FR24756-4
2 August, 1997

Twin Rotor Turbopump Program
Contract NAS8-97161

Progress Report
1 July 1997 through 31 July 1997
Data Item 832MA-002

Prepared for:
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

Prepared by:
Pratt & Whitney - Space Propulsion
P. O. Box 109600
West Palm Beach, FL 33410-9600

Introduction:

NASA Marshall Space Flight Center (MSFC) has committed its resources to develop the Bantam System Technology Program. This initiative seeks to demonstrate technology applicable to low-cost, innovative, and unique rocket system payoffs for the next generation rocket propulsion systems. One component of this project is the MSFC Ablative Engine. The objective of the Ablative Engine Program is to demonstrate low-cost hardware using low part count design, commercial off-the-shelf (COTS) materials, and low cost fabrication methods. Pratt & Whitney's Twin Rotor Turbopump (TRT) program will produce a demonstrator of an alternative turbopump configuration for the MSFC Ablative Engine.

The TRT is a liquid oxygen/kerosene (LOX/RP-1) turbopump that incorporates two similar counter-rotating rotors in a back-to-back configuration. These one-piece rotors have integrally bladed propellant impellers and drive turbines, and are supported by hydrostatic bearings. The rotors are housed in two similar housings, which are assembled back-to back. The configuration is shown in Figure 1.

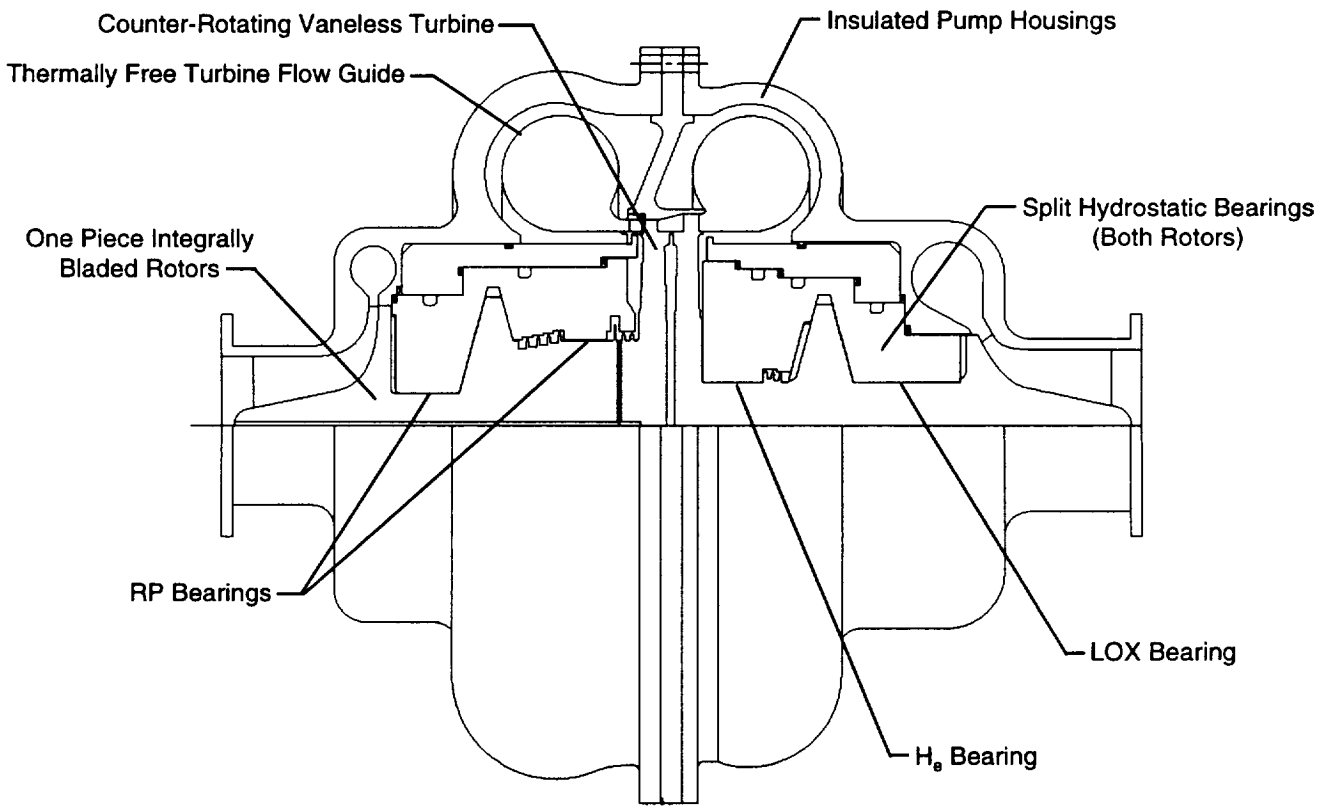


Figure 1. Twin Rotor Turbopump Configuration

The program consists of five tasks: (1) project direction; (2) systems engineering; (3) turbopump design; (4) hardware fabrication; (5) hardware assembly and delivery

Task 1 - Project Direction:

Weekly Integrated Product Team (IPT) meetings were held with participation from P&W functional groups. Additionally, the NASA technical lead has been supplied with updated technical information regarding the turbopump design. These changes are discussed in detail in the "Task 3" section of this progress report.

The program schedule has been updated to reflect the current program status. The updated schedule is shown in Attachment 1.

Task 2 - Systems Engineering:

A preliminary design table has been established for the TRT. The table is based on the pump and turbine flow conditions established for the TRT per the Contract Statement of Work, and supplemented by secondary flow conditions generated by P&W's design codes. The current design table for the TRT is shown in Attachment 2. Revisions from the table presented in last month's report are highlighted. The changes are primarily due to matching the pump and bearing components to the redesigned turbine identified in last month's report.

Task 3 - Turbopump Design:

An Interim Review was held at Pratt & Whitney's West Palm Beach facility on 1 July 1997. The attendees and minutes of the review are contained in Attachment 3. The focus of the review was to present the TRT design to NASA prior to proceeding with detail component design and analysis. The handout for the review is contained in Attachment 4.

Preliminary thermal analysis carried out during this reporting period indicated the need to isolate the split hydrostatic bearings from the housings to ensure dimensional stability of the bearings. It was also deemed to be necessary to reduce the heat transfer rate between the turbine drive fluid and the housings. The first objective was achieved by adding a sleeve each of the split bearing packages. The latter objective will be achieved by adding ceramic cloth insulation (Fiberfrax® AL_2O_3/SiO_2) between the turbine flow guides (volutes) and the housings.

The outside profile of the turbopump housings is being adjusted to reflect the revised aerodynamic contour of the selected turbine rotor design. In keeping with the program goal of producing low-cost components, the housings are generally cylindrical in cross-section to simplify the casting process.

Figure 2 illustrates the changes to the turbopump configuration.

Structural analysis of the final configuration has started with analysis of the RP-1 rotor. An electronic model of the rotor has been prepared and submitted to the Rocket Engine Structures department to carry out a 3-D analysis. The configuration of the model is illustrated in Figure 3.

Task 4 - Hardware Fabrication:

Preliminary sketches for the turbine flow guides and vanes, produced under the design task were been sent to suppliers to obtain price quotations and allow us to select a supplier. Dialogue with our currently selected suppliers to identify cost-effective configuration details, such as tolerances, fillet radii, surface finish, etc. is being carried out concurrently with the design activity.

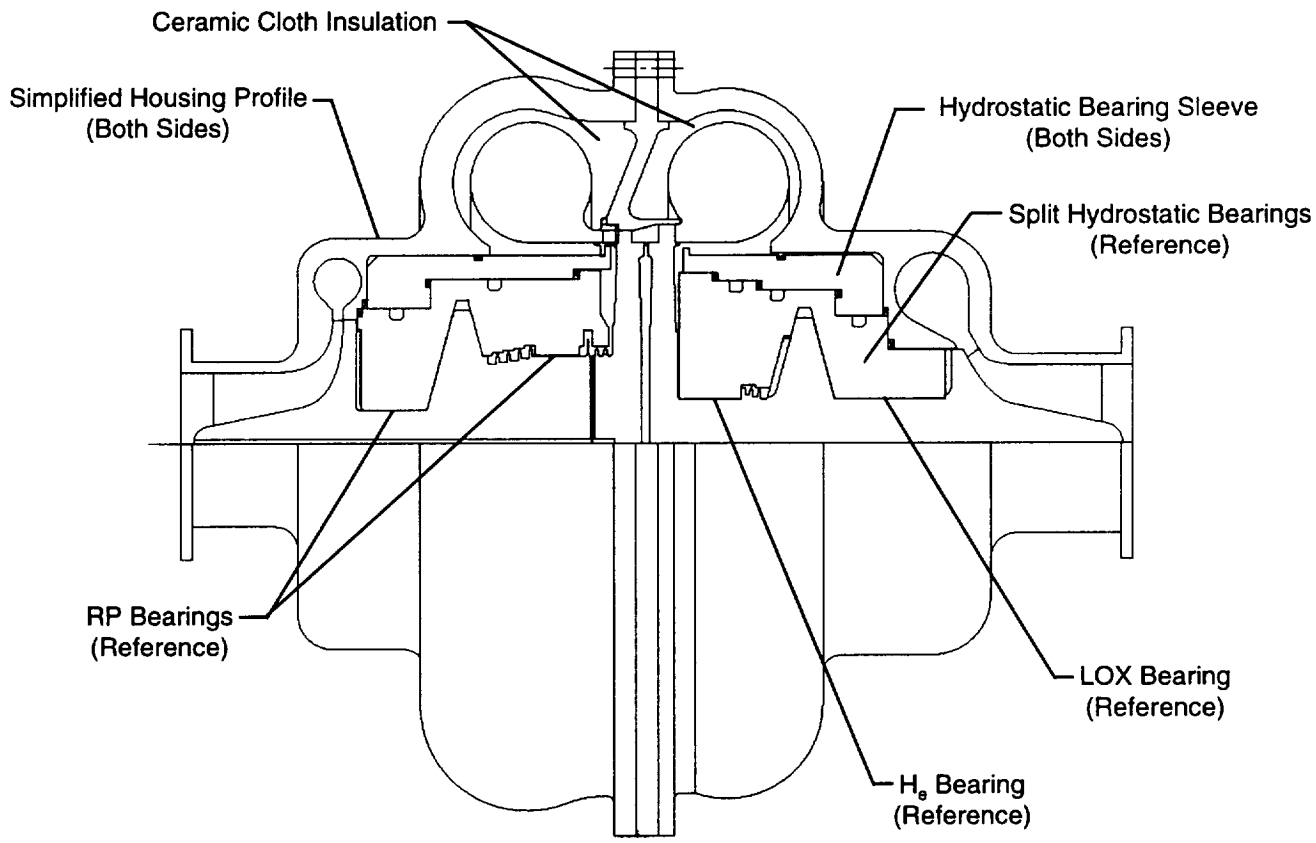


Figure 2. Twin Rotor Turbopump Configuration Changes

Task 5 - Hardware Assembly and Delivery:

Assembly activity is not scheduled to start until CY1998. The Rocket Assembly area is represented in the IPT.

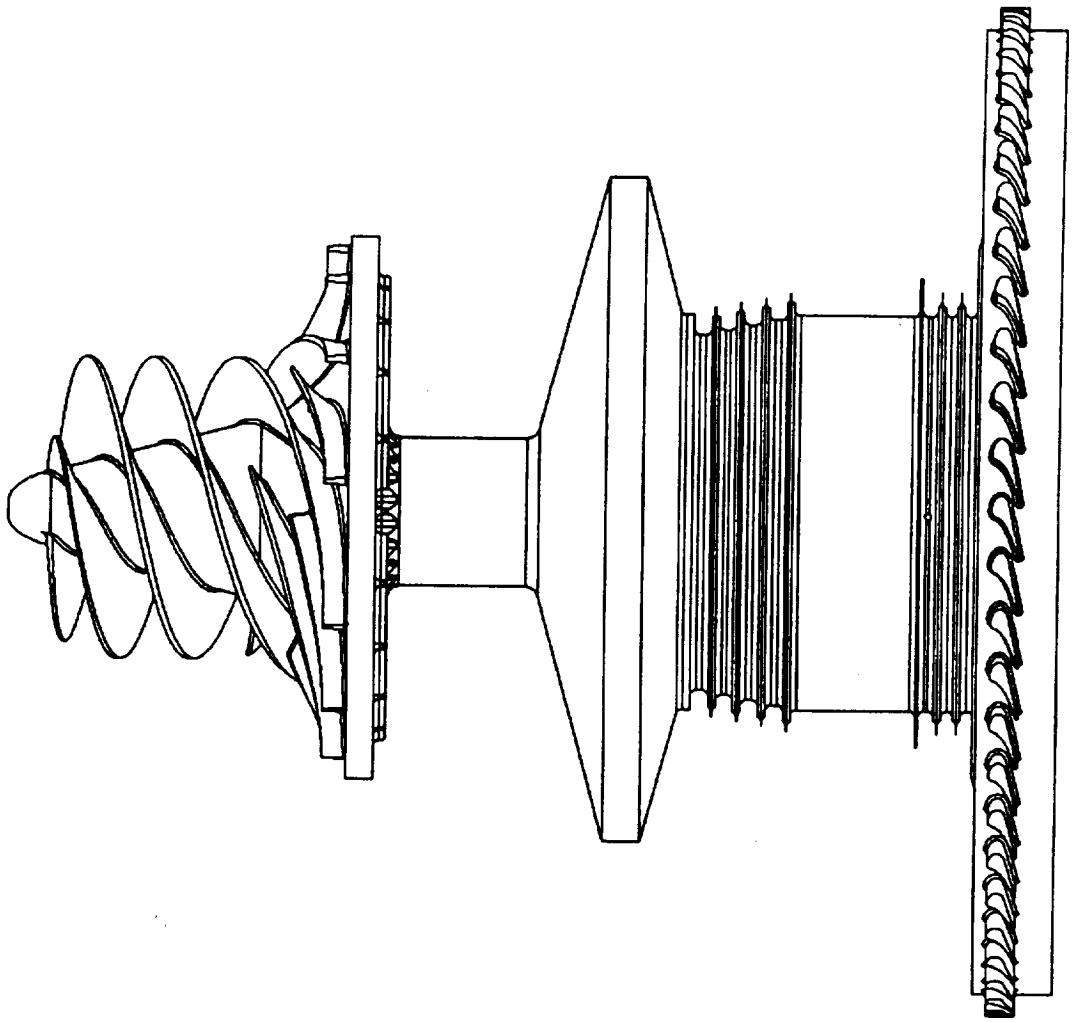
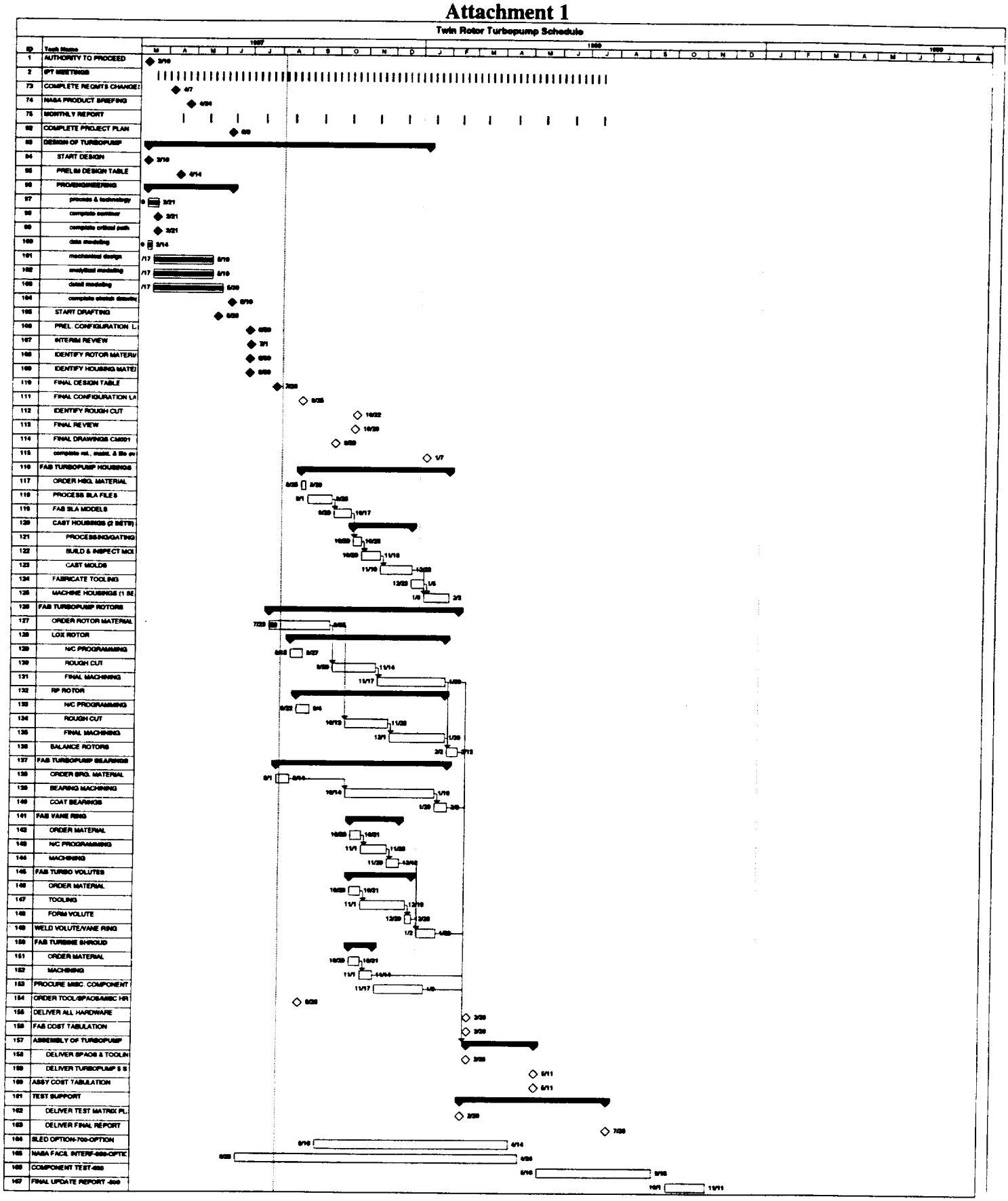


Figure 3. Illustration of RP-1 Rotor Model

Attachment 1



Attachment 2 - Design Table for the Twin Rotor Turbopump

Pump Performance Characteristics	RP-1	LOX
Delivered Flowrate, lb/s	***64.3***	***139.3***
Inlet Pressure, psi	***28***	***46***
Exit Pressure, psi	***960***	***919***
Inlet Temperature, R	***530***	***166***
NPSH Average, ft	73.3	56.9
Total Pump Flowrate, lb/s	69.0 *	141.8
Exit Temperature, R	537	171
Efficiency	67 *	66 *
Impeller Power, Hp	445 *	670 *
Backface Vane Power, Hp	58 *	27 *
Vaporizer Power, Hp	N/A	22.6 *
Windage Loss, Hp	124 *	63.4 *
Speed, RPM	18,000 *	23,000
Specific Speed	1200 *	2520
Head Rise, ft	2677 *	1780
Exit Diameter, in	5.30 *	3.9
Tip Speed, ft/s	416 *	390
Pump-End Bearing Flow, lb/s	0.72 *	1.06 *
Turbine-End Bearing Flow, lb/s	0.56 *	(He 1.1) *
Thrust Bearing Flow, lb/s	3.57 *	2.59 *

Turbine Performance Characteristics	RP-1	LOX
Flow Rate, lb/s	***7.1***	7.1
Inlet Pressure, psi	***540***	173 *
Exit Total Pressure, psi	210	***52.7 ****
Inlet Total Temp., R	***1600***	1497 *
Exit Static Pressure, psi	120 *	38
Efficiency (T/T)	62.4 *	78.4 *
Efficiency (T/S)	48.0 *	62.0 *
Pressure Ratio (T/T)	3.07 *	3.27 *
Pressure Ratio (T/S)	4.46	4.19
Power, Hp	627 *	783 *
Speed, RPM	18,000 *	23,000
Inlet Mean Diameter, in	9.80	9.80
Maximum Tip Speed, ft/s	806 *	1073 *
$AN^2 \times 10^8$	23 *	77
U/C, actual	0.435 *	0.495 *
Gas Constant, ft-lb/lb-R	45.8	45.8
Gamma	1.108	1.108
Exit Relative Mach No.	1.36 *	1.38 *
Exit Absolute Mach No.	0.81 *	0.77 *

Note: Parameters in italics represent requirements per tables 1 and 2 of the Contract SOW, with modifications as directed by NASA.
* Revised from previous reporting period

Attachment 3

Attendees
Twin Rotor Turbopump Interim Review - 1 July 1997
Pratt & Whitney - Space Propulsion Division

Name	Organization	Telephone
Jim Clark	P&W Aerotheral Group	561-796-4898
Don Connell	P&W Proect Engineering	561-796-3782
Andy Crocker	Rocket Systems Engr.	561-796-3215
Tony Crease	Rocket Systems Engr.	561-796-8984
Eric Earhart	NASA - Rotor Dynamics	205-544-2417
Scott Erler	LRE Analytical Engr	561-796-2868
Jim French	P&W Prog. Manager	205-721-2602
Roberto Garcia	NASA - Fluid Mech.	205-544-4974
Thomas Haykin	P&W LRE	561-796-6848
David Hudson	Structures	561-796-8831
Tim Jett	NASA - Bearings	205-544-2514
Kent Johnson	Production/Development	561-796-7042
Jack Macpherson	NASA Proj. Engr.	205-544-5936
W. Magrogran	PWA Projects	561-796-5232
J. C. Miller	P&W Contracts	561-796-6151
Stuart Montgomery	LRE Structures	561-796-8832
Bill Munn	LRE - Str./Dyn.	561-796-4047
Debbie Paul	P&W Project	561-796-3954
Eric Poole	LRE Structures	561-796-2604
Jorge Santiago	P&W Proj Engr	561-796-5131
Bruce Smith	Turbine Aero	561-796-4531
Ed Stastny	P&W Mechanical Design	561-796-4269
Carol W. Tevepaugh	P&W Huntsville Office	205-721-2609
David Wiley	P&W Mechanical Design	561-796-8862

MINUTES OF TWIN ROTOR TURBOPUMP INTERIM REVIEW
1 July 1997

The notes below correspond to the different sections of the presentation.

Turbopump System Performance

- Inlet total pressure figures on page 2 need correction. (Corrected sheets were supplied to all attendees prior to the end of the review.)

Pump Design

- NASA (Robert Garcia) is interested in doing CFD analysis of LOX pump. P&W to give NASA a target date when we would have a final design and when supplier needs to start machining to see if this effort would be timely.

Turbine Rotor Design

- NASA (Jack MacPherson) asked if we had a concern about erosion due to vortex shedding. P&W (Jim Clark) indicated past experience is that vortex shedding was strongly influenced by tip clearance and our experience indicated there wouldn't be much effect at the planned clearances for the TRT.
- NASA (Robert Garcia) asked about blockage due to soot buildup. He suggested talking to Shawn Fears to get estimate of potential reduction in area.
- NASA (Jack MacPherson) wanted to know what thermal margin the turbine would have to ensure the gas generator would not over-temperature the pump. Ed Stastny indicated preliminary calculations indicated the blades had approximately 50o margin. Jack indicated there was preliminary gas generator data available.

Bearing Design

- On page 8, the correct diameter/clearance ratio for the TAMU LOX Hydrostatic Journal Bearing is 486, not 1745.
- NASA (Robert Garcia) asked whether CalTech studies on predicting rotor dynamic coefficients for impeller shrouds, and subsequent discovery of destabilizing force were applicable to the thrust pistons. P&W (Dave Hudson) indicated we are familiar with those studies, and we'd review to determine if applicable.

Structural Analysis

- (NASA) Robert Garcia expressed a concern regarding the level of structural analysis as regards deflections. P&W (Eric Poole and Stu Mann) indicated the final design would be subject to a complete 3-D analysis.

Heat Transfer/Internal Flow

- (NASA) Robert Garcia suggested we look into reducing the backface vane count. This change might reduce power requirement without significantly reducing effectiveness. He also suggested making it same as the vane count to avoid introducing another driver.

(original signed by)_____
Jack MacPherson - NASA

(original signed by)_____
Jorge Santiago - Pratt & Whitney

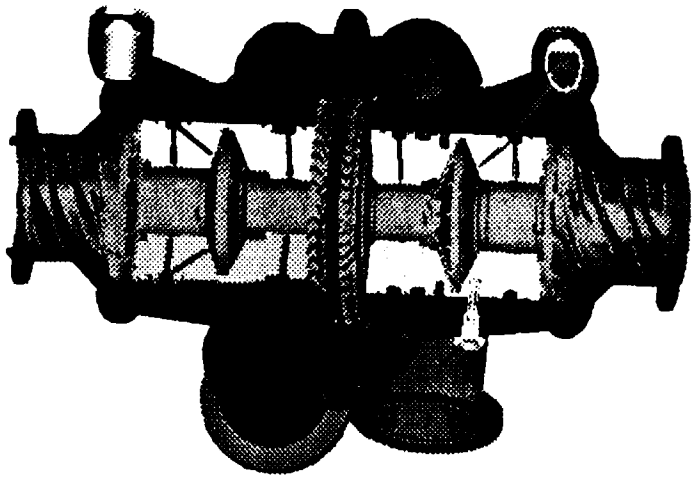
Attachment 4
Interim Review Handout

The handout for the Interim Review follows.

