE HEIGHT	(INCHES)	.163	.374	.000	.000	.000
VELOCITY RATIO	(NONE)	.256	.400	.714	.125	.000
INLET PRESSURE	(PSIA)	2268.47	3722.95	2854.71	2268.47	.00
OUTLET PRESSURE	(PSIA)	1950.88	2279.72	2721.53	1950.88	.00
EFFICIENCY	(FRACTION)	.595	.636	.800	.280	.000
PRESSURE RATIO	(NONE)	1.16	1.64	1.05	1.16	.00
MAIN TURBINE INLET TEMP	(DEG R)	1110.28	1206.93	.00	1110.28	.00
MAIN TURBINE EXIT TEMP	(DEG R)	1083.34	1110.20	.00	1098.72	.00
HORSE POWER	(HP)	201.37	861.48	5.35	9.25	.00
GAS SPECIFIC HEAT	(BTU/LB-DEG R)	3.643	3.716	.000	3.643	.000
GAS PROCESS GAMMA	(NONE)	1.399	1.399	.000	1.399	.000
INLET ENTHALPY	(BTU/LBS)	3842.76	4216.15	.00	3842.76	.00
OUTLET ENTHALPY	(BTU/LBS)	3741.51	3842.76	.00	3795.10	.00
INLET ENTROPY	(BTU/LBS-DEG R)	13.04	12.84	.00	.00	.00
NOZZLE AREA	(IN**2)	.23	.15			.00
FLOW PARAMETER	(NONE)	.00	.00			.00

GASEOUS OXIDIZER HEAT EXCHANGER DESCRIPTION

		OXIDIZER	FUEL
HEAT RATE	(BTU/SEC)	25.79	25.79
FLOW RATE	(LB/SEC)	.134	.280
PRESSURE LOSS	(PSID)	24.28	1.14
INLET PRESSURE	(PSIA)	76.37	1945.38
INLET TEMPERATURE	(DEG R)	178.72	1219.44
OUTLET TEMPERATURE	(DEG R)	699.55	1193.10

Note: OTV Off Design model output for the heat exchanger is inaccurate predicting pressure loss and temperatures & values are estimated on schematics

PERFORMANCE

THRUST	(LBF)	1500.00
CHAMBER PRESSURE	(PSIA)	1095.15
ENGINE MIXUTRE RATIO	(BY WEIGHT)	7.00
AREA RATIO	(AE/AT)	1034.40
ODE SPECIFIC IMPULSE	(LBF-SEC/LBM)	511.13
ODE CHARACTERISTIC VELOCITY	(FT/SEC)	7522.65
SPECIFIC IMPULSE ENERGY RELEASE EFFICIENCY	(PERCENT)	99.800
SPECIFIC IMPULSE REACTION KINETIC EFFICIENCY	(PERCENT)	98.907
SPECIFIC IMPULSE DIVERGENCE EFFICIENCY	(PERCENT)	99.574
SPECIFIC IMPULSE HEAT LOSS EFFICIENCY	(PERCENT)	99.729
SPECIFIC IMPULSE BOUNDARY LAYER EFFICIENCY	(PERCENT)	96.745
EFFECTIVE TDK SPECIFIC IMPULSE	(LBF-SEC/LBM)	501.03
BOUNDARY LAYER IS LOSS	(LBF-SEC/LBM)	16.64
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	485.75 (T/C)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	534.64 (DUMP)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	484.39 (ENGINE)

SYSTEM PRESSURES

	(UNITS)	PROPELLANT OXIDIZER	PROPELLANT FUEL	GAS OXIDIZER	GAS FUEL
ENGINE INLET PRESSURE	(PSIA)	16.	19.		
BOOST PUMP DISCHARGE PRESSURE	(PSIA)	92.	74.		
MAIN PUMP INLET PRESSURE		76.	66.		
MAIN PUMP DISCHARGE PRESSURE	(PSIA)	2839.	5056.		
COOLING JACKET INLET PRESSURE	(PSIA)		5016.		
COMBUSTOR DISCHARGE PRESSURE	(PSIA)				4177.
NOZZLE DISCHARGE PRESSURE	(PSIA)				4163.
BOOST TURBINE INLET PRESSURE	(PSIA)			2855.	2268.
BOOST TURBINE DISCHARGE PRESSURE	(PSIA)			2722.	1951.
MAIN TURBINE INLET PRESSURE	(PSIA)			2268.	3729.
MAIN TURBINE DISCHARGE PRESSURE	(PSIA)			1951.	2280.
CHAMBER INJECTION PRESSURE	(PSIA)	2399.			1944.
CHAMBER COMBUSTION PRESSURE	(PSIA)				1695.

NOZZLE SEGMENTATION SUMMARY

		REGEN. COOLED	RADIATION COOLED
BREAKPOINT EPSILON	(NONE)	427.93	1034.40
SEGMENT LENGTH	(INCHES)	32.54	89.54
B/L Q	(BTU/SEC)	4453.89	.00
TOTAL Q	(BTU/SEC)	7174.63	.00
ADIABATIC LOSS	(NONE)	.01732	.00591
NET HEAT LOSS	(NONE)	.02793	.00449

CHANGER DESIGN

	(UNITS)		
HEAT RATE	(BTU/SEC)	.96	
DELTA-T	(DEG-R)	1000.77	
DELTA-T (AVERAGE)	(DEG-R)	1000.77	
THERMAL EFFICIENCY	(FRACTION)	.000	
LENGTH	(INCH)	.00	
FRONTAL AREA	(IN**2)	16.00	
MATERIAL FLAG	(NONE)	.00	
CHANNEL DIAMETER	(INCH)	.00	
ALL THICKNESS	(INCH)	.025	
CHANNEL SPACING	(INCH)	.050	
EIGHT	(LBM)	.005	
		COLD SIDE	HOT SIDE
ANNEL HEIGHT	(INCH)	.100	.100
SS FACTOR	(NONE)	.500	.500
CTION FACTOR	(NONE)	.020	.020
OW RATE	(LBM/SEC)	1.929	1.631
AT TRANSFER	(BTU/SQIN-R-SEC)	.007	.008
OW AREA	(IN**2)	4.267	4.267
TAP	(PSID)	.06	.51
LET PRESSURE	(PSIA)	5027.50	1946.86
ET TEMPERATURE	(DEG R)	108.55	1085.93
LET TEMPERATURE	(DEG R)	108.74	1085.76
ET ENTHALPY	(BTU/LBM)	206.34	3750.43
LET ENTHALPY	(BTU/LBM)	206.83	3749.84

OTV OFF-DESIGN MODEL
VERSION 6.0

PROPELLANT PROPERTIES SUMMARY

BEFORE DENS CALL: 18.8160 37.8000 -106.6670 1.9983

	PRESSURE (PSIA)	TEMPERATURE (DEG R)	ENTHALPY (BTU/LB)	ENTROPY (BTU/LB-R)	DENSITY (LB/FT3)
ENGINE FUEL INLET	18.8	37.80	-106.67	2.00	4.37
ENGINE OXID INLET	16.3	162.70	-57.47	.70	71.15
BOOST PUMP OUTLET	73.7	38.58	-103.31	2.02	4.37
BOOST OXIDIZER PUMP OUTLET	92.3	163.16	-57.44	.70	71.14
MAIN PUMP OUTLET	5055.8	109.06	208.46	3.66	4.48
MAIN OXIDIZER PUMP OUTLET	2705.6	177.83	-47.05	.72	71.18
MAIN VALVE OUTLET	5036.4	109.23	209.45	3.67	4.47
MAIN OXIDIZER VALVE OUTLET	2417.4	179.47	-47.06	.73	70.68
HEAT EXCH OUTLET (COLD)	5027.5	108.74	206.83	3.68	4.48
COMBUSTOR OUTLET	4177.5	968.89	3394.64	11.70	.73
NOZZLE OUTLET	4163.3	1203.72	4216.14	12.45	.59
FUEL PRESSURIZATION TAP-OFF	4163.3	1203.72	4216.14	12.45	.59
MAIN FUEL TURBINE INLET	3729.0	1206.93	4216.14	12.57	.54
MAIN FUEL TURBINE OUTLET	2279.7	1110.20	3842.76	12.79	.37
MAIN OXID TURBINE INLET	2268.5	1110.28	3842.76	12.79	.36
MAIN OXID TURBINE OUTLET	1950.9	1083.34	3741.51	12.85	.32
BOOST FUEL TURBINE OUTLET	1950.9	1098.72	3795.10	12.91	.32
GASEOUS OXYGEN HEAT EXCHANGER	1943.6	1193.10	4124.13	13.22	.29
HEAT EXCH OUTLET (HOT)	1946.9	1085.76	3749.84	12.87	.32
MAIN FUEL INJECTOR INLET	1943.6	1103.15	3804.74	13.07	.32
MAIN OXIDIZER INJECTOR INLET	2399.0	181.37	-47.39	.74	70.37

FUEL PUMP OVERALL EFFICIENCY (PERCENT) = 60.039
FUEL PUMP IDEAL EFFICIENCY (PERCENT) = 58.442

ERROR SUMMARY

ERROR	TIMES
0115	2553

ENGINE DESCRIPTION

	(UNITS)		
THRUST	(LBF)	750.00 (ENG)	750.00 (T/C)
MIXTURE RATIO	(NONE)	4.0000 (ENG)	4.0449 (T/C)
DELIVERED SPECIFIC IMPULSE	(LB-SEC/LBM)	481.7952 (ENG)	483.6111 (T/C)
MAIN TURBINES BYPASS	(PERCENT)	59.011	
MAIN OX TURBINE BYPASS	(PERCENT)	8.484	
		OXIDIZER	FUEL
INLET PROPELLANT TEMPERATURE	(DEG R)	182.70	37.80
INLET NPSH	(FT)	2.00	15.00
PROPELLANT FLOW RATE	(LBS/SEC)	1.24342	.30741 (T/C)
PROPELLANT FLOW RATE	(LBS/SEC)	1.24534	.31134 (ENG)
OVERBOARD LEAKAGE FLOW RATE	(LBS/SEC)	.00173	.00384
PRESSURANT FLOW RATE	(LBS/SEC)	.13400	.00288

COMBUSTOR AND NOZZLE DESCRIPTION

CHAMBER PRESSURE	(PSIA)	188.99	
CHAMBER TEMPERATURE	(DEG R)	5726.50	
AREA RATIO	(AE/AT)	1034.40	
BREAKPOINT EPSILON	(NONE)	427.93	
NOZZLE PERCENT LENGTH	(PERCENT)	93.61	
FUEL INLET HEAT OF FORMATION	(KCAL/MOLE)	2.31	
DUMP COOLING FLOW RATE	(LBS/SEC)	.00	
NOZZLE LENGTH	(INCHES)	89.54	
COMBUSTOR LENGTH	(INCHES)	20.00	
ENGINE LENGTH (EXT)	(INCHES)	117.00	
ENGINE LENGTH (RET)	(INCHES)	60.00	
CONTRACTION RATIO	(NONE)	4.00	
C SUB F	(NONE)	1.868	
THROAT AREA	(IN**2)	2.125	
HEAT LOSS BEFORE BL ATTACH	(BTU/SEC)	96.36	
		COMBUSTOR	NOZZLE
COOLANT FLOW RATE	(LBS/SEC)	.310	.310
COOLANT DELTA P	(PSID)	102.00	1.50
HEAT INPUT	(BTU/SEC)	1067.99	265.14
OUTLET PRESSURE	(PSIA)	464.16	460.83
INLET TEMPERATURE	(DEG R)	52.51	991.27
OUTLET TEMPERATURE	(DEG R)	991.26	1236.80
INLET ENTHALPY	(BTU/LBS)	-53.11	3386.84
OUTLET ENTHALPY	(BTU/LBS)	3388.84	4243.33
COOLANT DENSITY	(LBS/FT**3)	2.093	.078

OTV OFF-DESIGN MODEL
VERSION 6.0

F = 750

MR = 4.0

PUMP DESCRIPTION	(UNITS)	MAIN PUMP OXIDIZER	MAIN PUMP FUEL	BOOST PUMP OXIDIZER	BOOST PUMP FUEL	AUXILIARY FUEL PUMP
PUMP						
WHEEL SPEED	(RPM)	16700.4	57310.0	1018.9	10726.7	.0
EFFICIENCY	(FRACTION)	.4289	.4379	.7049	.5563	.000
HORSEPOWER	(HP)	2.60	22.98	.01	.17	.00
INLET PRESSURE	(PSIA)	16.95	23.28	16.34	18.82	.00
OUTLET PRESSURE	(PSIA)	233.14	568.42	17.11	23.48	.00
FLOW RATE	(LBS/SEC)	1.38	.31	1.38	.31	.00
DIAMETER	(IN)	2.31	2.22	2.25	1.93	.00
EFFECTIVE DENSITY	(LB/FT**3.	71.14	4.94			.00
INDUCER						
INLET FLOW VELOCITY	(FT/SEC)	4.21	16.73	.78	3.89	
TIP SPEED	(FT/SEC)	70.21	232.94	10.02	90.45	
FLOW COEFFICIENT	(NONE)	.06	.07	.08	.04	
HEAD COEFFICIENT	(NONE)	.11	.10	.00	.60	
DELTA P	(PSID)	8.31	5.64	.78	4.66	
EFFICIENCY	(FRACTION)	.752	.752	.705	.556	
DELIVERED NPSH	(FT)	2.15	14.98	2.00	15.00	
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	5931.76	6670.86			
IMPELLER						
INLET FLOW VELOCITY	(FT/SEC)	3.84	16.87			.00
TIP SPEED	(FT/SEC)	168.50	555.17			.00
FLOW COEFFICIENT	(NONE)	.05	.07			.00
HEAD COEFFICIENT	(NONE)	.48	.41			.00
HEAD RISE PER STAGE	(FT)	420.79	3928.80			.00
EFFICIENCY	(FRACTION)	.43	.42			.00
DELIVERED NPSH	(FT)	1.32	10.87			.00
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	530.38	616.96			.00

TURBINE DESCRIPTION		MAIN TURBINE OXIDIZER	MAIN TURBINE FUEL	BOOST TURBINE OXIDIZER FF HYD	BOOST TURBINE FUEL COOLANT	AUXILIARY HPFT
TYPE						
DIAMETER	(IN)	4.229	1.761	2.132	1.684	.000
FLOW RATE	(LBS/SEC)	.089	.126	1.379	.011	.000
ADMISSION	(FRACTION)	.513	.421	.900	.080	.000
TIP SPEED	(FT/SEC)	308.38	440.73	9.48	78.90	.00
FIRST STG BLADE HEIGHT	(INCHES)	.141	.254	.031	.250	.000
SECOND STG BLADE HEIGHT	(INCHES)	.163	.374	.000	.000	.000
VELOCITY RATIO	(NONE)	.106	.186	.711	.125	.000
INLET PRESSURE	(PSIA)	260.59	350.20	233.30	260.59	.00
OUTLET PRESSURE	(PSIA)	248.86	261.23	231.94	248.86	.00
EFFICIENCY	(FRACTION)	.379	.371	.800	.280	.000
PRESSURE RATIO	(NONE)	1.05	1.34	1.01	1.05	.00
MAIN TURBINE INLET TEMP	(DEG R)	1201.07	1237.48	.00	1201.07	.00
MAIN TURBINE EXIT TEMP	(DEG R)	1195.15	1201.07	.00	1196.72	.00
HORSE POWER	(HP)	2.63	22.97	.01	.09	.00
GAS SPECIFIC HEAT	(BTU/LB-DEG R)	3.500	3.503	.000	3.500	.000
GAS PROCESS GAMMA	(NONE)	1.401	1.398	.000	1.401	.000
INLET ENTHALPY	(BTU/LBS)	4114.46	4243.33	.00	4114.46	.00
OUTLET ENTHALPY	(BTU/LBS)	4093.61	4114.46	.00	4099.06	.00
INLET ENTROPY	(BTU/LBS-DEG R)	15.45	15.26	.00	.00	.00
NOZZLE AREA	(IN**2)	.23	.15			.00
FLOW PARAMETER	(NONE)	.00	.00			.00

GASEOUS OXIDIZER HEAT EXCHANGER DESCRIPTION		OXIDIZER	FUEL
HEAT RATE	(BTU/SEC)	26.07	26.07
FLOW RATE	(LB/SEC)	.134	.181
PRESSURE LOSS	(PSID)	24.28	1.14
INLET PRESSURE	(PSIA)	16.95	254.47
INLET TEMPERATURE	(DEG R)	178.72	1238.07
OUTLET TEMPERATURE	(DEG R)	705.24	1196.88

Note: OTV Off Design model output for the heat exchanger is inaccurate predicting pressure loss and temperatures & values are estimated on schematics

PERFORMANCE

THRUST	(LBF)	750.00
CHAMBER PRESSURE	(PSIA)	188.99
ENGINE MIXUTRE RATIO	(BY WEIGHT)	4.00
AREA RATIO	(AE/AT)	1034.40
ODE SPECIFIC IMPULSE	(LBF-SEC/LBM)	520.86
ODE CHARACTERISTIC VELOCITY	(FT/SEC)	8331.64
SPECIFIC IMPULSE ENERGY RELEASE EFFICIENCY	(PERCENT)	100.000
SPECIFIC IMPULSE REACTION KINETIC EFFICIENCY	(PERCENT)	98.692
SPECIFIC IMPULSE DIVERGENCE EFFICIENCY	(PERCENT)	99.574
SPECIFIC IMPULSE HEAT LOSS EFFICIENCY	(PERCENT)	99.497
SPECIFIC IMPULSE BOUNDARY LAYER EFFICIENCY	(PERCENT)	94.559
EFFECTIVE TDK SPECIFIC IMPULSE	(LBF-SEC/LBM)	509.38
BOUNDARY LAYER IS LOSS	(LBF-SEC/LBM)	28.34
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	483.61 (T/C)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	534.64 (DUMP)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	481.80 (ENGINE)

SYSTEM PRESSURES	(UNITS)	PROPELLANT		GAS	
		OXIDIZER	FUEL	OXIDIZER	FUEL
ENGINE INLET PRESSURE	(PSIA)	16.	19.		
BOOST PUMP DISCHARGE PRESSURE	(PSIA)	17.	23.		
MAIN PUMP INLET PRESSURE		17.	23.		
MAIN PUMP DISCHARGE PRESSURE	(PSIA)	233.	568.		
COOLING JACKET INLET PRESSURE	(PSIA)		566.		
COMBUSTOR DISCHARGE PRESSURE	(PSIA)				464.
NOZZLE DISCHARGE PRESSURE	(PSIA)				461.
BOOST TURBINE INLET PRESSURE	(PSIA)			233.	261.
BOOST TURBINE DISCHARGE PRESSURE	(PSIA)			232.	249.
MAIN TURBINE INLET PRESSURE	(PSIA)			261.	350.
MAIN TURBINE DISCHARGE PRESSURE	(PSIA)			249.	261.
CHAMBER INJECTION PRESSURE	(PSIA)	195.			248.
CHAMBER COMBUSTION PRESSURE	(PSIA)				189.