Pratt & Whitney
A United Technologies Company

TWIN ROTOR TURBOPUMP PROGRAM

NAS8-97161



INTERIM REVIEW

PRESENTED TO

NASA MARSHALL SPACE FLIGHT CENTER

1 JULY 1997

Agenda

Subject	Presenter	Time
Introduction	Jim French	8:30
Overview	Jorge Santiago	8:45
Design Table	Andy Crocker	9:00
Mechanical Design	Ed Stastny	9:15
Pump Design	Scott Erler	10:00
Break		10:30
Turbine Volute Design	Jose Rodriguez	10:45
Turbine Rotor Design	Bruce Smith	11:00
Bearing Design	Tom Haykin	11:20
Rotordynamic Analysis	Bill Munn	11:40
Lunch		12:00
Structural Analysis	Eric Poole	1:00
Heat Transfer/Internal Flow	Jim Clark	1:20
Turbopump Test Support	Tony Crease	1:40
Summary	Jorge Santiago	2:00

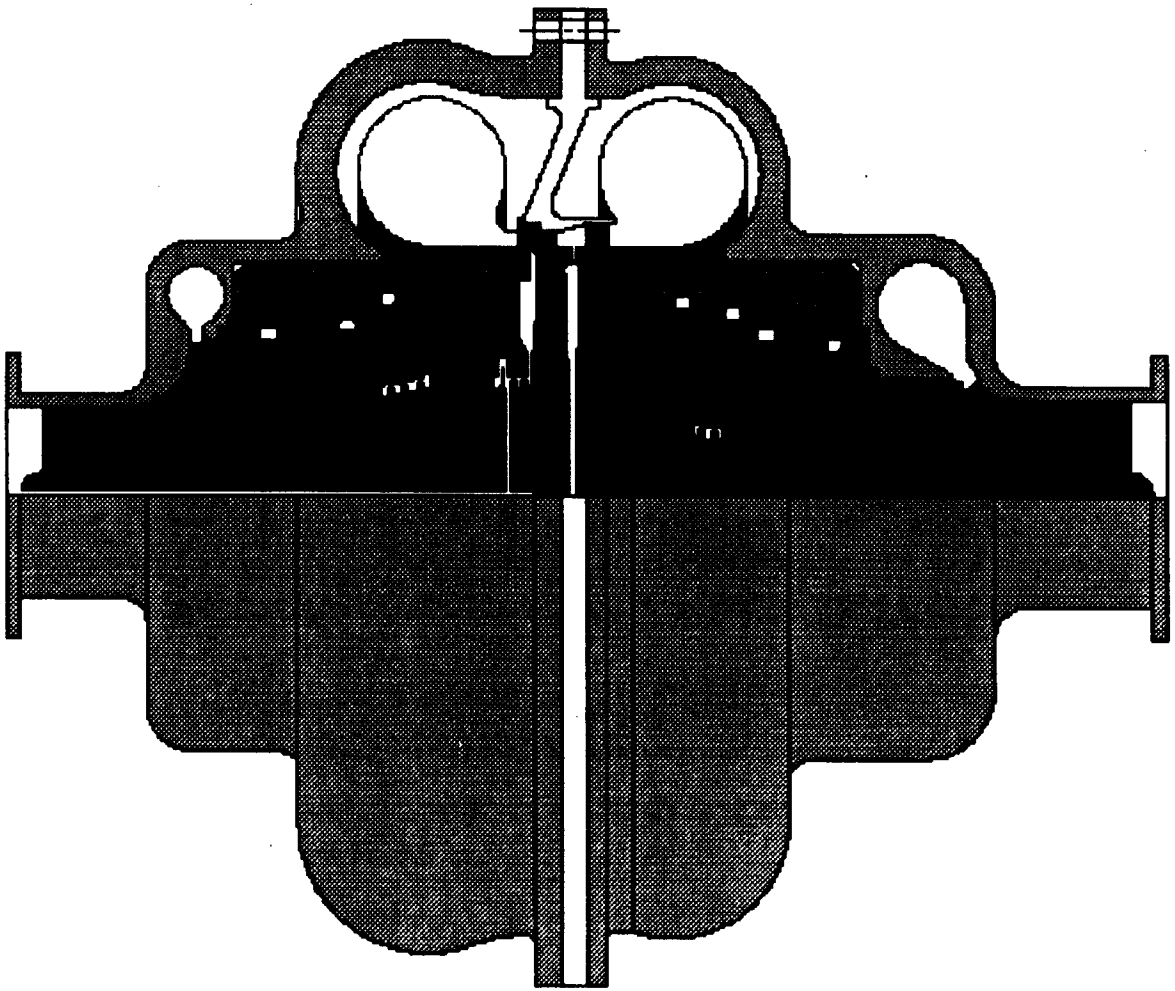
Overview

Jorge Santiago
Project Engineering

Overview

PRATT & WHITNEY - SPACE PROPULSION DIVISION

Pratt & Whitney Twin Rotor Turbopump



Overview

Program Objective

"The objective of the MSFC Ablative Engine Program is to demonstrate low cost hardware using low part count design, commercial off-the-shelf (COTS) materials, and low cost fabrication methods" *

* SOW paragraph 1.0

Overview

Progress Since Product Definition Briefing

- Project Plan submitted
- Interim design completed
  - Key features of conceptual design retained
    - Component arrangement
    - Hydrostatic rotor support
    - Counter-rotating vaneless turbine
- Major suppliers under contract
  - Housing castings - Wyman Gordon Investment Castings
  - Rotors - Paragon Precision Products
  - Bearings - Stein Seal

Overview

Special Studies (Contract Section H.6)

- FASTRAC Turbopump Thermal Analysis
  - P&W asked to carry out independent transient (chilldown) analysis of NASA design
  - ATP by NASA - 4/30/97
  - Analysis reviewed with NASA
    - Initial review - 5/29/97
    - Final review - 6/19/97
  - Comparison of NASA and P&W results underway
    - Joint NASA - P&W effort
    - No further P&W analysis planned

Overview

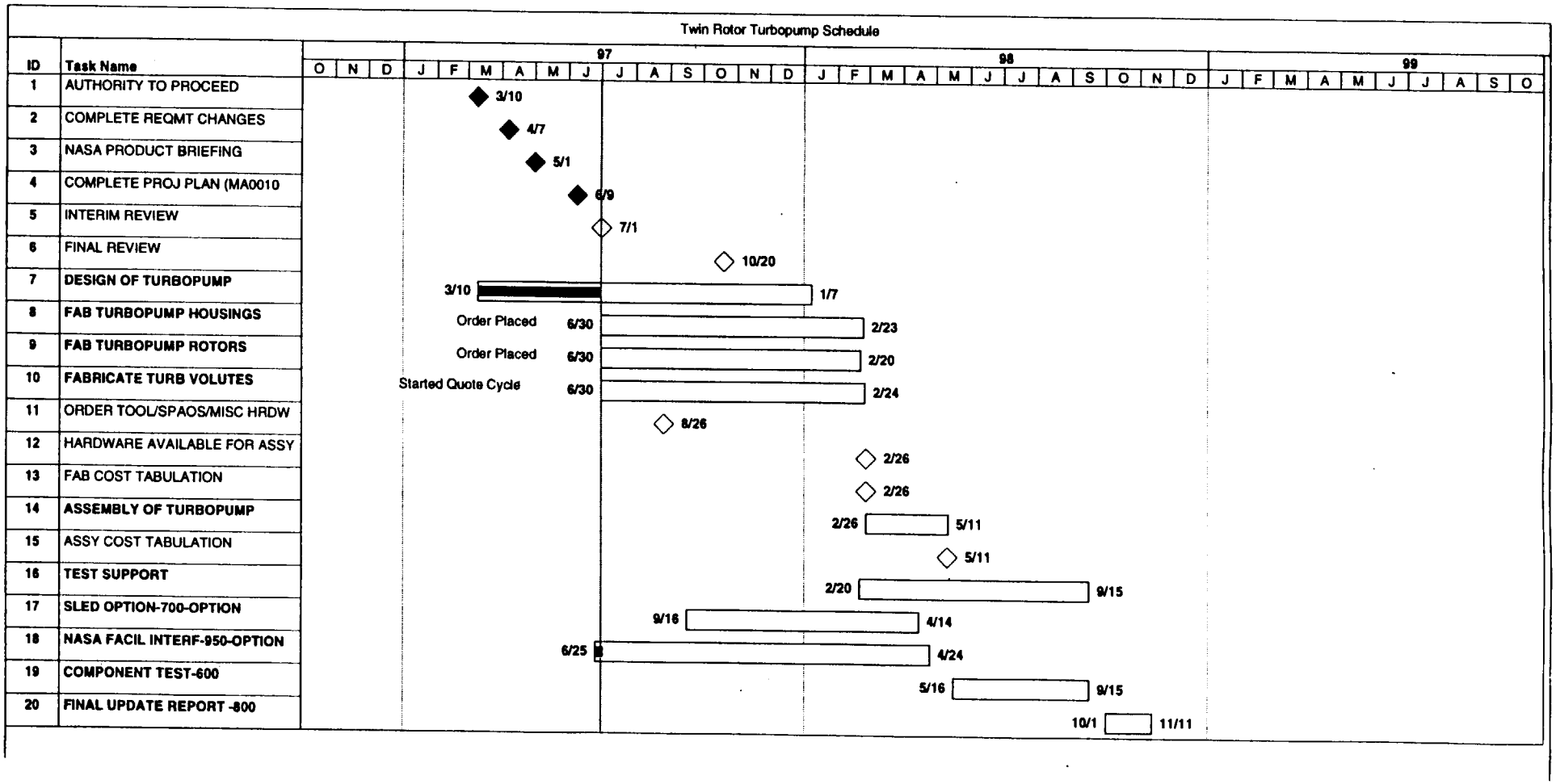
Major Issues

- Parasitic losses calculations creating higher than expected turbine power requirement
  - Affected rotor speed, pump design, thrust balance, internal flow
  - Turbine blade final design will provide required power

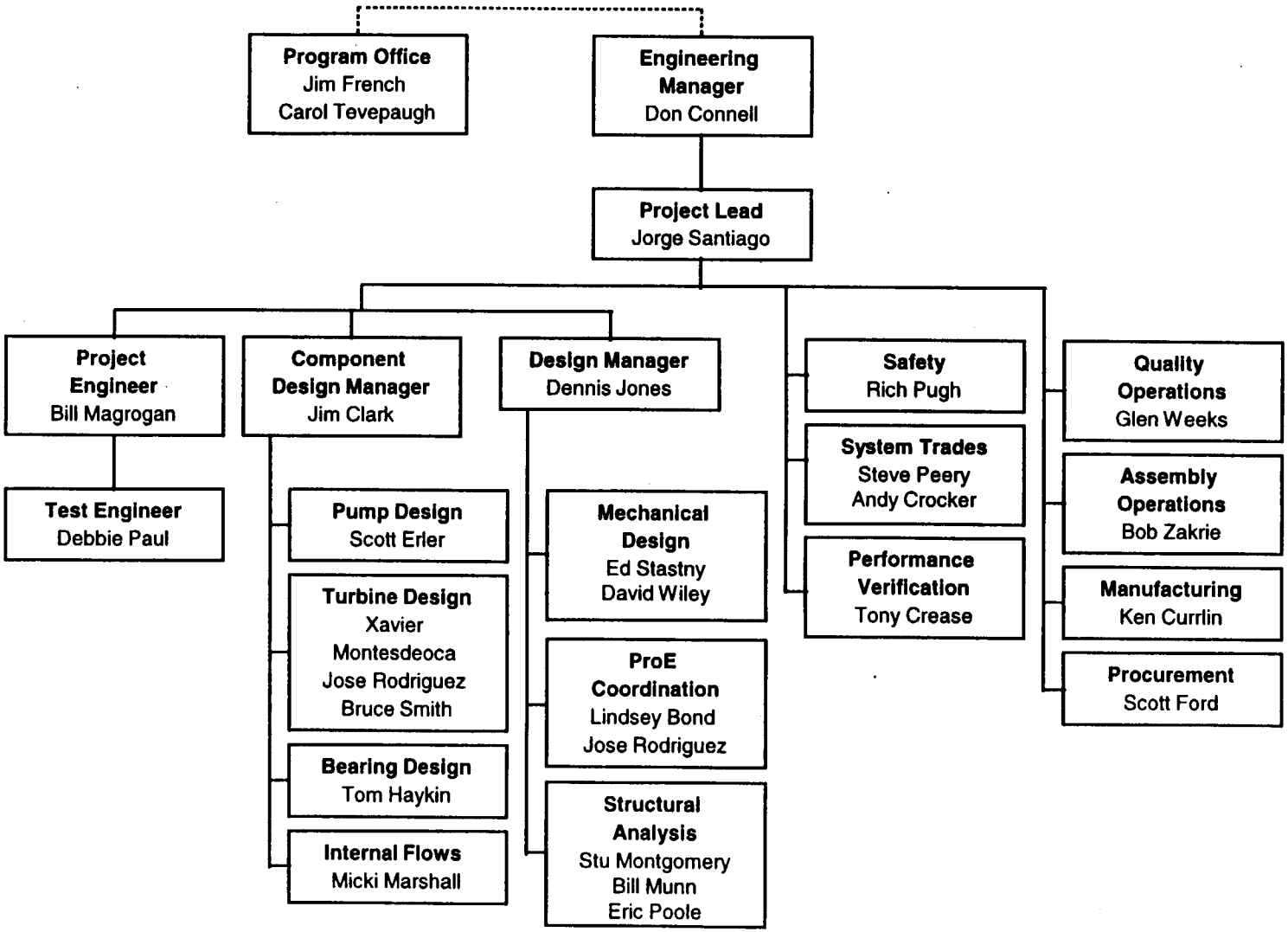
Overview

PRATT & WHITNEY - SPACE PROPULSION DIVISION

Program Schedule



TRT Program Functional Organization



Turbopump System Performance

Andy Crocker

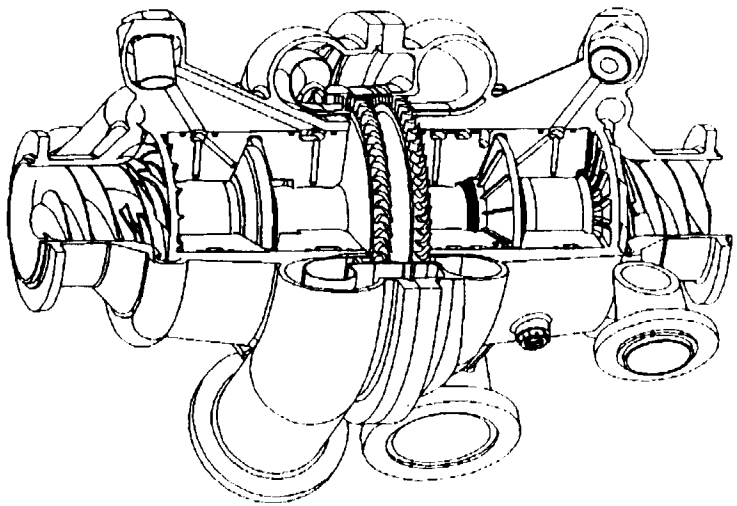
Advanced Engine Design

Turbopump System Performance

TRT Design Requirements

Pump Performance Characteristics

	RP-1	LOX
Delivered Flowrate, lb/s	*64.3*	*139.3*
Inlet Pressure, psi	*28*	*46*
Exit Pressure, psi	*960*	*919*
Inlet Temperature, R	*530*	*166*



Turbine Performance Characteristics

	RP-1	LOX
Flow Rate, lb/s	*7.1*	*7.1*
Inlet Pressure, psi	*540*	*159*
Exit Total Pressure, psi	*159*	*52.4*
Inlet Total Temp., R	*1600*	*1495*

TRT Current Performance Status

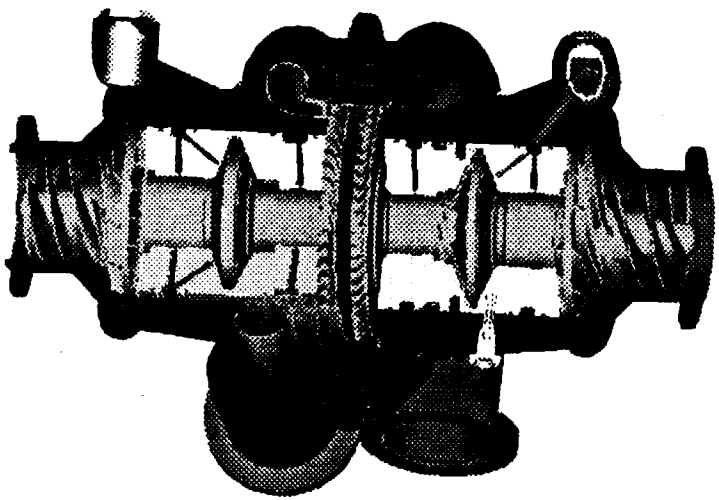
Pump Performance Characteristics

	RP-1	LOX
NPSH Ava., ft	73.3	56.9
Total Pump Flowrate, lb/s	69.9	141.7
Exit Temperature, R	537	171
Hydraulic Efficiency	68	66.5
Impeller Power, Hp	440	665
Windage Loss, Hp	80	40
Backvane Power Req't, Hp	65	35
Vaporizer Power Req't, Hp	-	20
Speed, RPM	16,600	22,000
Specific Speed	1150	2500
Head Rise, ft	2670	1780
Exit Diameter, in	5.6	4.1
Tip Speed, ft/s	414	394
PE Bearing Flow, lb/s	1.47	0.9
TE Bearing Flow, lb/s	0.58	(He 0.1)
Thrust Bearing Flow, lb/s	3.5	1.5

Turbine Performance Characteristics

	RP-1	LOX
Exit Static Pressure, psi	151	47
Efficiency (T/T)	61.2	74.3
Efficiency (T/S)	45.8	58.7
Pressure Ratio (T/T)	2.52	3.18
Pressure Ratio (T/S)	3.50	4.43
Power, Hp	585	760
Speed, RPM	16,600	22,000
Inlet Mean Dia, in	9.45	9.58
Max Tip Speed, ft/s	705	960
AN**2 x 10**8	24	61
U/C, actual	.422	.467
Gas Constant, ft-lb/lb-R	45.8	45.8
Gamma	1.108	1.108
Exit Rel. Mach No.	1.35	1.36
Exit Absolute Mach No.	0.78	0.78

TRT Performance Path - Where We're Going



	RP-1	LOX
Power, HP	627	783
Speed, RPM	18,000	23,000

	RP-1	LOX
Power, HP	585	760
Speed, RPM	16,600	22,000

Mechanical Design

Ed Stastny

Mechanical Design

Mechanical Design Goals

Reduce pump cost

- Minimize parts count
- Commercial grade materials
- Simplified fabrications requirements
- Conservative structural approach to reduce analysis effort
- Reduced procurement cycle

Mechanical Design

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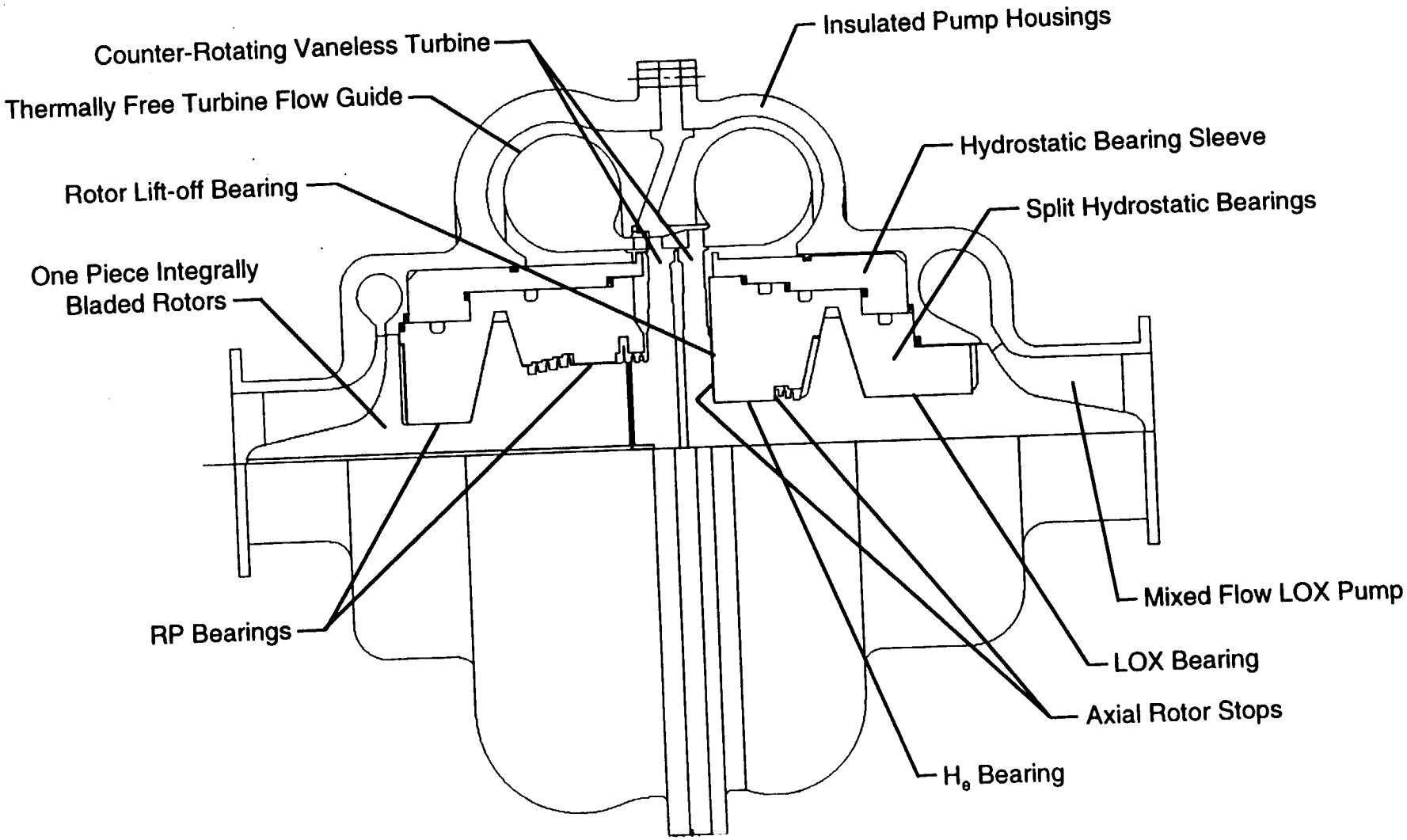
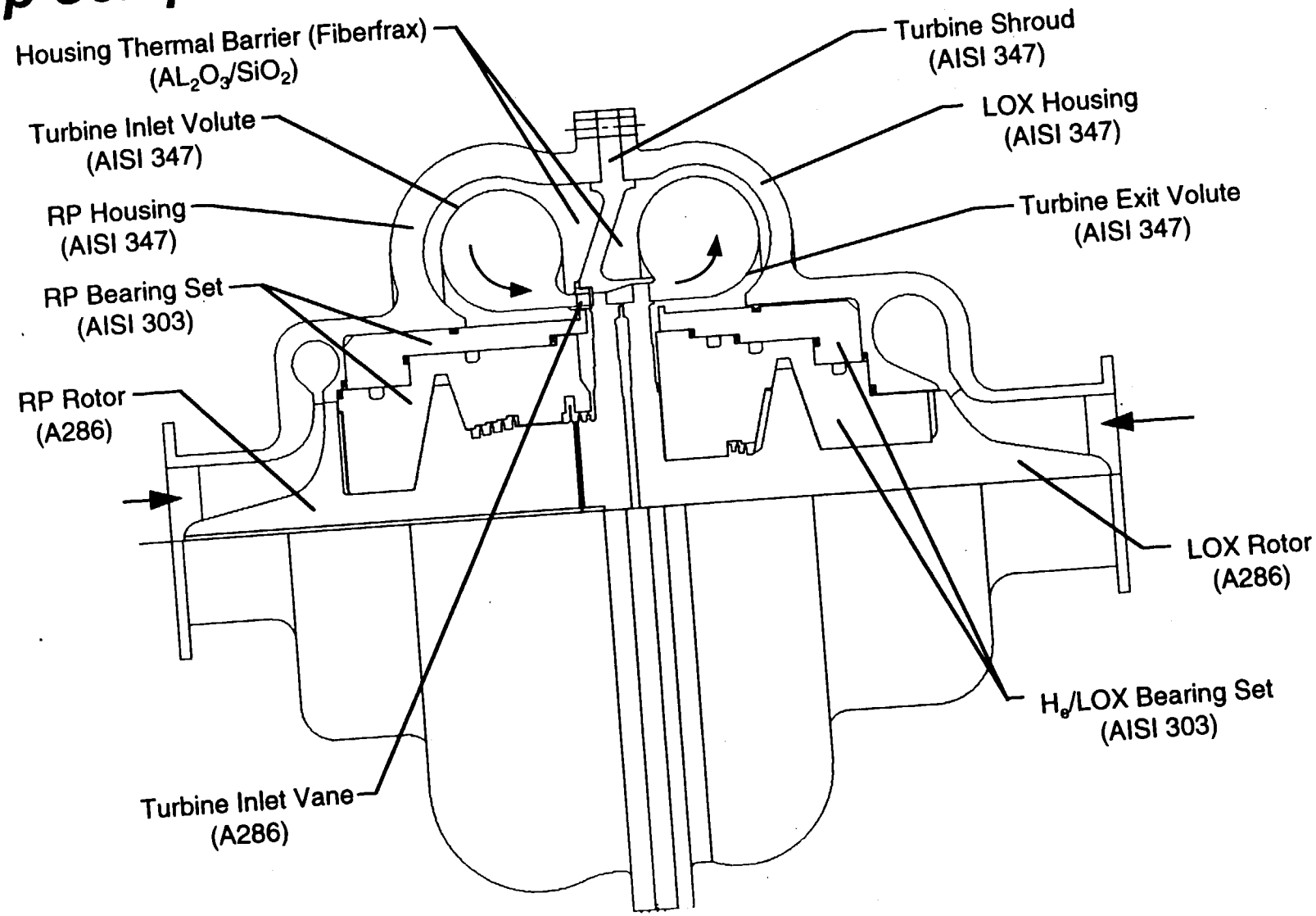
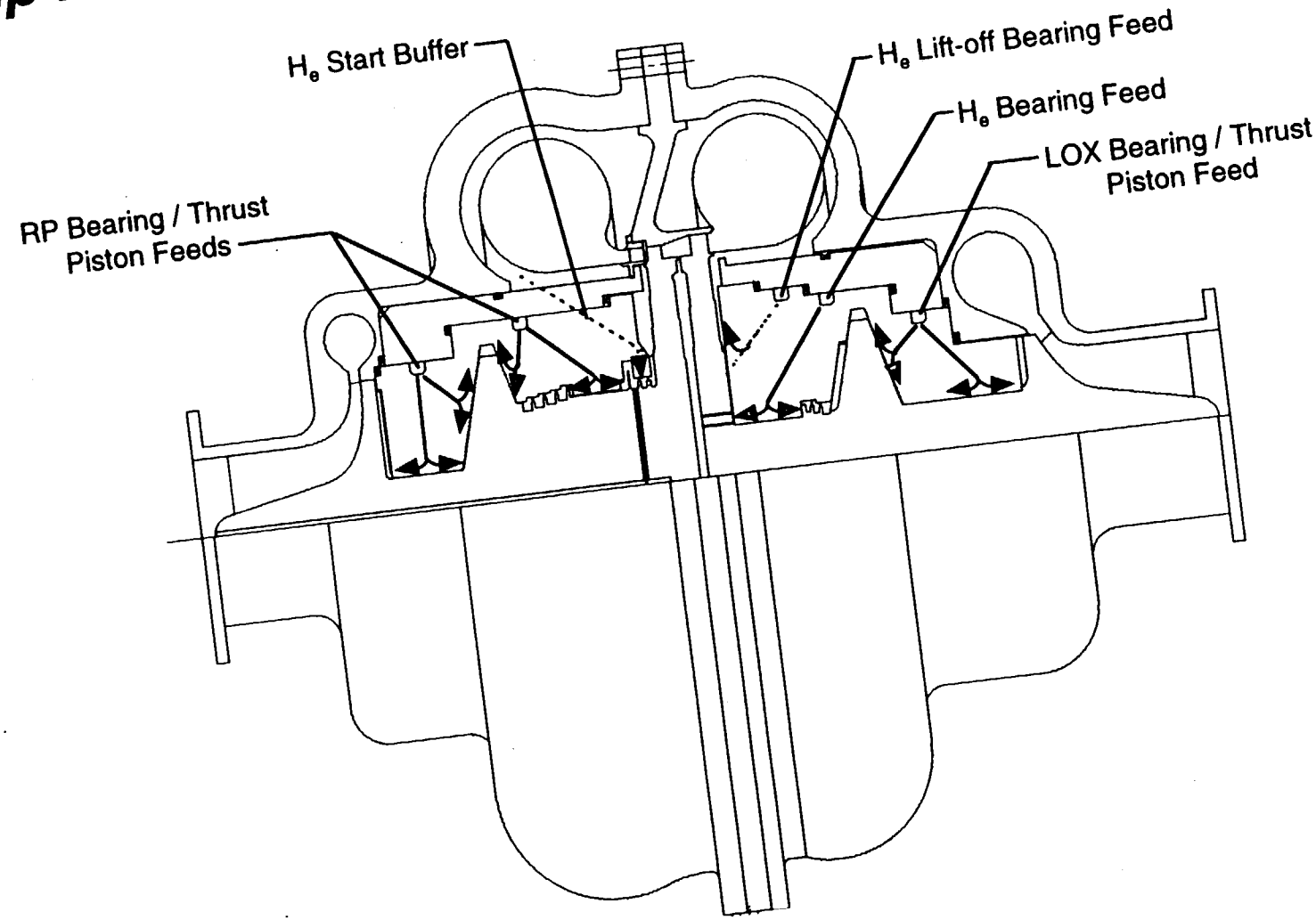
Pump Mechanical Features