OZZLE SEGMENTATION SUMMARY		REGEN. COOLED	RADIATION COOLED
BREAKPOINT EPSILON	(NONE)	427.93	1034.40
SEGMENT LENGTH	(INCHES)	32.54	89.54
B/L Q	(BTU/SEC)	866.62	.00
TOTAL Q	(BTU/SEC)	1236.77	.00
ADIABATIC LOSS	(NONE)	.02318	.00791
NET HEAT LOSS	(NONE)	.05404	.00786

HEAT EXCHANGER DESIGN

	(UNITS)	
HEAT RATE	(BTU/SEC)	.19
DELTA-T	(DEG-R)	1256.21
DELTA-T (AVERAGE)	(DEG-R)	1256.09
THERMAL EFFICIENCY	(FRACTION)	.000
LENGTH	(INCH)	.00
FRONTAL AREA	(IN**2)	16.00
MATERIAL FLAG	(NONE)	.00
CHANNEL DIAMETER	(INCH)	.100
WALL THICKNESS	(INCH)	.025
CHANNEL SPACING	(INCH)	.050
WEIGHT	(LBM)	.005

		COLD SIDE	HOT SIDE
CHANNEL HEIGHT	(INCH)	.100	.100
LOSS FACTOR	(NONE)	.500	.500
FRICTION FACTOR	(NONE)	.020	.020
FLOW RATE	(LBM/SEC)	.310	.126
HEAT TRANSFER COEF	(BTU/SQIN-R-SEC)	.002	.001
FLOW AREA	(IN**2)	4.267	4.267
DELTAP	(PSID)	.01	.03
OUTLET PRESSURE	(PSIA)	567.48	248.65
INLET TEMPERATURE	(DEG R)	52.31	1196.53
OUTLET TEMPERATURE	(DEG R)	52.50	1196.10
INLET ENTHALPY	(BTU/LBM)	-53.72	4098.40
OUTLET ENTHALPY	(BTU/LBM)	-53.11	4096.90

OTV OFF-DESIGN MODEL
VERSION 6.0

PROPELLANT PROPERTIES SUMMARY

BEFORE DENS CALL: 18.8160 37.8000 -106.6670 1.9983

	PRESSURE (PSIA)	TEMPERATURE (DEG R)	ENTHALPY (BTU/LB)	ENTROPY (BTU/LB-R)	DENSITY (LB/FT3)
ENGINE FUEL INLET	18.8	37.80	-106.67	2.00	4.37
ENGINE OXID INLET	16.3	162.70	-57.47	.70	71.15
BOOST PUMP OUTLET	23.5	37.91	-106.29	2.02	4.37
BOOST OXIDIZER PUMP OUTLET	17.1	163.16	-57.44	.70	71.07
MAIN PUMP OUTLET	568.4	52.02	-54.58	3.66	4.12
MAIN OXIDIZER PUMP OUTLET	231.8	165.52	-56.22	.72	70.88
MAIN VALVE OUTLET	567.9	52.02	-54.58	3.67	4.12
MAIN OXIDIZER VALVE OUTLET	195.3	165.66	-56.22	.73	70.82
HEAT EXCH OUTLET (COLD)	567.5	52.50	-53.11	3.68	4.10
COMBUSTOR OUTLET	464.2	991.26	3388.84	11.70	.09
NOZZLE OUTLET	460.8	1236.80	4243.33	12.45	.07
FUEL PRESSURIZATION TAP-OFF	460.8	1236.80	4243.33	12.45	.07
MAIN FUEL TURBINE INLET	350.2	1237.48	4243.33	12.57	.05
MAIN FUEL TURBINE OUTLET	261.2	1201.07	4114.46	12.79	.04
MAIN OXID TURBINE INLET	260.6	1201.07	4114.46	12.79	.04
MAIN OXID TURBINE OUTLET	248.9	1195.15	4093.61	12.85	.04
BOOST FUEL TURBINE OUTLET	248.9	1196.72	4099.06	12.91	.04
GASEOUS OXYGEN HEAT EXCHANGER	248.5	1196.89	4099.61	13.22	.04
HEAT EXCH OUTLET (HOT)	248.6	1196.10	4096.90	12.87	.04
MAIN FUEL INJECTOR INLET	248.5	1196.92	4098.50	13.07	.04
MAIN OXIDIZER INJECTOR INLET	195.2	165.94	-56.11	.74	70.77

FUEL PUMP OVERALL EFFICIENCY (PERCENT) = 43.795
FUEL PUMP IDEAL EFFICIENCY (PERCENT) = 58.442

ERROR SUMMARY

ERROR	TIMES
0115	4094+

ENGINE DESCRIPTION

	(UNITS)		
THRUST	(LBF)	750.00 (ENG)	750.00 (T/C)
MIXTURE RATIO	(NONE)	5.0000 (ENG)	5.0561 (T/C)
DELIVERED SPECIFIC IMPULSE	(LB-SEC/LBM)	477.3193 (ENG)	478.9378 (T/C)
MAIN TURBINES BYPASS	(PERCENT)	59.241	
MAIN OX TURBINE BYPASS	(PERCENT)	6.972	

		OXIDIZER	FUEL
INLET PROPELLANT TEMPERATURE	(DEG R)	162.70	37.80
INLET NPSH	(FT)	2.00	15.00
PROPELLANT FLOW RATE	(LBS/SEC)	1.30739	.25857 (T/C)
PROPELLANT FLOW RATE	(LBS/SEC)	1.30940	.26188 (ENG)
OVERBOARD LEAKAGE FLOW RATE	(LBS/SEC)	.00182	.00323
PRESSURANT FLOW RATE	(LBS/SEC)	.13400	.00242

COMBUSTOR AND NOZZLE DESCRIPTION

CHAMBER PRESSURE	(PSIA)	183.71
CHAMBER TEMPERATURE	(DEG R)	5962.00
AREA RATIO	(AE/AT)	1034.40
BREAKPOINT EPSILON	(NONE)	427.93
NOZZLE PERCENT LENGTH	(PERCENT)	93.61
FUEL INLET HEAT OF FORMATION	(KCAL/MOLE)	2.76
DUMP COOLING FLOW RATE	(LBS/SEC)	.00
NOZZLE LENGTH	(INCHES)	89.54
COMBUSTOR LENGTH	(INCHES)	20.00
ENGINE LENGTH (EXT)	(INCHES)	117.00
ENGINE LENGTH (RET)	(INCHES)	60.00
CONTRACTION RATIO	(NONE)	4.00
C SUB F	(NONE)	1.921
THROAT AREA	(IN**2)	2.125
HEAT LOSS BEFORE BL ATTACH	(BTU/SEC)	89.23

		COMBUSTOR	NOZZLE
COOLANT FLOW RATE	(LBS/SEC)	.261	.261
COOLANT DELTA P	(PSID)	81.05	1.30
HEAT INPUT	(BTU/SEC)	991.23	243.33
OUTLET PRESSURE	(PSIA)	417.86	414.99
INLET TEMPERATURE	(DEG R)	51.26	1092.42
OUTLET TEMPERATURE	(DEG R)	1092.41	1359.71
INLET ENTHALPY	(BTU/LBS)	-58.30	3739.56
OUTLET ENTHALPY	(BTU/LBS)	3739.56	4671.86
COOLANT DENSITY	(LBS/FT**3)	2.087	.064

OTV OFF-DESIGN MODEL
VERSION 6.0

F = 750

MR = 5.0

PUMP DESCRIPTION	(UNITS)	MAIN PUMP OXIDIZER	MAIN PUMP FUEL	BOOST PUMP OXIDIZER	BOOST PUMP FUEL	AUXILIARY FUEL PUMP
PUMP						
WHEEL SPEED	(RPM)	15830.8	53649.6	1066.2	10726.7	.0
EFFICIENCY	(FRACTION)	.4612	.4060	.7049	.4953	.000
HORSEPOWER	(HP)	2.29	18.30	.01	.16	.00
INLET PRESSURE	(PSIA)	17.01	23.42	16.34	18.82	.00
OUTLET PRESSURE	(PSIA)	211.67	500.62	17.19	23.56	.00
FLOW RATE	(LBS/SEC)	1.44	.26	1.44	.26	.00
DIAMETER	(IN)	2.31	2.22	2.25	1.93	.00
EFFECTIVE DENSITY	(LB/FT**3.	71.14	4.94			.00
INDUCER						
INLET FLOW VELOCITY	(FT/SEC)	4.41	14.08	.81	3.27	
TIP SPEED	(FT/SEC)	66.55	218.06	10.49	90.45	
FLOW COEFFICIENT	(NONE)	.07	.06	.08	.04	
HEAD COEFFICIENT	(NONE)	.11	.10	.00	.61	
DELTA P	(PSID)	7.48	4.94	.85	4.74	
EFFICIENCY	(FRACTION)	.752	.752	.705	.495	
DELIVERED NPSH	(FT)	2.07	12.22	2.00	15.00	
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	6222.76	6328.57			
IMPELLER						
INLET FLOW VELOCITY	(FT/SEC)	4.01	14.19			.00
TIP SPEED	(FT/SEC)	159.72	519.71			.00
FLOW COEFFICIENT	(NONE)	.06	.07			.00
HEAD COEFFICIENT	(NONE)	.48	.41			.00
HEAD RISE PER STAGE	(FT)	378.88	3439.20			.00
EFFICIENCY	(FRACTION)	.46	.39			.00
DELIVERED NPSH	(FT)	1.27	8.87			.00
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	556.40	585.30			.00

TURBINE DESCRIPTION

		MAIN TURBINE		BOOST TURBINE		AUXILIARY
		OXIDIZER	FUEL	OXIDIZER	FUEL	HPFT
TYPE				FF HYD	COOLANT	
DIAMETER	(IN)	4.229	1.761	2.132	1.684	.000
FLOW RATE	(LBS/SEC)	.078	.105	1.443	.010	.000
ADMISSION	(FRACTION)	.513	.421	.900	.080	.000
TIP SPEED	(FT/SEC)	292.32	412.58	9.92	78.90	.00
FIRST STG BLADE HEIGHT	(INCHES)	.141	.254	.031	.250	.000
SECOND STG BLADE HEIGHT	(INCHES)	.163	.374	.000	.000	.000
VELOCITY RATIO	(NONE)	.099	.170	.711	.125	.000
INLET PRESSURE	(PSIA)	243.63	319.20	211.84	243.63	.00
OUTLET PRESSURE	(PSIA)	232.95	244.16	210.35	232.95	.00
EFFICIENCY	(FRACTION)	.352	.352	.800	.280	.000
PRESSURE RATIO	(NONE)	1.05	1.31	1.01	1.05	.00
MAIN TURBINE INLET TEMP	(DEG R)	1325.71	1360.31	.00	1325.71	.00
MAIN TURBINE EXIT TEMP	(DEG R)	1319.86	1325.71	.00	1321.07	.00
HORSE POWER	(HP)	2.28	18.30	.01	.08	.00
GAS SPECIFIC HEAT	(BTU/LB-DEG R)	3.510	3.512	.000	3.510	.000
GAS PROCESS GAMMA	(NONE)	1.397	1.395	.000	1.397	.000
INLET ENTHALPY	(BTU/LBS)	4549.16	4671.86	.00	4549.16	.00
OUTLET ENTHALPY	(BTU/LBS)	4528.48	4549.16	.00	4532.69	.00
INLET ENTROPY	(BTU/LBS-DEG R)	15.86	15.68	.00	.00	.00
NOZZLE AREA	(IN**2)	.23	.15			.00
FLOW PARAMETER	(NONE)	.00	.00			.00

GASEOUS OXIDIZER HEAT EXCHANGER DESCRIPTION

		OXIDIZER	FUEL
HEAT RATE	(BTU/SEC)	28.99	28.99
FLOW RATE	(LB/SEC)	.134	.153
PRESSURE LOSS	(PSID)	24.28	1.14
INLET PRESSURE	(PSIA)	17.01	237.67
INLET TEMPERATURE	(DEG R)	178.72	1360.81
OUTLET TEMPERATURE	(DEG R)	764.19	1306.75

Note: OTV Off Design model output for the heat exchanger is inaccurate predicting pressure loss and temperatures & values are estimated on schematics

OTV OFF-DESIGN MODEL
VERSION 6.0

PERFORMANCE

THRUST	(LBF)	750.00
CHAMBER PRESSURE	(PSIA)	183.71
ENGINE MIXUTRE RATIO	(BY WEIGHT)	5.00
AREA RATIO	(AE/AT)	1034.40
ODE SPECIFIC IMPULSE	(LBF-SEC/LBM)	521.35
ODE CHARACTERISTIC VELOCITY	(FT/SEC)	8025.12
SPECIFIC IMPULSE ENERGY RELEASE EFFICIENCY	(PERCENT)	99.967
SPECIFIC IMPULSE REACTION KINETIC EFFICIENCY	(PERCENT)	97.392
SPECIFIC IMPULSE DIVERGENCE EFFICIENCY	(PERCENT)	99.574
SPECIFIC IMPULSE HEAT LOSS EFFICIENCY	(PERCENT)	99.543
SPECIFIC IMPULSE BOUNDARY LAYER EFFICIENCY	(PERCENT)	94.919
EFFECTIVE TDK SPECIFIC IMPULSE	(LBF-SEC/LBM)	503.12
BOUNDARY LAYER IS LOSS	(LBF-SEC/LBM)	26.49
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	478.94 (T/C)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	534.64 (DUMP)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	477.32 (ENGINE)

SYSTEM PRESSURES

	(UNITS)	PROPELLANT		GAS	
		OXIDIZER	FUEL	OXIDIZER	FUEL
ENGINE INLET PRESSURE	(PSIA)	16.	19.		
BOOST PUMP DISCHARGE PRESSURE	(PSIA)	17.	24.		
MAIN PUMP INLET PRESSURE		17.	23.		
MAIN PUMP DISCHARGE PRESSURE	(PSIA)	212.	501.		
COOLING JACKET INLET PRESSURE	(PSIA)		499.		
COMBUSTOR DISCHARGE PRESSURE	(PSIA)				418.
NOZZLE DISCHARGE PRESSURE	(PSIA)				415.
BOOST TURBINE INLET PRESSURE	(PSIA)			212.	244.
BOOST TURBINE DISCHARGE PRESSURE	(PSIA)			210.	233.
MAIN TURBINE INLET PRESSURE	(PSIA)			244.	319.
MAIN TURBINE DISCHARGE PRESSURE	(PSIA)			233.	244.
CHAMBER INJECTION PRESSURE	(PSIA)	191.			233.
CHAMBER COMBUSTION PRESSURE	(PSIA)				184.

OZZLE SEGMENTATION SUMMARY

		REGEN. COOLED	RADIATION COOLED
BREAKPOINT EPSILON	(NONE)	427.93	1034.40
SEGMENT LENGTH	(INCHES)	32.54	89.54
B/L Q	(BTU/SEC)	774.80	.00
TOTAL Q	(BTU/SEC)	1145.32	.00
ADIABATIC LOSS	(NONE)	.02320	.00792
NET HEAT LOSS	(NONE)	.04812	.00762

HEAT EXCHANGER DESIGN

	(UNITS)	
HEAT RATE	(BTU/SEC)	.18
DELTA-T	(DEG-R)	1408.33
DELTA-T (AVERAGE)	(DEG-R)	1408.19
THERMAL EFFICIENCY	(FRACTION)	.000
LENGTH	(INCH)	.00
FRONTAL AREA	(IN**2)	16.00
MATERIAL FLAG	(NONE)	.00
CHANNEL DIAMETER	(INCH)	.100
WALL THICKNESS	(INCH)	.025
CHANNEL SPACING	(INCH)	.050
WEIGHT	(LBM)	.005

		COLD SIDE	HOT SIDE
CHANNEL HEIGHT	(INCH)	.100	.100
LOSS FACTOR	(NONE)	.500	.500
FRICTION FACTOR	(NONE)	.020	.020
FLOW RATE	(LBM/SEC)	.261	.105
HEAT TRANSFER COEF	(BTU/SQIN-R-SEC)	.001	.001
FLOW AREA	(IN**2)	4.267	4.267
DELTAP	(PSID)	.01	.02
OUTLET PRESSURE	(PSIA)	499.95	232.77
INLET TEMPERATURE	(DEG R)	51.03	1320.98
OUTLET TEMPERATURE	(DEG R)	51.25	1320.49
INLET ENTHALPY	(BTU/LBM)	-59.00	4532.40
OUTLET ENTHALPY	(BTU/LBM)	-58.30	4530.67

PROPELLANT PROPERTIES SUMMARY

BEFORE DENS CALL: 18.8160 37.8000 -106.6670 1.9983

PROPELLANT PROPERTIES SUMMARY	PRESSURE (PSIA)	TEMPERATURE (DEG R)	ENTHALPY (BTU/LB)	ENTROPY (BTU/LB-R)	DENSITY (LB/FT3)
ENGINE FUEL INLET	18.8	37.80	-106.67	2.00	4.37
ENGINE OXID INLET	16.3	162.70	-57.47	.70	71.15
BOOST PUMP OUTLET	23.6	37.93	-106.23	2.02	4.36
BOOST OXIDIZER PUMP OUTLET	17.2	163.16	-57.44	.70	71.07
MAIN PUMP OUTLET	500.8	51.57	-57.28	3.66	4.09
MAIN OXIDIZER PUMP OUTLET	210.2	165.09	-56.44	.72	70.93
MAIN VALVE OUTLET	500.2	51.57	-57.28	3.67	4.09
MAIN OXIDIZER VALVE OUTLET	190.8	165.17	-56.44	.73	70.90
HEAT EXCH OUTLET (COLD)	499.9	51.25	-58.30	3.68	4.10
COMBUSTOR OUTLET	417.9	1092.41	3739.56	11.70	.07
NOZZLE OUTLET	415.0	1359.71	4671.86	12.45	.06
FUEL PRESSURIZATION TAP-OFF	415.0	1359.71	4671.86	12.45	.06
MAIN FUEL TURBINE INLET	319.2	1360.31	4671.86	12.57	.04
MAIN FUEL TURBINE OUTLET	244.2	1325.71	4549.16	12.79	.03
MAIN OXID TURBINE INLET	243.6	1325.71	4549.16	12.79	.03
MAIN OXID TURBINE OUTLET	233.0	1319.86	4528.48	12.85	.03
BOOST FUEL TURBINE OUTLET	233.0	1321.07	4532.69	12.91	.03
GASEOUS OXYGEN HEAT EXCHANGER	232.6	1306.75	4482.62	13.22	.03
HEAT EXCH OUTLET (HOT)	232.8	1320.49	4530.67	12.87	.03
MAIN FUEL INJECTOR INLET	232.6	1312.65	4502.20	13.07	.03
MAIN OXIDIZER INJECTOR INLET	190.6	165.18	-56.45	.74	70.89

FUEL PUMP OVERALL EFFICIENCY (PERCENT) = 40.604
FUEL PUMP IDEAL EFFICIENCY (PERCENT) = 58.442

ERROR SUMMARY

ERROR	TIMES
0115	4094+

ENGINE DESCRIPTION

	(UNITS)		
THRUST	(LBF)	750.00 (ENG)	750.00 (T/C)
MIXTURE RATIO	(NONE)	6.0000 (ENG)	6.0674 (T/C)
DELIVERED SPECIFIC IMPULSE	(LB-SEC/LBM)	468.8016 (ENG)	470.2641 (T/C)
MAIN TURBINES BYPASS	(PERCENT)	59.179	
MAIN OX TURBINE BYPASS	(PERCENT)	5.508	

		OXIDIZER	FUEL
INLET PROPELLANT TEMPERATURE	(DEG R)	162.70	37.80
INLET NPSH	(FT)	2.00	15.00
PROPELLANT FLOW RATE	(LBS/SEC)	1.36919	.22566 (T/C)
PROPELLANT FLOW RATE	(LBS/SEC)	1.37128	.22855 (ENG)
OVERBOARD LEAKAGE FLOW RATE	(LBS/SEC)	.00190	.00282
PRESSURANT FLOW RATE	(LBS/SEC)	.13400	.00211

COMBUSTOR AND NOZZLE DESCRIPTION

CHAMBER PRESSURE	(PSIA)	178.83
CHAMBER TEMPERATURE	(DEG R)	6142.00
AREA RATIO	(AE/AT)	1034.40
BREAKPOINT EPSILON	(NONE)	427.93
NOZZLE PERCENT LENGTH	(PERCENT)	93.61
FUEL INLET HEAT OF FORMATION	(KCAL/MOLE)	3.13
DUMP COOLING FLOW RATE	(LBS/SEC)	.00
NOZZLE LENGTH	(INCHES)	89.54
COMBUSTOR LENGTH	(INCHES)	20.00
ENGINE LENGTH (EXT)	(INCHES)	117.00
ENGINE LENGTH (RET)	(INCHES)	60.00
CONTRACTION RATIO	(NONE)	4.00
C SUB F	(NONE)	1.973
THROAT AREA	(IN**2)	2.125
HEAT LOSS BEFORE BL ATTACH	(BTU/SEC)	83.74

		COMBUSTOR	NOZZLE
COOLANT FLOW RATE	(LBS/SEC)	.228	.228
COOLANT DELTA P	(PSID)	67.60	1.16
HEAT INPUT	(BTU/SEC)	931.93	226.66
OUTLET PRESSURE	(PSIA)	385.29	382.73
INLET TEMPERATURE	(DEG R)	50.42	1175.98
OUTLET TEMPERATURE	(DEG R)	1175.97	1460.50
INLET ENTHALPY	(BTU/LBS)	-61.76	4029.68
OUTLET ENTHALPY	(BTU/LBS)	4029.68	5024.80
COOLANT DENSITY	(LBS/FT**3)	2.084	.055

OTV OFF-DESIGN MODEL
VERSION 6.0

F = 750

MR = 6.0

PUMP DESCRIPTION	(UNITS)	MAIN PUMP OXIDIZER	MAIN PUMP FUEL	BOOST PUMP OXIDIZER	BOOST PUMP FUEL	AUXILIARY FUEL PUMP
PUMP						
WHEEL SPEED	(RPM)	15274.7	51020.2	1112.1	10726.7	.0
EFFICIENCY	(FRACTION)	.4871	.3810	.7049	.4483	.000
HORSEPOWER	(HP)	2.11	15.39	.01	.16	.00
INLET PRESSURE	(PSIA)	17.07	23.49	16.34	18.82	.00
OUTLET PRESSURE	(PSIA)	198.43	454.27	17.26	23.60	.00
FLOW RATE	(LBS/SEC)	1.51	.23	1.51	.23	.00
DIAMETER	(IN)	2.31	2.22	2.25	1.93	.00
EFFECTIVE DENSITY	(LB/FT**3,	71.14	4.94			.00
INDUCER						
INLET FLOW VELOCITY	(FT/SEC)	4.60	12.28	.85	2.86	
TIP SPEED	(FT/SEC)	64.21	207.37	10.94	90.45	
FLOW COEFFICIENT	(NONE)	.07	.06	.08	.03	
HEAD COEFFICIENT	(NONE)	.11	.10	.00	.61	
DELTA P	(PSID)	6.97	4.46	.92	4.78	
EFFICIENCY	(FRACTION)	.752	.752	.705	.448	
DELIVERED NPSH	(FT)	2.03	10.44	2.00	15.00	
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	6465.55	6070.92			
IMPELLER						
INLET FLOW VELOCITY	(FT/SEC)	4.19	12.36			.00
TIP SPEED	(FT/SEC)	154.11	494.24			.00
FLOW COEFFICIENT	(NONE)	.07	.06			.00
HEAD COEFFICIENT	(NONE)	.48	.41			.00
HEAD RISE PER STAGE	(FT)	353.01	3104.61			.00
EFFICIENCY	(FRACTION)	.48	.37			.00
DELIVERED NPSH	(FT)	1.25	7.57			.00
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	578.11	561.47			.00

TURBINE DESCRIPTION		MAIN TURBINE OXIDIZER	MAIN TURBINE FUEL	BOOST TURBINE OXIDIZER FF HYD	BOOST TURBINE FUEL COOLANT	AUXILIARY HPFT
TYPE						
DIAMETER	(IN)	4.229	1.761	2.132	1.684	.000
FLOW RATE	(LBS/SEC)	.071	.092	1.505	.009	.000
ADMISSION	(FRACTION)	.513	.421	.900	.080	.000
TIP SPEED	(FT/SEC)	282.05	392.36	10.35	78.90	.00
FIRST STG BLADE HEIGHT	(INCHES)	.141	.254	.031	.250	.000
SECOND STG BLADE HEIGHT	(INCHES)	.163	.374	.000	.000	.000
VELOCITY RATIO	(NONE)	.094	.159	.712	.125	.000
INLET PRESSURE	(PSIA)	231.12	297.67	198.63	231.12	.00
OUTLET PRESSURE	(PSIA)	220.96	231.58	197.01	220.96	.00
EFFICIENCY	(FRACTION)	.330	.337	.800	.280	.000
PRESSURE RATIO	(NONE)	1.05	1.29	1.01	1.05	.00
MAIN TURBINE INLET TEMP	(DEG R)	1427.85	1461.03	.00	1427.85	.00
MAIN TURBINE EXIT TEMP	(DEG R)	1421.38	1427.85	.00	1422.88	.00
HORSE POWER	(HP)	2.09	15.38	.01	.08	.00
GAS SPECIFIC HEAT	(BTU/LB-DEG R)	3.522	3.523	.000	3.522	
GAS PROCESS GAMMA	(NONE)	1.391	1.390	.000	1.391	
INLET ENTHALPY	(BTU/LBS)	4906.76	5024.80	.00	4906.76	
OUTLET ENTHALPY	(BTU/LBS)	4885.93	4906.76	.00	4889.08	
INLET ENTROPY	(BTU/LBS-DEG R)	16.17	16.00	.00	.00	
NOZZLE AREA	(IN**2)	.23	.15			
FLOW PARAMETER	(NONE)	.00	.00			

GASEOUS OXIDIZER HEAT EXCHANGER DESCRIPTION		OXIDIZER	FUEL
HEAT RATE	(BTU/SEC)	31.36	31.36
FLOW RATE	(LB/SEC)	.134	.134
PRESSURE LOSS	(PSID)	24.28	.14
INLET PRESSURE	(PSIA)	17.07	225.04
INLET TEMPERATURE	(DEG R)	178.72	1461.49
OUTLET TEMPERATURE	(DEG R)	811.98	1394.64

Note: OTV Off D
the heat exchan
predicting press
& values are es

PERFORMANCE

THRUST	(LBF)	750.00
CHAMBER PRESSURE	(PSIA)	178.83
ENGINE MIXUTRE RATIO	(BY WEIGHT)	6.00
AREA RATIO	(AE/AT)	1034.40
ODE SPECIFIC IMPULSE	(LBF-SEC/LBM)	519.42
ODE CHARACTERISTIC VELOCITY	(FT/SEC)	7675.51
SPECIFIC IMPULSE ENERGY RELEASE EFFICIENCY	(PERCENT)	99.900
SPECIFIC IMPULSE REACTION KINETIC EFFICIENCY	(PERCENT)	95.864
SPECIFIC IMPULSE DIVERGENCE EFFICIENCY	(PERCENT)	99.574
SPECIFIC IMPULSE HEAT LOSS EFFICIENCY	(PERCENT)	99.601
SPECIFIC IMPULSE BOUNDARY LAYER EFFICIENCY	(PERCENT)	95.176
EFFECTIVE TDK SPECIFIC IMPULSE	(LBF-SEC/LBM)	49[illegible].34
BOUNDARY LAYER IS LOSS	(LBF-SEC/LBM)	25.06
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	470.26 (T/C)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	534.64 (DUMP)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	468.60 (ENGINE)

SYSTEM PRESSURES

	(UNITS)	PROPELLANT OXIDIZER	PROPELLANT FUEL	GAS OXIDIZER	GAS FUEL
ENGINE INLET PRESSURE	(PSIA)	16.	15.		
BOOST PUMP DISCHARGE PRESSURE	(PSIA)	17.	24.		
MAIN PUMP INLET PRESSURE		17.	23.		
MAIN PUMP DISCHARGE PRESSURE	(PSIA)	198.	454.		
COOLING JACKET INLET PRESSURE	(PSIA)		453.		
COMBUSTOR DISCHARGE PRESSURE	(PSIA)				385.
NOZZLE DISCHARGE PRESSURE	(PSIA)				383.
BOOST TURBINE INLET PRESSURE	(PSIA)			199.	231.
BOOST TURBINE DISCHARGE PRESSURE	(PSIA)			197.	221.
MAIN TURBINE INLET PRESSURE	(PSIA)			231.	298.
MAIN TURBINE DISCHARGE PRESSURE	(PSIA)			221.	232.
CHAMBER INJECTION PRESSURE	(PSIA)	186.			221.
CHAMBER COMBUSTION PRESSURE	(PSIA)				179.

OZZLE SEGMENTATION SUMMARY

		REGEN. COOLED	RADIATION COOLED
BREAKPOINT EPSILON	(NONE)	427.93	1034.40
SEGMENT LENGTH	(INCHES)	32.54	89.54
B/L Q	(BTU/SEC)	705.23	.00
TOTAL Q	(BTU/SEC)	1074.85	.00
ADIABATIC LOSS	(NONE)	.02322	.00792
NET HEAT LOSS	(NONE)	.04388	.00744

HEAT EXCHANGER DESIGN

	(UNITS)	
HEAT RATE	(BTU/SEC)	.18
DELTA-T	(DEG-R)	1530.05
DELTA-T (AVERAGE)	(DEG-R)	1529.88
THERMAL EFFICIENCY	(FRACTION)	.000
LENGTH	(INCH)	.00
FRONTAL AREA	(IN**2)	16.00
MATERIAL FLAG	(NONE)	.00
CHANNEL DIAMETER	(INCH)	.100
WALL THICKNESS	(INCH)	.025
CHANNEL SPACING	(INCH)	.050
WEIGHT	(LBM)	.005

		COLD SIDE	HOT SIDE
CHANNEL HEIGHT	(INCH)	.100	.100
LOSS FACTOR	(NONE)	.500	.500
FRICTION FACTOR	(NONE)	.020	.020
FLOW RATE	(LBM/SEC)	.228	.092
HEAT TRANSFER COEF	(BTU/SQIN-R-SEC)	.001	.001
FLOW AREA	(IN**2)	4.267	4.267
DELTAP	(PSID)	.00	.02
OUTLET PRESSURE	(PSIA)	453.75	220.81
INLET TEMPERATURE	(DEG R)	50.17	1422.87
OUTLET TEMPERATURE	(DEG R)	50.42	1422.33
INLET ENTHALPY	(BTU/LBM)	-62.53	4889.04
OUTLET ENTHALPY	(BTU/LBM)	-61.76	4887.13

PROPELLANT PROPERTIES SUMMARY

BEFORE DENS CALL: 18.8160 37.8000 -106.6670 1.9983

	PRESSURE (PSIA)	TEMPERATURE (DEG R)	ENTHALPY (BTU/LB)	ENTROPY (BTU/LB-R)	DENSITY (LB/FT3)
ENGINE FUEL INLET	18.8	37.80	-106.67	2.00	4.37
ENGINE OXID INLET	16.3	162.70	-57.47	.70	71.15
BOOST PUMP OUTLET	23.6	37.95	-106.18	2.02	4.36
BOOST OXIDIZER PUMP OUTLET	17.3	163.16	-57.44	.70	71.07
MAIN PUMP OUTLET	454.3	51.30	-59.00	3.66	4.07
MAIN OXIDIZER PUMP OUTLET	196.6	164.83	-56.57	.72	70.96
MAIN VALVE OUTLET	454.0	51.30	-59.00	3.67	4.07
MAIN OXIDIZER VALVE OUTLET	186.6	164.88	-56.57	.73	70.94
HEAT EXCH OUTLET (COLD)	453.8	50.42	-61.76	3.68	4.11
COMBUSTOR OUTLET	385.3	1175.97	4029.68	11.70	.06
NOZZLE OUTLET	382.7	1460.50	5024.80	12.45	.05
FUEL PRESSURIZATION TAP-OFF	382.7	1460.50	5024.80	12.45	.05
MAIN FUEL TURBINE INLET	297.7	1461.03	5024.80	12.57	.04
MAIN FUEL TURBINE OUTLET	231.6	1427.85	4906.76	12.79	.03
MAIN OXID TURBINE INLET	231.1	1427.85	4906.76	12.79	.03
MAIN OXID TURBINE OUTLET	221.0	1421.98	4885.93	12.85	.03
BOOST FUEL TURBINE OUTLET	221.0	1422.88	4889.08	12.91	.03
GASEOUS OXYGEN HEAT EXCHANGER	220.7	1394.64	4790.00	13.22	.03
HEAT EXCH OUTLET (HOT)	220.8	1422.33	4887.13	12.87	.03
MAIN FUEL INJECTOR INLET	220.7	1406.21	4829.65	13.07	.03
MAIN OXIDIZER INJECTOR INLET	186.4	164.83	-56.60	.74	70.95

FUEL PUMP OVERALL EFFICIENCY (PERCENT) = 38.100
FUEL PUMP IDEAL EFFICIENCY (PERCENT) = 58.442

ERROR SUMMARY

ERROR	TIMES
0115	4094+

ENGINE DESCRIPTION

	(UNITS)		
THRUST	(LBF)	750.00 (ENG)	750.00 (T/C)
MIXTURE RATIO	(NONE)	7.0000 (ENG)	7.0787 (T/C)
DELIVERED SPECIFIC IMPULSE	(LB-SEC/LBM)	454.0315 (ENG)	455.3547 (T/C)
MAIN TURBINES BYPASS	(PERCENT)	58.727	
MAIN OX TURBINE BYPASS	(PERCENT)	4.393	
		OXIDIZER	FUEL
INLET PROPELLANT TEMPERATURE	(DEG R)	162.70	37.80
INLET NPSH	(FT)	2.00	15.00
PROPELLANT FLOW RATE	(LBS/SEC)	1.44319	.20388 (T/C)
PROPELLANT FLOW RATE	(LBS/SEC)	1.44538	.20648 (ENG)
OVERBOARD LEAKAGE FLOW RATE	(LBS/SEC)	.00201	.00255
PRESSURANT FLOW RATE	(LBS/SEC)	.13400	.00191