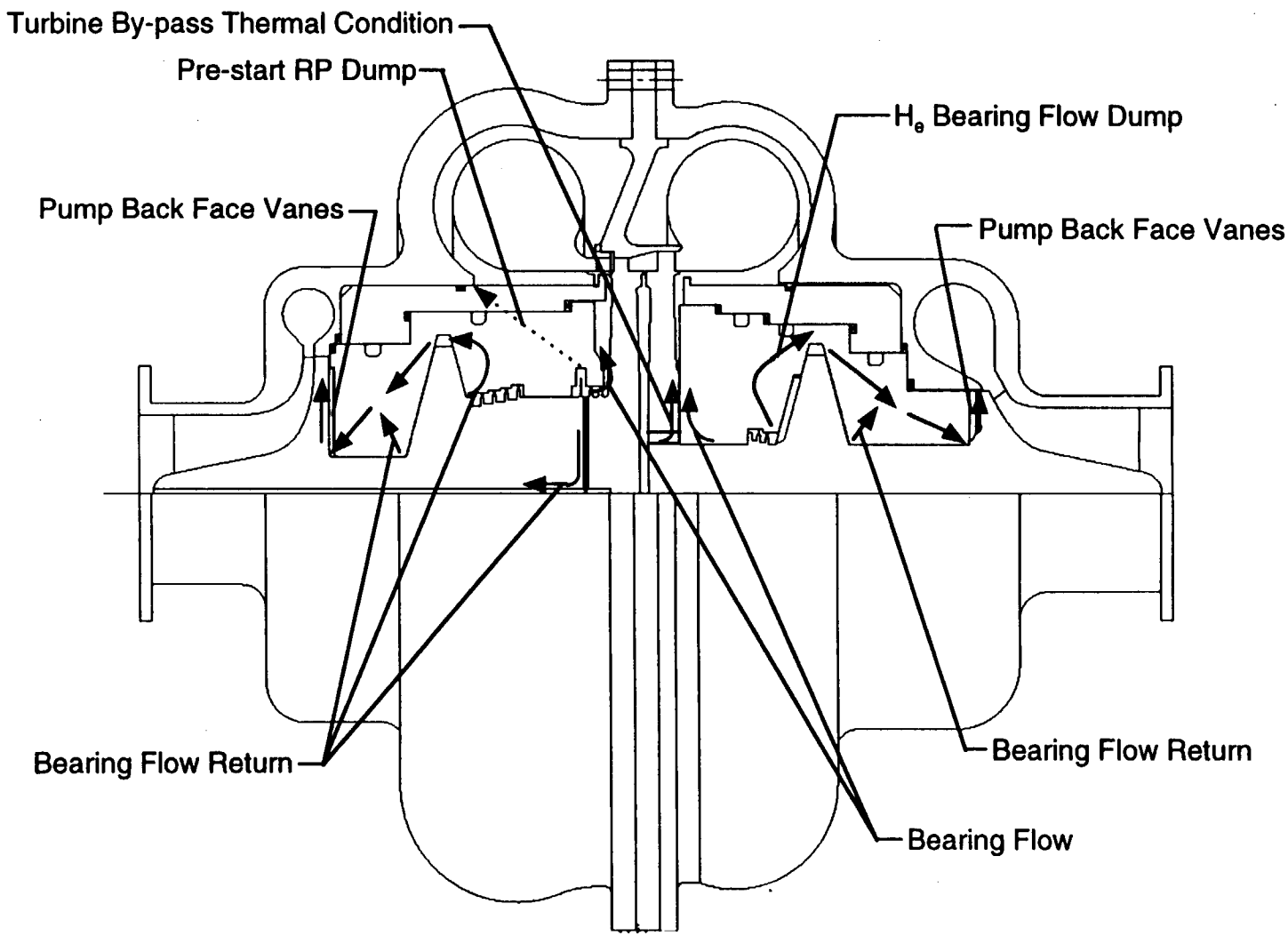
Pump Components / Material Selection



Pump Fluid Dynamics - Feed System



Pump Fluid Dynamics - Return System



echanical Desig.n
PRATT & WHITNEY - SPACE PROPULSION DIVISION

Preliminary Thrust Balance Calculations Establish Hetu Geometry

Thrust Balance RP Pump 1.5" brg

date 31-May

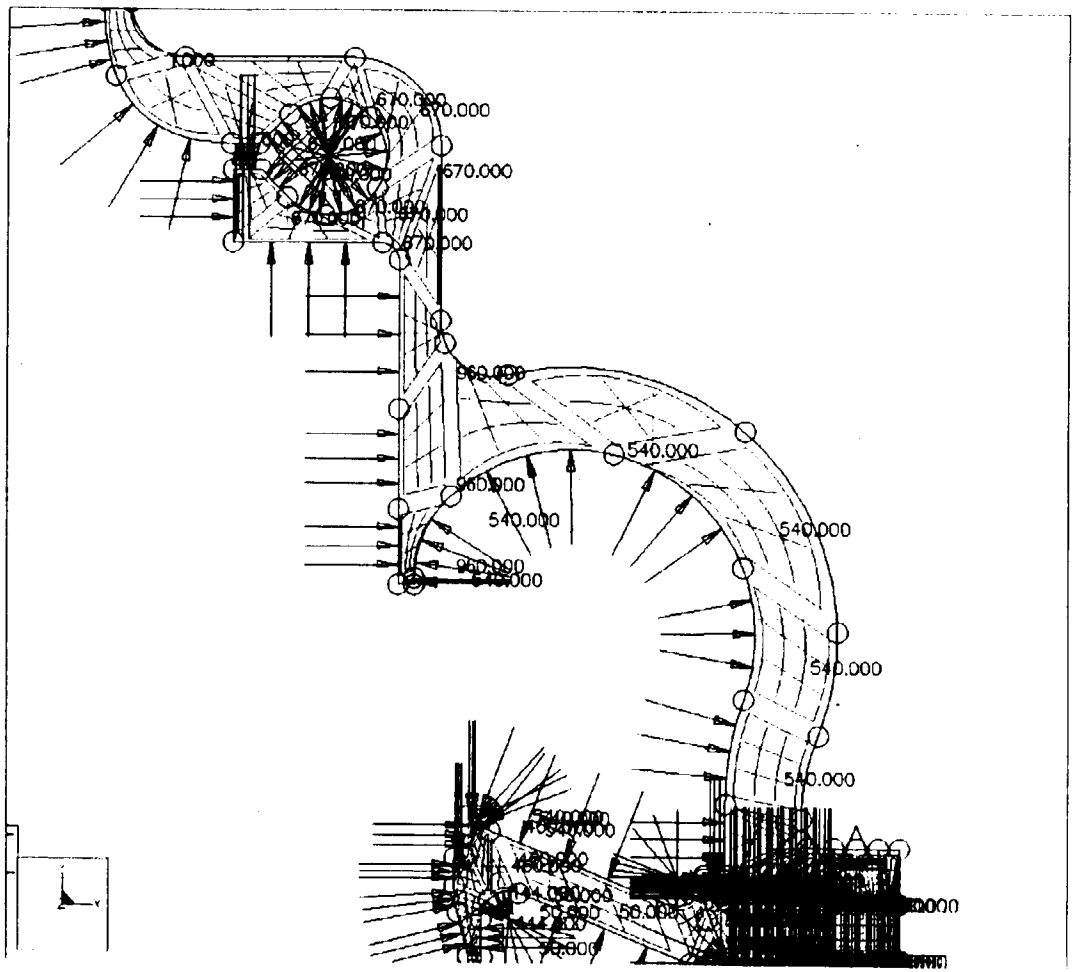
RPM 16800.00
Discharge press 960.00
turb blade load 2714.00

Thrust brg load 14848.33

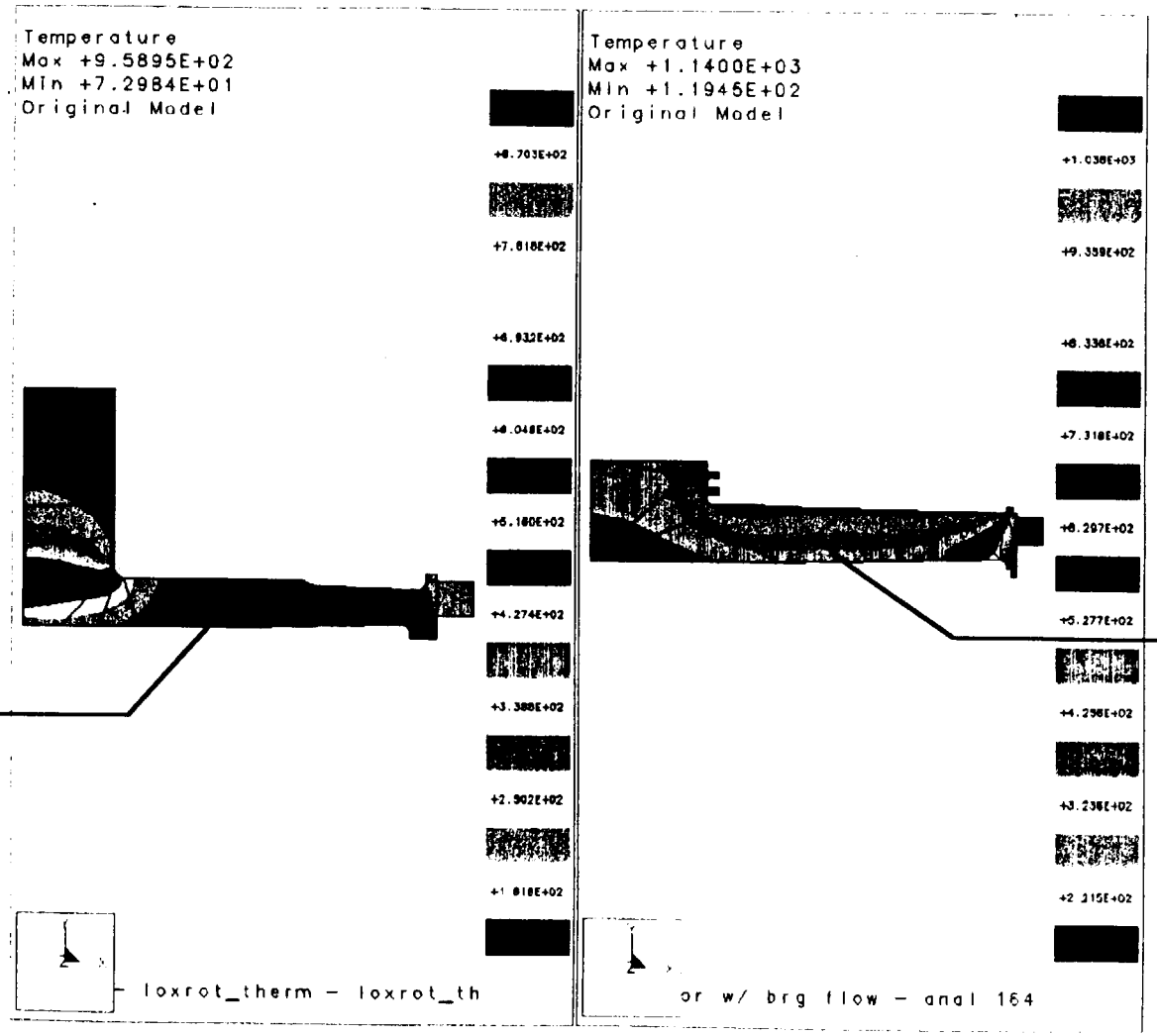
K1 0.10
K2 0.60

COMPONENT	FLUID DENSITY	THRUST DIRECTION	ROTATION FACTOR	INNER RADIUS	OUTER RADIUS	O.D. STATIC P	I.D. STATIC P	P.@I.D.	THRUST FORCE
impeller inlet	50.10	1	0.00	0.000	1.580	28.00	28.00	FALSE	219.6
impeller bladied	50.10	1	0.00	1.580	2.850	670.00	28.00	FALSE	6168.5
outer impeller backface	50.10	-1	0.50	2.600	2.850	670.00		630.41	-2825.5
impeller backface	50.10	-1	0.90	0.750	2.600	630.41		46.89	-9433.7
Fwd thrust brg. ID dump	50.10	1	0.50	1.000	1.000	66.89		66.89	0.0
Aft thrust brg. I.D. dump	50.10	1	0.50	2.000	2.000	86.89		86.89	0.0
turb disk inlet	0.91	1	0.50	2.000	4.580	455.00		446.09	24147.7
turb. blades	0.91	1	0.00	4.580	4.860	455.00	459.00	FALSE	2714.0
turb disk discharge side	0.33	-1	0.50	0.000	4.580	151.00		146.95	-9884.0
Fwd thrust bearing	50.10	1	0.00	0.750	3.030	138.20	138.20	FALSE	3741.8
									14848.33
Aft thrust bearing	50.10	-1	0.00	2.000	3.031	547.87	547.87	FALSE	-8931.8

2D Axisymmetric Models Used For Preliminary Thermal Studies And Structural Sizing



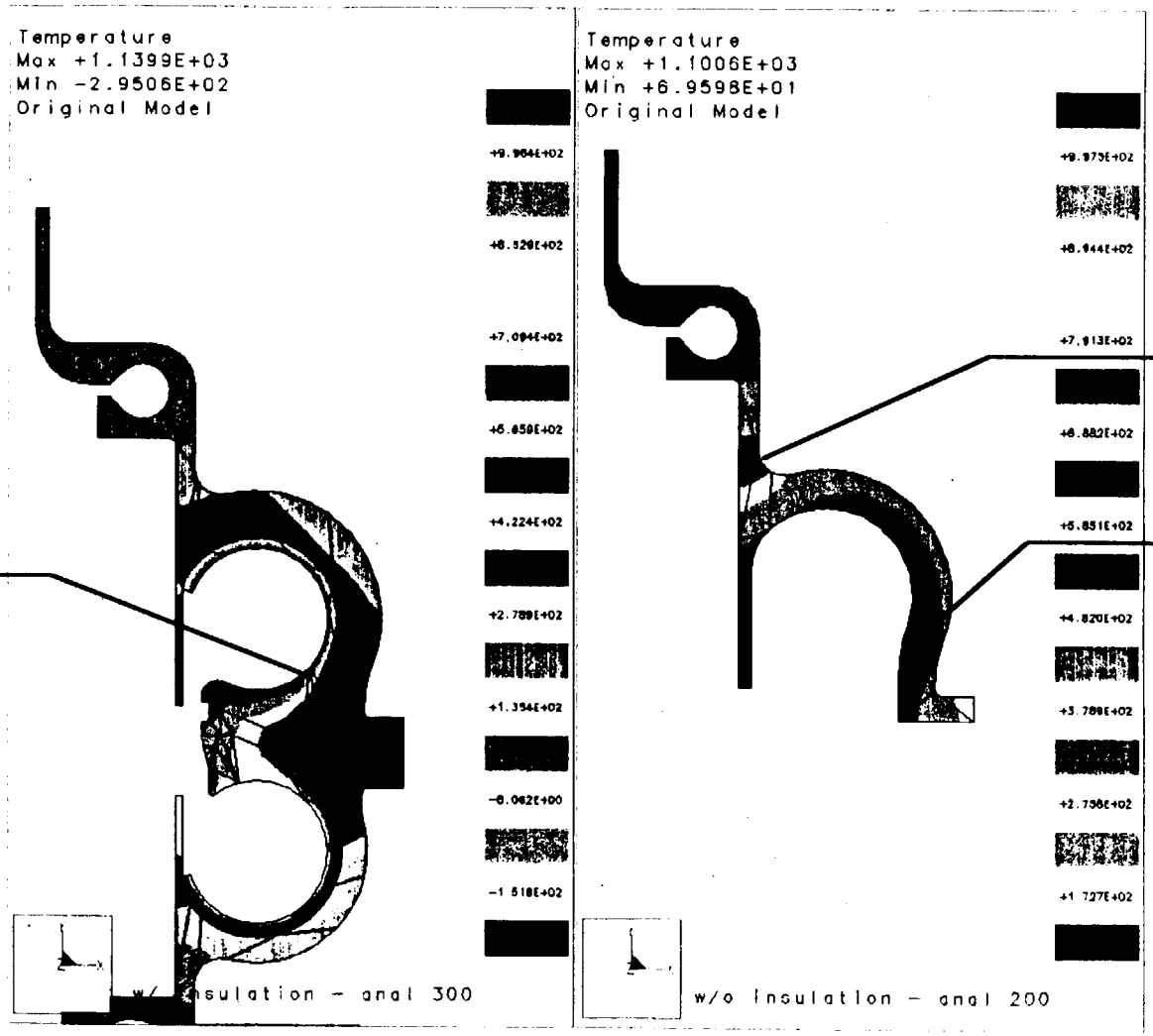
Thermal Conditioning Studies Address Turbine Rotor Deflections



Bending Reduced For Thermally Conditioned Rotor

Web Bending Caused By Axial Temperature Gradient

Insulation Enhances Usage Of Cast 347 Housing Material

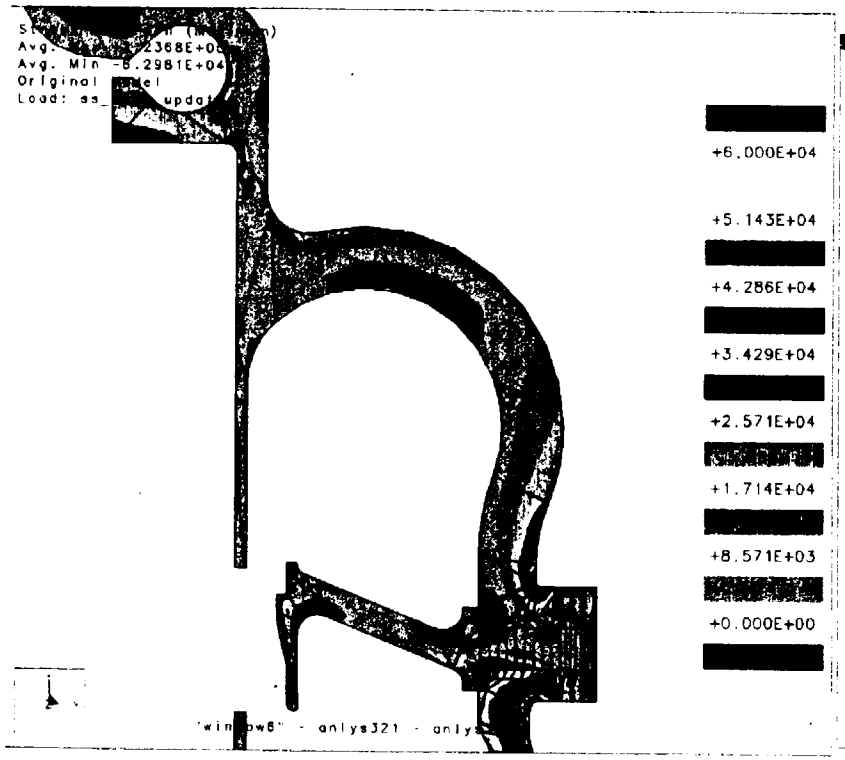


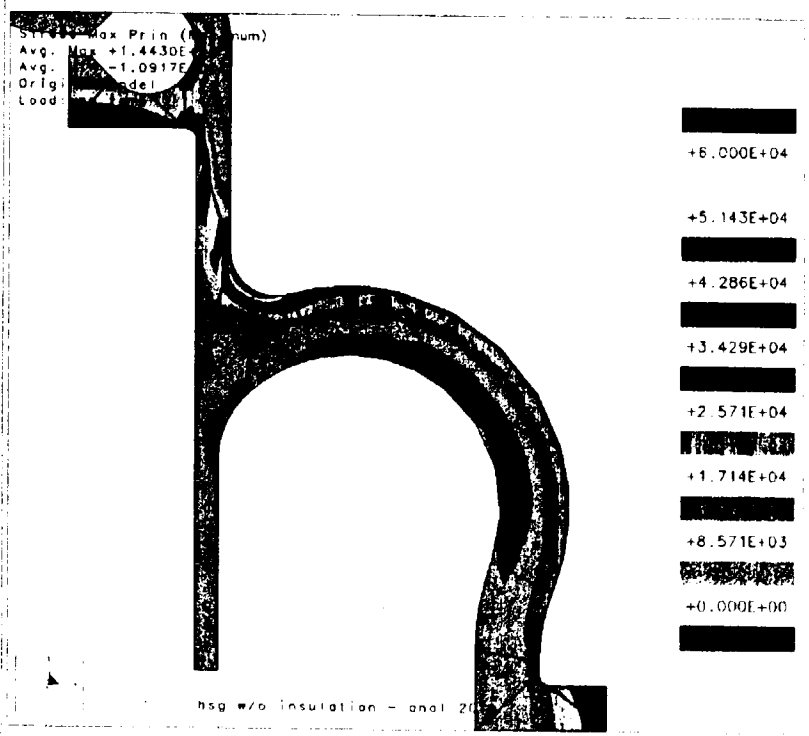
Housing Temperatures Reduced Up to 700°R

Steep Temperature Gradient

Reduced Material Strength

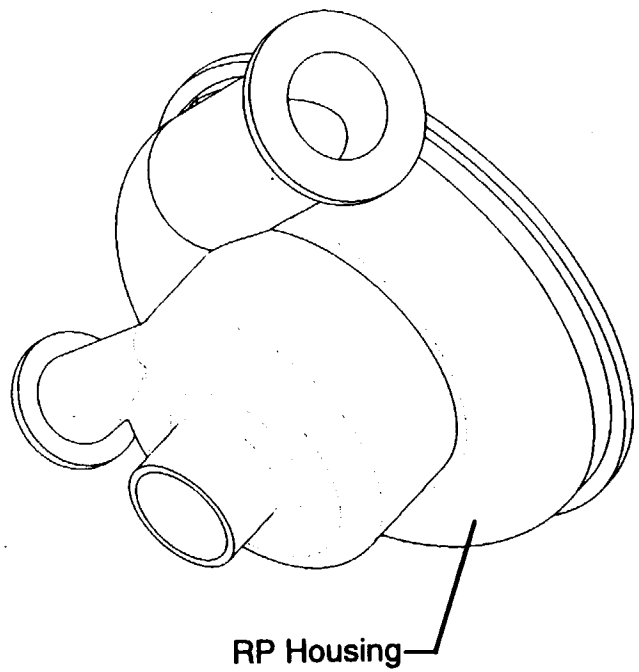
Preliminary Stress Predictions Verify Insulation Effectiveness

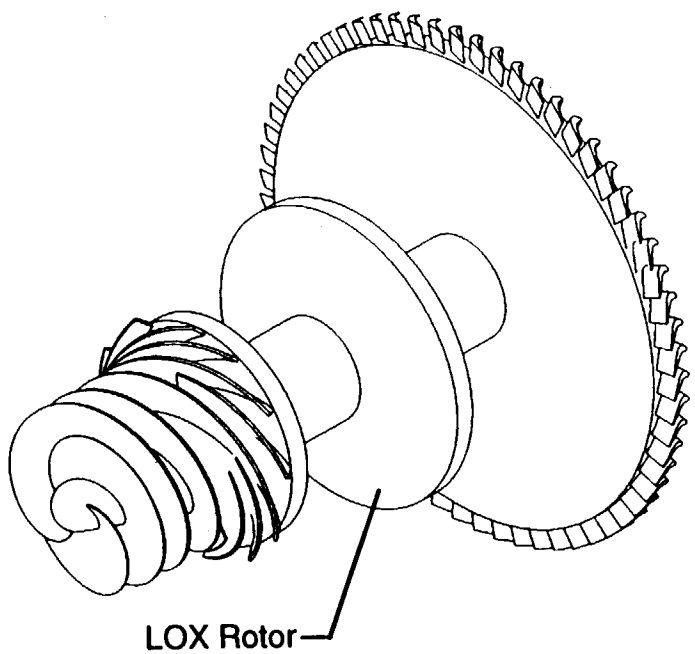




Mechanical Design

Preliminary Component Model Structure Matured With Preliminary Pump Configuration





Final models will feed

- Final structural analysis
- Part detail and assembly prints
- Assist fabricators as required

Mechanical Design Summary

- Preliminary turbine / pump definition complete
- Preliminary thrust balance / windage losses complete
- 2D axisymmetric analysis studies corrected unacceptable thermal conditions (global stresses and deflection established)
- Design driven electronic models in place for required design updates

Pump Design

Scott Erler
Component Design

Hydrodynamic Design Objective / Approach

OBJECTIVE

- "Demonstrate Low Cost Hardware Using Low Part Count Design ... And Low Cost Fabrication Techniques"

APPROACH

- Minimize Fabrication / Inspection / Assembly Costs Consistent With Good Hydrodynamic Design Practice
  - Straight Inlets
  - Unshrouded Impellers
  - Moderate Blade Counts
  - Moderate Tip Clearances
  - Generous Blade Thicknesses
  - Single Discharge Volute Collectors (No Splitters)

Design Requirements

Pump Requirement	LOX	RP-1
Flow Rate, lbm/sec	139.3	64.3
Inlet Pressure, psia	46	28
Exit Pressure, psia	919	962
Inlet Temperature, Deg. R	166	530
NPSHA, ft	56.9	73.3

Design Criteria

Turbines Require Highest Possible Operating Speeds To Achieve Power

Rotor Speeds Selected To Maximize Turbine Output Within Hydrodynamic Design Constraints And Low Cost Philosophy

- LOX Pump (High Work Turbine)
  - Suction Specific Speed (Higher Flow, Lower NPSHA Than Fuel)
    - NPSH Margin
    - Inlet Blade Angle / Thickness (Cost)
  - Diameter Ratio (Efficiency)
- RP-1 Pump
  - Turbine Velocity Triangle / Flowpath Matching

Hydrodynamic Design Parameters (Current)

Parameter	LOX	RP-1
Speed, rpm	23,000	18,000
$N_{ss,o}$	29,500	17,900
NPSH Margin	25%	60%
β'_{1t}, Deg.	8.5	12.5
D_{1t} / D_{2m}	0.88	0.57
N_s	2520	1200

Hydrodynamic Design - LOX Pump

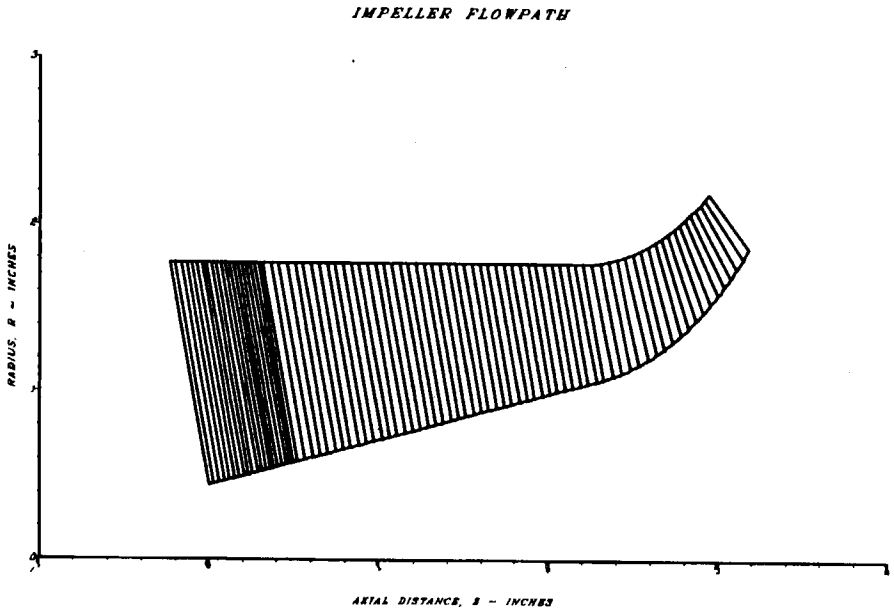
- Design Speed Selected To Maximize Turbine Work Output
- Resulting Impeller Is High Suction (Nss), High Diameter Ratio (Ns) Design
- Low Discharge Blade Angle, Mixed Flow Configuration Results In Low Hydrodynamic Loadings And Smooth Variations Of Velocity Throughout The Flowpath

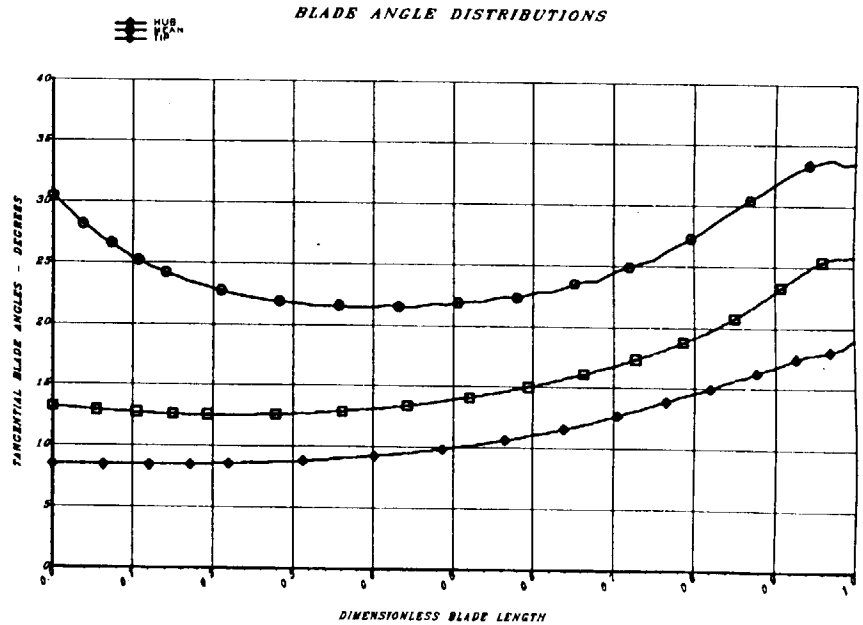
Design Parameters - LOX Pump (Current)