COMBUSTOR AND NOZZLE DESCRIPTION

CHAMBER PRESSURE	(PSIA)	176.95	
CHAMBER TEMPERATURE	(DEG R)	6214.00	
AREA RATIO	(AE/AT)	1034.40	
BREAKPOINT EPSILON	(NONE)	427.93	
NOZZLE PERCENT LENGTH	(PERCENT)	93.61	
FUEL INLET HEAT OF FORMATION	(KCAL/MOLE)	3.37	
DUMP COOLING FLOW RATE	(LBS/SEC)	.00	
NOZZLE LENGTH	(INCHES)	89.54	
COMBUSTOR LENGTH	(INCHES)	20.00	
ENGINE LENGTH (EXT)	(INCHES)	117.00	
ENGINE LENGTH (RET)	(INCHES)	60.00	
CONTRACTION RATIO	(NONE)	4.00	
C SUB F	(NONE)	1.994	
THROAT AREA	(IN**2)	2.125	
HEAT LOSS BEFORE BL ATTACH	(BTU/SEC)	79.07	
		COMBUSTOR	NOZZLE
COOLANT FLOW RATE	(LBS/SEC)	.206	.206
COOLANT DELTA P	(PSID)	58.95	1.05
HEAT INPUT	(BTU/SEC)	881.19	212.78
OUTLET PRESSURE	(PSIA)	363.39	361.07
INLET TEMPERATURE	(DEG R)	49.92	1230.19
OUTLET TEMPERATURE	(DEG R)	1230.19	1525.20
INLET ENTHALPY	(BTU/LBS)	-63.89	4218.16
OUTLET ENTHALPY	(BTU/LBS)	4218.16	5252.13
COOLANT DENSITY	(LBS/FT**3)	2.080	.050

OTV OFF-DESIGN MODEL
VERSION 6.0

PUMP DESCRIPTION	(UNITS)	MAIN PUMP OXIDIZER	MAIN PUMP FUEL	BOOST PUMP OXIDIZER	BOOST PUMP FUEL	AUXILIARY FUEL PUMP
PUMP						
WHEEL SPEED	(RPM)	14828.8	49207.4	1167.3	10726.7	.0
EFFICIENCY	(FRACTION)	.5131	.3624	.7048	.4146	.000
HORSEPOWER	(HP)	1.98	13.61	.01	.16	.00
INLET PRESSURE	(PSIA)	17.14	23.53	16.34	18.82	.00
OUTLET PRESSURE	(PSIA)	188.05	423.51	17.36	23.62	.00
FLOW RATE	(LBS/SEC)	1.58	.21	1.58	.21	.00
DIAMETER	(IN)	2.31	2.22	2.25	1.93	.00
EFFECTIVE DENSITY	(LB/FT**3,	71.14	4.94			.00
INDUCER						.00
INLET FLOW VELOCITY	(FT/SEC)	4.83	11.10	.89	2.58	
TIP SPEED	(FT/SEC)	62.34	200.00	11.48	90.45	
FLOW COEFFICIENT	(NONE)	.08	.08	.08	.03	
HEAD COEFFICIENT	(NONE)	.11	.10	.00	.62	
DELTA P	(PSID)	6.57	4.14	1.02	4.81	
EFFICIENCY	(FRACTION)	.752	.752	.705	.415	
DELIVERED NPSH	(FT)	2.01	9.30	2.00	15.00	
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	6722.38	5883.87			
IMPELLER						
INLET FLOW VELOCITY	(FT/SEC)	4.39	11.19			.00
TIP SPEED	(FT/SEC)	149.61	476.68			.00
FLOW COEFFICIENT	(NONE)	.07	.06			.00
HEAD COEFFICIENT	(NONE)	.48	.41			.00
HEAD RISE PER STAGE	(FT)	332.66	2882.63			.00
EFFICIENCY	(FRACTION)	.51	.35			.00
DELIVERED NPSH	(FT)	1.24	6.75			.00
STAGE SPECIFIC SPEED	(RPM*GPM**.5/FT**.75)	601.07	544.17			.00

$\dot{F} = 750$

$MR = 7$

TURBINE DESCRIPTION

		MAIN TURBINE OXIDIZER	MAIN TURBINE FUEL	BOOST TURBINE OXIDIZER FF HYD	BOOST TURBINE FUEL COOLANT	AUXILIARY HPFT
TYPE						
DIAMETER	(IN)	4.229	1.761	2.132	1.684	.000
FLOW RATE	(LBS/SEC)	.067	.084	1.579	.008	.000
ADMISSION	(FRACTION)	.513	.421	.900	.083	.000
TIP SPEED	(FT/SEC)	273.82	378.42	10.87	78.90	.00
FIRST STG BLADE HEIGHT	(INCHES)	.141	.254	.031	.250	.000
SECOND STG BLADE HEIGHT	(INCHES)	.163	.374	.000	.000	.000
VELOCITY RATIO	(NONE)	.091	.151	.712	.125	.000
INLET PRESSURE	(PSIA)	223.59	284.31	188.26	223.59	.00
OUTLET PRESSURE	(PSIA)	213.77	224.01	186.48	213.77	.00
EFFICIENCY	(FRACTION)	.315	.329	.800	.280	.000
PRESSURE RATIO	(NONE)	1.05	1.27	1.01	1.05	.00
MAIN TURBINE INLET TEMP	(DEG R)	1492.75	1525.68	.00	1493.75	.00
MAIN TURBINE EXIT TEMP	(DEG R)	1487.93	1493.74	.00	1488.58	.00
HORSE POWER	(HP)	1.96	13.56	.01	.07	.00
GAS SPECIFIC HEAT	(BTU/LB-DEG R)	3.531	3.532	.000	3.531	.000
GAS PROCESS GAMMA	(NONE)	1.387	1.386	.000	1.387	.000
INLET ENTHALPY	(BTU/LBS)	5133.27	5252.13	.00	5138.27	.00
OUTLET ENTHALPY	(BTU/LBS)	5117.56	5138.27	.00	5119.87	.00
INLET ENTROPY	(BTU/LBS-DEG R)	16.36	16.20	.00	.00	.00
NOZZLE AREA	(IN**2)	.23	.15			.00
FLOW PARAMETER	(NONE)	.00	.00			.00

GASEOUS OXIDIZER HEAT EXCHANGER DESCRIPTION

		OXIDIZER	FUEL
HEAT RATE	(BTU/SEC)	32.84	32.84
FLOW RATE	(LB/SEC)	.134	.120
PRESSURE LOSS	(PSID)	24.28	1.14
INLET PRESSURE	(PSIA)	17.14	217.31
INLET TEMPERATURE	(DEG R)	178.72	1526.10
OUTLET TEMPERATURE	(DEG R)	841.91	1448.21

Note. OTV Off Design model output for the heat exchanger is inaccurate predicting pressure loss and temperatures & values are estimated on schematics

PERFORMANCE

THRUST	(LBF)	750.00
CHAMBER PRESSURE	(PSIA)	176.95
ENGINE MIXUTRE RATIO	(BY WEIGHT)	7.00
AREA RATIO	(AE/AT)	1034.40
ODE SPECIFIC IMPULSE	(LBF-SEC/LBM)	513.74
ODE CHARACTERISTIC VELOCITY	(FT/SEC)	7361.47
SPECIFIC IMPULSE ENERGY RELEASE EFFICIENCY	(PERCENT)	99.800
SPECIFIC IMPULSE REACTION KINETIC EFFICIENCY	(PERCENT)	93.863
SPECIFIC IMPULSE DIVERGENCE EFFICIENCY	(PERCENT)	99.574
SPECIFIC IMPULSE HEAT LOSS EFFICIENCY	(PERCENT)	99.659
SPECIFIC IMPULSE BOUNDARY LAYER EFFICIENCY	(PERCENT)	95.358
EFFECTIVE TOM SPECIFIC IMPULSE	(LBF-SEC/LBM)	477.57
BOUNDARY LAYER IS LOSS	(LBF-SEC/LBM)	23.85
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	455.35 (T/C)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	534.64 (DUMP)
DELIVERED SPECIFIC IMPULSE	(LBF-SEC/LBM)	454.03 (ENGINE)

SYSTEM PRESSURES	(UNITS)	PROPELLANT		GAS	
		OXIDIZER	FUEL	OXIDIZER	FUEL
ENGINE INLET PRESSURE	(PSIA)	16.	19.		
BOOST PUMP DISCHARGE PRESSURE	(PSIA)	17.	24.		
MAIN PUMP INLET PRESSURE		17	24.		
MAIN PUMP DISCHARGE PRESSURE	(PSIA)	188.	424.		
COOLING JACKET INLET PRESSURE	(PSIA)		422.		
COMBUSTOR DISCHARGE PRESSURE	(SIA)				363.
NOZZLE DISCHARGE PRESSURE	(PSIA)				361.
BOOST TURBINE INLET PRESSURE	(PSIA)			188.	224.
BOOST TURBINE DISCHARGE PRESSURE	(PSIA)			186.	214.
MAIN TURBINE INLET PRESSURE	(PSIA)			224.	284.
MAIN TURBINE DISCHARGE PRESSURE	(PSIA)			214.	224.
CHAMBER INJECTION PRESSURE	(PSIA)	185.			214.
CHAMBER COMBUSTION PRESSURE	(PSIA)				177.

OZZLE SEGMENTATION SUMMARY		REGEN. COOLED	RADIATION COOLED
BREAKPOINT EPSILON	(NONE)	427.93	1034.40
SEGMENT LENGTH	(INCHES)	32.54	89.54
B/L Q	(BTU/SEC)	649.21	.00
TOTAL Q	(BTU/SEC)	1014.90	.00
ADIABATIC LOSS	(NONE)	.02322	.00793
NET HEAT LOSS	(NONE)	04077	.00742

HEAT EXCHANGER DESIGN

	(UNITS)		
HEAT RATE	(BTU/SEC)	.17	
DELTA-T	(DEG-R)	1610.87	
DELTA-T (AVERAGE)	(DEG-R)	1610.89	
THERMAL EFFICIENCY	(FRACTION)	.000	
LENGTH	(INCH)	.00	
FRONTAL AREA	(IN**2)	16.00	
MATERIAL FLAG	(NONE)	.00	
CHANNEL DIAMETER	(INCH)	.100	
WALL THICKNESS	(INCH)	.025	
CHANNEL SPACING	(INCH)	.050	
WEIGHT	(LBM)	.005	
		COLD SIDE	HOT SIDE
CHANNEL HEIGHT	(INCH)	.100	.100
LOSS FACTOR	(NONE)	.500	.500
FRICTION FACTOR	(NONE)	.020	.020
FLOW RATE	(LBM/SEC)	.208	.084
HEAT TRANSFER COEF	(BTU/SQIN-R-SEC)	.001	.001
FLOW AREA	(IN**2)	4.267	4.267
DELTAP	(PSID)	.00	.02
OUTLET PRESSURE	(PSIA)	423.08	213.63
INLET TEMPERATURE	(DEG R)	49.65	1488.62
OUTLET TEMPERATURE	(DEG R)	49.92	1488.04
INLET ENTHALPY	(BTU/LBM)	-64.72	5119.99
OUTLET ENTHALPY	(BTU/LBM)	-63.89	5117.95

PROPELLANT PROPERTIES SUMMARY

BEFORE DENS CALL: 18.8160 37.8500 -106.6670 1.9983

	PRESSURE (PSIA)	TEMPERATURE (DEG R)	ENTHALPY (BTU/LB)	ENTROPY (BTU/LB-R)	DENSITY (LB/FT3)
ENGINE FUEL INLET	18.8	37.80	-106.67	2.00	4.37
ENGINE OXID INLET	16.3	162.70	-57.47	.79	71.15
BOOST PUMP OUTLET	23.6	37.96	-106.14	2.02	4.36
BOOST OXIDIZER PUMP OUTLET	17.4	163.16	-57.44	.70	71.07
MAIN PUMP OUTLET	423.5	51.16	-59.96	3.66	4.05
MAIN OXIDIZER PUMP OUTLET	186.3	164.63	-56.67	.72	70.98
MAIN VALVE OUTLET	423.3	51.16	-59.96	3.67	4.05
MAIN OXIDIZER VALVE OUTLET	185.3	164.63	-56.67	.73	70.98
HEAT EXCH OUTLET (COLD)	423.1	49.92	-63.89	3.68	4.11
COMBUSTOR OUTLET	363.4	1230.19	4218.16	11.70	.06
NOZZLE OUTLET	361.1	1525.20	5252.13	12.45	.04
FUEL PRESSURIZATION TAP-OFF	361.1	1525.20	5252.13	12.45	.04
MAIN FUEL TURBINE INLET	284.3	1525.68	5252.13	12.57	.03
MAIN FUEL TURBINE OUTLET	224.0	1493.74	5133.27	12.79	.03
MAIN OXID TURBINE INLET	223.6	1493.75	5138.27	12.79	.03
MAIN OXID TURBINE OUTLET	213.8	1437.93	5117.56	12.85	.03
BOOST FUEL TURBINE OUTLET	213.8	1488.58	5119.87	12.91	.03
GASEOUS OXYGEN HEAT EXCHANGER	213.5	1448.21	4977.87	13.22	.03
HEAT EXCH OUTLET (HOT)	213.6	1488.04	5117.95	12.87	.03
MAIN FUEL INJECTOR INLET	213.5	1464.88	5035.68	13.07	.03
MAIN OXIDIZER INJECTOR INLET	185.3	164.59	-56.70	.74	70.99

FUEL PUMP OVERALL EFFICIENCY (PERCENT) = 36.244
FUEL PUMP IDEAL EFFICIENCY (PERCENT) = 58.442

ERROR SUMMARY

ERROR	TIMES
0115	4094+

APPENDIX B

OTVE HIGH-PRESSURE FUEL TURBOPUMP ROTORDYNAMIC ANALYSIS

ANALYSIS: CROSS SECTION 1

The first cross section analyzed is shown in Figure B-1. It employs an inducer stage and four pump stages. The turbine has two stages and is of the partial emission/expander cycle variety. The shaft is radially supported by two hydrostatic bearings, located axially as shown, using liquid hydrogen as their working fluid. Wherever possible damper seals are utilized to help control the rotordynamics. These include the pump impeller wear ring seals, and the pump and turbine interstage seals. Figure B-2 shows the finite element beam model for this configuration. Table B-1 shows the stiffness, damping and cross coupling for the seals and bearings. All values are for a shaft speed of 200,000 rpm.

Figures B-3 and B-4 show the natural frequency and stability maps for this model. Note that the first two criticals are below 50,000 rpm and the third is at about 80,000 rpm. The fourth mode is the natural frequency of the draw bolt and is not important due to the presence of deflection limiters. The fifth mode is thus actually the fourth rotor mode. Note that each mode appears as two curves which diverge at increasing speed. The lower frequency curve is the backward component of the mode, and is not important. The higher frequency curve is the forward component of the mode. When a forward component frequency equals shaft speed that speed is a critical speed.

The stability map of Figure B-4 shows the log decs for the first two rotor modes only. Note that the first mode is unstable for all speeds, and the second mode is unstable for all speeds above 170,000 rpm.

These results are summarized in Table B-2.

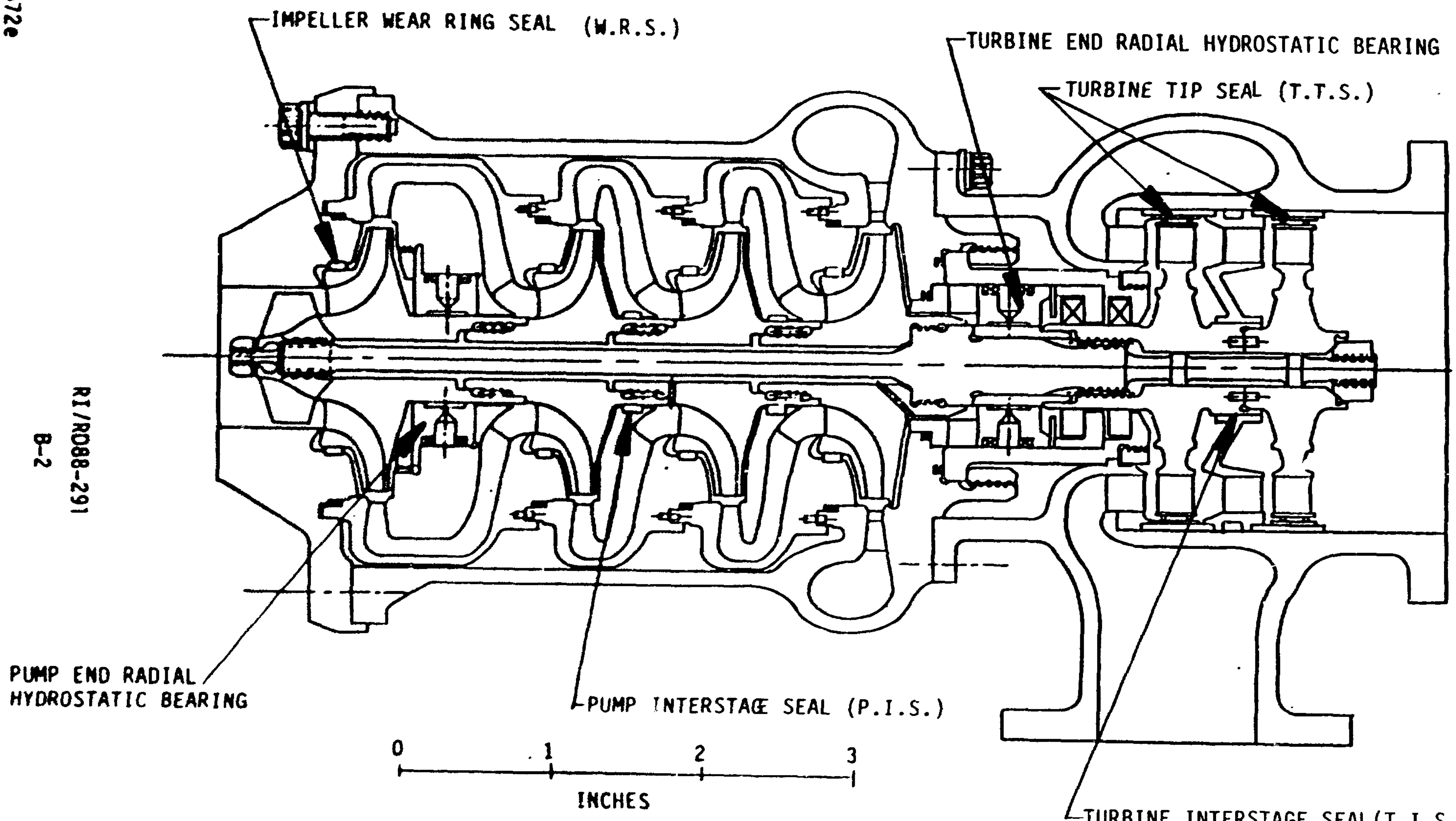


Figure B-1. OTV High-Pressure Fuel Turbopump Preliminary Configuration

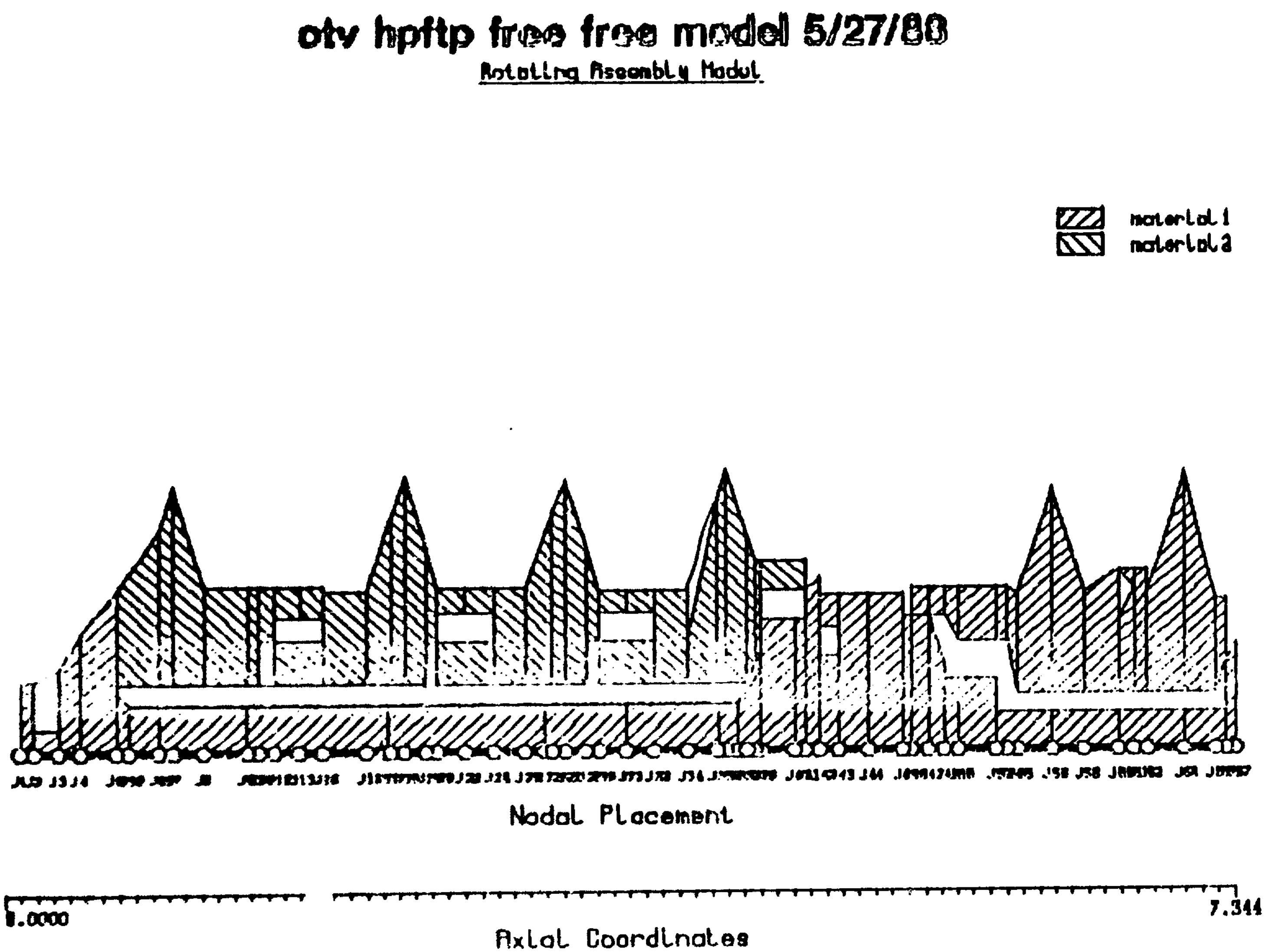


Figure B-2. Finite Element Beam Model Preliminary Configuration -

5472e

Table B-1. KXX, KXY, and CXX for Seals and Bearings, etc. at 200,000 rpm

	Kxx lb-s/in	Kxy lb-s/in	Cxx lb-s/in
P/E BEARING	188620	16726	1.6
1ST P.I.S.	0	0	0
2ND P.I.S.	8100	1800	.17
3RD P.I.S.	8100	1800	.17
1ST W.R.S.	14550	5445	.31
2ND W.R.S.	14550	5445	.31
3RD W.R.S.	14550	5445	.31
4TH W.R.S.	14550	5445	.31
T/E BEARING	188620	16726	1.6
T.T.S. (EACH)	0	0	0
T.I.S.	405	126	.065
ALFORD BETA=1.5		483	

P.I.S.=PUMP INTERSTAGE SEAL

W.R.S.=WEAR RING SEAL

T.T.S.=TURBINE TIP SEAL

T.I.S.=TURBINE INTERSTAGE SEAL

To improve the rotordynamics of the turbopump the first step taken was to consider lengthening the W.R.S. from 0.1 to 0.2 in., and to include a swirl brake on each W.R.S. to reduce the inlet swirl ratio from 0.5 to 0.25. Table B-3 lists the new rotordynamic coefficients and the analysis results.

The only significant change is that the second mode has been stabilized by the reduced cross coupling and increased damping. The first mode is still unstable throughout the entire operating range.

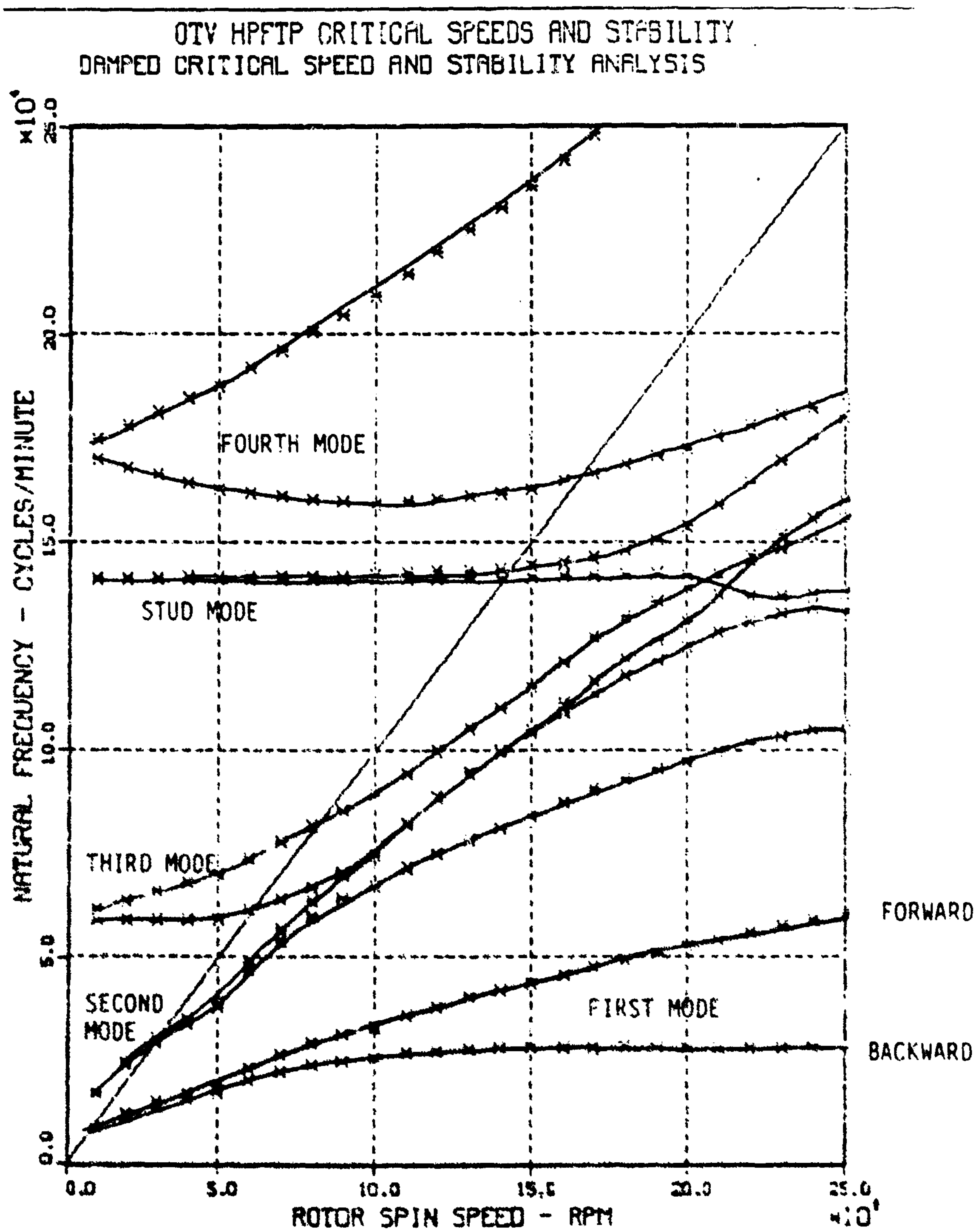


Figure B-3. Rotordynamic Critical Speed Plot

5472e

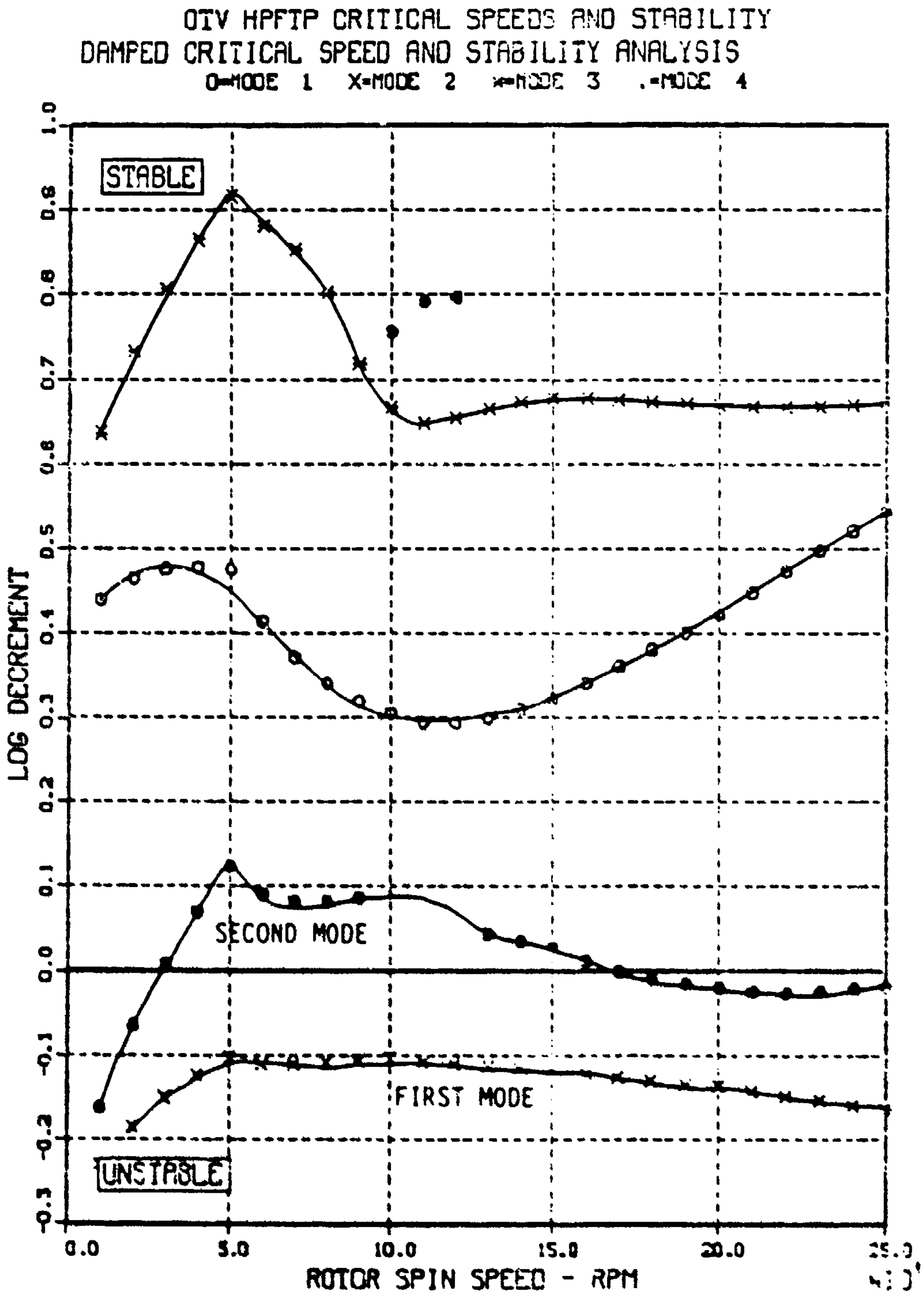


Figure B-4. Log Decrement Stability Plot

Table B-2. Summary of Results for Initial Model

FIRST CRITICAL SPEED	= 10,000 RPM
SECOND CRITICAL SPEED	= 30,000 RPM
1ST MODE LOG DEC @ 200 KRPM	= -.14 (UNSTABLE)
2ND MODE LOG DEC @ 200 KRPM	= -.02 (UNSTABLE)
FREQ. OF 1ST MODE @ 200 KRPM	= 55,000 CPM

Table B-3. Seal and Bearing Parameters and Results for First Iteration. Lengthened W.R.S with Swirl Brakes.

	Kxx lb-s/in	Kxy lb-s/in	Cxx lb-s/in
P/E BEARING	188620	16726	1.6
1ST P.I.S.	0	0	0
2ND P.I.S.	8100	1800	.17
3RD P.I.S.	8100	1800	.17
1ST W.R.S.	29303	5066	1.13
2ND W.R.S.	29303	5066	1.13
3RD W.R.S.	29303	5066	1.13
4TH W.R.S.	29303	5066	1.13
T/E BEARING	188620	16726	1.6
T.T.S. (EACH)	0	0	0
T.I.S.	405	126	.065
ALFORD BETA=1.5		483	

FIRST CRITICAL SPEED	= < 50,000 RPM
SECOND CRITICAL SPEED	= < 50,000 RPM
1ST MODE LOG DEC @ 200 KRPM	= -.12 (UNSTABLE)
2ND MODE LOG DEC @ 200 KRPM	= +.17 (STABLE)
FREQ. OF 1ST MODE @ 200 KRPM	= 55,000 CPM

ANALYSIS: CROSS SECTION 2

The second cross section analyzed, Figure B-5, employs a turbine end bearing with a diameter of 0.723 in. (increased from 0.6 in., length still the same at 0.4 in.). Table B-4 lists the rotordynamic coefficients used, and summarizes the results.

ANALYSIS: CROSS SECTION 3

The third cross section analyzed, Figure B-6, employs the same enlarged turbine end bearing in conjunction with a pump end bearing enlarged to a diameter of 0.723 in. (increased from 0.6 in., length still same 0.4 in.). Table B-5 lists the rotordynamic coefficients used in the analysis.

In this case there also was a small benefit, but not very substantial.

ANALYSIS: CROSS SECTION 4

The fourth cross section analyzed, Figures B-7 and B-8, employs the same enlarged turbine end bearing in conjunction with a pump end bearing moved out onto the first stage pump impeller shroud by making the inducer now out of Titanium and integral with the first impeller. The cross over between the first and second stage pump impellers is made identical to those between the other pump impellers. The diameter of the pump end bearing is now 1.25 in. (length still same 0.4 in.). Table B-6 lists the rotordynamic coefficients used, and summarizes the results.

Figures B-9 and B-10 show the natural frequency and stability maps for this analysis. The change to the pump end bearing is seen to have a substantial improvement on the frequency and stability of the second rotor mode. Also, the third rotor mode has now been moved entirely out of the operating range. The first rotor mode, however, is still unstable and has too low a frequency at 200,000 rpm.