Parameter	Description	Value
N	Rotational Speed, rpm	23,000
NPSHA	Available NPSH, ft	56.9
$N_{ss,o}$	Operating Suction Specific Speed	29,500
NPSHM	NPSH Margin, percent	25
β'_{1t}	Inlet Tip Blade Angle, degrees	8.5
σ	Inducer Solidity	2.5
U_{2m}	Impeller Tip Speed, ft/sec	390
β'_{2m}	Impeller Discharge Blade Angle, degrees	25
ψ	Stage Head Coefficient	0.38
η	Stage Efficiency, percent	67*

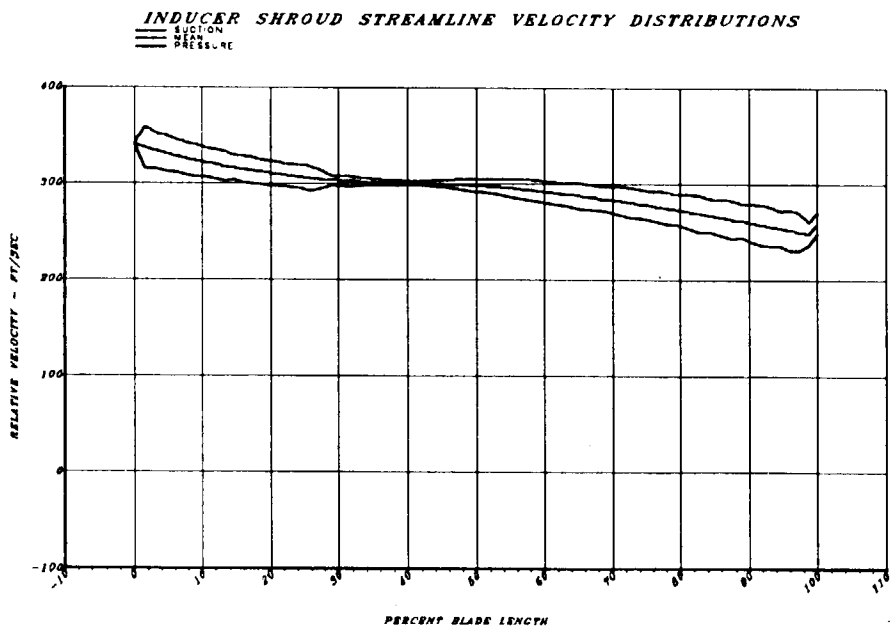
* *does not include impeller backvane windage*

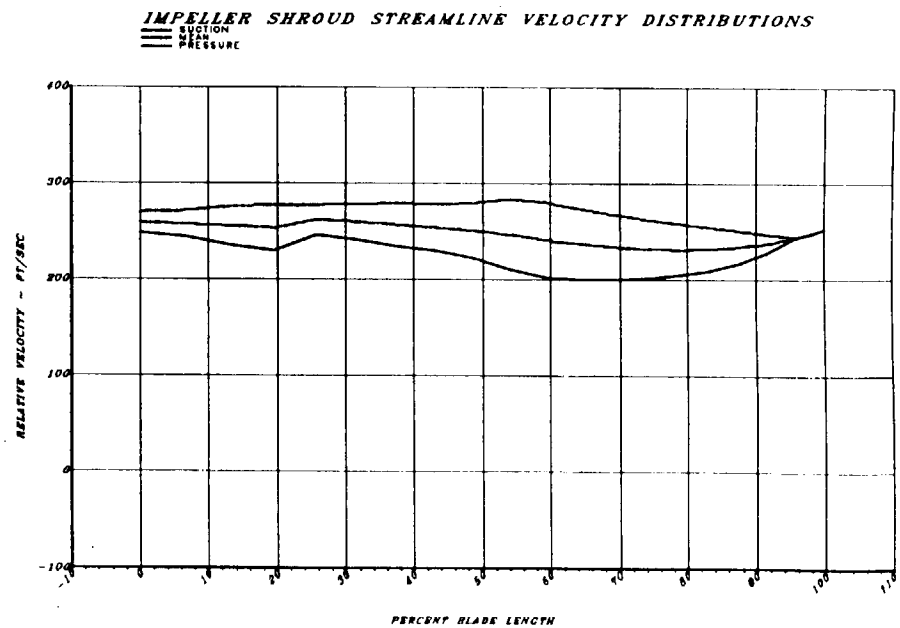
Impeller Geometry - LOX Pump (22,000 rpm)





Hydrodynamic Analysis - LOX Impeller (22,000 rpm)





Hydrodynamic Design - RP-1 Pump

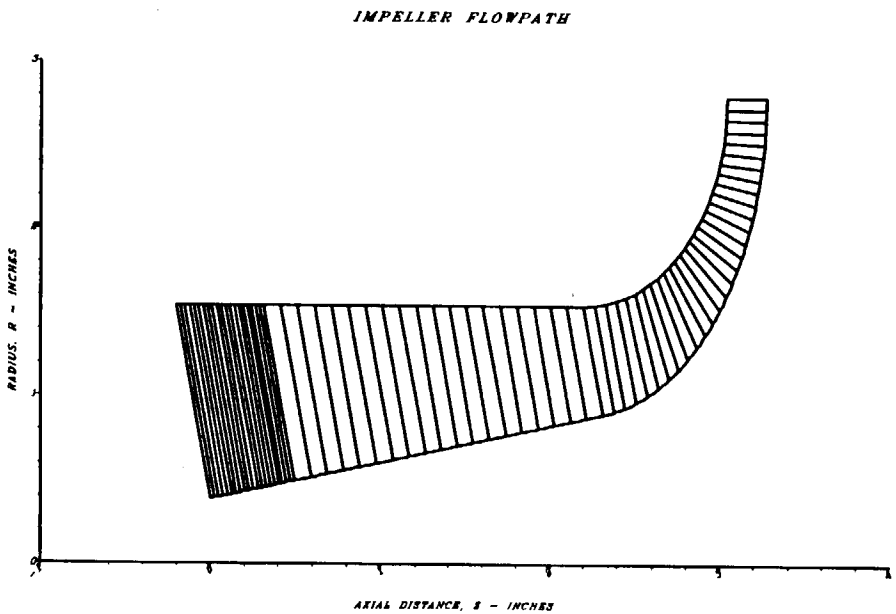
- Design Speed Selected For LOX / RP-1 Turbine Matching
- Resulting Design Is Moderate Suction (Nss), Low Diameter Ratio, Moderate Ns
- All Hydrodynamic Parameters Well Within Design Experience

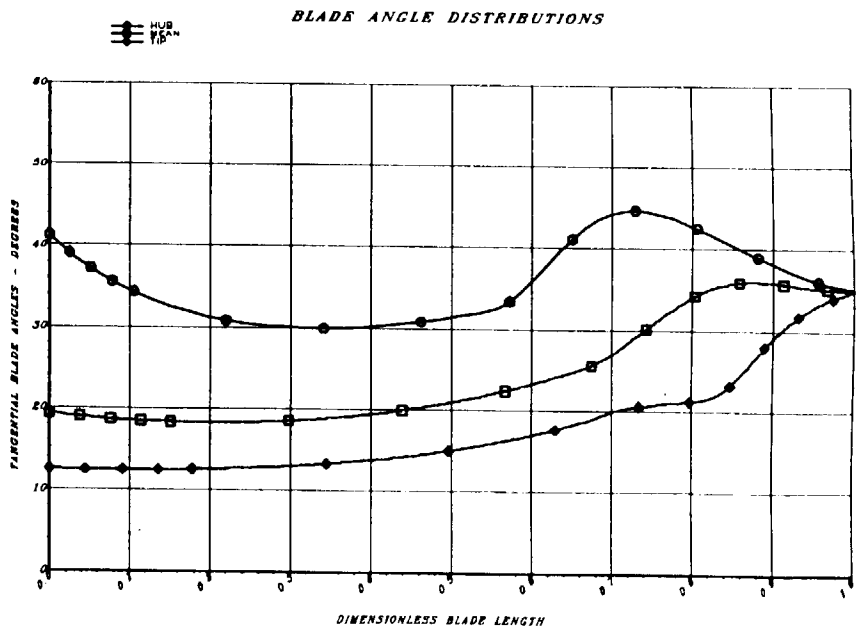
Design Parameters - RP-1 Pump (Current)

Parameter	Description	Value
N	Rotational Speed, rpm	18,000
NPSHA	Available NPSH, ft	73.3
$N_{ss,o}$	Operating Suction Specific Speed	17,900
NPSHM	NPSH Margin, percent	60
β'_{1t}	Inlet Tip Blade Angle, degrees	12.5
σ	Inducer Solidity	2.0
U_{2m}	Impeller Tip Speed, ft/sec	416
β'_{2m}	Impeller Discharge Blade Angle, degrees	35
ψ	Stage Head Coefficient	0.50
η	Stage Efficiency, percent	70*

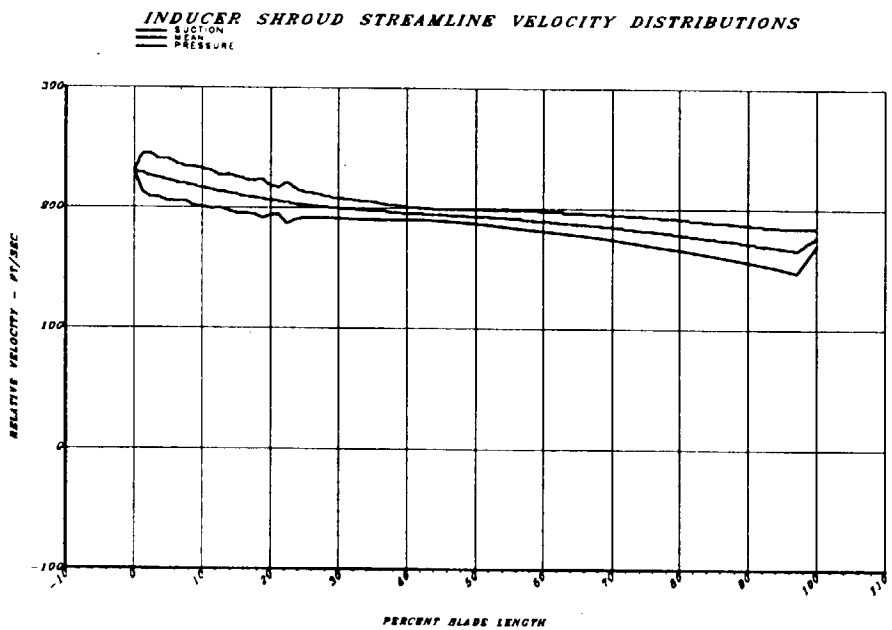
* *does not include impeller backvane windage*

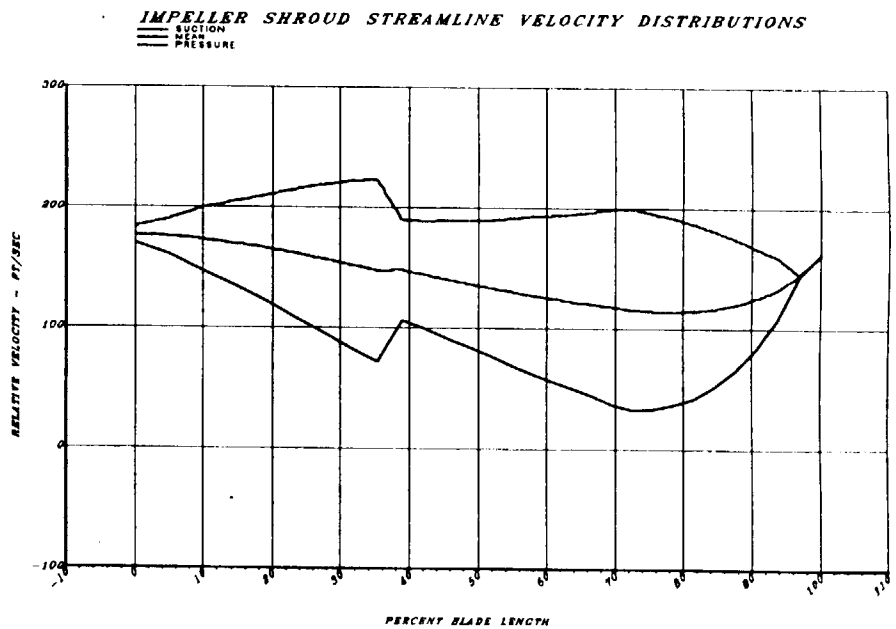
Impeller Geometry - RP-1 Pump (17,000 rpm)





Hydrodynamic Analysis - RP-1 Impeller (17,000 rpm)





Discharge Collector / Diffuser - LOX and RP-1 Pumps

- Single Discharge Volute Collectors Used For Simplicity And Low Cost
- Volutes Designed For Constant Angular Momentum To Promote Uniform Circumferential Pressure Distribution, Reducing Hydraulic Losses And Radial Loads
- Discharge Conical Diffusers Designed For Optimum Pressure Recovery
- Secondary Discharges Designed To Maximize Hydrostatic Bearing Supply Pressures

Summary

Status

- Preliminary Hydrodynamic Designs Of LOX and RP-1 Impellers Performed At 22,000 rpm and 17,000 rpm, respectively
  - Velocity Distributions, Loadings Within Design Experience
  - No Significant Hydrodynamic Issues Encountered

Plans

- Revise LOX and RP-1 Impellers For Final Design Speeds
- Finalize Primary And Secondary Discharge Volutes Based On Updated Leakage Rates

Turbine Volute Design

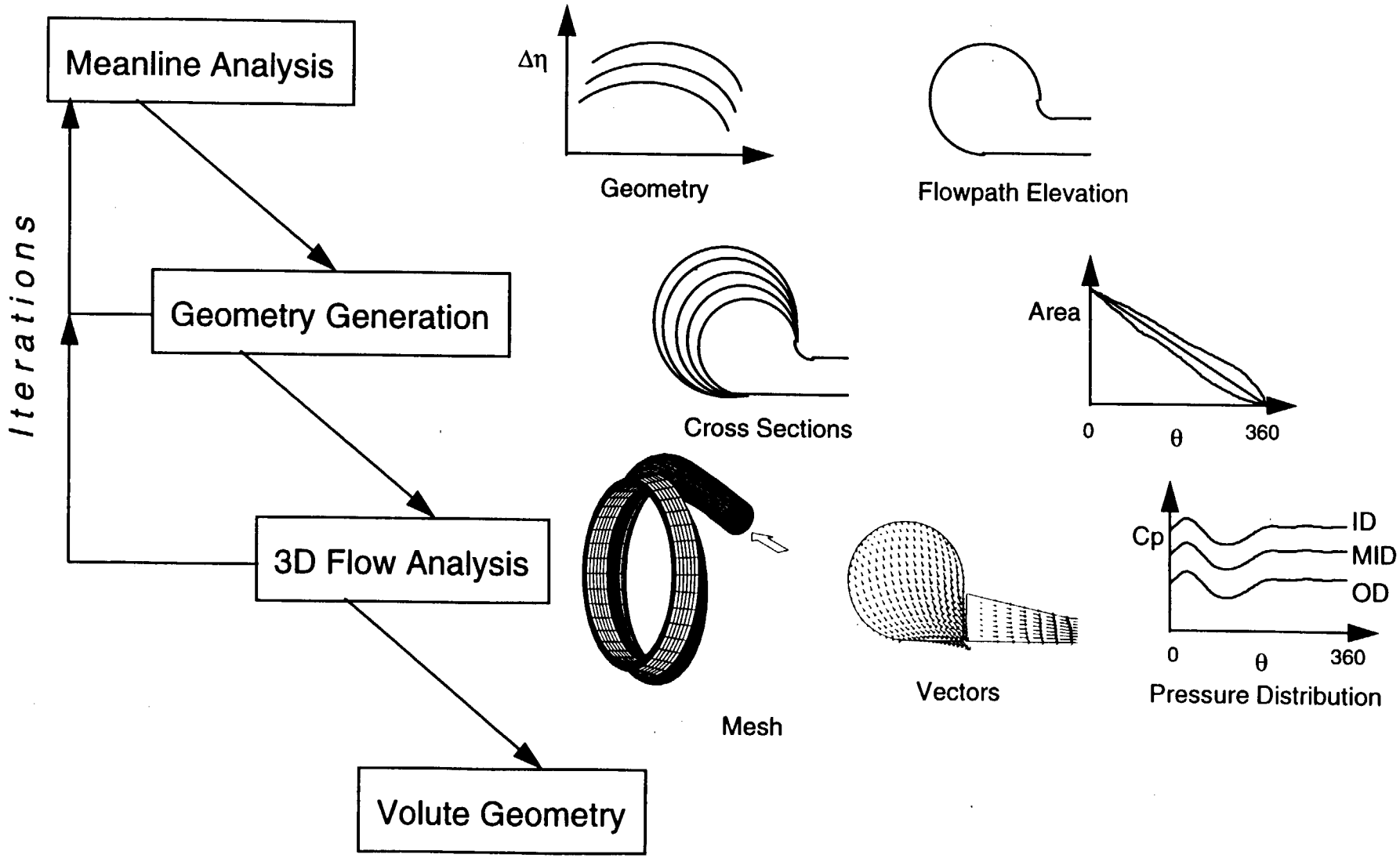
Jose Rodriguez
Component Design

Design Goals

- Uniform pressure distribution at inlet vanes
- Minimize areas of stagnant flow at the exit
- Low radial side loads
  - Uniform flow conditions throughout volute
  - Minimize effect of volute tongue

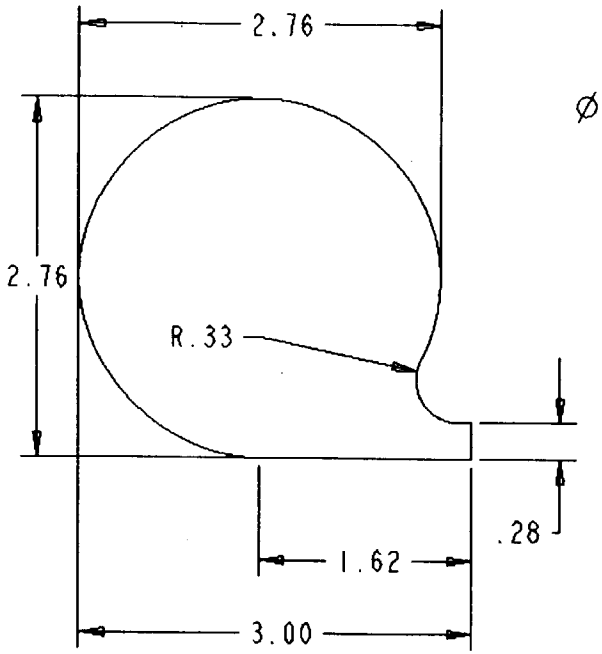
Turbine Volute Design

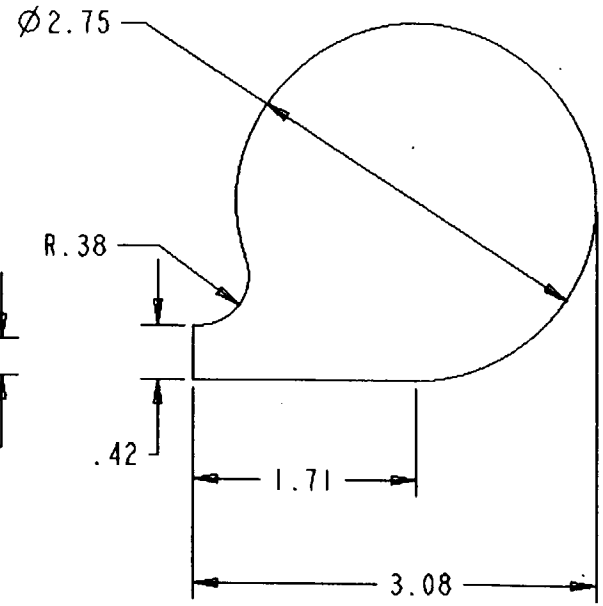
Volute Design Approach

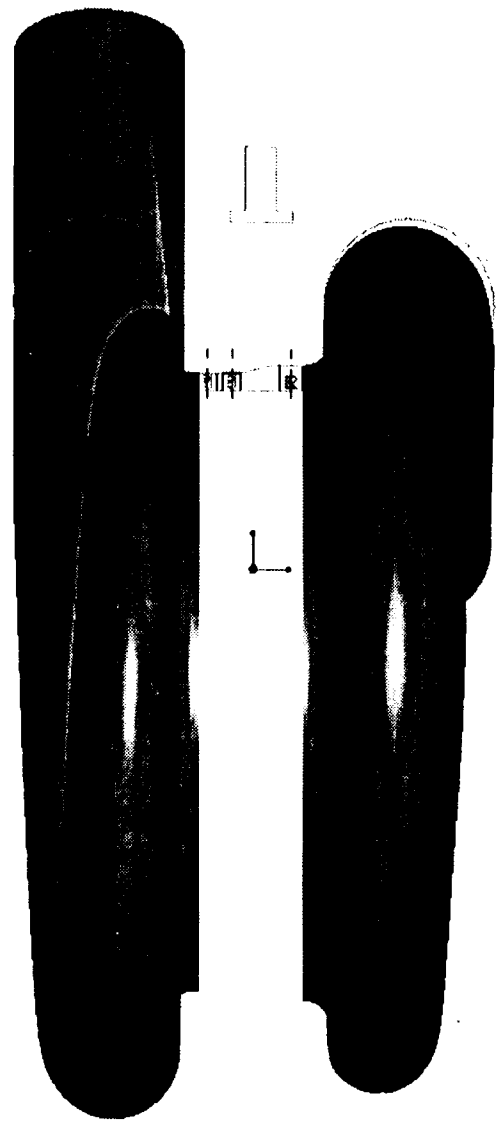


Turbine Volute Design

Volute Preliminary Geometry







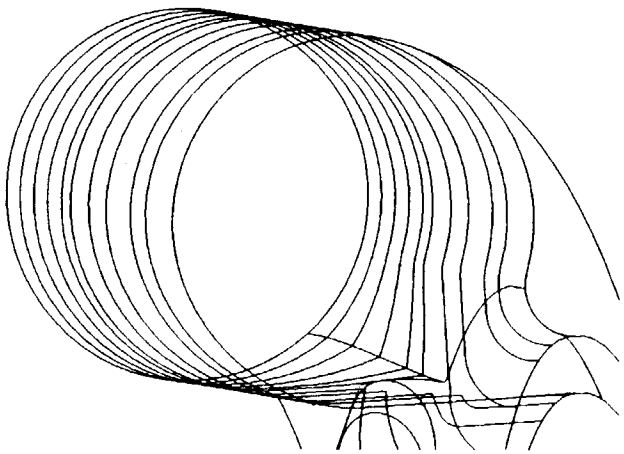
- Inlet

Exit

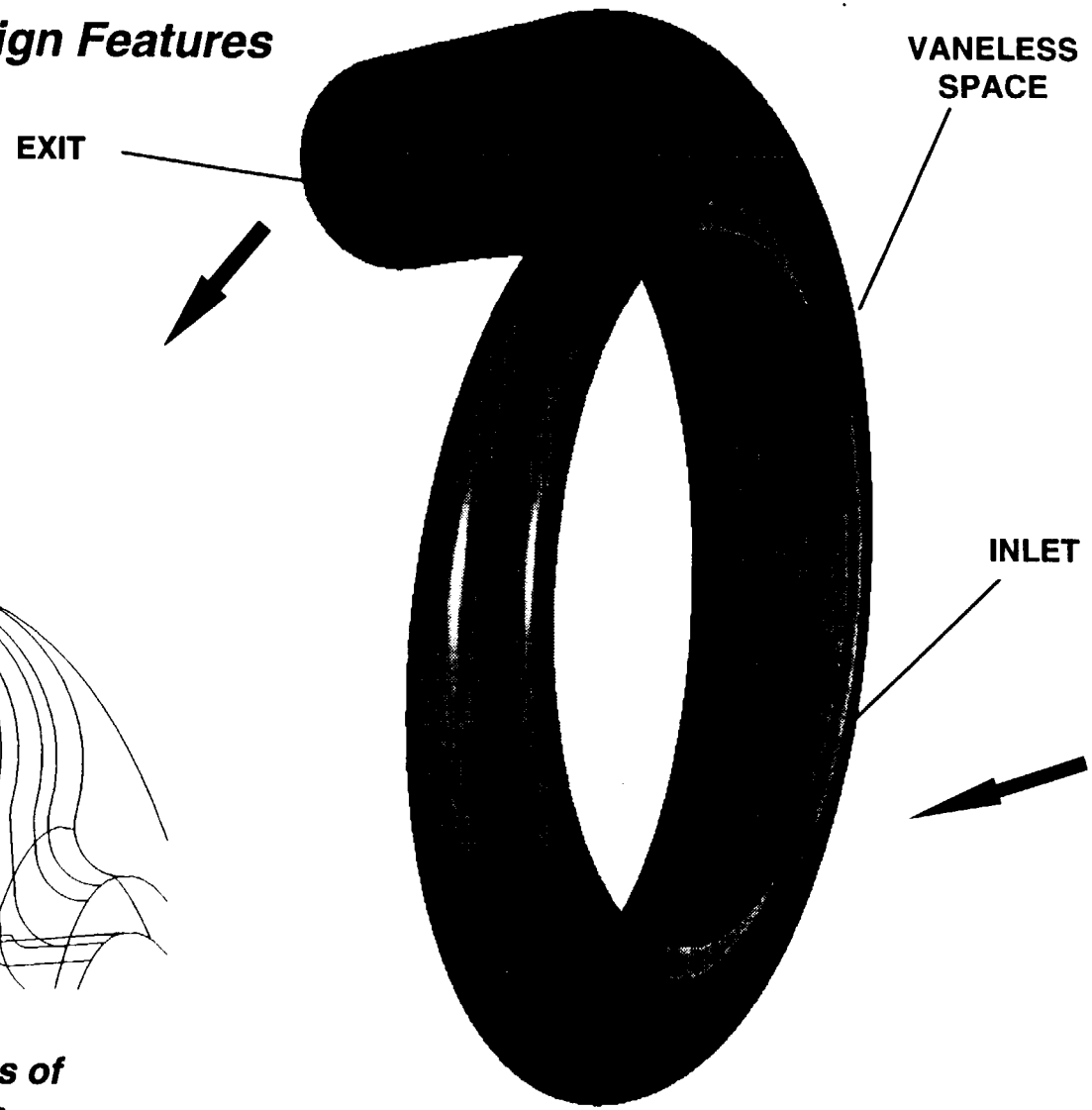
Turbine Volute Design

Exit Volute Aerodynamic Design Features

- Vaneless for simplicity
- Axial inlet
- Tangential discharge
- Linear area distribution
- Defined using a spinal bend within Pro/Engineer