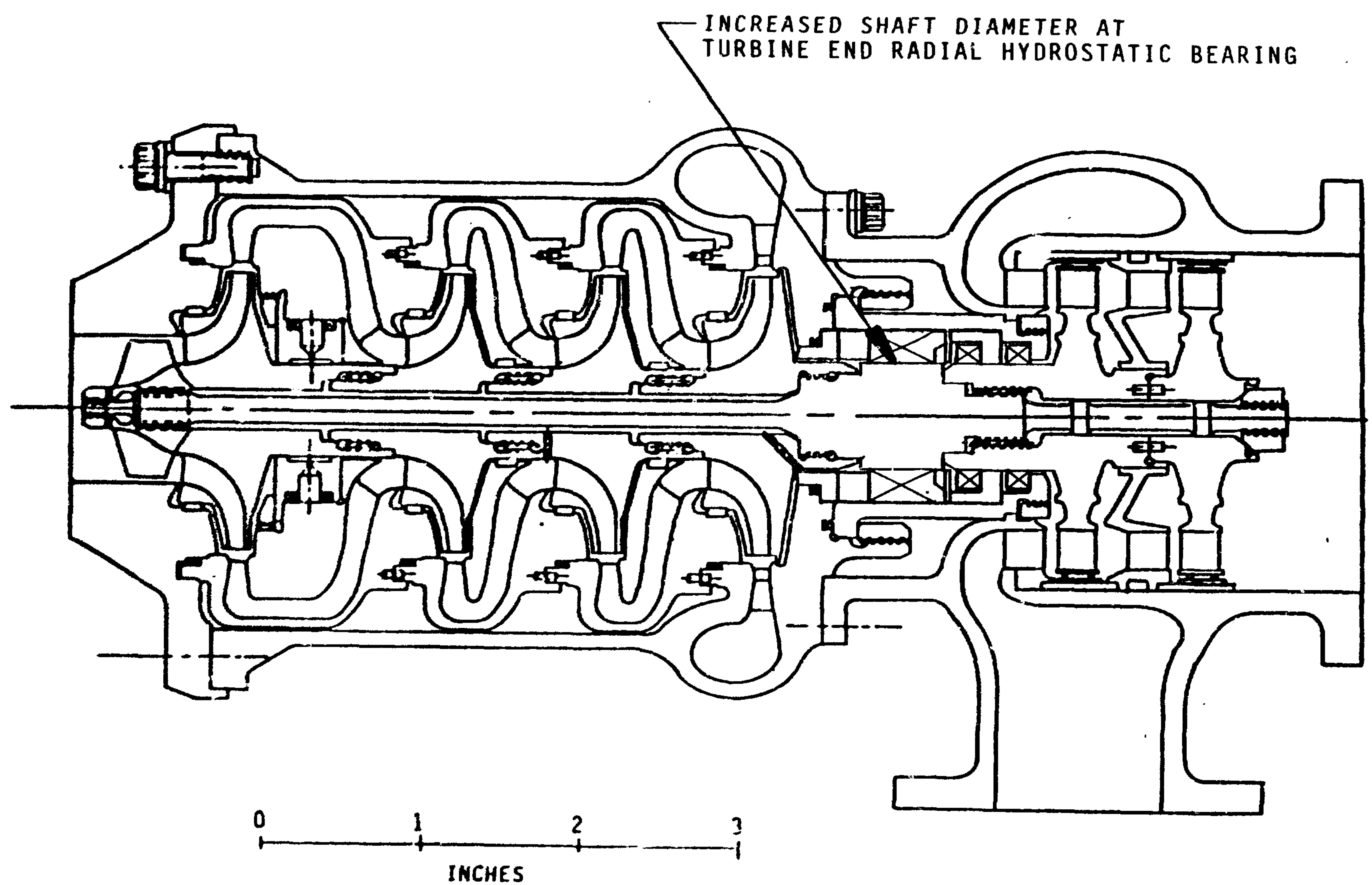


Figure B-5. OTVE High-Pressure Fuel Turbopump Cross Section No. 2

Table B-4. Seal and Bearing Parameters and Results for Second Iteration. Increased Diameter T/E Bearing.

	Kxx lb-s/in	Kxy lb-s/in	Cxx lb-s/in
P/E BEARING	188620	16726	1.6
1ST P.I.S.	0	0	0
2ND P.I.S.	8100	1800	.17
3RD P.I.S.	8100	1800	.17
1ST W.R.S.	29303	5066	1.13
2ND W.R.S.	29303	5066	1.13
3RD W.R.S.	29303	5066	1.13
4TH W.R.S.	29303	5066	1.13
T/E BEARING	299157	20656	2.0
T.T.S. (EACH)	0	0	0
T.I.S.	405	126	.065
ALFORD BETA=1.5		483	

FIRST CRITICAL SPEED = < 50,000 RPM
SECOND CRITICAL SPEED = < 50,000 RPM
1ST MODE LOG DEC @ 200 KRPM = -.07 (UNSTABLE)
2ND MODE LOG DEC @ 200 KRPM = +.09 (STABLE)
FREQ. OF 1ST MODE @ 200 KRPM = 60,000 CPM

On all rotordynamic analyses to this point, both turbine stages have been assumed to be unshrouded. Thus a blade tip efficiency factor (Beta) of 1.5 had been used to compute the Alford's force aerodynamic cross coupling for each turbine wheel. If the blades are shrouded then the Beta factor would be more on the order of 0.25. Table B-7 summarizes the reanalysis of the case in Table B-6 using a Beta factor of 0.25.

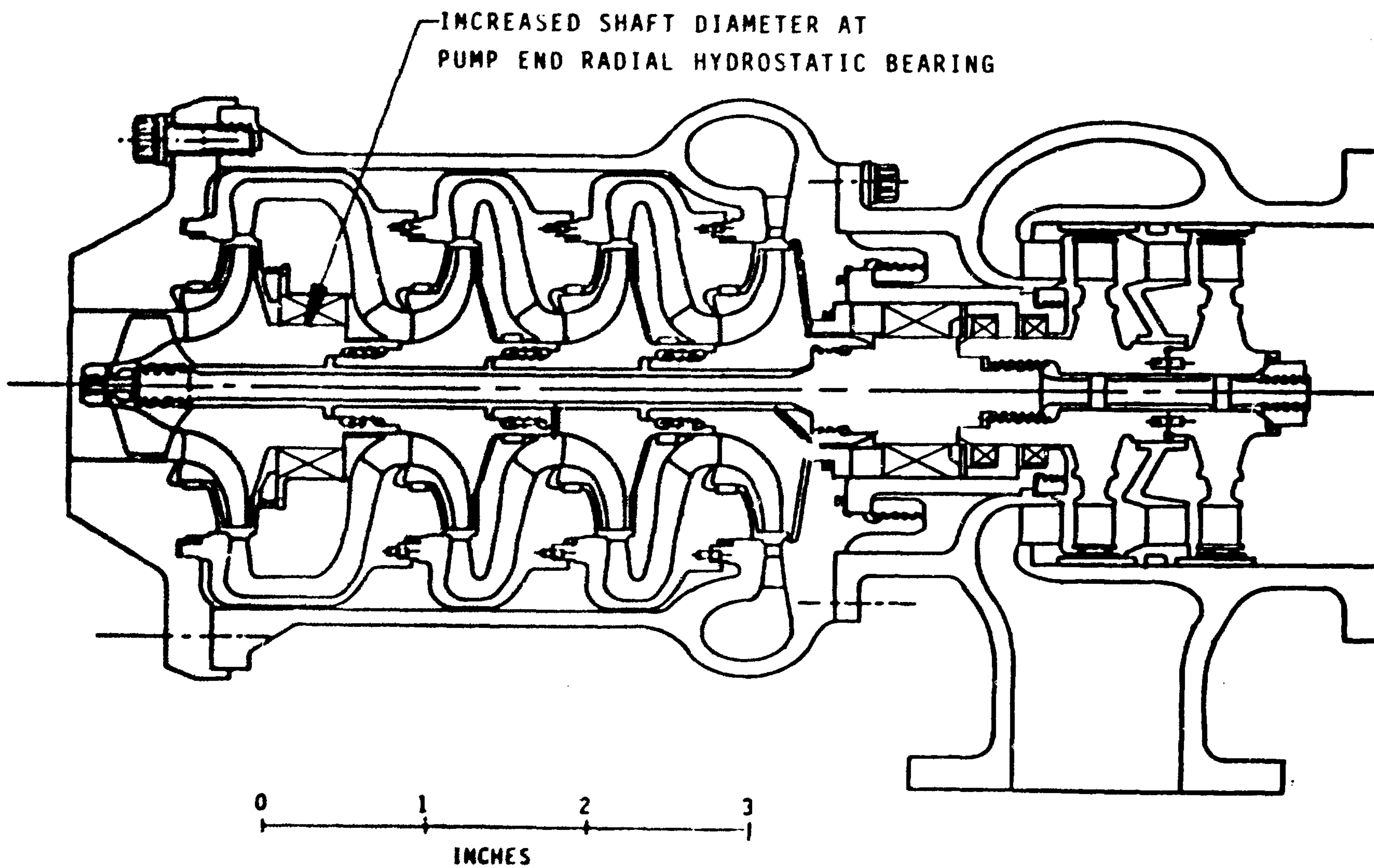


Figure B-6. OTVE High-Pressure Fuel Turbopump Cross Section No. 3

Table B-5. Seal and Bearing Parameters and Results for Third Iteration. Increased Diameter T/E Bearing and Increased Diameter P/E Bearing.

	Kxx LB-S/in	Kxy LB-S/in	CXX LB-S/in
P/E Bearing	299157	20656	2.0
1ST P.I.S.	0	0	0
2ND P.I.S.	8100	1800	.17
3RD P.I.S.	8100	1800	.17
1ST W.R.S.	29303	5066	1.13
2ND W.R.S.	29303	5066	1.13
3RD W.R.S.	29303	5066	1.13
4TH W.R.S.	29303	5066	1.13
T/E Bearing	299157	20656	2.0
T.T.S. (Each)	00	0	0
T.I.S.	405	126	.065
ALFORD BETA = 1.5		483	

There is seen to be an enhancement to the stability of the first rotor mode, but it is still predicted to be unstable throughout the entire operating speed range.

On all analyses described thus far the rotordynamic coefficients of the turbine interstage seal have been based on a pressure differential of 50 psi. This seal delta p was then revised to 647 psi. New rotordynamic coefficients were calculated and are listed in Table B-8 along with the results of the reanalysis.

This modification to the turbine interstage seal has stabilized the first rotor mode. The log dec for this mode is greater than 0.07 throughout the entire operating speed range. The frequency of this mode, however, is still less than 50% of running speed at 200,000 rpm. Also, the log dec of 0.41 for the second rotor mode is still too small to permit sustained operation at the second critical speed of 90,000 rpm.

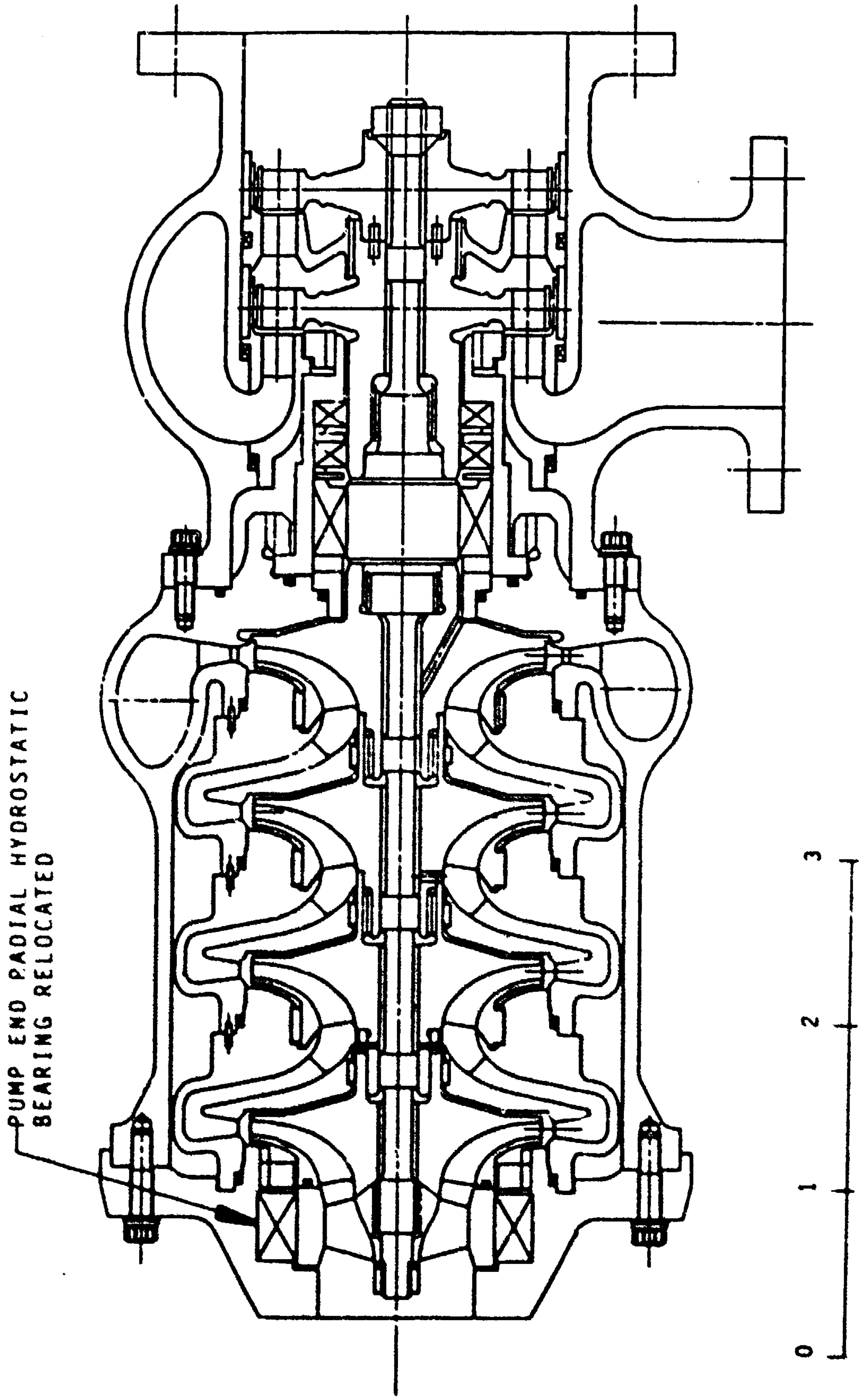


Figure B-7. OTVE High-Pressure Fuel Turbopump Cross Section No. 4

Rotating Assembly Model

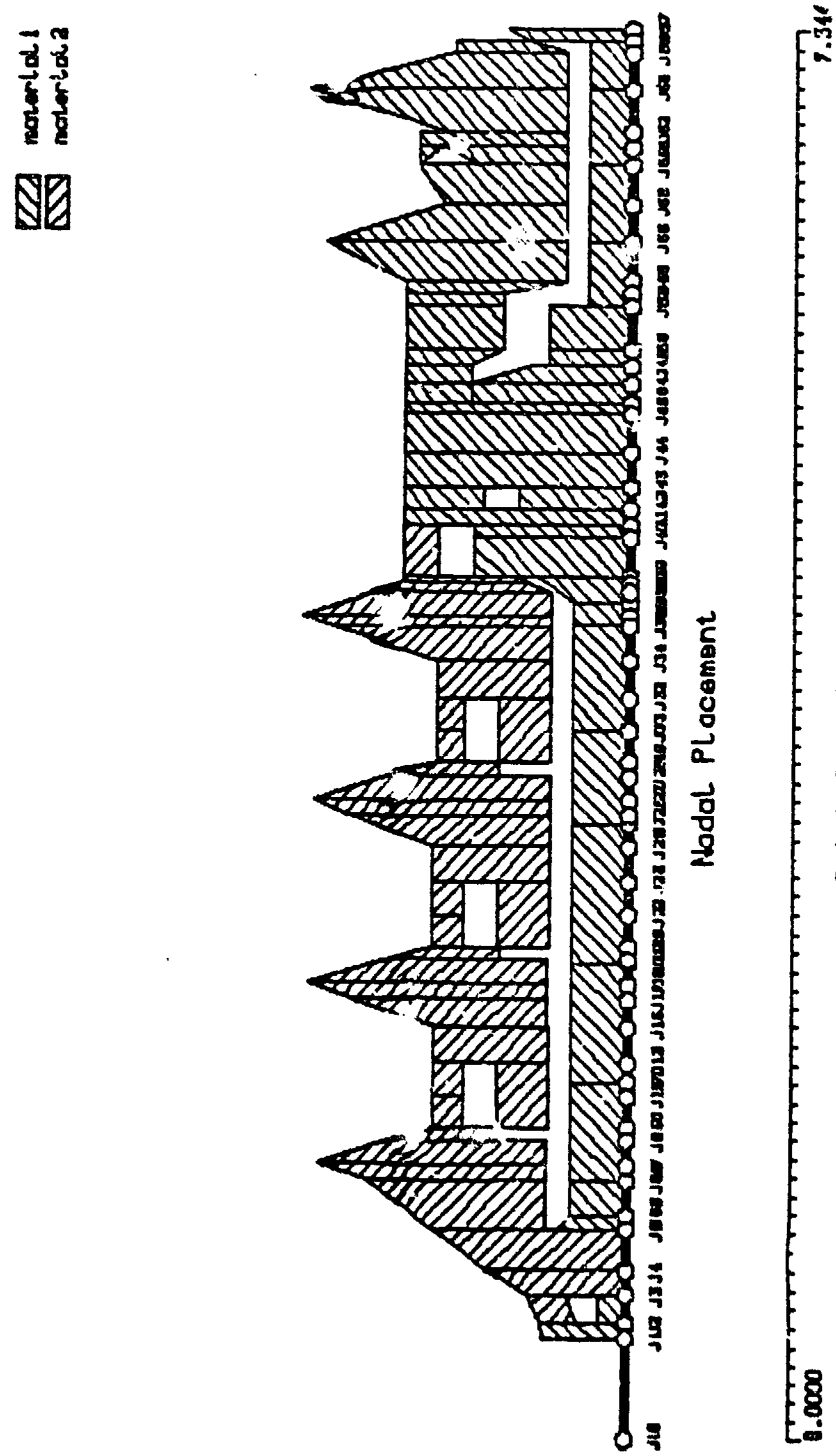


Figure B-8. Finite Element Beam Model Cross Section No. 4

Table B-6. Seal and Bearing Parameters and Results for Fourth Iteration. Increased Diameter T/E Bearing and P/E Bearing on 1st Impeller Shroud.