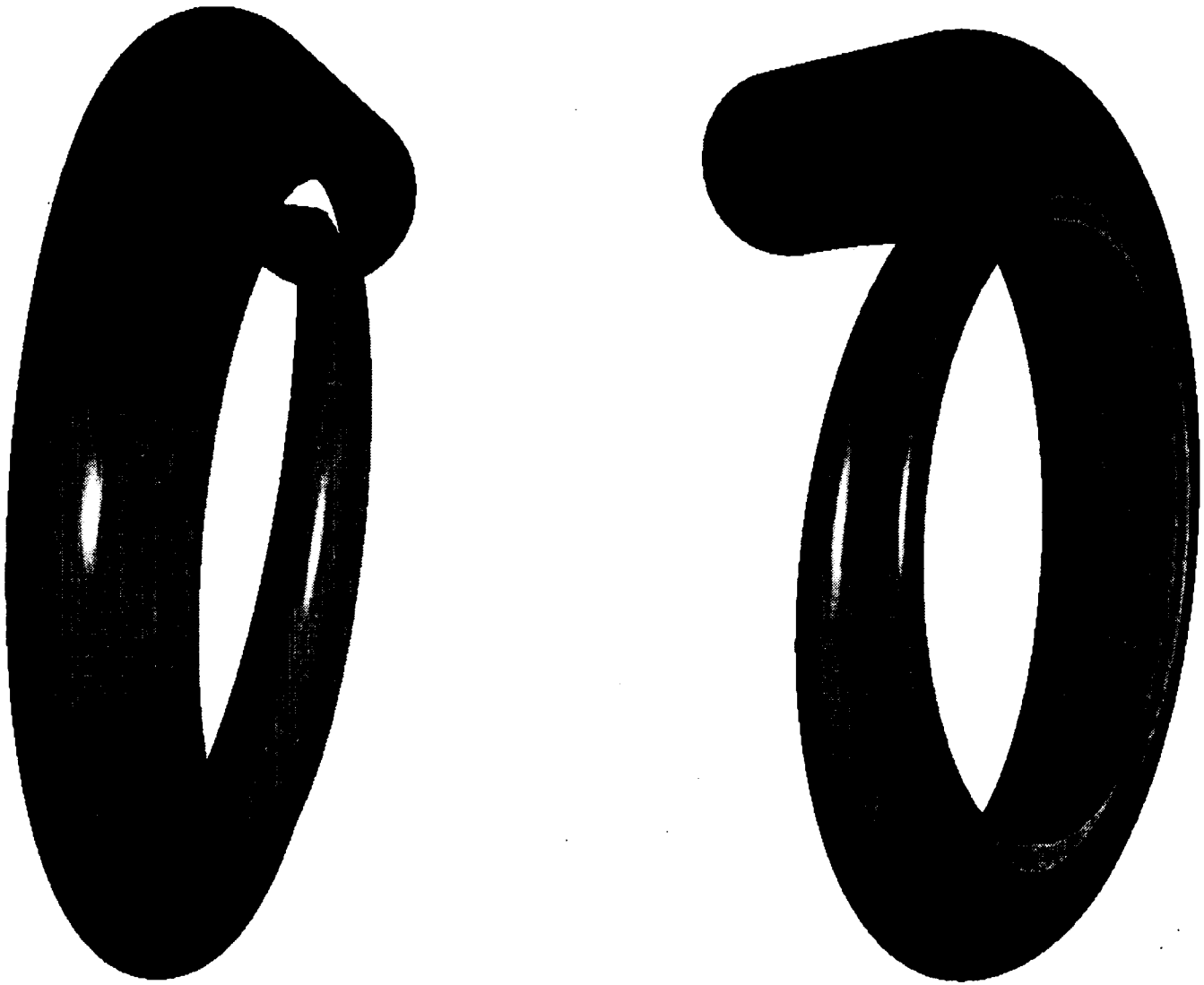


Cross sections of pipe transition

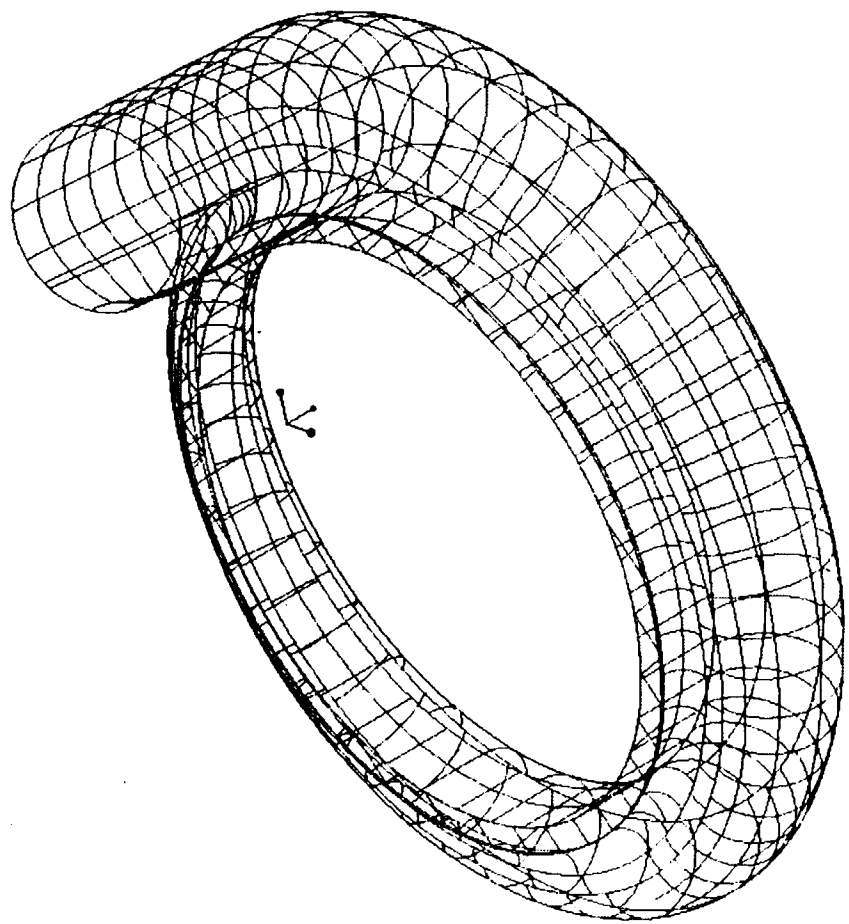


Turbine Volute Design

Exit Volute



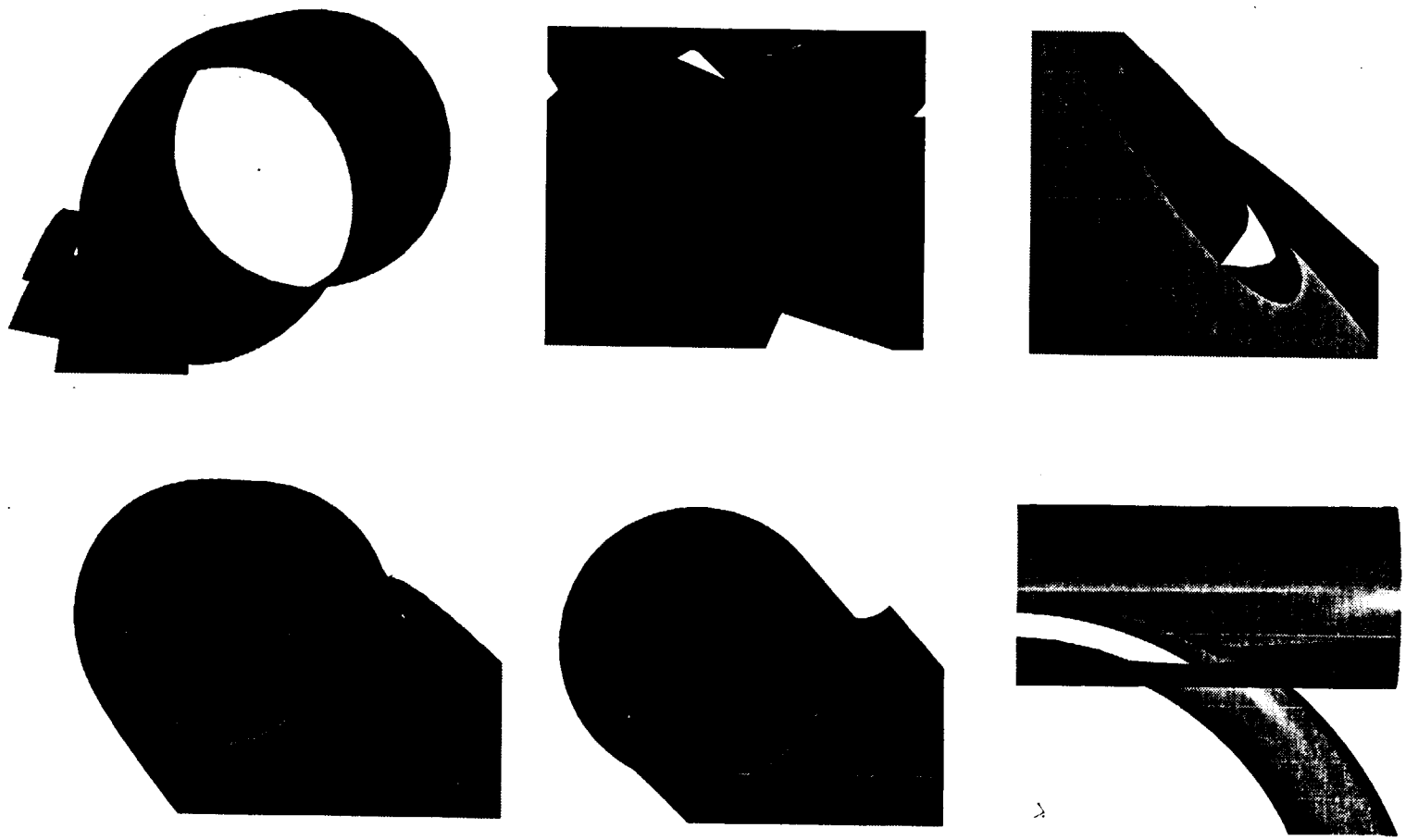
Wireframe View Showing Flow Path Sections



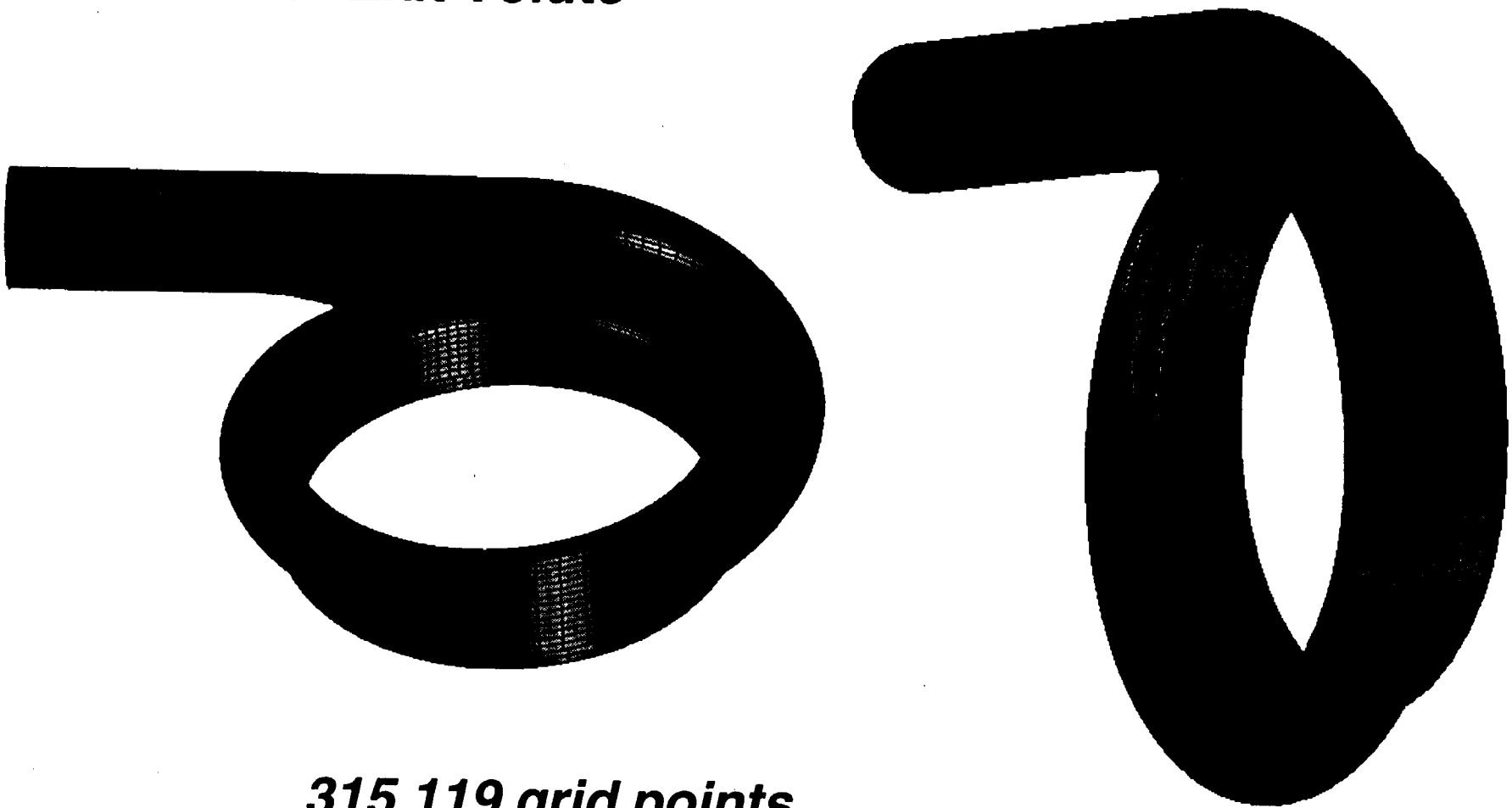
Turbine Volute Design

PRATT & WHITNEY - SPACE PROPULSION DIVISION

Cutwater Views - Exit Volute



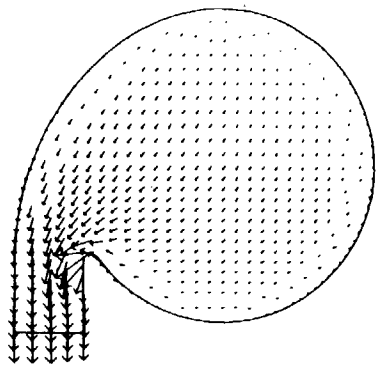
CFD Grid For Exit Volute



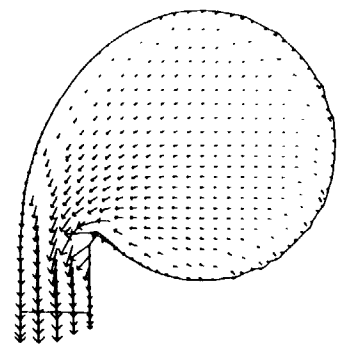
315,119 grid points

Turbine Volute Design

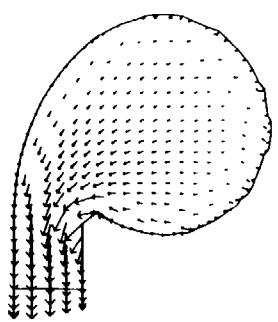
Volute Preliminary CFD Results - Flowpath Vectors (SAMPLE)



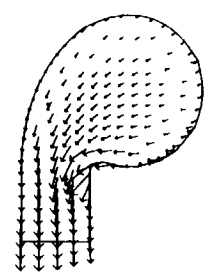
θ = 0



θ = 90



θ = 180

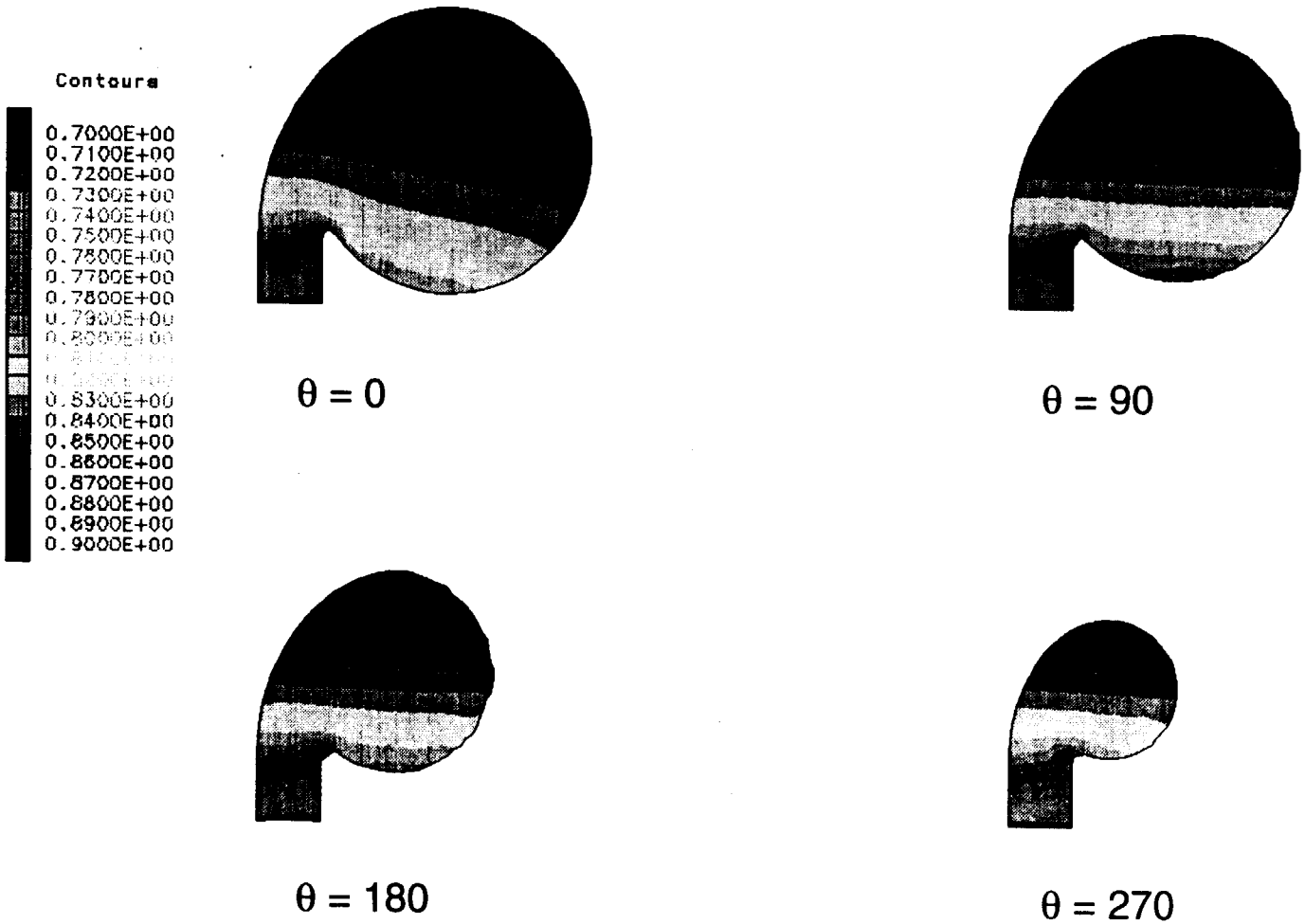


θ = 270

Turbine Volute Design

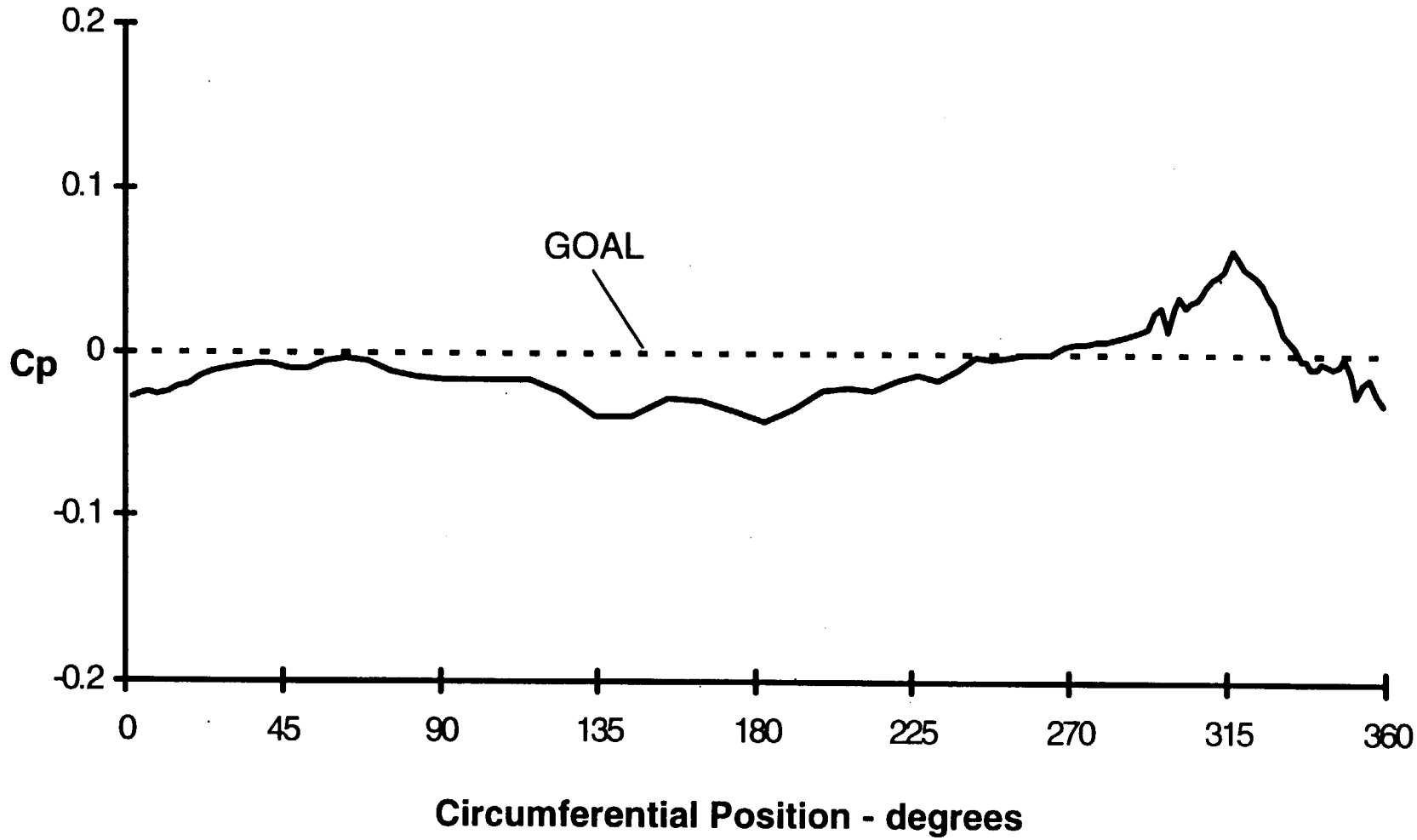
PRATT & WHITNEY - SPACE PROPULSION DIVISION

Volute Preliminary CFD Results - Static Pressure Contours (SAMPLE)



Turbine Volute Design

Volute Preliminary CFD Results - Transverse Pressure Gradient (SAMPLE)



Turbine Volute Design

Summary

- Preliminary Inlet and Exit Volutes Defined
- Current CFD Results Look Encouraging
- Plan to Perform Optimization with Integrated Volute/Turbine CFD Model
- Final Aerodynamic Configuration will Minimize Turbine Sideload, Maintain State-of-the-Art Performance, and will be Low Risk

Turbine Rotor Design

Bruce Smith

Component Design

Turbine Rotor Design

Goals

- Performance
  - RP-1 Power
  - LOX Power
- Low Cost
  - Low Airfoil Count
  - Constant Section Airfoils

Turbine Rotor Design

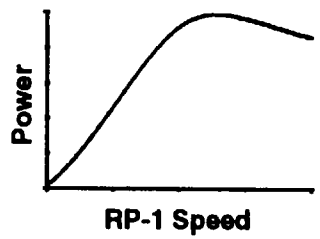
Requirements

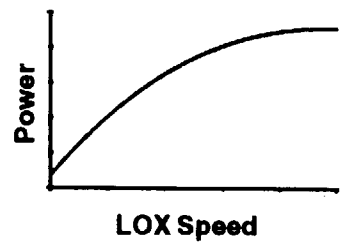
		RP-1	LOX
Reference Geometry :	Speed (rpm)	18000.	23000.
	I.D. Radius (in)	5.900	5.900
Conditions :	Total Pressure (psi)	540.	---
	Total Temperature (R)	1600.	---
	Flow Rate (lbm/s)	7.1	7.1
	Gamma	1.108	1.108
	Gas Constant (ft-lbf/lbm-R)	45.8	45.8
Power :	Impeller	445. hp	673. hp
	Backvane	56.	27.
	Vaporizer	---	20.
	Bearings, Disk & Seals	126.	63.
	Total	627. hp	783. hp

Turbine Rotor Design

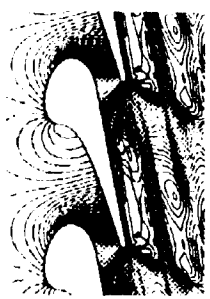
Design Approach

- **Meanline (1-D)**

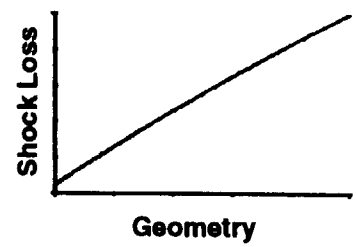




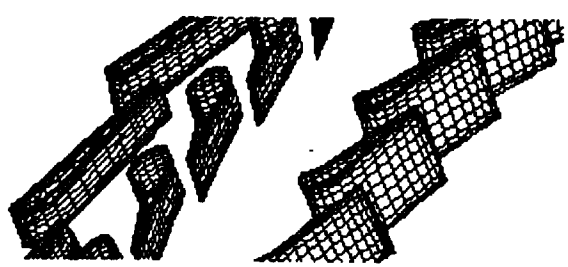
- **2-D Navier-Stokes**
  (20K grid nodes)



Shock Field



- **3-D Navier-Stokes**
  (1.3M grid nodes)

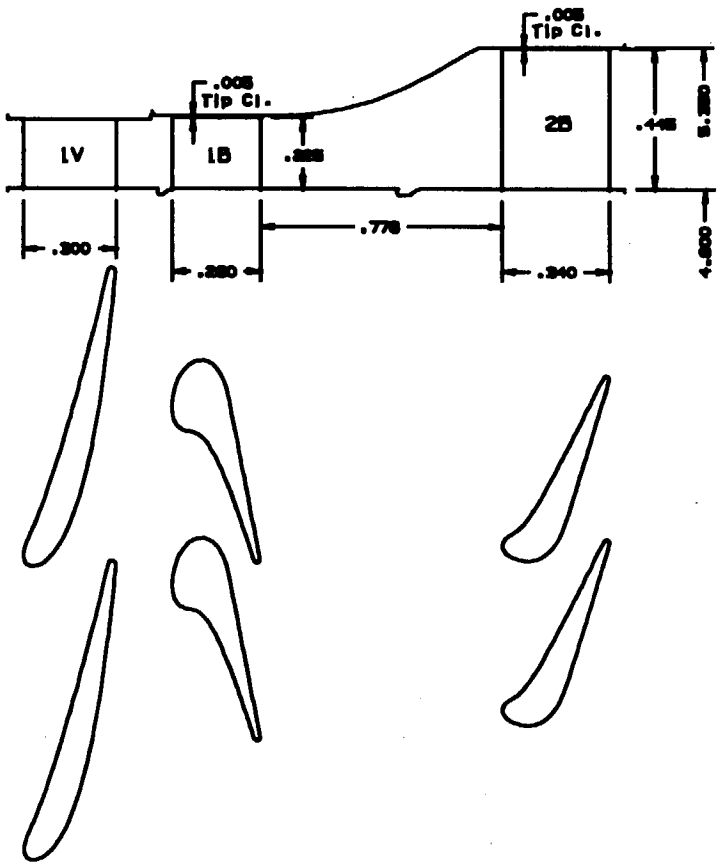


Turbine Rotor Design

PRATT & WHITNEY - SPACE PROPULSION DIVISION

Geometry

RP-1 LOX

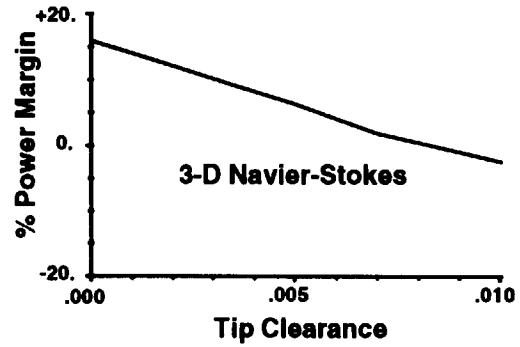


	1st Vane	1st Blade	2nd Blade
Exit Rel. Mach	0.68	1.34	1.39
Gas Turning	20.	128.	56.
Zweifel Loading	0.8	1.1	1.0
Airfoil Count	34	56	62

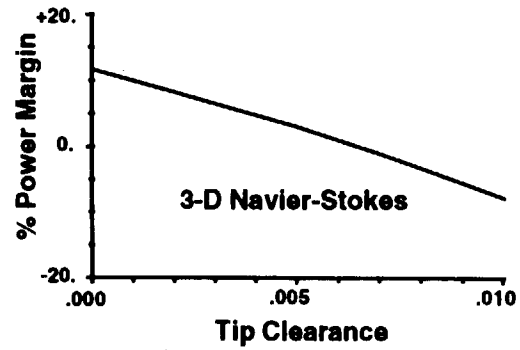
Turbine Rotor Design

Performance

- **RP-1 Power Achieved**



- **LOX Power Achieved**



Summary

- Geometry Definition Near Final
- Current 3-D Navier-Stokes Results Look Encouraging
- Low Airfoil Count (152)
- Constant Section Airfoils

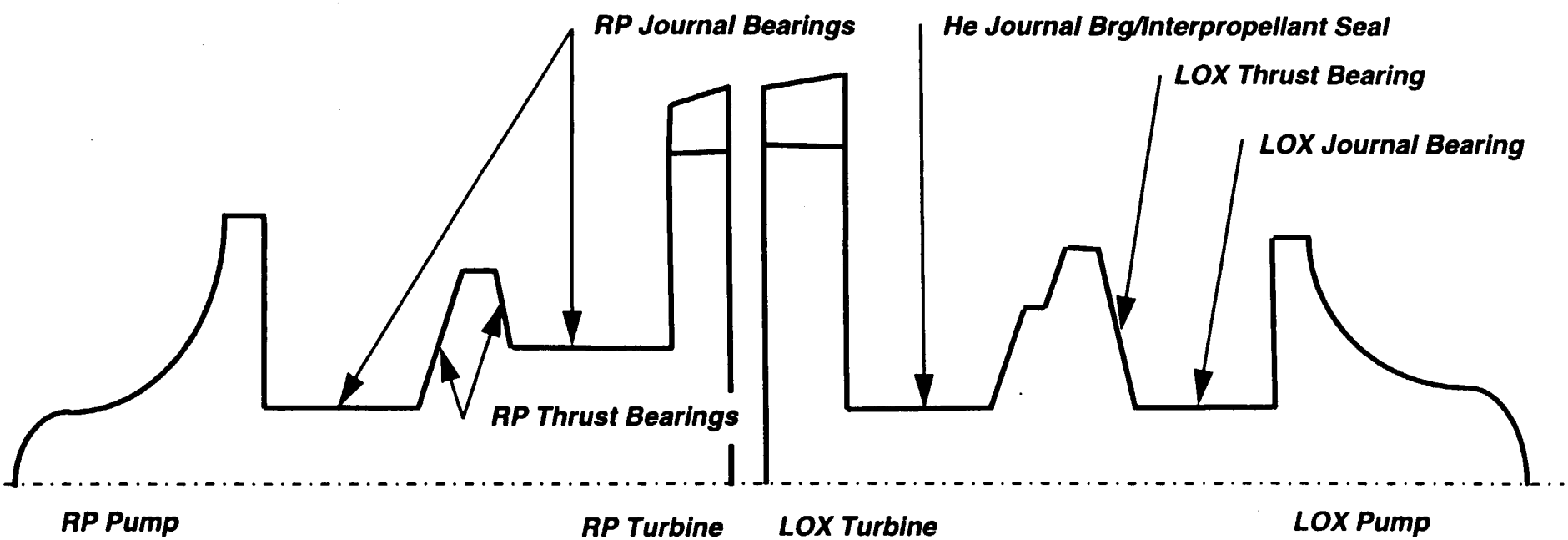
Bearing Design

Tom Haykin
Component Design

Bearing Design

Bearing Schematic

- **Hydrostatic Bearings used in Twin Rotor Turbopump**



Design Tools

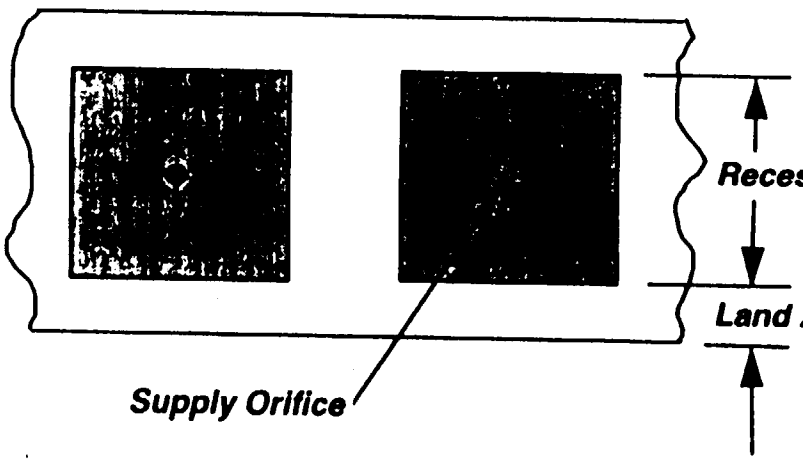
- Journal Bearings: *hydrojet*
  - Texas A&M University, Dr. L. San Andres; released 1995
  - Lands: fully developed, single-phase fluid with thermal energy transport. Turbulent bulk-flow model with local Moody friction factors.
  - Recesses: Fully developed single-phase fluid. Subsonic flow in orifice restrictors. Injection angled against rotation to reduce cross-coupled stiffness. Compressibility effects.
  - Variable fluid properties. Cryogenic fluids use 32 term state equation from MIPROPS 86
- Thrust Bearings: *hydrob*
  - Pratt & Whitney proprietary; released 1995
  - Compressible Reynolds Equation with turbulent correction; step effects in recesses; inertia effects at recess edge.
  - Barotropic fluid properties. Cryogenic fluid properties from GASP.

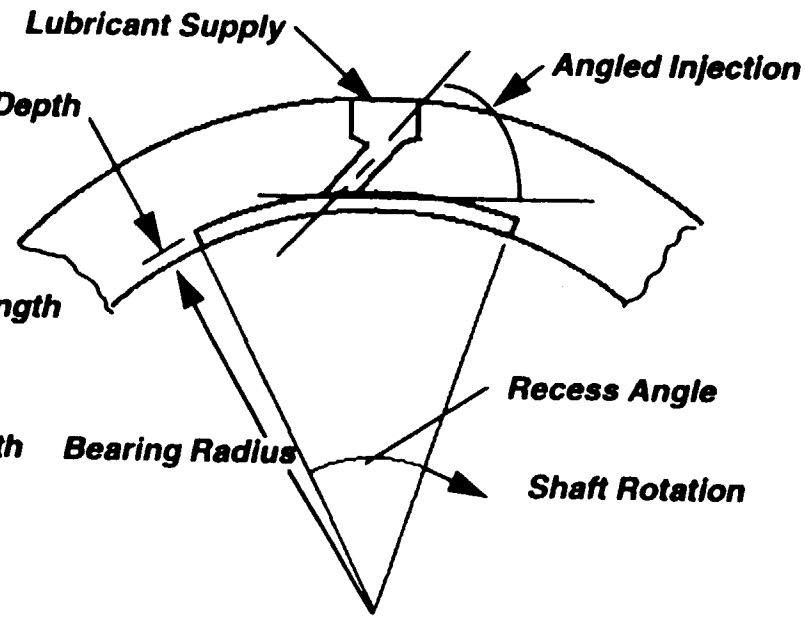
Design Tools, concluded

- Gas Bearing/Interpropellant Seal: *gcyl*
  - NASA LeRC; Dr. Wilbur Shapiro, Mechanical Technology Inc
  - Reynolds equation for turbulent flow
  - Fluid film discretized into two-dimensional mesh of cells
  - Pressure distribution determined by solving flow balance through cell volumes
  - Flowrate, load, righting moments calculated for off-center and misaligned shafts
  - Frequency dependent dynamic coefficients calculated

Hydrostatic Bearing Design Parameters

- **Journal Bearings**

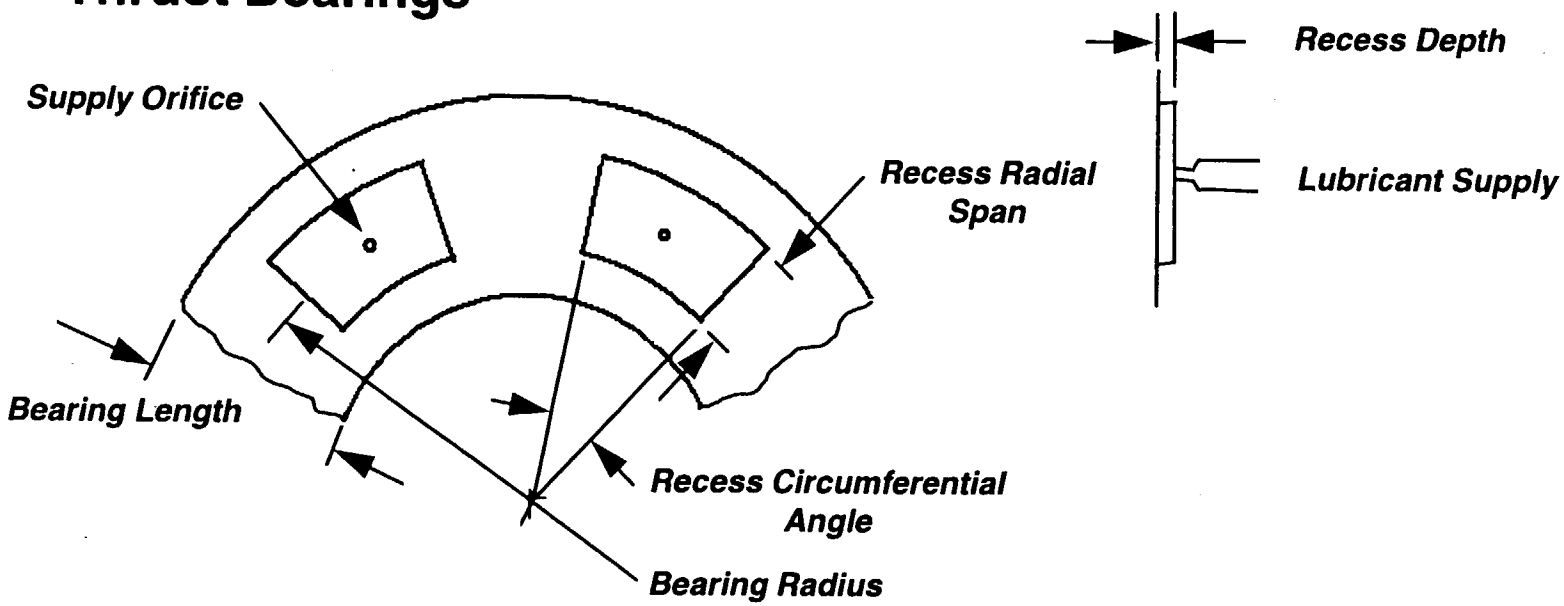




Key Parameters Affecting Performance:
- *Recess Area Ratio*
- *Recess Volume (area*depth)*
- *Supply Orifice ACd*
- *Radial Clearance*
- *Supply Pressure/Fluid Properties*
- *Surface Finish; Flow Resistance*

Hydrostatic Bearing Design Parameters

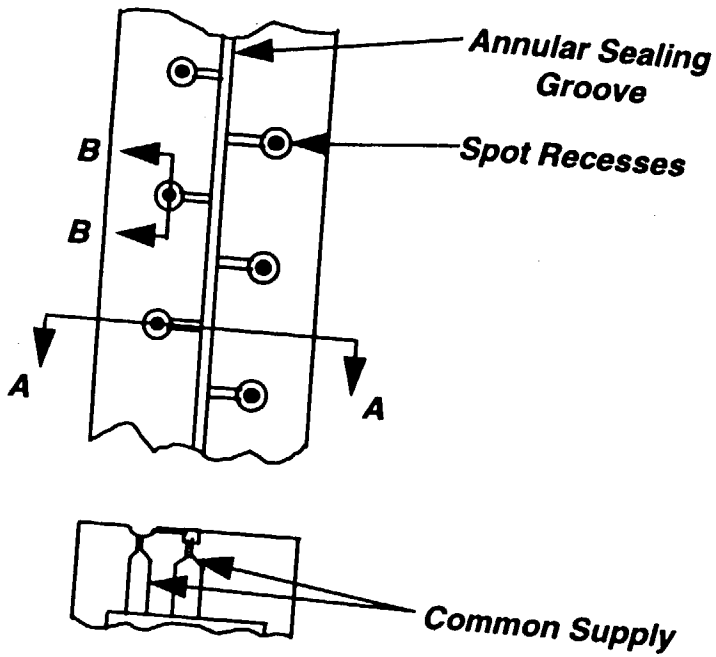
- **Thrust Bearings**



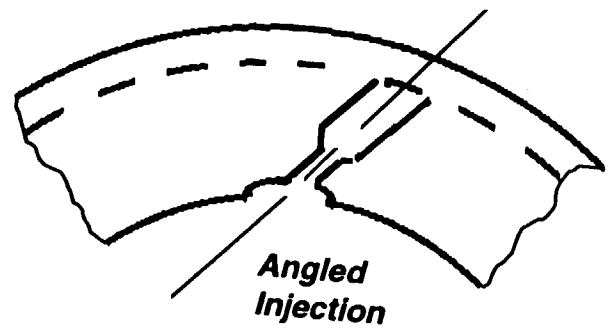
Key Parameters Affecting Performance:
- *Recess Area Ratio*
- *Recess Volume (area*depth)*
- *Supply Orifice ACd*
- *Radial Clearance*
- *Supply Pressure/Fluid Properties*

Hydrostatic Bearing Design Parameters

- Gas Bearing/ Interpropellant Seal



View A-A



View B-B

Hydrostatic Bearing Design Parameters

Bearing	Speed (rpm)	Supply Pressure (psi)	Discharge Pressure (psi)	Supply Temp. (R)	Diameter (in)	Radial Clearance (mils)	Axial Length (in)	No. Recesses	Recess Angle (deg)	Recess Axial Length (in)	Recess Depth (mils)	Surface Finish (inX10E6)
LOX Pump End Journal	22000	900	175	170	2	2	1.25	7	30	0.535	8	63
LOX Turbine End Journal	22000	800	50	548	2	2	1.3	16	N/A	0.2	8	63
RP Pump End Journal	16600	950	67	548	1.5	2	0.9375	5	36	0.469	8	63
RP Turbine End Journal	16600	950	456	548	4	2	2	7	32	1.124	8	63
LOX Thrust	22000	900	194	170	6.1/2.0	2	2.1	9	32	1.181	8	63
RP Pump Side Thrust	16600	950	77	548	6.6/1.5	6	2.55	5	15	0.95	15	63
RP Turbine Side Thrust	16600	950	87	548	6.6/4.0	2	1.3	9	25	0.728	8	63

Hydrostatic Bearing Design Comparison

Bearing	Speed (rpm)	Supply Pressure (psi)	Discharge Pressure (psi)	Diameter (in)	Radial Clearance (mils)	Axial Length (in)	No. Recesses	Dia/c	L/D	Recess Area Ratio	Recess Depth (mils)	Hrec/c
LOX Pump End Journal	22000	900	175	2	2	1.25	7	1000	0.63	0.25	8	4
RP Turbine End Journal	16600	950	456	4	2	2	7	2000	0.5	0.35	8	4
TAMU LOX HJB	26000	5744	303	3.35	6.9	1.92	6	1745	0.57	0.25	20	2.9
TAMU Water HJB	24600	1015	0	3	4.5	3	5	667	1	0.2	10	2.2

Hydrostatic Journal Bearing Performance:

	Centered					50% Eccentricity					
Bearing	Flow Rate (#/s)	Direct Stiffness (lbf/in)	Cross Coupled Stiffness (lbf/in)	Direct Damping (lbf-s/in)	Cross Coupled Damping (lbf-s/in)	Flow Rate (#/s)	Direct Stiffness (lbf/in)	Cross Coupled Stiffness (lbf/in)	Direct Damping (lbf-s/in)	Cross Coupled Damping (lbf-s/in)	Load (lbf)
LOX Pump End Journal	1.05 (0.8%)	681774	-231541	264	-15.59	0.97 (0.7%)	539310	-254323	270	-12.59	741
LOX Turbine End Journal	0.09	327000	1551	-1.27	-0.13	0.09	466200	-4095	5	0.38	395
RP Pump End Journal	0.72 (1.1%)	346425.7	-527	72	-0.24	0.67 (1%)	348139	-39136	71	-2.64	350
RP Turbine End Journal	0.69 (1.1%)	1559972	-1229934	1410	-51.12	0.62 (1%)	867920	-1148852	1350	-86.45	1917

Hydrostatic Bearing Performance Comparison

Bearing	Direct- to-Cross Coupled Stiffness Ratio	Direct Stiffness-to-Damping Ratio	Cross Coupled Stiffness-to-Damping Ratio
LOX Pump End Journal	2.94	2582	877
RP Turbine End Journal	1.26	1106	872
TAMU LOX HJB	3.13	3759	1206
TAMU Water HJB	0.561	765	1391

Hydrostatic Thrust Bearing Performance:

Bearing	Flow Rate (lb/s)	Stiffness (lbf/in)	Load (lbf)
LOX Thrust	1.56	49229	12440
RP Pump Side Thrust	1.42	26130	4350
RP Turbine Side Thrust	1.83	103300	8990

Plan for Final Design

- Approach: RP Turbopump
  - High recess area ratio for RP bearings; RP has low compressibility; pneumatic hammer instability should not be a problem; reduce hydrodynamic effects on lands
  - Roughened land surfaces to reduce leakage
  - Optimize geometric configuration within envelope
- Approach: LOX Turbopump
  - Optimize geometric configuration of LOX journal bearing to meet rotordynamic requirements
  - Refine Helium journal bearing/interpropellant seal to minimize complexity; reduce number of spot recesses

Plan for Final Design

- Thrust Bearings:
  - Optimize geometric configuration as system-driven thrust balance requirements change.
  - Support trade studies on distribution of thrust balance area and secondary flow.

Hydrostatic Bearing Results

- Preliminary Design performance shows that hydrostatic bearings will meet design requirements
- Goals for Final Design
  - Finalize rotordynamics requirements: stiffness, damping
  - Minimize parasitic losses: windage, leakage flowrate

Rotordynamic Analysis

Bill Munn

Rocket Engine Structures

Rotordynamic Analysis

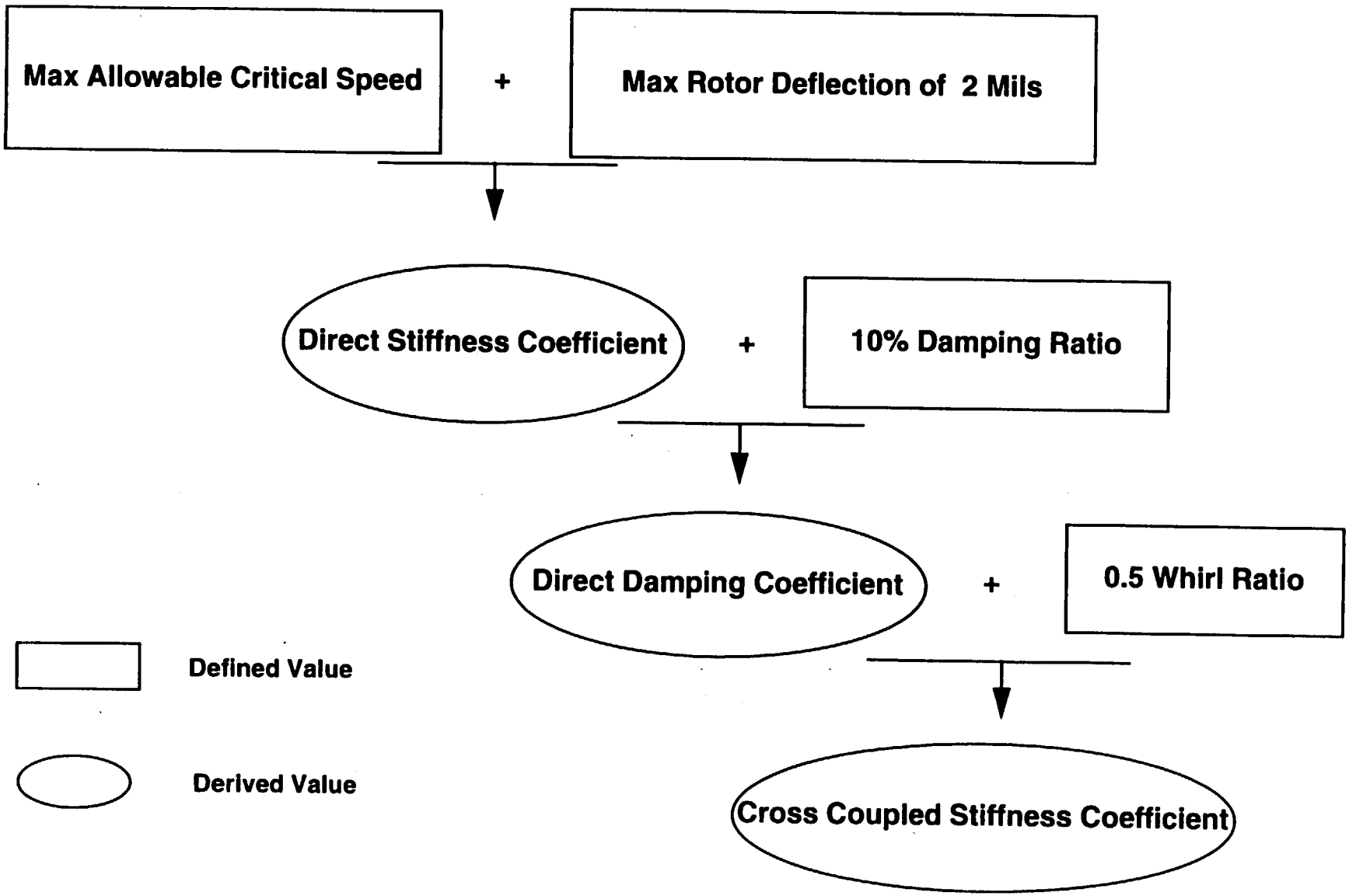
Goals

- Provide Subcritical Speed Operation
- Minimum of 20% Speed Margin on Rotor Modes
- Onset Speed of Instability (OSI) > Max Speed
- Establish Dynamic Mass Balance Requirements
- Minimize Bearing Deflections
- Bearing Loads within Bearing Capability

Analysis Model - Current Assumptions

- Dynamic analysis only
  - Sideload information will be incorporated for final design
- Rotor Imbalance based on assumed eccentricity of 1 mil for the entire rotor
- Constant material properties throughout speed range
- Constant temperature of 70 degrees F. throughout models
- Minimal bearing coefficients based on:
  - 2 mil max. deflection
  - Minimum allowable Critical speed
  - Damping ratio of 10%
  - Whirl ratio of 0.5