	Kxx lb-s/in	Kxy lb-s/in	Cxx lb-s/in
P/E BEARING	494671	39486	4.9
1ST P.I.S.	0	0	0
2ND P.I.S.	8100	1800	.17
3RD P.I.S.	8100	1800	.17
1ST W.R.S.	29303	5066	1.13
2ND W.R.S.	29303	5066	1.13
3RD W.R.S.	29303	5066	1.13
4TH W.R.S.	29303	5066	1.13
T/E BEARING	299157	20656	2.0
T.T.S. (EACH)	0	0	0
T.I.S.	405	126	.065
ALFORD BETA=1.5		483	

FIRST CRITICAL SPEED = < 50,000 RPM

SECOND CRITICAL SPEED = 90,000 RPM

1ST MODE LOG DEC @ 200 KRPM = -.07 (UNSTABLE)

2ND MODE LOG DEC @ 200 KRPM = +.41 (STABLE)

FREQ. OF 1ST MODE @ 200 KRPM = 60,000 CPM

Another iteration that was tried was to put damper seals on the turbine shrouds. Table B-9 shows the rotordynamic coefficients and summarizes the results obtained.

This change further enhances the stability of the first rotor mode to the point that its log dec is now greater than 0.12 throughout the operating speed range. Its frequency has also increased to 71,000 cpm at 200,000 rpm, but is still less than 50%. The second mode is unaffected.

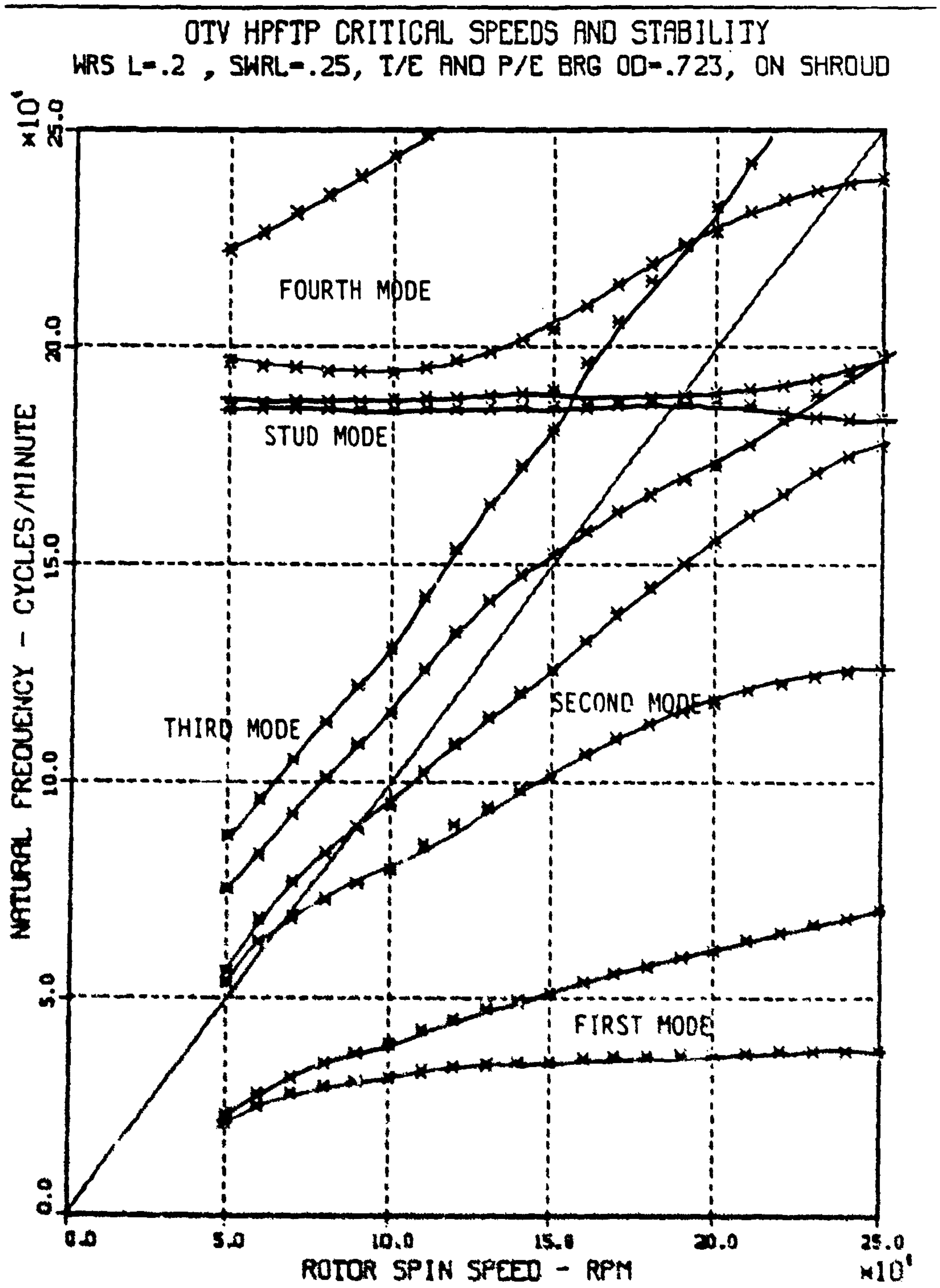


Figure B-9. Rotordynamic Critical Speed Plot Cross Section No. 4

5472e

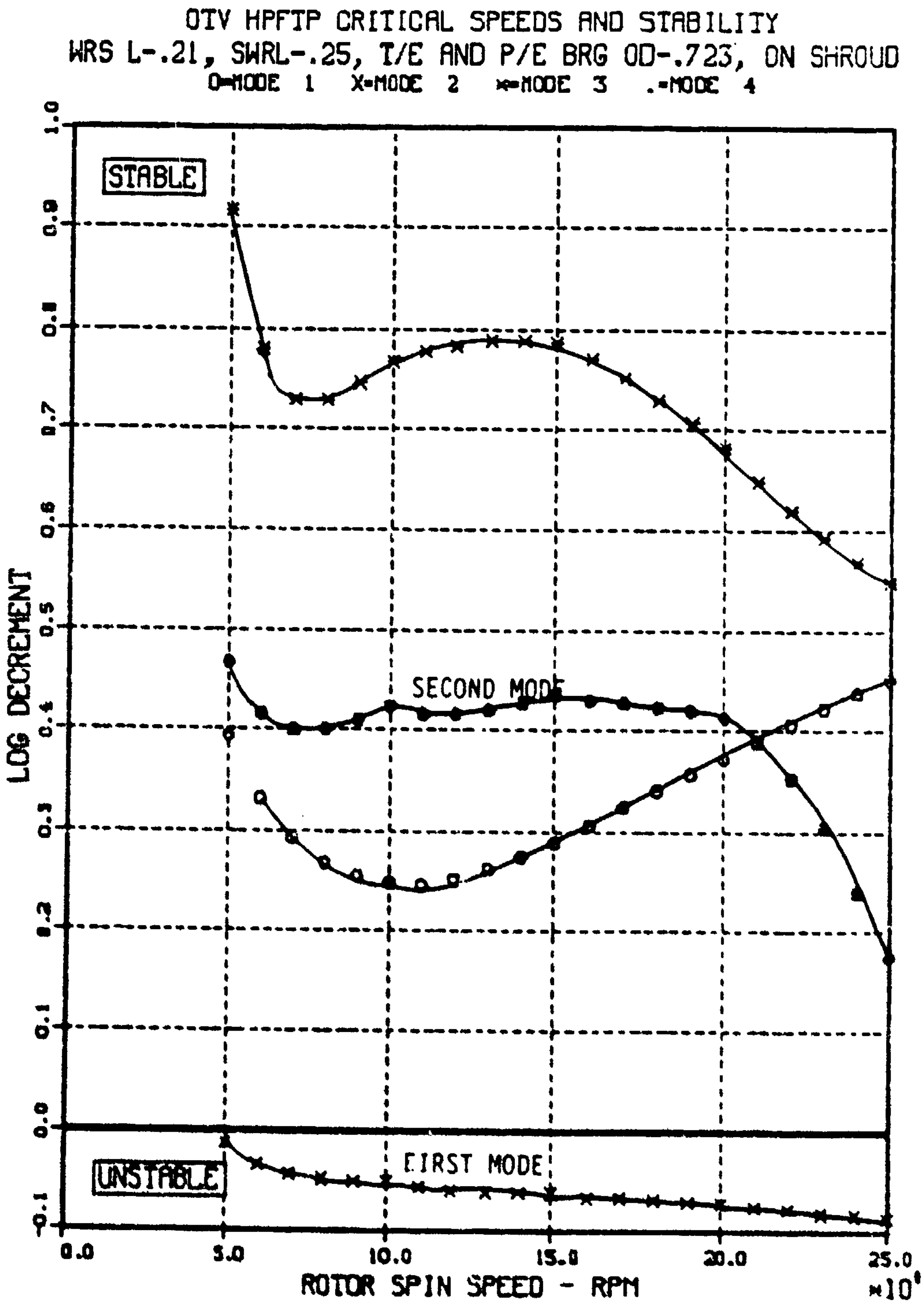


Figure B-10. Log Decrement Stability Plot Cross Section No. 4

Table B-7. Seal and Bearing Parameters and Results for Fifth Iteration. Increased Diameter T/E Bearing P/E Bearing on 1st Impeller Shroud and a Beta Factor of 0.25.

	Kxx lb-s/in	Kxy lb-s/in	Cxx lb-s/in
P/E BEARING	494671	39486	4.9
1ST P.I.S.	0	0	0
2ND P.I.S.	8100	1800	.17
3RD P.I.S.	8100	1800	.17
1ST W.R.S.	29303	5066	1.13
2ND W.R.S.	29303	5066	1.13
3RD W.R.S.	29303	5066	1.13
4TH W.R.S.	29303	5066	1.13
T/E BEARING	299157	20656	2.0
T.T.S. (EACH)	0	0	0
T.I.S.	405	126	.065
ALFORD BETA=0.25		121	

FIRST CRITICAL SPEED = < 50,000 RPM

SECOND CRITICAL SPEED = 90,000 RPM

1ST MODE LOG DEC @ 200 KRPM = -.015 (UNSTABLE)

2ND MODE LOG DEC @ 200 KRPM = +.41 (STABLE)

FREQ. OF 1ST MODE @ 200 KRPM = 60,000 CPM

The last iteration performed on this cross section was to increase the diameter of the turbine interstage seal from 0.65 in. to 1.10 in., and employ a honeycomb stator. Its length and delta p remain unchanged. Table B-10 shows the rotordynamic coefficients and summarizes the results obtained.

The added direct stiffness of the large diameter seal raises the frequency of the first mode to 83,000 cpm, but it is still below 50% of running speed. The log dec of the first mode decreased a small amount which can be neglected. The second rotor mode was unaffected.

Table B-8. Seal and Bearing Parameters and Results for Sixth Iteration. Increased Diameter T/E Bearing P/E Bearing on 1st Impeller Shroud, a beta Factor of 0.25, 647 psi T.I.S. Delta P.

	Kxx lb-s/in	Kxy lb-s/in	Cxx lb-s/in
P/E BEARING	494671	39486	4.9
1ST P.I.S.	0	0	0
2ND P.I.S.	8100	1800	.17
3RD P.I.S.	8100	1800	.17
1ST W.R.S.	29303	5066	1.13
2ND W.R.S.	29303	5066	1.13
3RD W.R.S.	29303	5066	1.13
4TH W.R.S.	29303	5066	1.13
T/E BEARING	299157	20656	2.0
T.T.S. (EACH)	0	0	0
T.I.S.	6000	750	.44
ALFORD BETA=0.25		121	

FIRST CRITICAL SPEED = < 50,000 RPM
SECOND CRITICAL SPEED = 90,000 RPM
1ST MODE LOG DEC @ 200 KRPM = +.10 (STABLE)
2ND MODE LOG DEC @ 200 KRPM = +.41 (STABLE)
FREQ. OF 1ST MODE @ 200 KRPM = 65,000 CPM

ANALYSIS: CROSS SECTION 5

The fifth and final cross section analyzed, Figures B-11 and B-12, has several changes to the shaft including: shortened turbine overhang, an added rolling element thrust bearing, and a kicker stage between the inducer and first impeller to carry the pump end bearing. Table B-11 lists the rotordynamic coefficients used in this analysis and summarizes the results. The turbine end bearing diameter is 0.723 in. and the pump end bearing diameter is 1.08 in. The turbine interstage seal diameter is 0.65 in.

Table B-9. Seal and Bearing Parameters and Results for Seventh Iteration. Increased Diameter T/E Bearing P/E Bearing on 1st Impeller Shroud, a Beta Factor of 0.25, 647 psi T.I.S. Delta P, and Turbine Tip Damper Seals.

	Kxx lb-s/in	Kxy lb-s/in	Cxx lb-s/in
P/E BEARING	494671	39486	4.9
1ST P.I.S.	0	0	0
2ND P.I.S.	8100	1800	.17
3RD P.I.S.	8100	1800	.17
1ST W.R.S.	29303	5066	1.13
2ND W.R.S.	29303	5066	1.13
3RD W.R.S.	29303	5066	1.13
4TH W.R.S.	29303	5066	1.13
T/E BEARING	299157	20656	2.0
1ST T.T.S.	5000	450	.16
2ND T.T.S.	4500	420	.14
T.I.S.	6000	750	.44
ALFORD BETA=0.25		121	

FIRST CRITICAL SPEED = < 50,000 RPM

SECOND CRITICAL SPEED = 90,000 RPM

1ST MODE LOG DEC @ 200 KRPM = +.17 (STABLE)

2ND MODE LOG DEC @ 200 KRPM = +.41 (STABLE)

FREQ. OF 1ST MODE @ 200 KRPM = 71,000 CPM

This new cross section has raised the frequency of the first rotor mode to 96,000 cpm, almost to 50% of shaft speed, Figure B-13. The log dec is an acceptable 0.14 and is above 0.10 throughout the entire operating range, Figure B-14. The log dec of the second mode, however, has decreased considerably with this cross section and is even below 0.05 through part of the operating range. The log dec of the second mode needs to be increased not only to give it sufficient margin against instability, but also to permit sustained operation at the second critical speed at 60,000 rpm. One analysis which has not

Table B-10. Seal and Bearing Parameters and Results for Eighth Iteration. Increased Diameter T/E Bearing P/E Bearing on 1st Impeller Shroud, a Beta Factor of 0.25, Large Diameter T.I.S., and Turbine Tip Damper Seals.

	Kxx lb-s/in	Kxy lb-s/in	Cxx lb-s/in
P/E BEARING	494671	39486	4.9
1ST P.I.S.	0	0	0
2ND P.I.S.	8100	1800	.17
3RD P.I.S.	8100	1800	.17
1ST W.R.S.	29303	5066	1.13
2ND W.R.S.	29303	5066	1.13
3RD W.R.S.	29303	5066	1.13
4TH W.R.S.	29303	5066	1.13
T/E BEARING	299157	20656	2.0
1ST T.T.S.	5000	450	.16
2ND T.T.S.	4500	420	.14
T.I.S.	30000	1350	.46
ALFORD BETA=0.25		121	

FIRST CRITICAL SPEED	= < 50,000 RPM
SECOND CRITICAL SPEED	= 90,000 RPM
1ST MODE LOG DEC @ 200 KRPM	= +.15 (STABLE)
2ND MODE LOG DEC @ 200 KRPM	= +.41 (STABLE)
FREQ. OF 1ST MODE @ 200 KRPM	= 83,000 CPM

been performed with this final cross section is one employing the large diameter turbine interstage seal. Incorporating this change should raise the frequency of the first mode above 50% of running speed, but its effect on the stability of the second mode may be beneficial or detrimental.