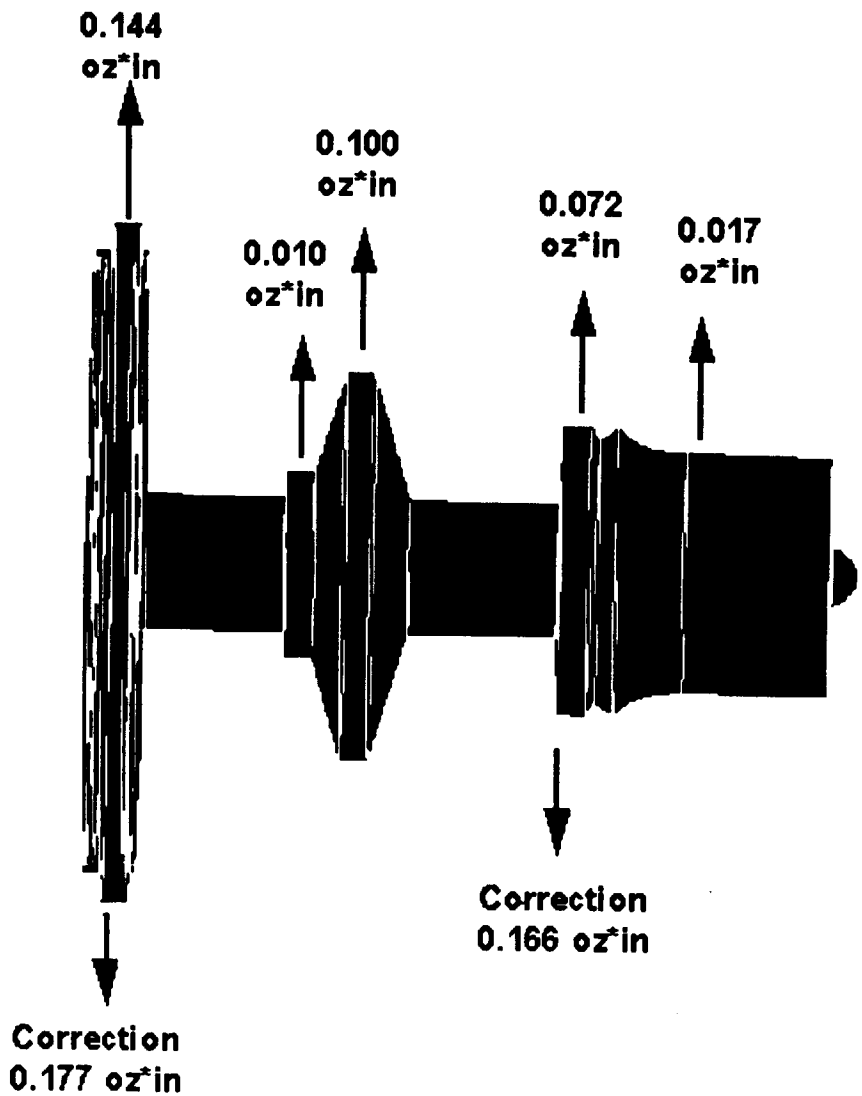
Minimum Bearing Coefficient Derivation



Forced Response Analysis - Imbalance Distribution

- All Imbalances are based on a 1 mil eccentricity

LOX Rotor

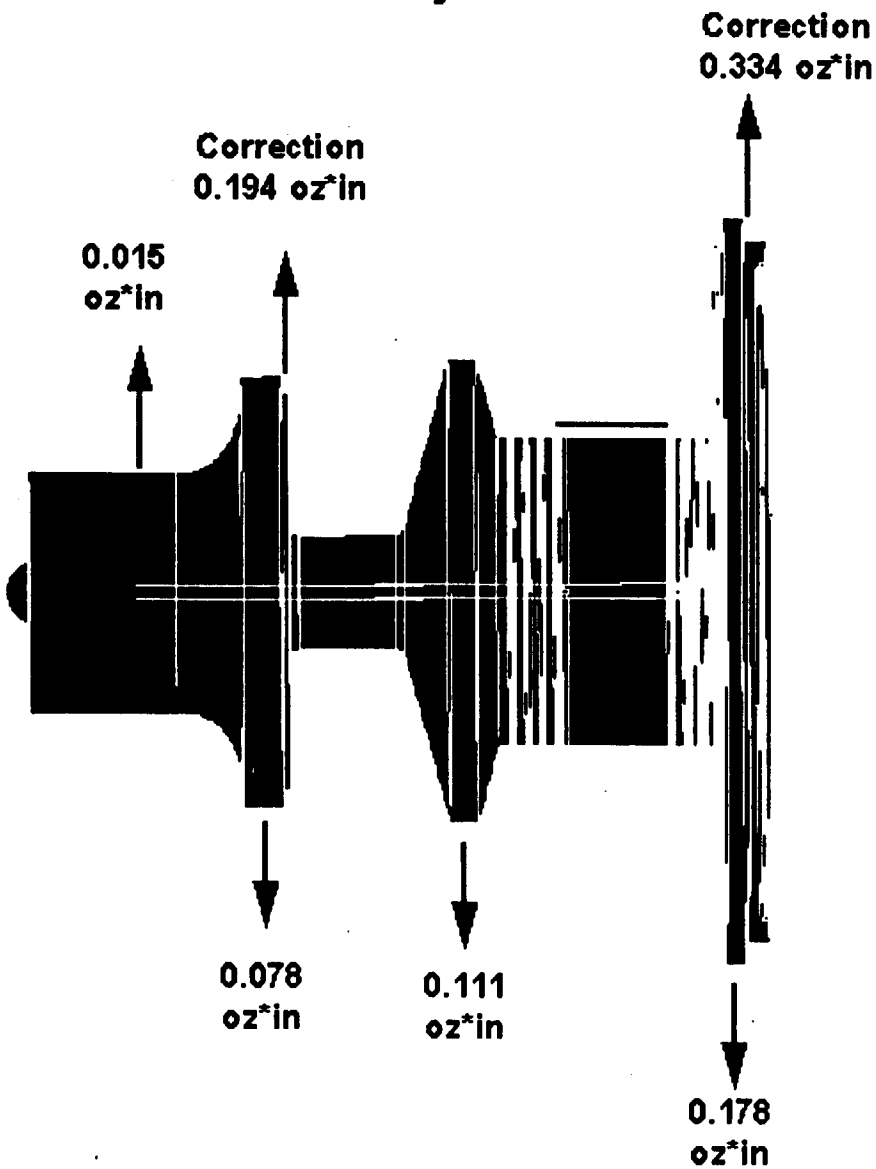


Rotordynamic Analysis

Forced Response Analysis - Imbalance Distribution

- **All Imbalances are based on a 1 mil eccentricity**

RP1 Rotor

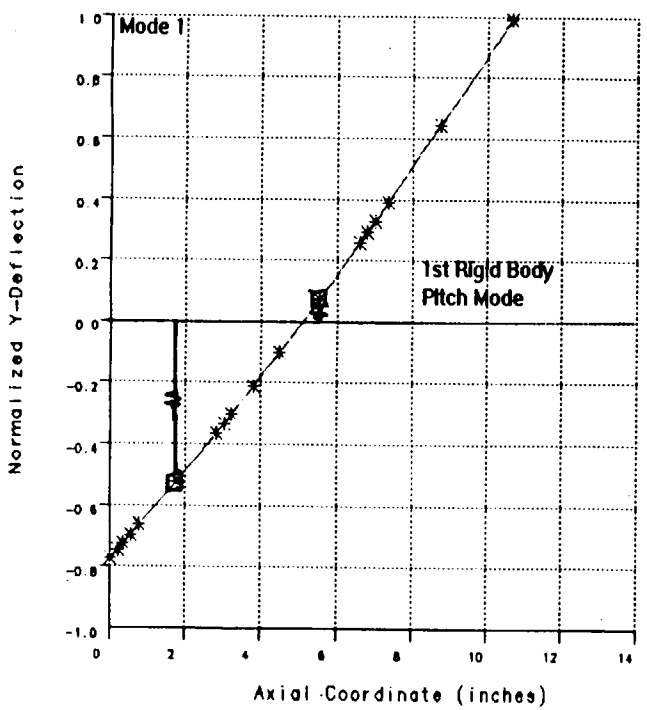


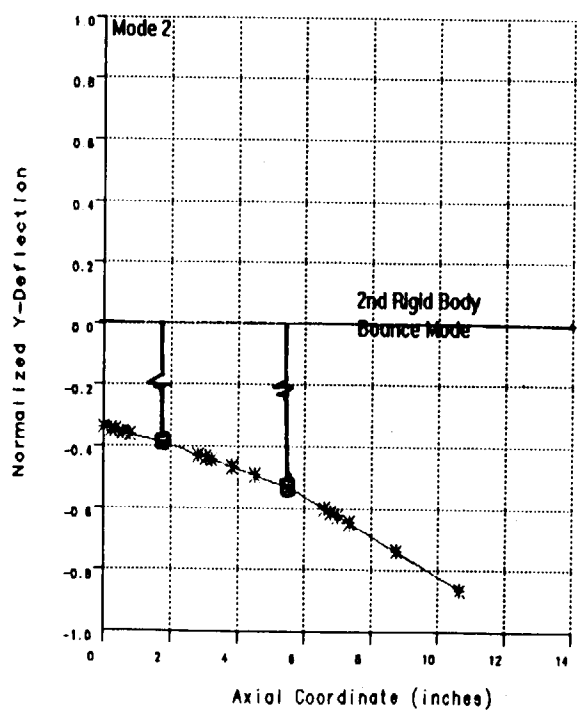
Rotordynamic Analysis

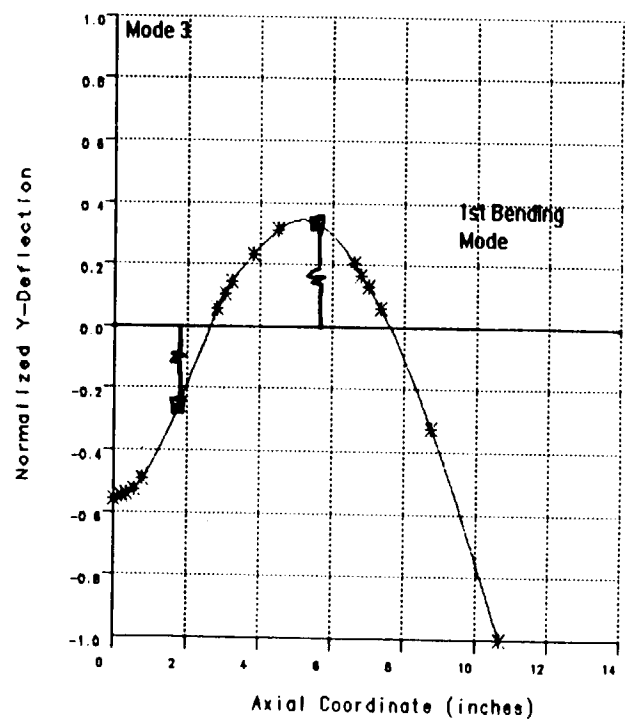
LOX System Mode Shapes at 100% Power

- **Positive Log-dec values indicate stable operation**
- **Subcritical Design**

Mode	Freq. @ Max Speed	Speed Margin	Log Dec
1	30,873	38%	0.19
2	42,500	88%	1.03
3	109,254	397%	0.03





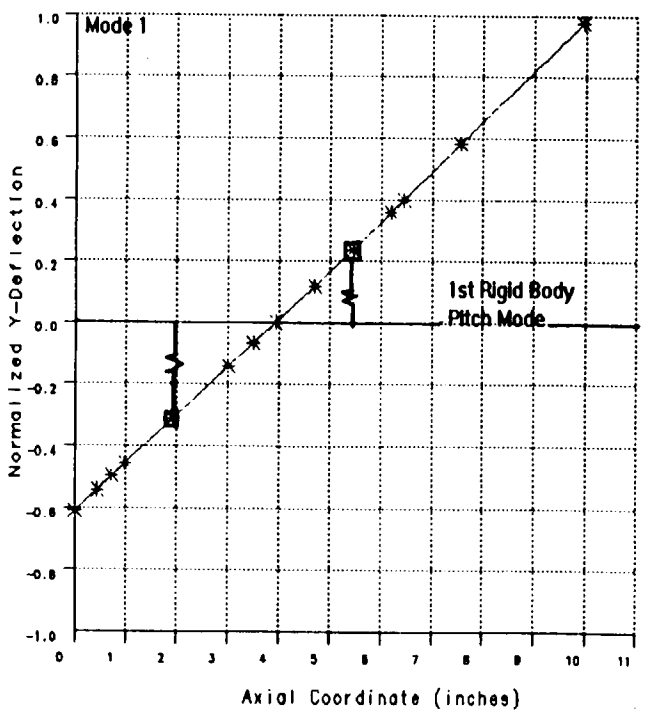


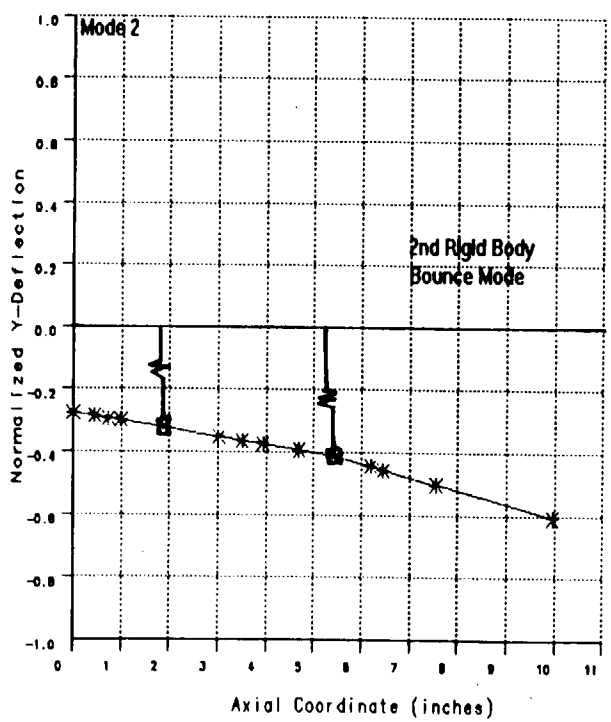
Rotordynamic Analysis

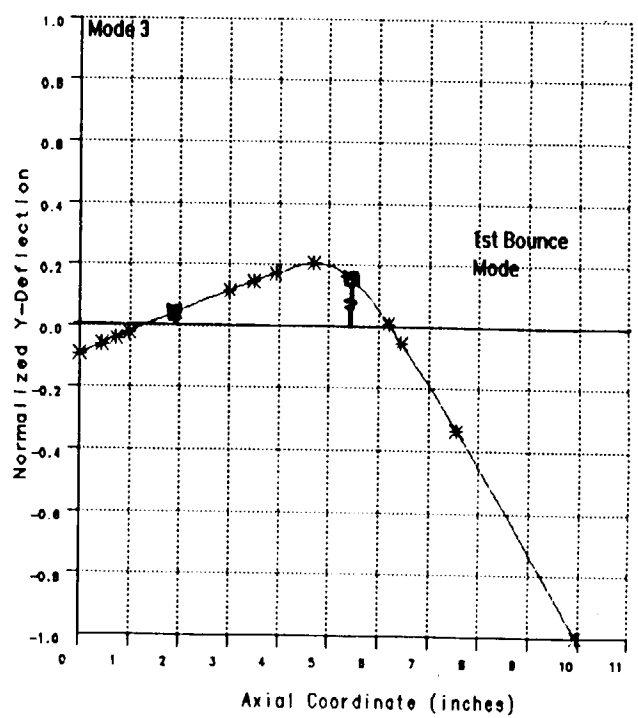
RP-1 System Mode Shapes at 100% Power

- **Positive Log-dec values indicate stable operation**
- **Subcritical Design**

Mode	Freq. @ Max Speed	Speed Margin	Log Dec
1	20,307	22%	0.61
2	25452	53%	0.89
3	99,858	501%	0.04







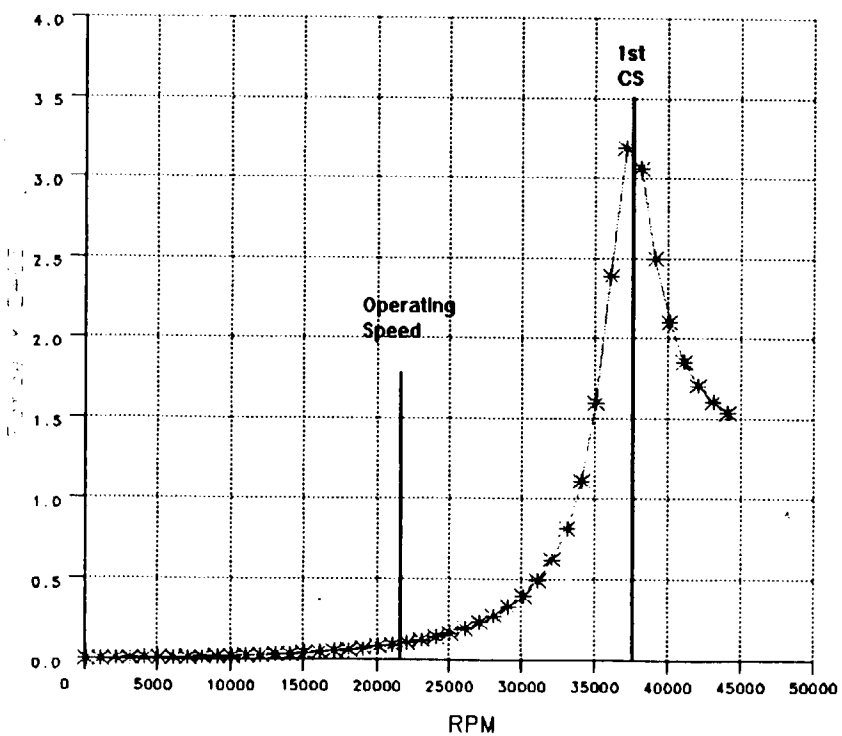
Rotordynamic Analysis

Forced Response Analysis - Peak Radial Bearing Loads

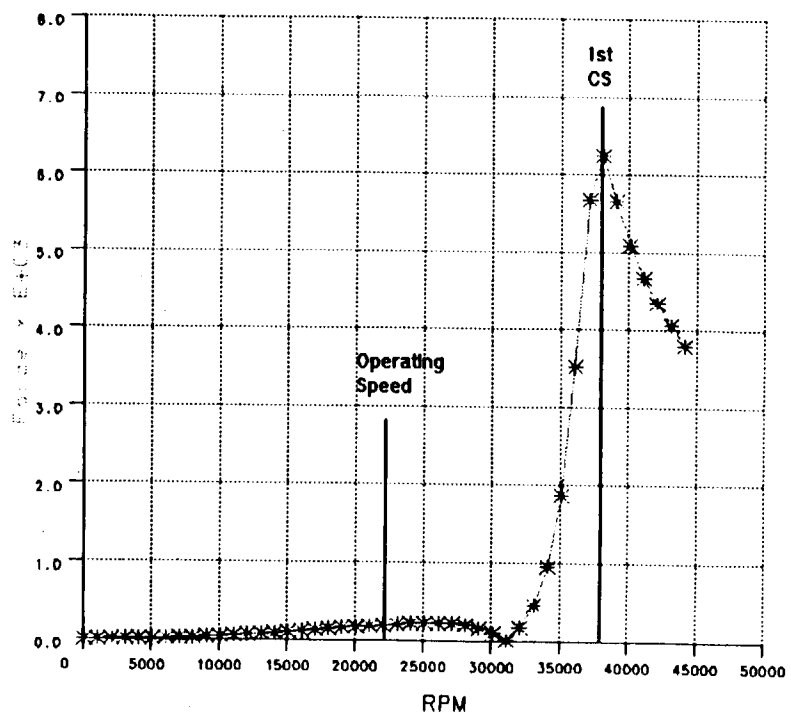
- Bearing Radial Loads are within load carrying capability
- Sideloads are not included in analysis

LOX Rotor

LOX He Gas Bearing



LOX PE Journal Bearing



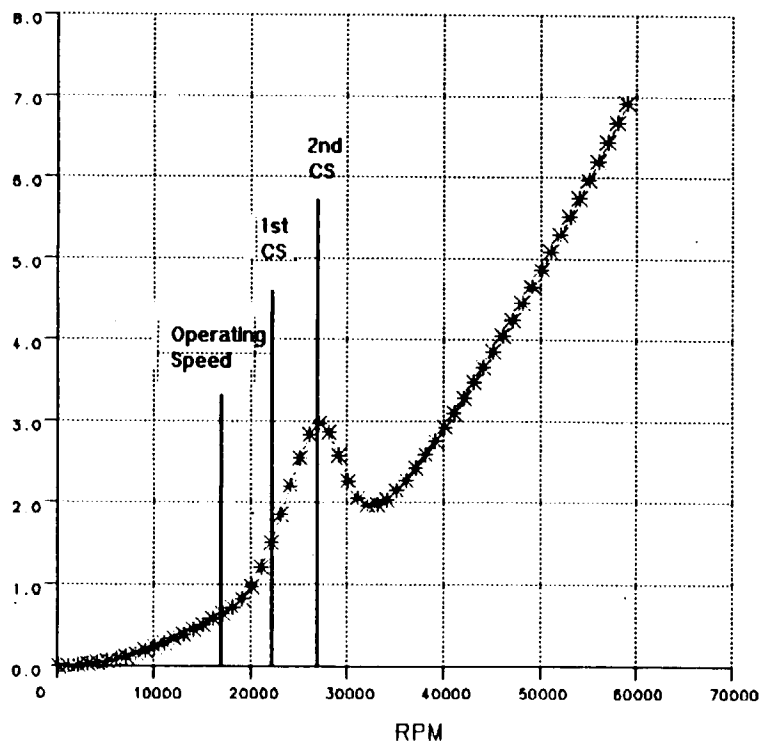
Rotordynamic Analysis

Forced Response Analysis - Peak Radial Bearing Loads

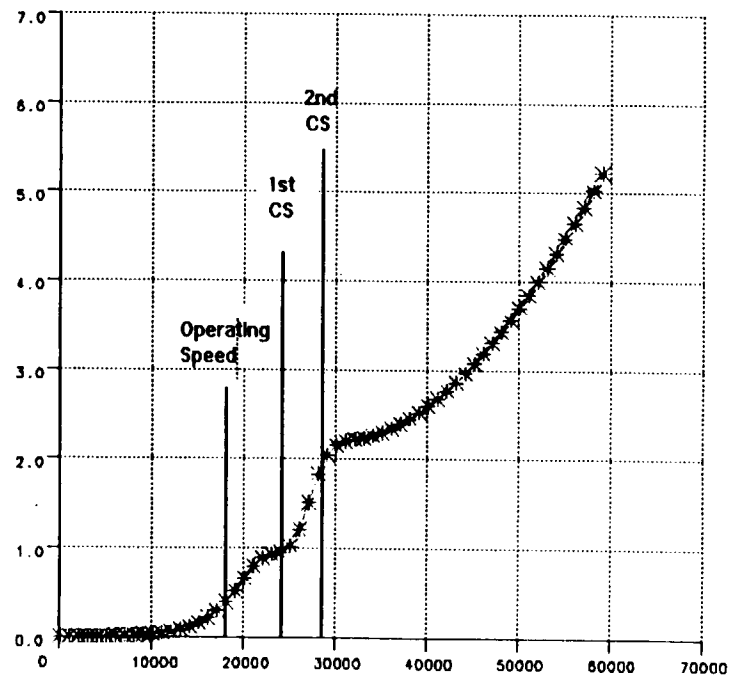
- Bearing Radial Loads are within load carrying capability
- Sideloads are not included in analysis

RP-1 Rotor

RP-1 PE Bearing



RP-1 TE Bearing



LOX Rotordynamic Summary

Minimum Critical speed (with 20% safety margin) = 26,400 rpm

Date 6/20/97

Mode	Damped Critical Speed	
1	37,153.60	RPM
2	42475.3	RPM
3	275187.5	RPM

Impeller Coeff.			Alfords forces:	
Direct Stiffness =	-7398	lbf/in	0	lbf/in
C.C. Stiffness =	4465	lbf/in	1057	lbf/in
Direct Damping =	3.8	lbf*s/in	0	lbf*s/in
C.C. Damping =	9.8	lbf*s/in	0	lbf*s/in

He Bearing	Derived Coeff.	Predicted Coeff.	
Direct Stiffness =	250000	466200	lbf/in
C.C. Stiffness =	4095	4095	lbf/in
Direct Damping =	5	5	lbf*s/in
C.C. Damping =	0.38	0.38	lbf*s/in
Whirl Ratio=	0.355		
Damping Ratio	0.049		
Deflection:	1.94E-03	in.	
Slope:	4.03E-04	in.	
Force:	103.9	lbs.	
Moment:	212.7	in*lbs.	

Pump Journal	Derived Coeff.	Predicted Coeff.	
Direct Stiffness =	650000	681774	lbf/in
C. C Stiffness =	95000	231541	lbf/in
Direct Damping =	80	264	lbf*s/in
C.C. Damping =	10	15.59	lbf*s/in
Whirl Ratio=	0.5		
Damping Ratio	0.092		
Deflection:	4.56E-04	in.	
Slope:	3.88E-04	in.	
Force:	193.8	lbs.	
Moment:	225.9	in*lbs.	

**NOTE All Critical Speed, Shape, and Load information is based on DYNAMIC information only.
Static Input is NOT included in these analysis.
No Trunnion Data is incorporated in the model

Rotordynamic Analysis

RP-1 Rotor Dynamic Summary

Minimum Critical speed (with 20% safety margin) = 19920 rpm

Date 6/24/97

Mode	Damped Critical Speed		Impeller Coeff.			Alfords forces:	
1	22197	rpm	Direct Stiffness =	-8343	lbf/in	0	lbf/in
2	27416	rpm	C.C. Stiffness =	5036	lbf/in	999	lbf/in
3	250855	rpm	Direct Damping =	5.7	lbf*s/in	0	lbf*s/in
			C.C. Damping =	14.6	lbf*s/in	0	lbf*s/in

TE Journal	Derived Coeff.	Predicted Coeff.	
Direct Stiffness =	400000	1559972	lbf/in
C.C. Stiffness =	86917	1229934	lbf/in
Direct Damping =	100	1410	lbf*s/in
C.C. Damping =	5	51.12	lbf*s/in
Whirl Ratio=	0.5		
Damping Ratio=	0.106		
Deflection:	7.85E-04	in.	
Slope:	2.46E-04	in.	
Force:	66.02	lbs.	
Moment:	269.3	in*lbs.	

PE Journal	Derived Coeff.	Predicted Coeff.	
Direct Stiffness =	200000	346425	lbf/in
C. C Stiffness =	13037	527	lbf/in
Direct Damping =	15	72	lbf*s/in
C.C. Damping =	1	0.24	lbf*s/in
Whirl Ratio=	0.5		
Damping Ratio=	0.108		
Deflection:	1.54E-04	in.	
Slope:	2.45E-04	in.	
Force:	97.33	lbs.	
Moment:	80.62	in*lbs.	

**NOTE All Critical Speed, Shape, and Load information is based on DYNAMIC information only.
Static Input is NOT included in these analysis.
No Trunnion Data is incorporated in the model

Rotordynamic Analysis

Conclusions

- All Critical speeds are out of the operating range and above the 20% safety margin
- Analysis indicates stable rotor operation
- Radial bearing loads and rotor deflections are within limits
- Plans For Final Design
  - Adjust material characteristics to represent operating temperatures
  - Include Static Sideloads
  - Include housings in rotordynamics models
  - Update bearing coefficients
  - Incorporate geometry updates

Structural Analysis

Eric Poole

Rocket Engine Structures

Structural Analysis

- Overview
- Current Status
- Future Plans

Structural Analysis

Overview

- Limited structural analysis consistent with program definition
  - Analysis limited to critical components
  - Analysis at a single design point
- Standard P&W structural analysis techniques
  - Simplified models during design process
  - Refined models for CDR design
- Structural design goals based on standard P&W LRE criteria
  - Strength margin w/safety factors (1.1 yield / 1.4 ultimate)
  - Infinite HCF life (10^8 cycles)
  - 1000 cycles LCF life
  - No formal fracture control plan
    (critical hardware within stable crack growth range)

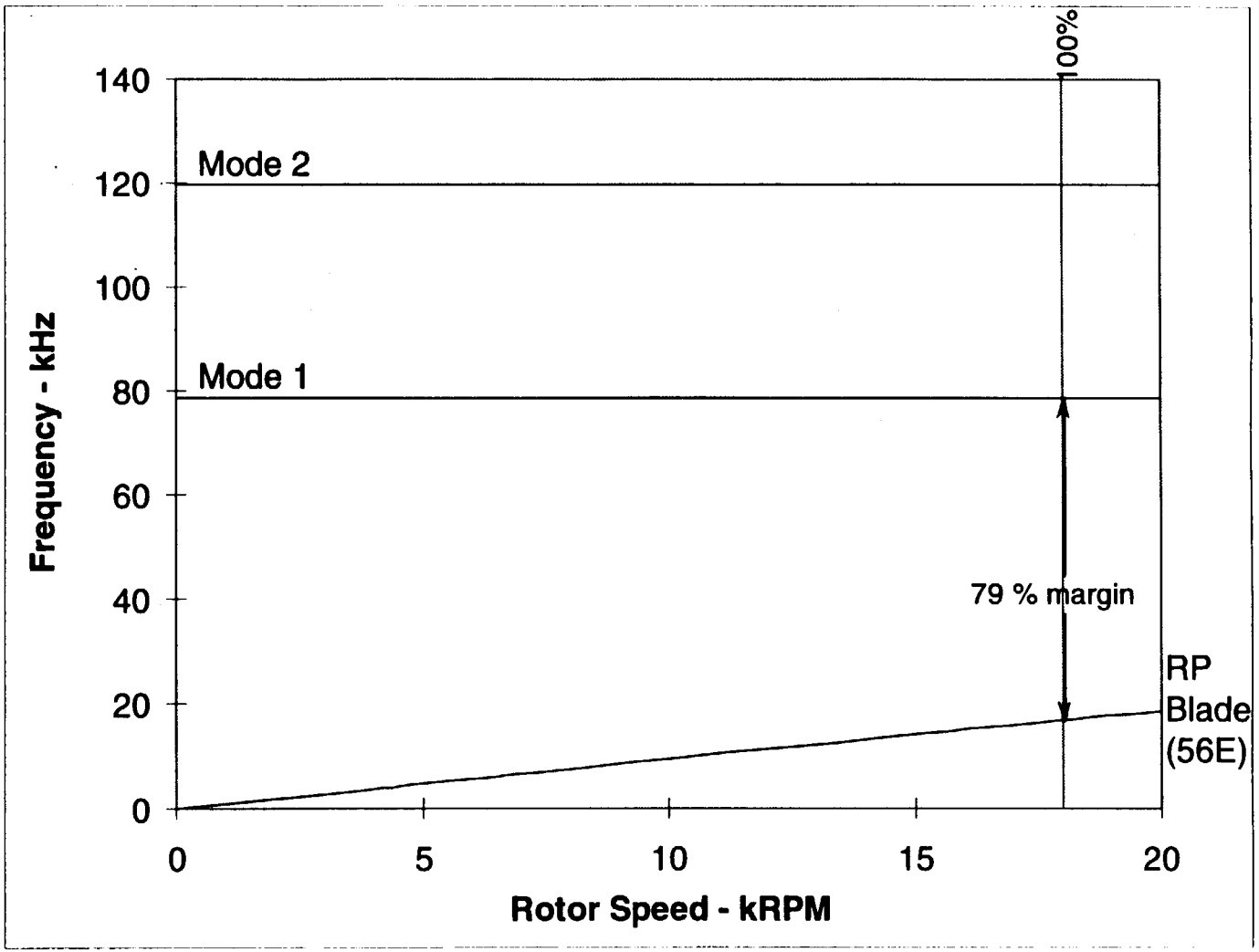
Structural Analysis

Current Status

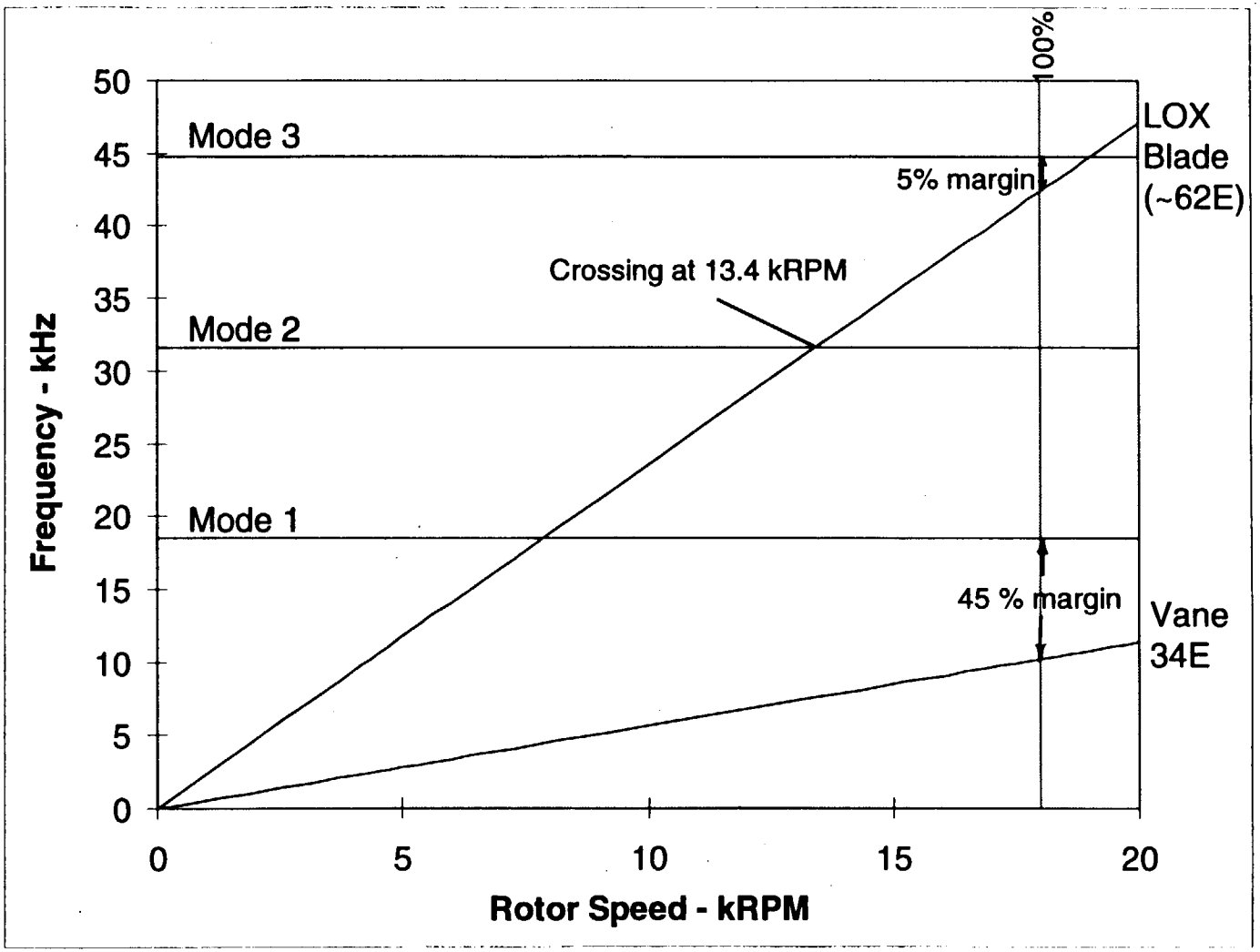
- Analyzed several iterations of the turbine flow path airfoils
  - Preliminary assessments revised counts and geometry
  - Latest configuration meets design goals
- Analyzed preliminary LOX turbine disk for dynamic modes
  - Dynamic margins satisfy design goals
- Impeller structural geometry definition pending
  - Geometry, low speed and pressure minimize structural concerns
  - Preliminary analysis anticipated 7/10/97

Structural Analysis

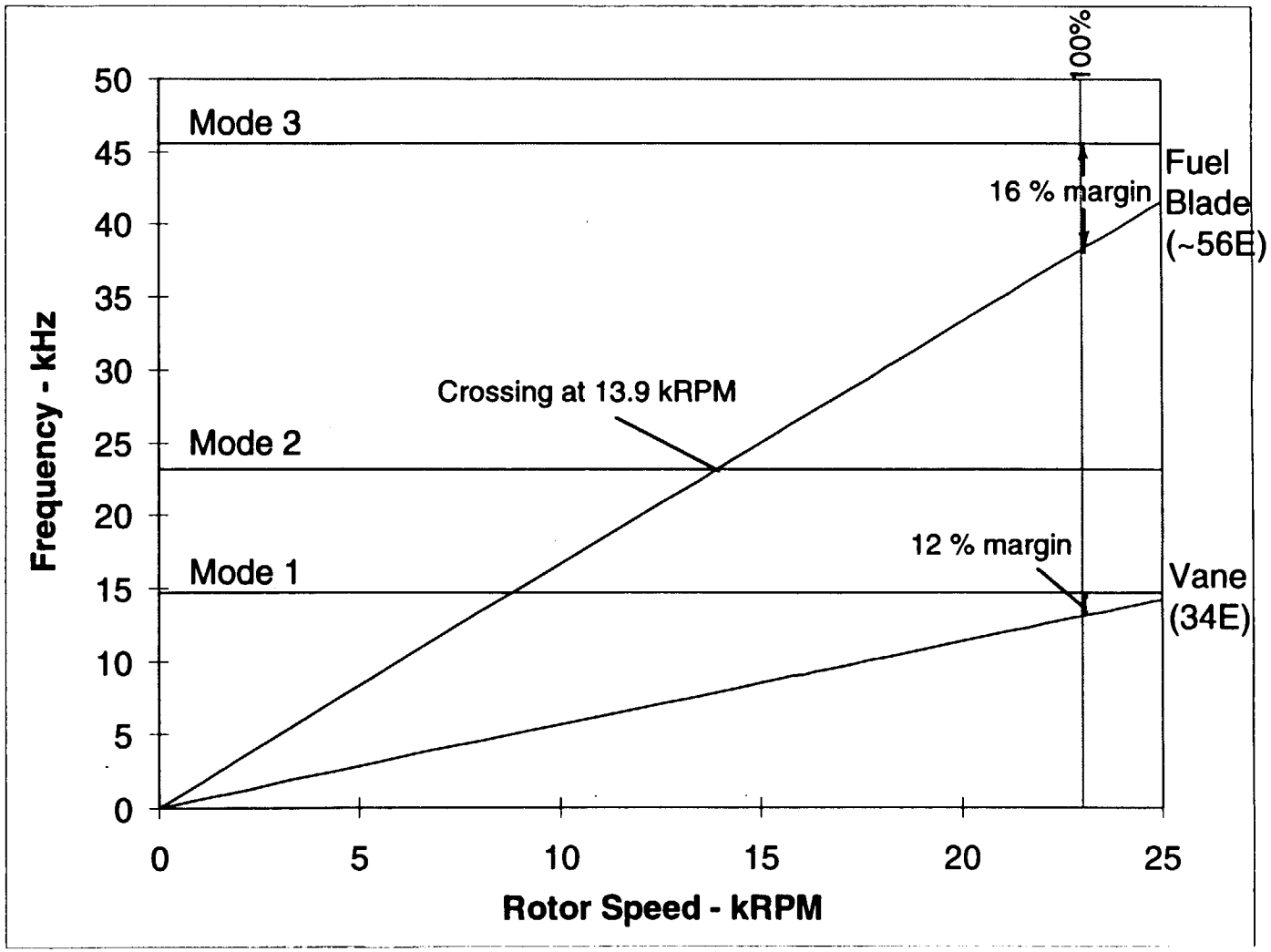
Vane Vibration



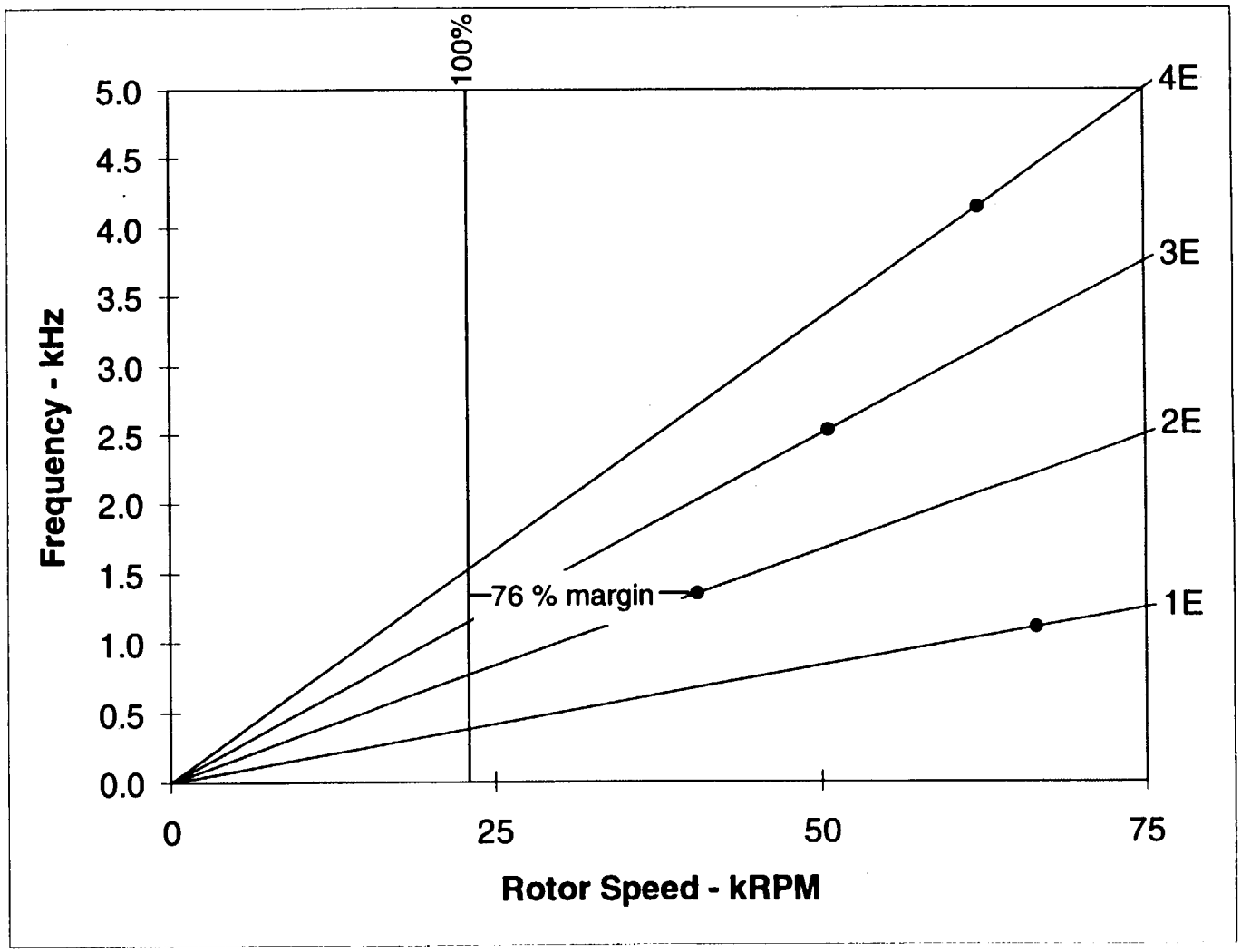
RP Side Blade Vibration



LOX Side Blade Vibration



LOX Side Disk Vibration



Future Plans

- Complete peliminary structural analysis
  - Steady stress analysis of airfoils
  - RP turbine disk and impeller dynamic assessment
- Local 3-D models of significant features
  - Cutwaters, housing supply port, main turbine flange
- Global 3-D analysis of rotors and housings
  - Refined / local breakout models as needed

Analysis	Analyst	Schedule		
Preliminary	In-House	current	thru	7/18/97
Local 3-D	Pro/mechanica	7/7/97	thru	7/11/97
Global 3-D	ADAPCO	7/14/97	thru	8/25/97

Heat Transfer/Internal Flow

Micki Marshall

Presented by Jim Clark

Component Design

Introduction

- Design Objective
- Design Approach
- Analysis Results
- Continuing Efforts
- Summary

Heat Transfer / Internal Flow

Design Objectives Focus On Meeting Turbopump Design Goals

- **INTERNAL FLOW**
  - Provide Steady State Analysis Of All Non-Mainstream Flows
  - Design Internal Flow System To Meet System Performance Requirements
  - Provide Adequate Bearing Flow At Design Point
- **AXIAL THRUST BALANCE**
  - Provide Steady State Evaluation Of Turbopump Axial Thrust Loads
  - Design Internal Flow System To Produce Acceptable Thrust Bearing Loads At Design Point
- **HEAT TRANSFER**
  - Evaluate Windage Losses
  - Provide Boundary Conditions For Rotor Thermal Model
  - Provide Boundary Conditions For Housings Thermal Model

Heat Transfer / Internal Flow

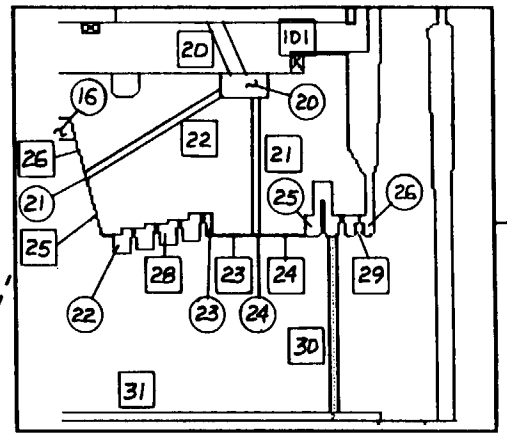
Design Approach

- MECHANICAL DESIGN
- SYSTEMS PERFORMANCE
- PUMP DESIGN
- TURBINE DESIGN
- BEARING DESIGN

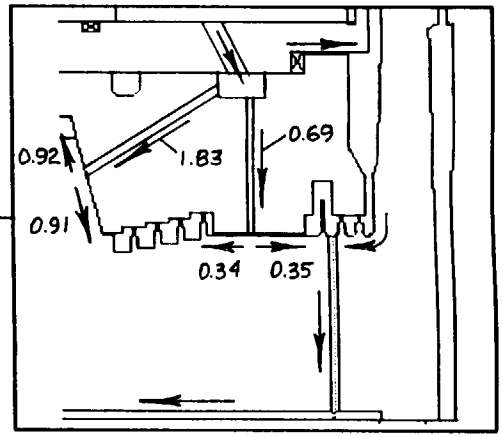
INTERNAL FLOW AND THRUST BALANCE ANALYSIS

HEAT TRANSFER BOUNDARY CONDITIONS

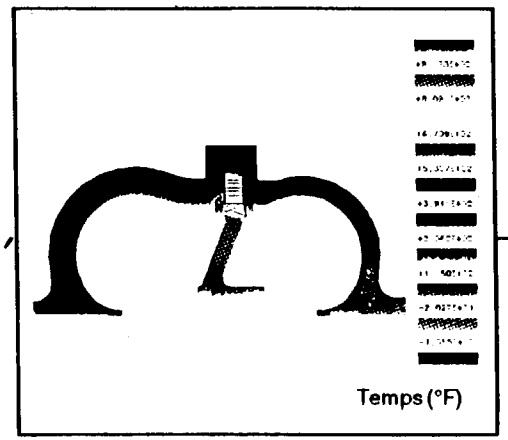
THERMAL / STRUCTURAL MODELS



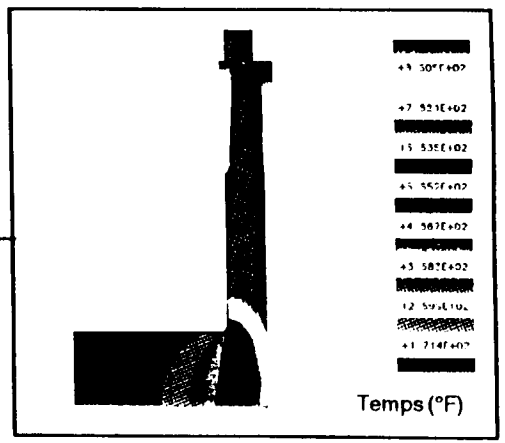
V169 FLOW NETWORK



FLOW AND PRESSURE DISTRIBUTION



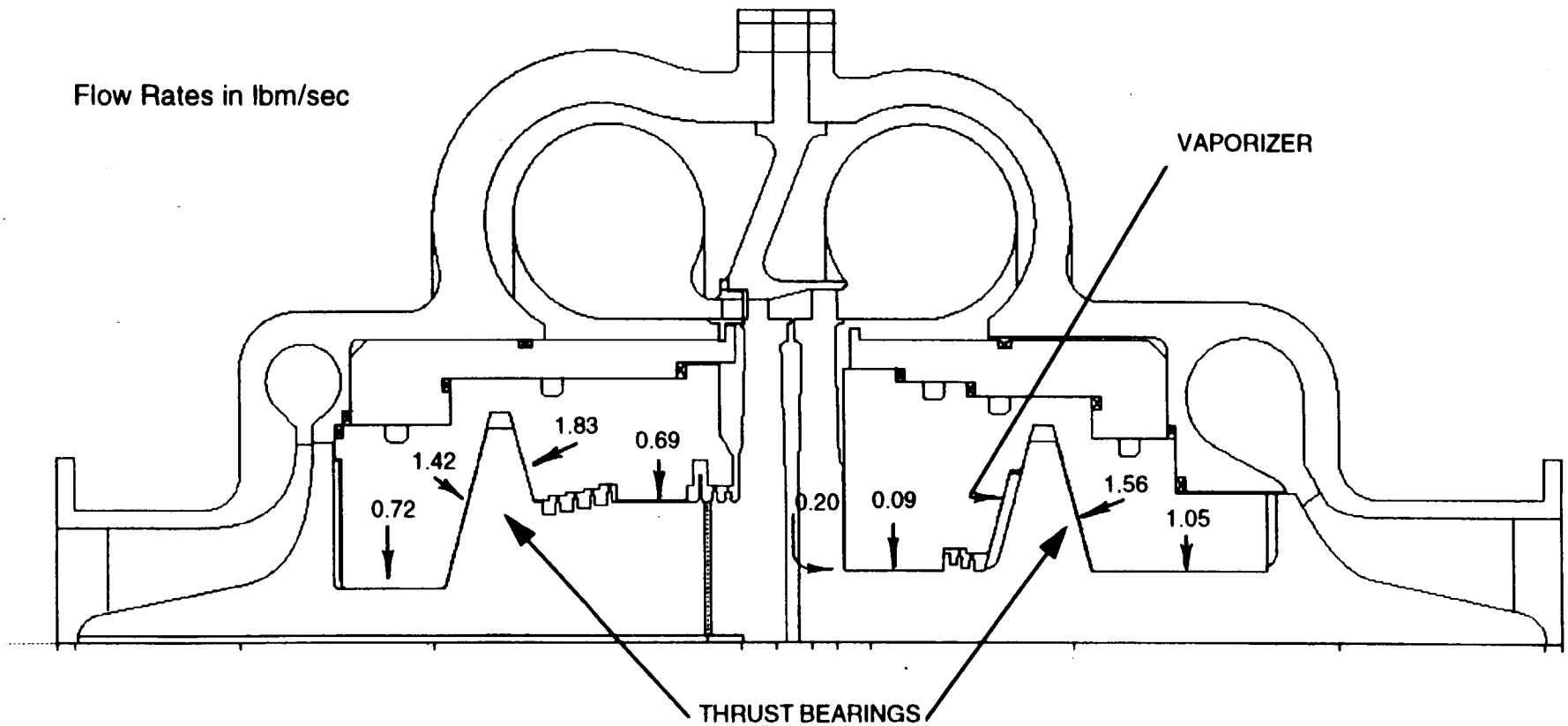
HOUSINGS MODEL



ROTOR MODEL

Internal Flow Requirements At Design Point

- ADEQUATE BEARING FLOW
- ADEQUATE THRUST BEARING AXIAL LOAD



Windage Losses Included In Total Power Requirements

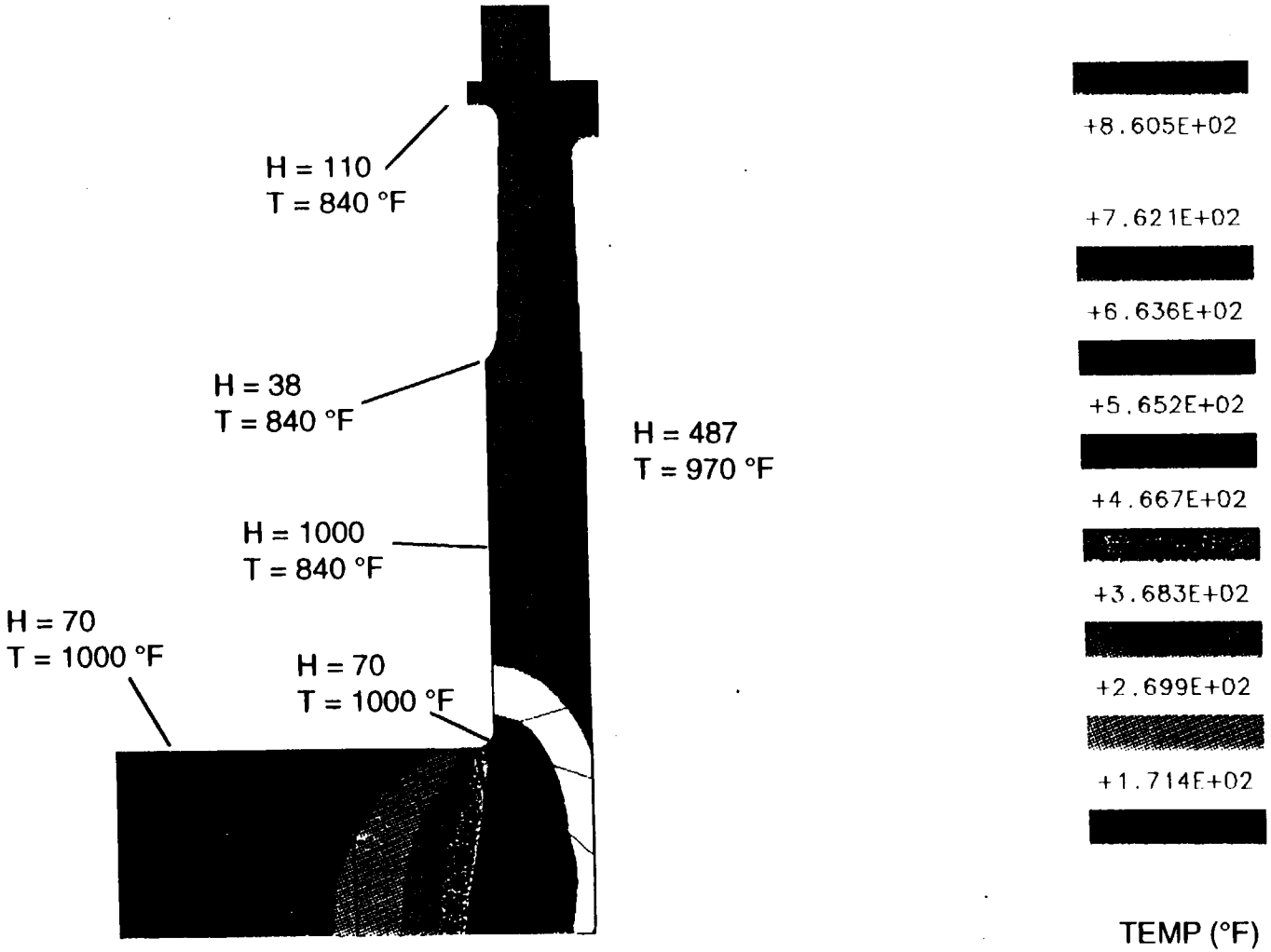
	RP-1 Pump	LOX Pump
I.D. Radius (inches)	4.58	4.58
Speed (RPM)	16600	22000
Windage Losses:		
Turbine Disk	15	21
Thrust Bearing:		
pump side	13.6	18.3
turbine side	17.8	0
Journal Bearings:		
pump side	0.31	6.0
turbine side	29.2	1.0
Labyrinth Seals	19	2
Total Windage Loss (HP):	**94.91**	**48.3**
Other Power Requirements:		
Vaporizer	0	20
Impeller	440	665
Back-Face Vanes	65	35
Total Power Requirement (HP):	**599.91**	**768.3**

Rotor Thermal Boundary Conditions At Design Point

LOX ROTOR

$$H \sim \frac{BTU}{HR - FT^2 - °R}$$

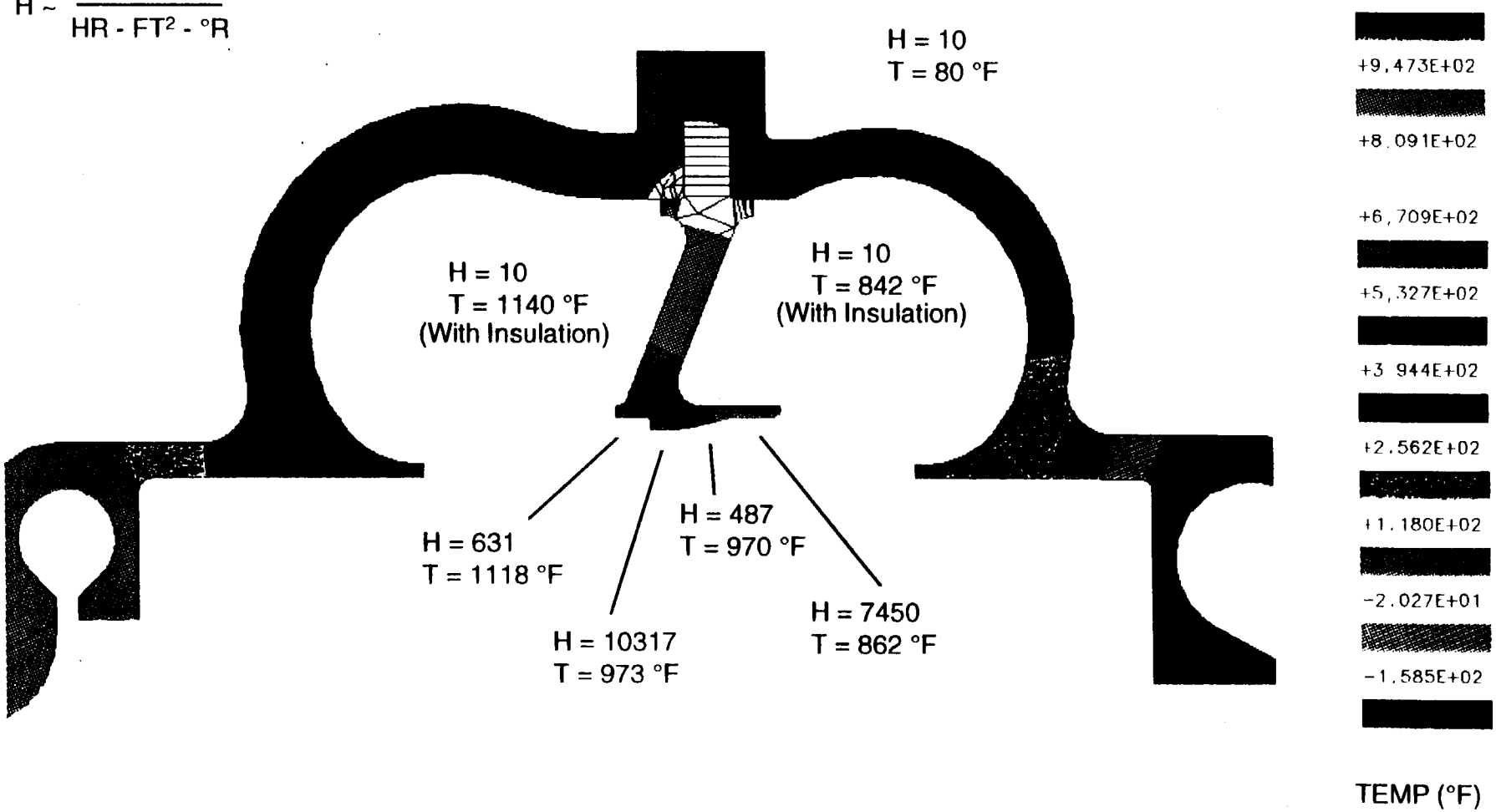
T = °F



Heat Transfer / Internal Flow

Housings Thermal Boundary Conditions At Design Point

$$H \sim \frac{BTU}{HR \cdot FT^2 \cdot {}^\circ R}$$



Continuing Efforts - Scheduled To Be Complete 8/97

- **INTERNAL FLOW**
  - Steady State Model Of Final Turbopump Configuration Evaluated At Design Point
  - Review Internal Flow Bearing Design Model With Bearing Design Group Detailed Solution Model

- **AXIAL THRUST BALANCE**
  - Evaluate Net Axial Load For Both RP-1 And LOX Rotors At Design Point
  - Finalize Thrust Bearing Design To Balance Turbopump

- **HEAT TRANSFER**
  - Update Windage Losses
  - Modify Boundary Conditions Based On Mechanical Design Revisions To Structure
  - Update Thermal Model Boundary Conditions To Represent Final Turbopump Performance

Summary

- Steady State Internal Flow And Thrust Balance Model Is Being Created For Design Point
- Preliminary Windage Losses Have Been Calculated And Are Included In Total Power Requirements
- Preliminary Steady State Thermal Boundary Conditions Have Been Calculated For The Rotor And Housings At Design Point
- Continuing Efforts Include Addressing Thrust Balance Concerns And Updating Analysis To Final Turbopump Configuration

Turbopump Test Support

Tony Crease

Rocket Systems Analysis

Turbopump Test Support

P&W Responsibilities (preliminary effort complete)

- Assist/*Suggest facility instrumentation* and safety monitoring
- *Define TRT instrumentation*, safety monitoring parameters and provide bosses
- Define/Integrate w/NASA P&W's TRT test requirements with facility capabilities (data system and transmission, valve perf., purges, etc.) (forthcoming info request to Richard Cooper/NASA)
- Define/Integrate w/ NASA, STE and interface requirements for TS 116 and TRT operation
- Assist development of facility/component transient and SS simulations
- Develop TRT maps/characteristics and integrate into facility/component simulations
- Develop TRT data reduction models
- *Define test plan*
- Request pre-test simulations and assist in results analysis
- Participate in pre-test readiness reviews
- Assist TRT testing
- Assist/Participate in test data analysis and reviews
- Assist in integrating test results into simulations
- Provide final test series report

Turbopump Test Support

NASA Responsibilities (recommended highest priority items)

- Define/Provide facility instrumentation and safety monitoring
- Assist TRT instrumentation definition and provide sensors
- *Assist/Integrate P&W's TRT test requirements with facility capabilities* (data system and transmission, valve perf., purges, etc.)
- *Assist definition of and provide STE and interface requirements for TS 116 and TRT operation*
- *Develop facility/component transient and SS simulations*
- *Assist TRT maps/characteristics definition and integrate into facility/component simulations*
- Assist TRT data reduction model development
- Assist test plan development
- Conduct pre-test simulations and results analysis
- Conduct pre-test readiness reviews
- Conduct TRT testing
- Conduct test data analysis and reviews
- Integrate test results into simulations
- Assist final test series report

Summary

Jorge Santiago
Project Engineering

Summary

Ready to Proceed to Final Design Phase

- Configuration defined in Interim Design phase
- Suppliers under contract for major components
- Preliminary test plan and requirements defined