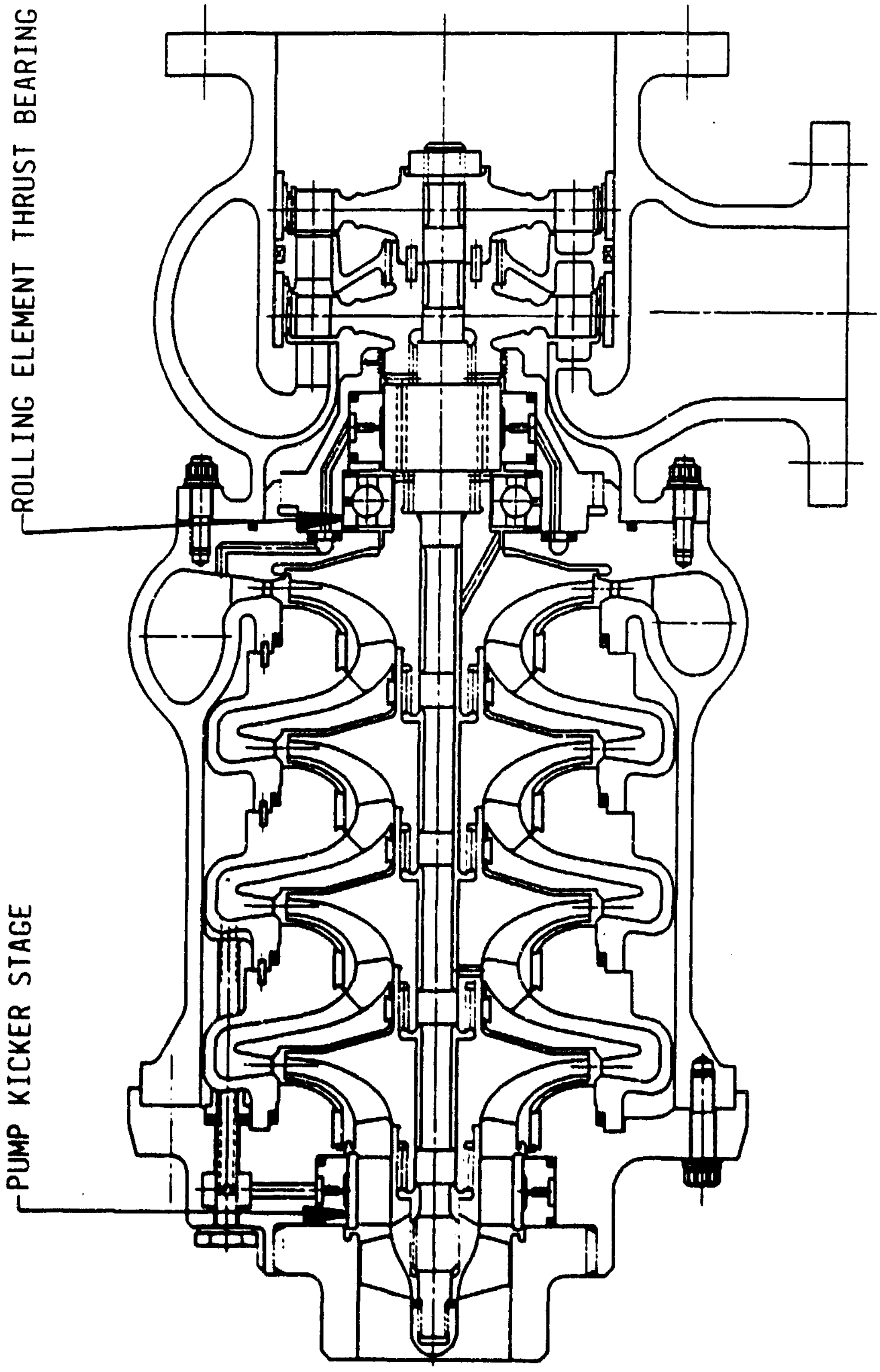


Figure B-11. OTVE High-Pressure Fuel Turbopump Cross Section No. 5

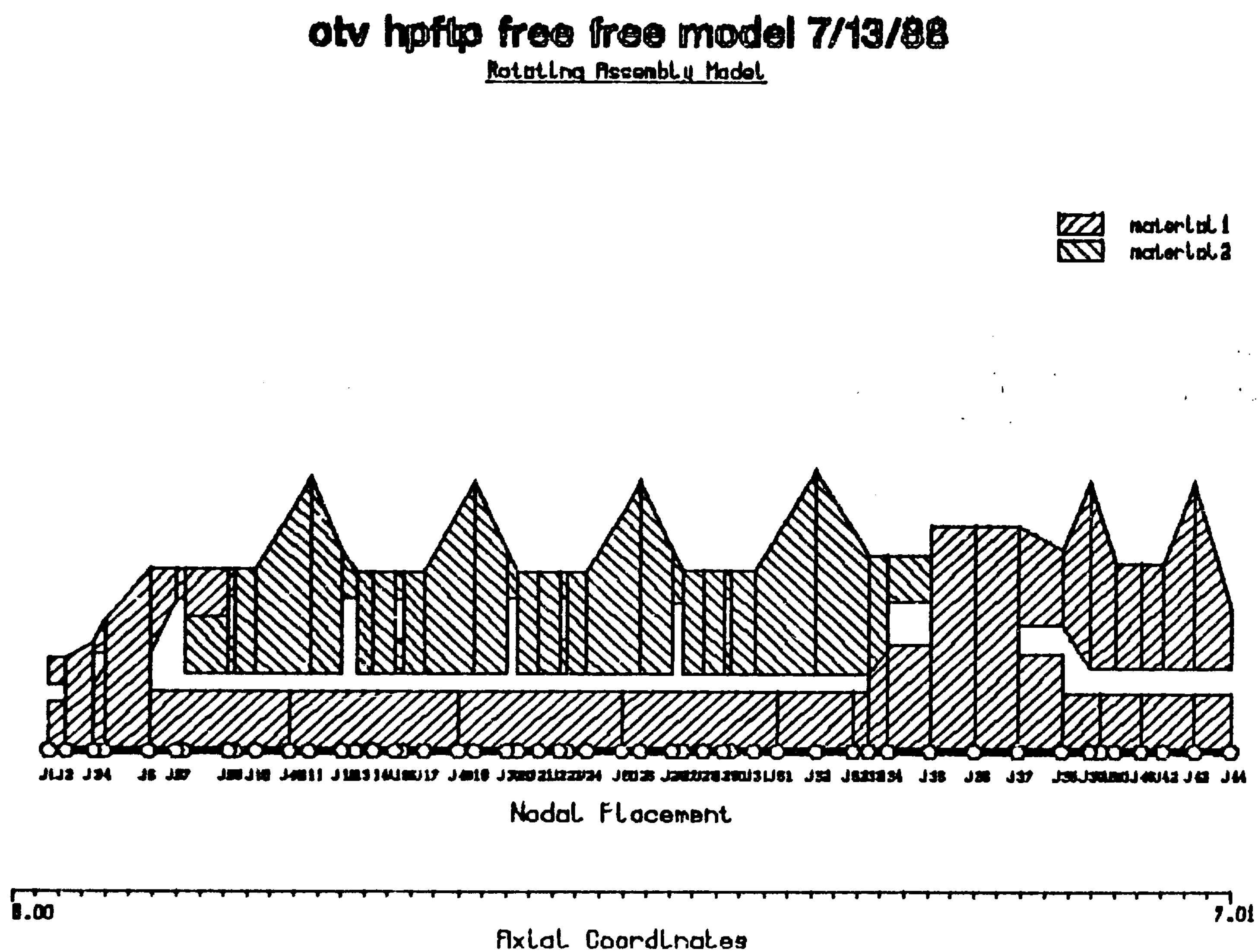


Figure B-12. Finite Element Beam Model -- Cross Section No. 5

5472e

Table B-11. Seal and Bearing Parameters and Results for Ninth Iteration. Increased Diameter T/E Bearing, P/E Bearing on Kicker Shroud, a Beta Factor of 0.25, and Turbine Tip Damper Seals.

	Kxx lb-s/in	Kxy lb-s/in	Cxx lb-s/in
P/E BEARING	511200	38030	3.64
1ST P.I.S.	8100	1800	.17
2ND P.I.S.	8100	1800	.17
3RD P.I.S.	8100	1800	.17
1ST W.R.S.	29303	5066	1.13
2ND W.R.S.	29303	5066	1.13
3RD W.R.S.	29303	5066	1.13
4TH W.R.S.	29303	5066	1.13
T/E BEARING	327130	24380	2.33
1ST T.T.S.	5000	450	.16
2ND T.T.S.	4500	420	.14
T.I.S.	5150	667	.27
ALFORD BETA=0.25		121	

FIRST CRITICAL SPEED = < 50,000 RPM
SECOND CRITICAL SPEED = 60,000 RPM
1ST MODE LOG DEC @ 200 KRPM = +.14 (STABLE)
2ND MODE LOG DEC @ 200 KRPM = +.06 (STABLE)
FREQ. OF 1ST MODE @ 200 KRPM = 96,000 CPM

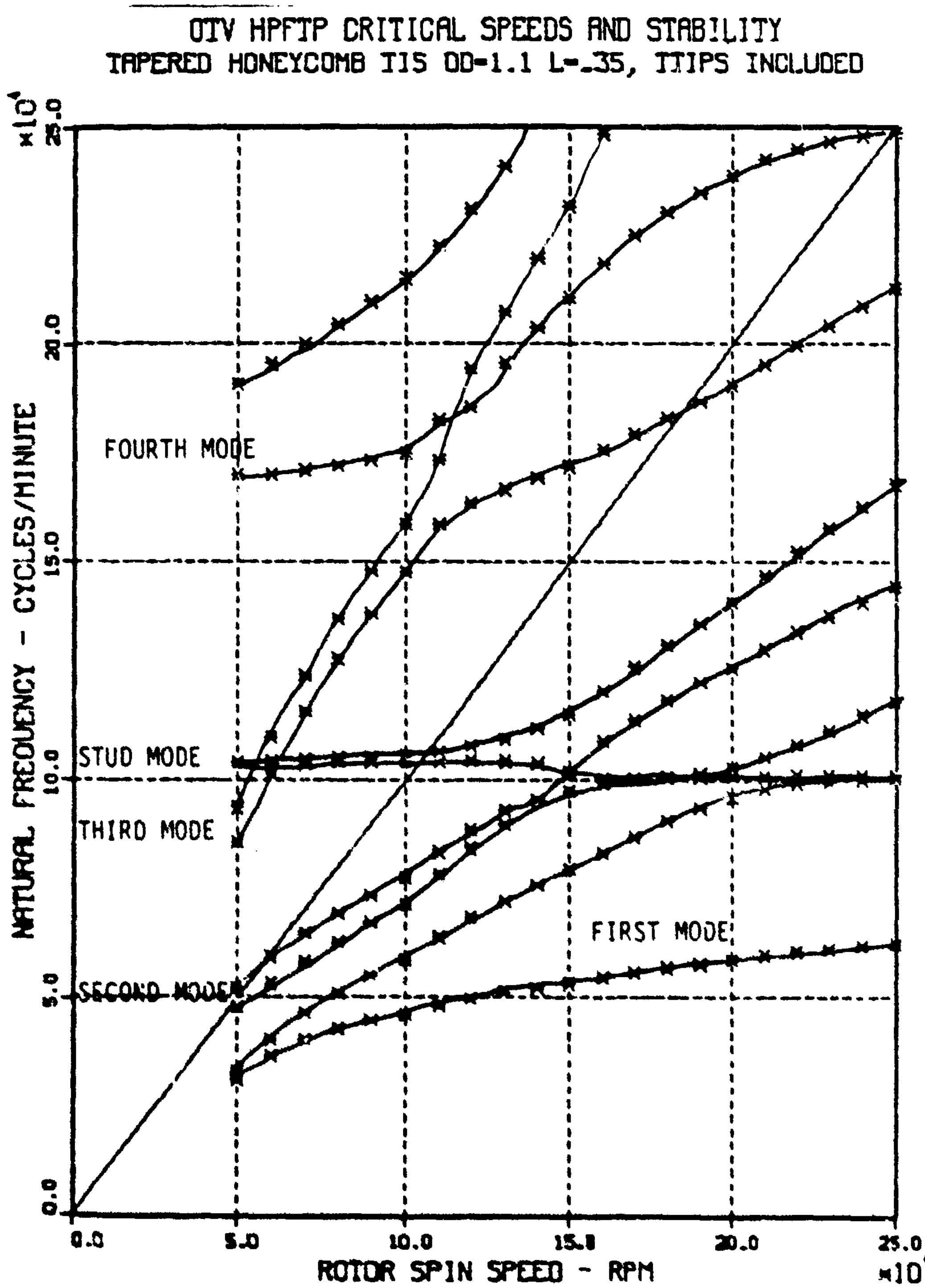


Figure B-13. Rotordynamic Critical Speed Plot Cross Section No. 5

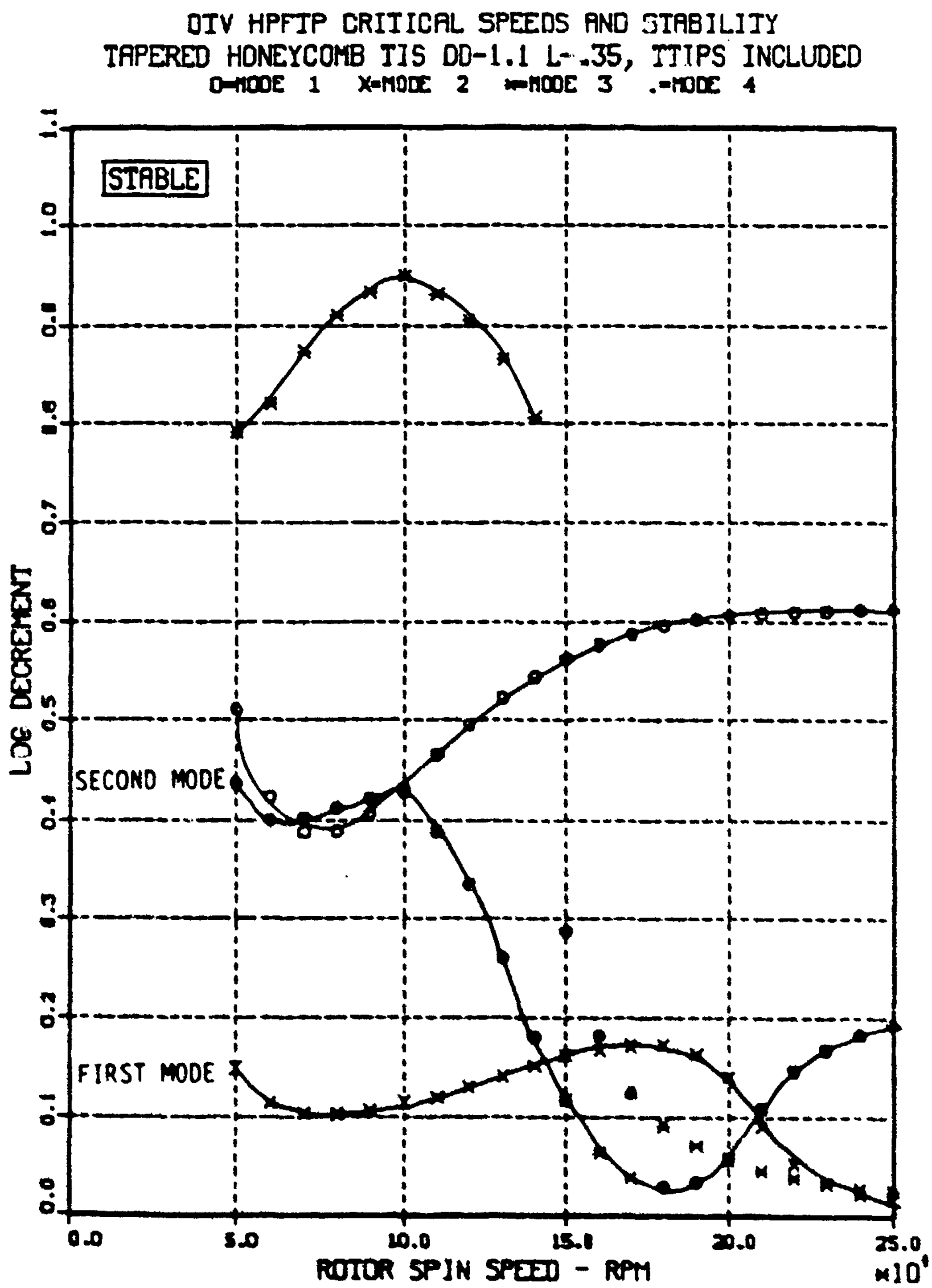


Figure B-14. Log Decrement Stabilty Plot Cross Section No. 5

CONCLUSIONS:

The OTV HPFTP has been analyzed for critical speeds and stability. The primary rotordynamic concerns are: the low frequency, and thus, stability of the first rotor mode, potentially excessive rotor response while operating at or near the second mode critical speed, and the stability of the second rotor mode while at high power level. Potential design changes which may benefit the turbopump's rotordynamics, but have not yet been analyzed include: a foil bearing damper at the turbine interstage seal location, supporting the entire rotor on foil bearings, or incorporating a pressurized damper near the middle of the bearing span. Modifications such as these have the potential to enhance the frequency/stability of the first rotor mode, and raise the damping of the second mode to the level required to permit sustained operation at its critical speed.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CR-190754		

4. Title and Subtitle

Orbit Transfer Rocket Engine Technology - 7.5 Klb Thrust Rocket Engine Preliminary Design

5. Report Date

October 15, 1993

6. Performing Organization Code

7. Author (s)

T. J. Harmon & E. Roschak

8. Performing Organization Report No.

RI/RD88-291

9. Performing Organization Name and Address

Rocketdyne Division, Rockwell International
6633 Canoga Avenue
Canoga Park, California 91303

10. Work Unit No.

Tasks D.5 and B.7

11. Contract or Grant No.

NAS3-23773

12. Sponsoring agency Name and Address

National Aeronautics & Space Administration
Lewis Research Center, Space Vehicle Propulsion Branch,
21000 Brookpark Rd., Cleveland, Ohio 44135

13. Type of Report and Period Covered

Final Report 12/87-10/88

14. Sponsoring Agency Code

15. Supplementary Notes

Program Manager: G. P. Richter, NASA-Lewis Research Center; Cleveland, OH

16. Abstract

A preliminary design of an advanced LOX/ LH2 expander cycle rocket engine producing 7,500 lbf thrust for Orbital Transfer vehicle missions was completed. Engine system, component and turbomachinery analysis at both on design and off design conditions were completed. The preliminary design analysis results showed engine requirements and performance goals were met. Computer models are described and model outputs are presented. Engine system assembly layouts, component layouts and valve and control system analysis are presented. Major design technologies were identified and remaining issues and concerns were listed.

17. Key words (Suggested by author (s))

Orbit Transfer Vehicle (OTV)
Expander Cycle
Hydrogen/Oxygen Rocket Engine
Space Based Engine
High Pressure Fuel Turbopump

18. Distribution Statement

Publicly Available
Unclassified

19. Security Classif. (of this report)	20. Security Classif. (of this report)	21. No. of Pages	22. Price*
Unclassified	Unclassified	131	

* For sale by the National Technical Information Service, Springfield, Virginia 22151